NEW PRODUCTION TECHNOLOGIES AND MATERIALS
Abstract: Kinematic state of a working-piece at bulk metal forming of axial-symmetrical pieces has been determined in this paper. Strain rate tensor components are determined by the known theory, as partial strain rate component derivatives. Displacement rate points of meridional section are basic for kinematic state determination. As non-stationary deformation process is concerned, it is necessary to determine initial and final points displacements when a relatively short observed interval is constant. Point displacements are determined by known geometry of groove-like plates before deformation and measured coordinate points out of digitalized picture of meridional section after deformation. Measure means are done by setting the lines with sufficient number of points. At the end, a graphic interpretation of the obtained results is given, their analysis and conclusions are made.

Key words: Bulk Metal Forming, Open Die, Finite Element Method (FEM), Strain Rate, Displacement Rate

1. INTRODUCTION

The importance of knowing the kinematic state of a working-piece in deformation process is pointed out by a hypothesis on similarity and coaxiality of deviators of stress tensor and strain rate tensor growth, being the base of Levy-Mises’s theory of plastic yield [1]. Determining kinematic state is a quantitative determination of kinematic parameters in the form of components of strain rate tensor in all the points of the piece section. To reach the research goal, appropriate pieces were developed. After several trials, more or less successful ones, there resulted the idea of making pieces in segments of groove-plate forms. Plate grooves practically represent finite elements physical discretized, and this method is called Physical Discretization Method (PDM).

By a suitable mechanical and chemical forming after deformation, it is possible to get a deformed image of meridional section. First, a part of the piece till its symmetry axis, i.e. meridional section is removed by cutting. Then the surface is finely polished and chemically immersed into NaOH solution, after which deformed contours of groove plates become visible by a naked eye. The section is scanned and its digital version is obtained, being suitable for further computerization.

2. STRAIN RATES

To define strain rate displacement velocity is defined first as an expression of time displacement. Strain rate, in its general sense, represents the expression of time forming, or the ratio of strain rate of two points displacement to the distance of this points, when the distance tends to be zero. For axis-symmetrical stress state of strain rate tensor components in cylindrical coordinate system are [2]:

\[
\begin{align*}
\dot{e}_r &= \frac{\partial v_r}{\partial r} = 0 \\
\dot{e}_\theta &= \frac{v_z}{r} = 0 \\
\dot{e}_z &= \frac{\partial v_z}{\partial z} + \frac{\partial v_r}{\partial r} \\
\end{align*}
\]

Effective strain rate or intensity strain rate is a quantitative velocity change measure, expressed by [6]:

\[
\dot{\varepsilon} = \sqrt{\frac{1}{2} [I_1(T) - \frac{3}{2}] + [\dot{\varepsilon}_r - \dot{\varepsilon}_\theta]^2 + [\dot{\varepsilon}_r - \dot{\varepsilon}_z]^2 + \frac{3}{2} \dot{\varepsilon}_z^2}
\]

With unsteady processes such as bulk forming at open dies, kinematics and stress fields in an immovable space point where the forming originates are changed in the course of time. In such processes, an analysis of a forming growth can not illustrate kinematics and stress fields during the whole process, only the observed growth can be clear. Thus, it is necessary to determine an interval (step), at the end of which the stress state in the working piece volume could be determined. Kinematics field is found by virtue of the known parameters of meridional cross-section point displacement and interval duration. Displacement velocity components are expressed by:

\[
\begin{align*}
\dot{v}_r &= \frac{v_0 - r}{\Delta t} \\
\dot{v}_z &= \frac{z_0 - z}{\Delta t}
\end{align*}
\]
velocities to the cross-section meridial points (1), where partial derivatives are determined for sufficiently small values of $\Delta r$, $\Delta z$ and $\Delta t$, using these expressions [3]:

$$
\begin{align*}
\frac{\partial v_r}{\partial r} &= \frac{\Delta v_r}{\Delta r} \\
\frac{\partial v_z}{\partial z} &= \frac{\Delta v_z}{\Delta z} \\
\frac{\partial v_r + \partial v_z}{\partial r + \partial z} &= \frac{\Delta v_r + \Delta v_z}{\Delta r + \Delta z}
\end{align*}
$$

(4)

3. EXPERIMENTAL RESEARCHES

There have been adopted two levels of height from the upper side and one level of height from the low side of the die plane [4,5,6]. Research works are carried out on a real material in laboratory conditions and are adjusted in the way to be as much similar to real (production) conditions being present in direct industrial environment. As the investigated material there has been used an aluminum alloy AlMgSi0.5, which is very often used in processes of bulk metal forming, above all in extrusion processes and bulk metal forming in open dies. Experiment is carried out at temperatures of hot forming of the mentioned alloy, namely at $t=440 \ [^\circ C]$. Deformation is realized by constant deformation velocity: $v=2 \ [mm/s]$. Process is carried out by graphite grease lubrication, being applied in production conditions.

To determine kinematics state, compression of two working-pieces of $h_a=3 \ [mm]$ wreath height and final $h_b=h_c=1 \ast mm\ast$ is done. An optimal forming interval at the end of forming process for tool stroke growth $\Delta z=2 \ [mm]$ is chosen. These values are ensured by non-deformable steel rings. Otherwise, it is necessary for this interval to be little enough to maintain a real state of displacement velocities, but not too much little as to avoid the influence of anisotropy forming. The parameters at the end of the interval observed are marked with index b, whereas initial one is marked with a.

The process of preparing cross-section working-piece surface, and the image digitalization of deformed mesh in the meridial cross-section are described in the introductory part and papers [4,5]. The treated surface of the meridional cross-section with initial and final radial and axial lines are given in Fig.1.-Fig.4.

4. RESULT PROCESSING

A program for complete kinematics analysis is made in MATLAB, input data are the values of coordinate points of deformed both radial and axial mesh. This program automatically determines node points of the deformed mesh, namely cross-section points of the deformed radial and axial lines, i.e. points whose displacement is determined.

The displacement growth in the node points of deformed mesh is determined as a displacement difference at the beginning and end of the observed interval:

$$
\begin{align*}
\Delta u_r &= u_{rb} - u_{ra} = r_{pb} - r_{pa} = \Delta r \\
\Delta u_z &= u_{zb} - u_{za} = z_{pb} - z_{pa} = \Delta z
\end{align*}
$$

(5)

By expression (3) it is possible to determine displacement velocities in the node points of the deformed mesh. Displacement velocity values in other points are
approximated by the cube interpolation, thus a continual displacement velocity function in the meridional plane of the working-piece in function of radius and height coordinates are practically obtained. For the known displacement velocities of cross-section points, it is possible to determine partial expressions of velocity displacements per radius and height (4), to obtain forming velocities (1). The tangential strain rate component is not determined by partial derivate of displacement, the division result of radial displacement velocity and radius (1). Effective strain rate is obtained by expression (2).

Using cube interpolation radial, axial, tangential and shear components of strain rates and effective strain rate whose change in the meridional cross-section of the working-piece are given in the form of 3D diagrams in the function of radius and height of the working-piece in Fig.5.-Fig.9.

Fig.5: Radial strain rate

Fig.6: Aksial strain rate

Fig.7: Tangential strain rate

Fig.8: Shear strain rate

Fig.9: Effective strain rate
5. CONCLUSION

Using the Physical Discretization Method, it is possible to successfully obtain all the components of strain rates tensor and effective determination of meridial cross-section of axis-symmetrical working-piece formed in open dies.

With all components of strain rates, a zone is discreted clearly and it corresponds to the inner part of the die and wreath zone.

Radial and effective strain rates have an equal, very low absolute value in die zone whereas their extreme value is of the same size order and is in the end of the wreath. Tangential and axial strain rates have a less extreme value of the given components and are at the end of the wreath. With shear strain rate extreme values are obtained for the middle wreath zone.

An expressive difference in the values of strain rates components in the die and wreath zones is due to the observing of final forming process when the material has filled a complete die engraving, which is not deformed any longer, if not distinguished in the wreath.

REFERENCES


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TOPOGRAPHY OF CHARACTERISTIC SURFACES OF MODEL HOB MILLING TOOLS FOR MACHINING OF GEAR SERRATION

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Sandra SOVILJ-NIKIĆ
Bogdan SOVILJ
Vladimir BLANUŠA

Abstract: The problem of generating is analyzed in science and practice in various ways by identifying it once as an element of the machine, and the second time as a part of production, that is, a final product. The nature of the materials of the machine elements, the loads in the contact zone, the relative velocities, the topography of the contact surfaces, and the temperature in the contact zone influence on the tribological characteristics of the elements, and hence on the characteristics of the tribomechanical systems. There is a significant number of tribomechanical systems in the energy sector. Serration of gear machining is the most important operation in the production of gears. The gear is an element of a large number of tribomechanical systems.
In this paper, the topography of the characteristic surfaces of the model hob milling tools is analyzed before and after machining of serration of the gears.

Key words: tribomechanical systems, tribological characteristics, topography, roughness, model hob milling tools

1. INTRODUCTION

The contemporary characteristics of the society and the desire for continuous improvement of the quality of life require continuous improvement of the quality of production. The product is the most characteristic parameter of the technical development of a country. Analyzing the century-long coupling and mutual relations between man and the industrial product, at each stage of their life cycle, it can be concluded that the industrial product is material creation which is consciously developed and realized in industrial conditions of production. By directing the process of development of production to the development of various systems, it is especially important to find ways to improve the quality of products.
In tribological processes, the very small mass of the tool material and the large mass of the material of the workpiece are involved in the machining of serration of the gear. The consequences of the development of tribological processes in the zones of contact are the friction and wear of the cutting elements of hob milling tools. In the Figure 1 [1] examples of tribomechanical systems are given, and with the number one the critical element of each tribomechanical system is marked, that is, the element which is worn at the most in the process of achieving contact. The contact surface of the tribo elements after final machining is never absolutely smooth. Numerous unevennesses resulting from previous and final operations can have different geometric parameters and cause greater or minor irregularities in triboelements.

It is indisputable that the change in system structure, energy losses and material losses are very complex processes and depend on a large number of factors. Numerous studies have shown that the quality of the contact surface significantly affects the wear resistance. Reducing the roughness increases the wear resistance.
In this paper a part of the results of the research of tribological processes in the machining of serration of gears with uncoated and coated model hob milling tools is presented.
2. MACHINING OF GEAR SERRATION AND THE TOPOGRAPHY OF THE SURFACE

The occurrence of the power transmitter and movement dates back to ancient times. In China, Mesopotamia and Egypt, parts and assemblies of irrigation devices with toothed portable elements have been found, which according to the kinematic principle are still used today. In addition to agriculture, such devices have been developed for war and civil engineering purposes (Fig 2.) [2].

Machining of gear serration can be done by various methods and procedures. Thanks to the high productivity of the process, the hob milling has the widest application in the machining of serration of spur wheels. Integral hob milling tools are tools used in machining of gear serration by means of relative rolling method (Fig.3).

In defining the tool life of hob milling tool, it is necessary to perform long-term experimental tests which require considerable resources and efforts, and it is difficult to implement them in the real production process. In order to simplify this experimental research, there is a need for quick and cheaper testing procedures that will provide reliable information on the examined machining process. For the process of hob milling of gear serration, there is a possibility that instead of the integral hob milling tool, model single-tooth hob milling tool can be used in research (Figure 4 [3]).

For the process of machining of gear serration, a method has been developed, device for accepting a cutting element (teeth) for model testing in laboratory conditions instead of an integral hob milling tool has been designed and manufactured (Figure 5 [1]).

Significantly the largest percentage of all breakdowns and slowdown in production is initiated through the surface of the elements of the tribomechanical system through mechanisms such as fatigue fracture, fracture due to stress corrosion, contact wear due to friction, erosion, etc. It is clear that it is important to know the properties of surfaces and zones near the surface of the elements. The answer to these problems can be given by tribology.

The interdisciplinary character of tribology and a wide array of possible aspects of the study have conditioned that in the process of tribologically correct design and construction, it has to be equipped with a large number of precisely defined tribological information. Due to the complexity of the tribological processes and the large number of influencing factors, it is necessary to possess information from various disciplines of this broad scientific field. In that sense, the development of triboinformatics encourages as the necessity of systematizing an increasing number of tribological information and the need for a more efficient exchange between scientific institutions and other potential users of tribological knowledge [4].

Technologists study technical drawings and they try to produce elements by defined dimensions within the limits of tolerance. Characteristic parameters formed during the technological process define macrogeometry and microgeometry of contact surfaces. For the correct analysis of tribological processes, but also tribologically correct construction, the roughness of the contact surfaces is especially significant. Macrogeometry can be repaired during the technological process itself by working properly on the system; machine-fittings-tool-work-piece. Roughness has a stochastic element and it is a consequence of random processes, it cannot be avoided,
but it can be managed to a large extent in the technological process of machining [5].

For analysis of the roughness of the machined surface of the elements, there are more than 30 parameters that are less and those that are more represented. The basic parameters of roughness are defined according to national and international standards. The first three parameters $R_a$, $R_{max}$ and $R_z$ represent a small group of the three most common parameters, while $R_q$, $R_p$ and $R_t$ are the parameters that are also used, but considerably less than the three previously mentioned roughness parameters. Roughness significantly affects the actual surface of the contact, that is, the surface on which the contact of the micronuclei that forms the topography is realized. The actual surface of the contact depends on the micro and macro geometric characteristics of the surfaces in contact, from the corrugation, form errors, physical mechanical properties of the surface layer, from the load, etc. With the load parameter, the actual surface of the contact increases, and the growth is conditioned by the emergence of new contact points.

3. EXPERIMENTAL RESEARCH

According to research plan in the project entitled by Modeling and optimization of hob milling the analysis of the topography of tools for machining of serration and machined teeth of spur wheels was planned. Within this paper, only parts of the results related to the topography for machining of serration are given. Based on the experiment plan, the research was carried out on uncoated and coated model hob milling tools with modules $m = 3$ and $m = 5$.

At the beginning of experimental topography research 392 model hob milling tools were identified based on certain characteristics. The roughness parameters were first measured on unworn tools, and then on the same tools after reaching the wear criterion. Roughness parameters are measured on model tools, which were already worn before this research. From the group of 392 tools 104 model hob milling tools have been allocated with module $m = 3$ (Table 1) and $m = 5$ (Table 2). In each subtype, there are 13 model hob milling tools, and in Figure 6 a subtype of uncoated worn-out model hob milling tools with the module $m = 5$ is given.

<table>
<thead>
<tr>
<th>MODUL m=3</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tr>
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<td>COATED</td>
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<tr>
<td>UNWORN</td>
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<td>WORN-OUT</td>
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In these experiments, a model hob milling tools made of HS 6-5-25 was used and a number of tools were coated with TiN. To measure roughness parameters, a MahrSurf PS1 device was connected to a computer, so the measurement results were obtained in electronic form (Figure 7).

Fig. 6: Uncoated worn-out model hob milling tools with the module $m = 5$

Fig. 7: MahrSurf device connected to computer

Surfaces of model hob milling tools and measuring directions are shown in Figure 8.

Fig. 8: Tool surfaces and directions of measuring

In this paper the roughness parameters for two characteristic surfaces: the input lateral back surface and the outlet lateral back surface were analyzed. The results of the research are shown in diagrams and a part of the results is given in this paper in next figure.

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Fig. 9: Diagram of roughness parameters the input lateral back surface of uncoated tool 7 unworn module $m=3$

Fig. 10: Diagram of roughness parameters the input lateral back surface of uncoated tool 7 worn-out module $m=3$

Fig. 11: Diagram of roughness parameters the outlet lateral back surface of uncoated tool 7 unworn module $m=3$

Fig. 12: Diagram of roughness parameters the outlet lateral back surface of uncoated tool 7 worn-out module $m=3$

Fig. 13: Diagram of roughness parameters the input lateral back surface of coated tool 13 unworn module $m=3$

Fig. 14: Diagram of roughness parameters the input lateral back surface of coated tool 13 worn-out module $m=3$

Fig. 15: Diagram of roughness parameters the outlet lateral back surface of coated tool 13 unworn module $m=3$

Fig. 16: Diagram of roughness parameters the outlet lateral back surface of coated tool 13 worn-out module $m=3$
On the basis of the first and the second part of the experimental research it can be concluded that all the maximum values of roughness parameters at characteristic surfaces of the model hob milling tools are represented in longitudinal direction of measurement, while all minimum value of roughness parameters are represented in the cross-direction of measurement. Explanation arises from the fact that the measuring needle for measurements in the directions of 1, 2 and 3, respectively and 10, 11 and 12 was moving in the direction of the normal to the grooves resulting from the final machining of the characteristic surface of model hob milling tools. The movement of the measuring needle was parallel with the aforementioned grooves for the directions 4, 5 and 6, respectively and 13, 14 and 15.

4. CONCLUSION

Today, great efforts are being made to penetrate into the essence of the nature of the contact surface, and this is facilitated by new technologies and devices. The consequences of tribological processes are the changes that occur on the surface layer.

Research of the topography of the characteristic surfaces of the model hob milling tools have been performed on one of the most modern devices MahrSurf PS1 for testing the roughness parameters.

Based on the results of measuring the six most commonly used roughness parameters (R_p, R_q, R_z, R_t, R_max, R_p) or the entire experimental research in this paper it can be concluded that the topography of unworn coated model hob milling tools is better than the topography of worn coated model hob milling tools noting that the results of each of the parameters vary differently.
To complete the picture of the topography of the contact surfaces of the model hob milling tools, it is necessary in future investigations a precise definition of surface roughness through defining the distribution of the ordinates and the tops, the distribution of the inclination, the radius of the tops and recess of unevenness, carrying capacity curves of profile and others.

A two-dimensional analysis can often be used as a process monitoring that is limited in scope, but provides a simple indication, regardless of whether the topography changes. For a more complete understanding, a three-dimensional analysis of the topography of the characteristic surfaces of the model hob milling tools is necessary.

REFERENCES


ACKNOWLEDGEMENT

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia, within the projects TR 35015 and III 43008, and it is also the result of the cooperation within CEEPUS project CIII-RO-0058-07-1415 supported by Secretary of Science and Technological Development of the Autonomous Province of Vojvodina.
Abstract: Impact toughness of samples with three different relative positions of V-notch and multipass V-butt welded joint at high-strength low-alloy steel S690 are considered in this paper. The aim of this paper is to analyze the influence of material degradation due to welding to impact toughness of samples made of considered steel. Impact toughness was analyzed by experimental approach objected to including as many influential factors as it is possible. The main objective of impact toughness testing is to evaluate the influence of welding to overall load capacity and stability of welded mechanical construction made of high-strength low-alloy steels. Fully understanding of transformation processes provoked by welding of high-strength low-alloy steels and impact toughness testing as resulting property of those processes are crucial to perform integrity, safety and reliability analysis. This paper pointed out the necessity of analyzing the welded constructions on different dimension levels. Further investigations in this area have to be a continued through more quantitative analysis of welded joints which will, established precise analytical model of zones of welded joints, and furthermore, in involvement with adequate software, a complete evaluation of the experimentally obtained results. As the chemical composition and microstructural state of high-strength low-alloy steel originate from special production process their nature must be fully understood during selection and definition of welding even during the design process of mechanical construction. As experimentally obtained results of impact toughness that correlate to microstructure and microhardness distribution implicated that development of those steels must be followed with improving weld processes and development, adjusting and modification of the design.

Keywords: impact toughness, high-strength, low-alloy steel, welded joint

1. INTRODUCTION

Welding procedures are continually developing due to the intensive applications of the obtained results in fundamental and applied scientific disciplines to meet present demands in mechanical constructions. An ordinary welding process in present industry is based on localized heating and cooling, which creates inhomogeneous temperature fields at zones of welded joints. The consequences of applied welding technology processes are numerous and heterogeneous by its nature, such as material inhomogeneity, alteration of its chemical compositions, different microstructural transformations, etc.

On the other side, welded constructions are complex systems of heterogeneous elements with mechanical properties that are highly dependent on its welded joints. The present demands that are put on welded constructions caused significant increases in applications of high-strength low-alloy steels. Applications of those steels instead of conventional, general purpose structural steels provide many advantages. But, high-strength low-alloy steels due to specific chemical composition and microstructure are highly sensitive to influences of welding. High-strength low-alloy steels, so as considered S690QL have beneficial mechanical properties, but full benefit of applications of those steels can be obtained only by its adequate welding. Optimal welding technology is the main condition for preserving characteristics and microstructural state of material after welding, which are the basis of beneficial mechanical properties, and condition of joining.

High-strength low-alloy steels due to conditional weldability often require additional procedures to obtain an intended characteristic of welded joints. The processes of material degradation due to welding at those steels can be related to increasing of hardness, a decrease of toughness, an increase of transition temperature, the presence of different material discontinuities and so on. Initialization of cracks and formation of brittle structures due to welding are related to the high cooling speed of weld metal and its surrounding zone in diapason of temperature in which austenite is highly unstable. Considerations of mechanical properties of high-strength low-alloy steels must be based on its specific characteristics, as limited plasticity reserve due to high strength of steels, possible formation of local zones with
lower plasticity in relation to rest of the construction and possibility of material discontinuities and initialization of cracks (primarily, hydrogen) during welding at weld metal and heat affected zone.

As material discontinues (inclusions, defects, cracks, sharp cuts, etc.) and imperfections are usually present at zones of welded joints, those zones are most dangerous from the aspect of loss of structural integrity. From the aspect of structural integrity, safety and reliability analysis, the measure the amount of energy required to cause fracture is crucial. The welded construction ability to absorb energy without compromising of integrity comes in focus of many different types of research. Panmnani with associates in ref. [1] evaluate the mechanical properties across the SMAW, SAW, FCAW and A-GTAW weld joints of micro-alloyed HSLA steel. The correlation between microstructure, microhardness and tensile properties obtained using automated ball indent has been undertaken.

Multi-pass submerged arc welding at high-strength low-alloy steels using multi micro-alloy electrodes with three different heat input processes was analyzed by Lan and associates in ref. [2] to investigate the microstructure evolution and corresponding mechanical properties of weldments. The emphasis was placed on studying the influence of microstructure aspects on impact toughness of weld metal and heat affected zone (HAZ) with different heat inputs to reveal fracture micro-mechanism and to optimize the welding system.

In ref. [3] Costa et al. present a study of the thermal behavior and its effect on phase transformations in the HAZ, depending on cooling rates to obtain continuous cooling transformation (CCT) curves for an high-strength low-alloy steel. The results presented in ref. [3] showed that, with the used cooling conditions, the steel did not provide formation of brittle structures.

The results of research presented in ref. [4] by Sadeghian et al. implicated that the results of impact tests revealed that the specimen with low heat input exhibited brittle fracture and that with high heat input had a higher strength than the base metals.

The presented results of researches in literature overview point out those properties of welded joints are a key element of structural integrity of the welded constructions. Welded structure is a complex system that can be considered from many aspects. Safety and reliability requirements for welded construction point out that welded joint zones have to be considered adequately.

The essence of determining impact toughness so as a type of fracture in zones of welded joints is the qualitative analysis of structural integrity due to the integrity of its welded joints. Capacity calculations analyze and prove mechanical resistance and stability of welded structures for the expected loads and exploitative conditions. The multiple stress concentrations at zones of welded joint and mechanical properties of welded joints are a major dominant factor to the precision of analytical models used for calculations. Data obtained from exploitation of welded constructions showed that mechanical properties of welded joints due to are nature were not adequately take in consideration in present analytical models and capacity calculations. Only results obtained by experimental testing can be taken as relevant to a high degree.

2. EXPERIMENTAL TESTING

The testing was done on models made of high-strength low-alloy steel S690QL, as the parent metal, commercially nominated as Weldox 700. The used steel is produced by SSAB Oxelösund AB, 613 80 Oxelösund, Sweden and fullfills requirement classified for EN 10025-6:2004 [5]. The chemical composition of Weldox 700 steel, according to the producer is presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Chemical composition of Weldox 700 steel</th>
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<td><strong>Chemical element</strong></td>
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<td>C</td>
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<td>Mn</td>
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<td>S</td>
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<td>B</td>
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<tr>
<td>Nb</td>
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<td>Cr</td>
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Mechanical properties of considered high-strength low-alloy steel S690QL related to specific plate thickness according to producer data are min. yield strength - R_{p0,2}=700 MPa; tensile strength - R_{m}=780 – 930 MPa; elongation – A=14%. The used steel is produced in two grades, nominated with suffix E and F in relation to impact toughness. Values of impact energy for Weldox 700 steel determined at V-notch Sharp specimens (EN ISO 148-1:2010 and EN 10045-1:1990) are presented at Tab. 2 [6 and 7].

<table>
<thead>
<tr>
<th>Table 2. Impact energy of Weldox 700 steel</th>
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<tr>
<td><strong>Weldox 700E</strong></td>
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<td><strong>Min. impact energy</strong></td>
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<tr>
<td>69 J</td>
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<tr>
<td>27 J</td>
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Butt V-joint is done by welding at plates with a thickness of 15 mm. Microphotography of cross sections of considered welding joints after metallographic preparation and chemical etching by 4% nitric acid in alcohol is presented in Fig. 1.

Fig. 1. Microphotography of cross-sections of considered welded joint
The root pass is done by MMA welding process and welding consumables with a lower strength (pass - 1), while other passes are done by MAG welding process and welding consumables with higher strength (passes - 2, 3 and 4). Welding parameters for each pass and mechanical characteristics of related welding consumables are presented in Table 3.

Table 3. Welding parameters and mechanical characteristics of related welding consumables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Root pass MMA</th>
<th>Root pass MIG</th>
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<tr>
<td>Current, I, A</td>
<td>≈ 120 A</td>
<td>≈ 110 A</td>
</tr>
<tr>
<td>Voltage, U, V</td>
<td>≈ 24 V</td>
<td>≈ 24 V</td>
</tr>
<tr>
<td>Welding speed, v, cm/s</td>
<td>≈ 0.2 cm/s</td>
<td>≈ 0.35 cm/s</td>
</tr>
<tr>
<td>Heat input, q, kJ/cm</td>
<td>≈ 12 kJ/cm</td>
<td>≈ 13 kJ/cm</td>
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<tr>
<td>Penetration, δ, mm</td>
<td>≈ 1.8 mm</td>
<td>≈ 1.8 mm</td>
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<td>Protective atmosphere</td>
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<td>100% Ar (M11)</td>
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<td>Welding consumables</td>
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<td>MIG 18/8/6 Si; Ø 1.2 mm</td>
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<tr>
<td>Mechanical properties</td>
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<td>560 - 660</td>
</tr>
<tr>
<td>Rp0.2, MPa</td>
<td>&gt; 350</td>
<td>&gt; 380</td>
</tr>
<tr>
<td>As, %</td>
<td>&gt; 40</td>
<td>&gt; 55</td>
</tr>
<tr>
<td>KV, J</td>
<td>&gt; 80</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>(+ 20°C)</td>
<td>(+ 20°C)</td>
<td></td>
</tr>
</tbody>
</table>

Charpy V-notched samples are prepared according to related standards and norms. The preparation of samples is done with minimal additional heat input. The Charpy method of impact toughness test is a standardized high strain-rate test for determination of the energy absorbed by a sample to fracture. The standard dimensions of the sample for Charpy impact toughness test are presented in Fig. 2.

Fig. 2. Standard sample for Charpy impact testing

As the zone of welded joint is indicated as critical from the aspect of material degradation V-notch is done at its specific zones; weld metal, fusion zone, and heat affected zone. The method of the preparation of samples from the aspect of the relative positioning of V-notch and welded joint is presented in Fig. 3. Preparing of samples is done with special care in order to avoid additional heat input, corrosion and other types of material degradation. Visualization of welded joins is done by metallurgical preparation in order to obtain specific relative position between welded joint and V-notch. Testing procedure was design and done in order to obtained relevant tasting data related to current industrial practice and usual exploitative conditions. Impact toughness is a very important mechanical characteristic of the material that can be defined as a measure of the energy need to be absorbed to cause fracture of the sample or the compromise the integrity of the structure of materials. When this energy is less material having a higher brittleness, and when this energy is greater material having a higher toughness.

Fig. 3. Positions of V-notch for preparation of samples for impact toughness testing

The appearance of prepared samples after preparation for metallurgical preparation and chemical etching by 4% nitric acid in alcohol before testing are presented in Fig. 4. The metallurgical preparation and chemical etching were done in order to visualize specific zones of welded joint.

Fig. 4. Charpy V-notched samples

Testing was done using a pre-defined standardized procedure on a series of samples for each position of V-notch at a temperature of 20°C. Testing machine is based on the computerized Charpy pendulum, presented at Fig. 5. The used computerized Charpy pendulum is a device for measuring the energy absorbed by the samples to a fracture, which is a measure of toughness. The test procedure, the shape, and dimensions of the samples are defined by the standard EN ISO 148-1: 2010 and EN 10045-1: 1990 - Metallic materials - Test impact strength Charpy impact, i.e. SRPS EN ISO 148-1: 2012. Speed pendulum during impact strength test is from 5 to 5.5 m / s, while the energy losses are less than 1%.
The force and energy during testing of impact toughness were registered. The obtained results show very small relative exceptions and can be taken as relevant for further analysis.

3. TESTING RESULTS

The experimentally obtained values of fracture energy and force - time depending during the fracture of the tested samples show very small mutual deviations and consistent behavior so the results can be taken as relevant for further consideration. Experimental results indicate a mixed character of fracture of the tested samples. Force-time dependence to fracture during impact toughness testing of samples with V-notch at weld metal from the face of welded joint is presented in Fig. 6.

The changing of the absorbed energy to fracture for the sample with V-notch at weld metal from the face of welded joint at testing temperature is shown diagrammatically in Fig. 7.

The appearance of sample with V-notch in welded joint after testing is presented in Fig. 8. The appearance of the surface created by fracture indicates its mixed character means both brittle and ductile fracture. The appearance of the fracture surfaces is in accordance with certain mechanical characteristics during testing impact toughness and character of force-time and energy-time relations. The test procedure is then done at specimens notched in the fusion zone, as at the test samples with the notch in the heat affected zone towards face of the welded joint.

The changing of the absorbed energy to fracture for the sample with V-notch at fusion zone from the face of welded joint is shown diagrammatically in Fig. 10.

Force-time dependence to fracture during impact toughness testing of samples with V-notch at fusion zone from the face of welded joint at testing temperature is shown in Fig. 9.

The appearance of sample with V-notch in welded joint after testing is presented in Fig. 8. Force-time dependence to fracture during impact toughness testing of samples with V-notch at fusion zone from the face of welded joint is presented in Fig. 9.

The changing of the absorbed energy to fracture for the sample with V-notch at fusion zone from the face of welded joint at testing temperature is shown diagrammatically in Fig. 10.

Force-time dependence to fracture during impact toughness testing of samples with V-notch at HAZ from the face of welded joint is presented in Fig. 11.
The changing of the absorbed energy to fracture for the sample with V-notch at HAZ from the face of welded joint at testing temperature is shown diagrammatically in Fig. 12.

Experimentally determined values of fracture energy have small mutual deviation, the relations force - time show the same character, so testing results can be taken as relevant for further analysis. The histogram presented in Fig. 13 show experimentally obtained fracture energy for samples with different positions of V-notch towards to weld face.

4. EVALUATION OF THE OBTAINED RESULTS

Experimentally obtained the value of energy that is absorbed to fracture for different positions of V-notch toward to the face of welded joint it can be concluded that the maximal energy is obtained for samples with the V-notch in the heat affected zone, while slightly less for samples with the V-notch at fusion zone. The lowest values of absorbed energy were obtained for samples with a notch at the axis of weld metal. The experimentally obtained values of energy are lower than at control samples made of parent material without welded joint. The appearance of the fracture surface for samples notched in the fusion zone toward the face of the welded joints after impact toughness testing at room temperature is presented in Fig. 14.

The appearance of the fracture surface shows a mixed character of fracture with distinct zones of brittle and ductile fracture. The appearance of the fracture surface for samples notched at the heat affected zone toward the face of the welded joints after impact toughness testing at room temperature is shown in Fig. 15.

On fracture surface differ brittle and ductile fracture zone, indicating a mixed fracture character of tested sample, which is in agreement with the experimental values of impact strength and theoretical considerations related to this area.

5. CONCLUSION

Due to welding microstructural state at heat affected zone will be transformed in relation to the chemical composition of parent and filler metal, thermal cycles due to welding etc. High heat input affected the growth of metal grain that means degradation of strength and toughness, while low heat input during welding caused low penetration of fusion zone. As chemical compositions and microstructural state are complex altogether with high sensitivity to heat input, producers of those steels provide recommendations for filler metal and preheating temperatures, limitations for heat input and interpass temperatures [8, 9, 10].

Present norms, standards, and recommendations for the design of welding joints at high-strength low-alloy steels are based on heterogeneous backgrounds. Also, limitations are established for different reasons in order to
provide welded joint with adequate mechanical properties. On the other side, methods for improving the impact toughness and load capacity of welded joints to forming of defect and inclusions are based, primarily, on relaxing residual stress state, reducing hydrogen content and obtaining preferred thermal cycles during welding and cooling. Due to the complexity of factors and their interactions, present standards and recommendations are still not fully developed and precise, especially related to effects of specific welding parameters to chemical compositions and microstructural state at specific zones of welding joints and by that to impact toughness as complex general characteristic caused by a large number of factors. From the practical aspect and obtaining relevant data for design optimization, mechanical characteristics, and properties, stability and integrity analyses of welded joints at this steel grade is crucial. Due to complex nature of welded joints, only experimental testing can provide relevant data and information about the mechanical behavior of welded joints at high strength low alloyed steels during exploitation.

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REFERENCES


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Abstract: Resistance spot welding (RSW) is considered as the dominant process for joining similar and dissimilar sheet metals in automotive industry. In this paper will be present the strength analyze of spot weld joint and analyze the transition between interfacial and pull-out failure modes for resistance spot weld joints of aluminium and austenitic stainless steel sheet, during the tensile-shear test, by usage analytical and experimental approach. For experimental testing, the specimen of 1 mm and 2 mm thickness were used, welded with different welding parameters.

Key words: resistance spot welding, failure mode, tensile-shear test

1. INTRODUCTION

Lightweight design (LW) is resulting from the need for sustainable design and product development [1]. Material, design and manufacturing technologies remain key technologies in vehicle development [2] and also in other products development. The essence of success at global world market is integration, so the multi-material design has been developed as a modern concept of LW design, aimed at integrating different types of materials into one structure. For example, vehicle body weight can be reduced by the use of multiple materials without cost increase [2]. Various lightweight automotive bodies have been developed using high strength steels, aluminium alloys, and composite materials. One prerequisite for multi-material structures for car bodies is the availability of material-capable and cost-efficient joining technologies [4].

Aluminium, aluminium alloys, and steel are often used in multi-material structures, so there are various studies [4,5] that analyze how these materials are bonded. Very often in these studies can be saw the resistance spot welding (RSW) [6-8] as one solution. Despite the emergence of new technologies, RSW is still a dominant process for joining similar and dissimilar sheet metals in automotive industry.

Joint failure, e.g. resistance spot weld (RSW) joint failure, was identified as one of the key failure types when a vehicle crash occurs [9]. Failure mode of resistance spot welds is indicator of weld quality. Two major types of spot weld failure are pull-out and interfacial fracture [9,10]. The aim of this paper is strength analyze of spot weld joint and analyze the transition between interfacial and pull-out failure modes for resistance spot weld joints of aluminium 99.5 (1050A) and austenitic stainless steel X2CrNi18-9 sheet during the tensile-shear test, by the use of analytical and experimental approach.

Austenitic stainless steels, and therefore the steel X2CrNi18-9 is often used as construction material in the chemical- and food-processing industry [11] and also, this steel is applied in the automotive industry [12]. In order to develop lightweight structures, stainless steel is tended to replace, primarily because of their weight. However, steel structures can not be completely replaced, it is possible to replace parts of constructions with lightweight materials, such as aluminium. In this case, it is necessary to join stainless steels and aluminium [13].

The chemical composition and basic mechanical properties of steel X2CrNi18-9 and aluminium 99.5 (1050A), that were used for research present in this paper, are given in Table 1.

Table 1: Chemical composition and basic mechanical properties of steel X2CrNi18-9 and aluminium 99.5 (1050A)
2. THEORETICAL STRESS ANALYSES AND FAILURE MODE TRANSITION

Basically, spot welds can fail in three distinct different modes, shown on figure 1, described as follows [9]:

- Interfacial failure (IF) in which, fracture propagates through the fusion zone (FZ)
- Pull-out failure (PF) in which, failure occurs via the withdrawal of weld nugget from one sheet. In this mode, fracture may initiate in base metal (BM), heat affected zone (HAZ) or HAZ/FZ depending on the base metal and the loading condition.
- Partial interfacial mode (PIF) in which, fracture first propagates in fusion zone (FZ) and then is redirected through thickness.

![Fig.1: Schematic of various failure modes during mechanical testing [14]](image)

The failure of resistance spot welds during the tensile–shear test can be described as a competition between the shear plastic deformation of the fusion zone (i.e. IF mode) and the necking in the base metal (i.e. PF mode) [9]. At the nugget circumference, shown on figure 2, stresses are shear tensile at position A and shear compression at position B [10].

![Fig.2: Distribution at nugget centerline and circumference during shear tensile test [16]](image)

According to [9], the failure load at the interfacial failure mode (IF mode) can be expressed using Eq. 1:

$$ F_{IF} = \frac{\pi}{4} \cdot d^2 \cdot \tau_{FZ} $$  \hspace{1cm} (1)

where \( d \) is the diameter of the weld nugget and \( \tau_{FZ} \) is shear strength of the fusion zone.

For PM mode, failure is initiated when the maximum experienced radial tensile stress at nugget circumference reaches the ultimate tensile strength of the failure location. Therefore, failure load in the PF mode can be expressed using Eq. 2 [9]:

$$ F_{PF} = \pi \cdot t \cdot d \cdot \sigma_{PFL} $$  \hspace{1cm} (2)

where \( t \) is the thickness of the base metal sheet and \( \sigma_{PFL} \) is the ultimate tensile strength of the PF location.

For Sawhill and Baker, equation 2 can be written as Eq. 3 [10]:

$$ F_{PF} = c \cdot t \cdot d \cdot \sigma_{BM} $$  \hspace{1cm} (3)

Where \( \sigma_{BM} \) is the ultimate tensile strength of base material and \( c \) is a constant between 2.5 and 3.1.

According to previous equations, the comparative stress of spot weld joint can be calculated using Eq. 4:

$$ \sigma_s = \max \left( \frac{4F}{i \cdot \pi \cdot d^2 \cdot \alpha_1 \cdot i \cdot t \cdot d \cdot \alpha_2} \right) $$  \hspace{1cm} (4)

where \( F \) is applied load, \( i \) number of welds and \( \alpha \) coefficient of weld joint. Coefficient \( \alpha_1 \) is 0.65 and \( \alpha_2 \) is 0.5 [15].

Comparative stress is approach to calculate stresses in spot weld joint. Generally, the stress in welds has normal and tangential components. The method of comparative stresses is based on the fact that the shear strength of weld metal is lower than the tensile strength [15].

3. EXPERIMENTAL PROCEDURE

Specimens for this study are prepared in accordance with EN ISO 14273: 2001, the dimensions of specimens are shown on Figure 3.

![Fig. 3: Dimensions of specimen](image)

The process of spot welding was done on the machine shown in Figure 4, manufactured by DALEX WERK, located in the TMD dommers factory in Gradačac, BiH. Welding parameters for all specimens are given in Table 2. For the welding of all specimen, class 2 electrodes (Cu + Zr + Cr) were used. The head of the upper electrode is 5 mm and the lower electrode type is beck-up. Also, the electrode force for all specimens was 2 kN.

![Fig. 4: Spot weld machine and specimen after spot welding](image)
### Table 2: Welding parameters for all specimens

<table>
<thead>
<tr>
<th>Marks</th>
<th>Mat. 1</th>
<th>Mat. 2</th>
<th>Thic. 1 (mm)</th>
<th>Thic. 2 (mm)</th>
<th>Weld current (kA)</th>
<th>Weld time [1/100 sec]</th>
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<td>1</td>
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</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>6</td>
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<td>* *</td>
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<td></td>
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<tr>
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<td>1</td>
<td>6</td>
<td>32</td>
<td>* *</td>
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<tr>
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<td>32</td>
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<td></td>
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<tr>
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<td>1</td>
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<td>32</td>
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<tr>
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<td>7</td>
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<td>*</td>
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<td>1</td>
<td>7</td>
<td>72</td>
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<td></td>
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<td>E50</td>
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<td>72</td>
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<td>1</td>
<td>7</td>
<td>72</td>
<td>* *</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The steel was in direct contact with the upper electrode.  
** For one spot steel was in contact with the upper electrode and for other one spot aluminum was in contact with the upper electrode.

For further analysis, it is very important to know which material is in contact with the upper electrode. Steel and aluminum are not the same conductors of electricity, so different parameters are required in welding if the same quality of welding is desired. It is visually possible to perceive the difference in the appearance of the weld, depending on that which material is in a contact with the upper electrode, as shown in Figure 5.

The tensile -shear test of all specimens welded by RSW with welding parameters shown in Table 2, was carried out according to the recommendations of the aforementioned standard EN ISO 14273: 2001, on the test machine AGS-X 20 kN, manufactured by SCHIMDZU (Figure 5).

![Fig. 5: Specimen prepared for testing set in jaws of test machine (1- shim plates)](image)

### 4. RESULTS AND DISCUSSION

In this section it will be shown illustration of two major types of spot weld failure: pull-out (PF) and interfacial fracture (IF) and tensile-shear strength for previously shown specimens.

Pull-out failure (PF) is illustrated in Figure 6a for all three specimens marked as E24, E26 and E27. These are specimens with one spot and sheet thickness of both materials (aluminum and steel) of 1 mm. In standard EN ISO 14273:2001 pull-out failure shown on Figure 6a is called spot weld with partial pull-out failure.

![Fig. 6: Illustration of failures: a) pull-out failure (PF); b) interfacial failure (IF)](image)

A specimen with one spot with aluminum thickness of 2 mm, and steel 1 mm marked E32-E35 after the testing are shown on Figure 6b, where interfacial failure (IF) can be seen. The force/displacement diagram for the E24 specimen for static tensile-shear test is shown in Figure 7.
Specimens marked with E32 and E33 were welded so that the steel was in contact with the upper electrode, and the specimens E34 and E35 were welded so that the aluminum was in contact with the upper electrode. In terms of failure mode, this is not important. Figure 8a shows the force/displacement diagram for E32 specimen (steel in contact with the upper electrode) and Figure 8b shows same diagram for E35 specimen (aluminum in contact with the upper electrode).

One of very important parameter for spot weld obtained from force/displacement curves is energy absorption [16, 17]. The amount of energy absorption can be digitally calculated by measuring the area under the force/displacement curve up to failure using the Eq. 5 [16]:

\[ Q = \sum_{n=1}^{N} F(n) \cdot [x(n) - x(n-1)] \]  

where \( F \) is force, \( x \) the displacement, \( n \) the sampled data and \( N \) the peak failure load.

Load carrying capacity and energy absorption capability for those welds fail under interfacial mode, are much less than those which fail under pull-out mode. To ensure reliability of spot welds during vehicle lifetime, process parameters should be adjusted so that pull-out failure mode is guaranteed [10].

When the spot weld joint is with two spot, for the same specimen thickness, the fail is dominant in the PF mode, regardless of whether the spots are arranged vertically or horizontally (Figure 9a). For the same spot weld joint, but with different thickness of aluminum (2 mm) and steel (1 mm), the fail is dominant in the IF mode (Figure 9b).

The tensile-shear strength of the specimens with the vertical spots marked E28 and E29 is somewhat higher than the specimens with horizontal spots E30 and E40, although the same welding parameters. One of the reasons is the fact that for a vertical weld joint one spot is welded when aluminum being in contact with the upper electrode and other one when steel being in contact with the upper electrode, differing from the horizontal layout, where both spots are welded when aluminum being in contact with the upper electrode.

The values of tensile-shear strength and comparative stress for all specimens are shown in Table 3. Tensile-shear strength of specimen marked E49 i E50 is higher than tensile-shear strength of E28 i E29 specimens, especially because of different thickness, weld current and weld time. This four specimens have same layout of spots. The force/displacement diagram for the E29 specimen is shown in Figure 10a and for the E50 specimen is shown in Figure 10b.
In this paper was analyzed the tensile-shear strength and failure mode of the spot weld joint of X2CrNi18-9 steel and aluminum 99.5. The theoretical analysis was showed, that spot welds for tensile-shear load general can fail in two distinct different modes: IF (Interfacing) in which, fracture propagates through the fusion zone (FZ) and pull-out failure (PF). The analytical comparative stress of the spot weld joint is determined by selecting the maximal value between the stresses received by the IF and the PF mode.

The experimental testing of the spot weld joint of the aforementioned two materials for different welding parameters and the thickness of the material was done, as a confirmation of the theoretical analysis. After the experiment, it is easy to recognize which mode belongs to the fail of the specimen and it was found that comparative stress is analytical obtained from the same failure mode. The thickness of the material is one of the parameters that largely indicate in which failure mode will fail spot weld joint.

Many previous studies, referenced here, together with this one shown that, in terms of the tensile-shear, the strength material thickness and the welding current are very important. Also, the tensile-shear strength depends on which material is in contact with upper electrode, when dissimilar material welding, which has been shown here.

The influence of the weld time on the tensile-shear strength was shown in [18] and the analysis in [19] shows the percentage contribution of individual parameters on the weld strength. The percentage contribution of the welding current is 49.81%, the thickness of 37.94% and the cycle time of 2.61%.

Table 3: The values of tensile-shear strength and comparative stress

<table>
<thead>
<tr>
<th>Mar.</th>
<th>Fmax [N]</th>
<th>i</th>
<th>4F 1 (\text{[N/mm}^2)</th>
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<th>(\sigma_s \text{[N/mm}^2)</th>
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<td>89,51</td>
</tr>
</tbody>
</table>

The analytically obtained stress values based on equation 4 shown in Table 3 confirm the previous experimental test, in terms of failure mode. For example, specimens E24 to E30 and E40 have higher stress analytically obtained for PF mode, than stress analytically obtained for IF mode. Also, previous Figures (Fig. 6a and Fig 9a) confirm that these specimens fail in PF mode in experimentally test.

5. CONCLUSION

In this paper was analyzed the tensile-shear strength and failure mode of the spot weld joint of X2CrNi18-9 steel and aluminum 99.5. The theoretical analysis was showed, that spot welds for tensile-shear load general can fail in two distinct different modes: IF (Interfacing) in which, fracture propagates through the fusion zone (FZ) and pull-out failure (PF). The analytical comparative stress of the spot weld joint is determined by selecting the maximal value between the stresses received by the IF and the PF mode.

The experimental testing of the spot weld joint of the aforementioned two materials for different welding parameters and the thickness of the material was done, as a confirmation of the theoretical analysis. After the experiment, it is easy to recognize which mode belongs to the fail of the specimen and it was found that comparative stress is analytical obtained from the same failure mode. The thickness of the material is one of the parameters that largely indicate in which failure mode will fail spot weld joint.

Many previous studies, referenced here, together with this one shown that, in terms of the tensile-shear, the strength material thickness and the welding current are very important. Also, the tensile-shear strength depends on which material is in contact with upper electrode, when dissimilar material welding, which has been shown here.

REFERENCES


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ADVANCED FW AND AFP/ATL TECHNOLOGIES FOR PRODUCTION OF COMPLEX PARTS OF COMPOSITE MATERIALS

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Blagoja SAMAKOSKI
Vladimir DUKOVSKI

Abstract: Composites have emerged in recent years as a valuable class of engineering materials. They offer many attributes not attainable with other materials – they are lightweight, yet offer stiffness – and as a result can be found in a range of tech application with advanced technologies.

One from advanced technology for manufacture a composite is FW. This process is primarily used for hollow, generally circular or oval sectioned components, such as pipes and tanks. Filament winding technology are use and in wind energy. A coupling and a torque shaft are normally part of a classic drive train configuration in wind power generators. Both parts are critical from a cost/performance and maintenance point of view. Steel as well as composite materials are involved in shaft designs. Flexible torque shaft from composite was developed for turbine to eliminate the need for a coupling for steel shaft. The new composite shaft combines the key features of a drive shaft with a coupling – in a single, integrated component provide maximum torque strength for high torque transmission, while offering low bending stiffness. The main advantage of composites is that they have a high strength and high stiffness to weight ratio. They are also corrosion resistant, are electrical insulators, and lend themselves to a variety of fabrication methods.

Second advanced technology is ATL machine, who is the capability for fast automated laying of tape. As the application of lasers in tape placement is relatively new, and laser heating has some distinct differences from other forms of heating such as hot gas or infrared heating, it is important to understand how the LATP process influences the morphology development. Mikrosam enables high quality of the automated fiber/tape placement manufacturing process via its own tools: MikroPlace - an intelligent machine-independent software for off-line programming, design, simulation and analysis.

Key words: composite, shaft, machine, robot, laser,

1. INTRODUCTION

1.1. FW technology

Filament winding is a process for fabricating composite materials in which continuous fibers, either previously impregnated with a matrix material or impregnated during winding, are wound onto a rotating mandrel in a precise, predetermined pattern.

With help of design of experiment (DOE) can be investigated the complex interaction between filament winding manufacturing and design variables, which affect tensile strength and composite quality of specimens [1-4]. Tension control is important factor for better winding patterns, which is the main reason for composite high strength. Therefore, tension control system was designed and manufactured to understand the effect of it parameters on the end product. There are a number of parameters that affect the breaking of fiber during it transport in FW process, which influence the composites mechanical properties [5-10].

If a composite materials tower in wind energy industries is used instead of the existing steel tower, the production cost can be reduced by using of low cost composite materials, simple manufacturing process, easy transportation and easy assembly [11-14]. In this study will present and discuss some process variables parameters in final properties of composite specimens, manufactured with conventional filament winding equipment.

1.2. AFP/ATL (LATP) machine for thermoplastics

Automated fiber placement and tape laying (AFP/ATL) are the technologies that for more than two decades have revolutionized the production of composite structures for the aviation and space industry, and nowadays are entering into new industries such as wind energy. While AFP places multiple individual tows, ATL lays unidirectional tapes or strips of fabric. Both processes apply thermoset, thermoplastic resin-impregnated or dry continuous fibers.
The laser-assisted tape placement (LATP) process is a promising manufacturing technology for thermoplastic composites [14-17], combining high productivity with the ability to manufacture complex geometries. The process comprises the automated lay-up and (in the ideal case) consolidation of pre-impregnated fiber reinforced thermoplastic tapes to incrementally shape a composite structure.

The present work aims to determine some parameters for to optimize the LATP process. Advanced parts can now be produced, whether flat or highly contoured, with automated computer controlled placement of the UD carbon thermoplastic prepreg tape. The temperature control of the thermoplastic material is controlled via a compaction surface laser (heating temperature up to 500°C) integrated to the ATL head. MikroPlace - an intelligent machine-independent software for off-line programming, design, simulation and analysis; and Mikro Automate - a software for online process control and data acquisition system tailored to the specific need of ATL production.

2. EKSPERIMENTAL PART

2.1. Example 1

Filament Winding machines nowadays are widely used in the production of high efficiency carbon fiber parts for the winding energy industry. This series of Filament Winding machines are specially designed to meet specific requirements and in the process of production of carbon fiber shift. This composite shaft is ideal for the specific load requirements of a drive shaft in continuous operation between the ship’s engine and the propellers. It’s outstanding damping performance ensures propulsion at low-noise and low-vibration levels. Handling and transportation are much easier thanks to the much lighter construction compared to drive shafts made of steel.

The influence of parameters in the FW process, speed of winding, angles, and transport of fiber in the rollers are key parameters for determining high strength and high stiffness of composite shafts. Variable parameters who are using in this tests are show in Table 1.

<table>
<thead>
<tr>
<th>No</th>
<th>shaft prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Material</td>
</tr>
<tr>
<td>2.</td>
<td>Tension of fiber</td>
</tr>
<tr>
<td>3.</td>
<td>Winding speed</td>
</tr>
<tr>
<td>4.</td>
<td>Angles</td>
</tr>
</tbody>
</table>

Table 1: Composite shaft instructions

The aim of this study is to investigate the mechanical properties of continuous fiber reinforced composite tubes, produced by filament winding technique. For this purpose, the full factorial experimental design was implemented. When designing the filament winding composites, three major factors are the most important: fiber orientation, fiber tension and velocity of the filament winding. The ultimate target is to achieve the composite pipes with good characteristics as material for construction with the lowest possible weight. The filament winding composite pipes were made of carbon fiber and epoxy resin.

This study used highest strength, standard modulus single carbon fiber Torayca T700S 24K from Toray. Carbon fiber was impregnated into commercially available epoxy resin system with anhydride hardener and amine accelerator for filament winding processing from Huntsman, Araldite® LY 1135-1 / Aradur® 917 / Accelerator 960-1. Wet winding process was carried out on Filament winding machine with roller type resin bath and electrical creel manufactured from Mikrosam A.D (fig.1 and fig. 2).
The preparation of the composites was done by applying the $2^3$ full factorial experimental design. For the purposes of these investigation, eight test specimen configurations are made and on the basis that test results should provide material properties useful in the design stage. The velocity of the filament winding was taken to be the first factor, the second – fiber tension and the third – winding angle. The effect of a filament-winding processing variables on longitudinal and hoop tensile and bending properties of the prepared composites will be investigated according to American Society for Testing and Materials (ASTM) standards ASTM D 2290 and D 790.

Different values of the process parameters have been considered by means of design of experiment (D.O.E) technique used for Carbon fiber/ epoxy with FW, as shown in Table 1.

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>Tension of fiber (N)</th>
<th>Winding speed (V m/min)</th>
<th>Angle (α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>50</td>
<td>21</td>
<td>90°</td>
</tr>
<tr>
<td>2.</td>
<td>20</td>
<td>21</td>
<td>90°</td>
</tr>
<tr>
<td>3.</td>
<td>50</td>
<td>5</td>
<td>90°</td>
</tr>
<tr>
<td>4.</td>
<td>20</td>
<td>5</td>
<td>90°</td>
</tr>
<tr>
<td>5.</td>
<td>50</td>
<td>21</td>
<td>45°</td>
</tr>
<tr>
<td>6.</td>
<td>20</td>
<td>21</td>
<td>45°</td>
</tr>
<tr>
<td>7.</td>
<td>50</td>
<td>5</td>
<td>45°</td>
</tr>
<tr>
<td>8.</td>
<td>20</td>
<td>5</td>
<td>45°</td>
</tr>
</tbody>
</table>

### 2.2. Example 2

The part of experimental research will be realized at AD Mikrosam from Prilep on their equipment for manufacturing composite materials - LATP machine (fig.3).

As the laser is mounted at a fixed point on the tape placement heat, the laser angle governs the distribution of the power between the tape and the laminate. The effect of the laser angle influence the mechanical properties of laminates. At lower angles the majority of energy is supplied to the tape, while at higher angles more energy is supplied to the laminate. In these experiments the laser angle is a constant 22.5°. The LATP equipment allowed the variation of some process parameters. Experimental studies were performed with changing parameters – temperature, pressure of contacted roller and placement velocity. A set of experimental tests have been carried out by a ATL machine.

Different values of the process parameters have been considered by means of design of experiment (D.O.E) technique for PEEK/Carbon and PPS/Carbon tape 25mm width, as shown in Table 2 and 3.

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>Temperature (T °C)</th>
<th>Placement velocity (V m/min)</th>
<th>Pressure of contacted roller ( P bar)</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>420</td>
<td>9</td>
<td>3.8</td>
<td>0°</td>
</tr>
<tr>
<td>2.</td>
<td>360</td>
<td>9</td>
<td>3.8</td>
<td>0°</td>
</tr>
<tr>
<td>3.</td>
<td>420</td>
<td>3</td>
<td>3.8</td>
<td>0°</td>
</tr>
<tr>
<td>4.</td>
<td>360</td>
<td>3</td>
<td>3.8</td>
<td>0°</td>
</tr>
<tr>
<td>5.</td>
<td>420</td>
<td>9</td>
<td>2.8</td>
<td>0°</td>
</tr>
<tr>
<td>6.</td>
<td>360</td>
<td>9</td>
<td>2.8</td>
<td>0°</td>
</tr>
<tr>
<td>7.</td>
<td>420</td>
<td>3</td>
<td>3.8</td>
<td>0°</td>
</tr>
<tr>
<td>8.</td>
<td>360</td>
<td>3</td>
<td>3.8</td>
<td>0°</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

3.1. FW technology

Tests describes optimal processing conditions that maximize the mechanical properties of the composites with different process parameters in FW technology. Higher speed, higher tension of fiber without carbon fiber breakage in transport in fiber creel and the use of angles of 40 to 80, give the best results at composite shafts. Larger tensions and angles decrease pores up to 1-2% in this technology, and increase mechanical properties to 20%.

With using composite shafts are reduces the weight of the shafts. The transmission energy is reduced by reducing the weight of the shaft. Replacement of transmission shafts of steel with carbon (positive experiences and benefits) Are examples where this is produced.

Composite shaft (tube) with FW technology with better process parameter can be used in shafts for wind power and other industry.

Some of the benefits are:

- Best results in mechanical properties obtained from winding speed V2, tension of fiber N2 and angle α2
- Change of tension and angles increase mechanical properties to 20% in final mechanical results
- Low upfront investment (due to reduced design complexities and simplified layouts)
- Significantly reduced weight (for faster, simplified handling)
- Outstanding damping (for low noise and low vibration operation)
- High operational reliability (on account of a fully integrated in situ manufacturing process and significantly improved fatigue strength)

The process parameters of this technology are a key choice in the design of new advance materials for the replacement of conventional materials.

3.2. LATP technology

Tests describes the investigation of the optimal processing conditions that maximize the mechanical properties of the composites. However, uncertainties exist on the mechanical performance of the final product which are associated with the process induced defects. Tests have revealed the minimal defects (void) and good interfacial properties in laminate.

From the present numerical and experimental studies, the following conclusions are made:
- Obtained function from the factorial design concludes that researched parameters and the interaction between them has to be taken into account in LATP process.

The experimental procedure described in the present work is suitable to study the consolidation behavior of thermoplastic matrix composite. The results shown, that good interaction between the layers is strongly dependent on the temperature of the laser, which should ideally be greater than the thermoplastic melt temperature. Rising of the temperature from 280oC to 350oC for PPS matrix and
from 360°C to 420°C for PEEK matrix is followed by sharp fall of voids percent due to the good melting of the PPS and PEEK. Also, higher pressure of the consolidation roller will decrease the percent of voids in the final composite, along with 9 m/min speed of the LATP machine.

High number of voids in the material causes a problem on the forces that influence the final product. Therefore, this study focused on these three parameters, and was done in two steps. Firstly, a two-factor central composite design of experiments was used to define the combination of processing parameters. The flexural strength was calculated according to ASTM D 790 standard (Fig 4 and Fig 5) and second the void content was calculated (Fig 6 and fig 7).

Some of the benefits are:

- Best results in flexural strength obtained from velocity $V_2$, temperature $T_2$ and $P_2$
- Change of temperature causes variation from 1.9-9% to 60% in final mechanical results
- Pressure of the contact roller shows an influence in final mechanical results
- Researched parameters and interactions between them has to be taken into account in LATP process

4. CONCLUSION

From experimental work conducted in this research following conclusions can be made:

1. Larger tensions and angles decrease pores up to 1-2% in FW technology for thermosetting matrix, and increase mechanical properties to 20%.
2. Larger temperature, speed and pressure of contacted roller decrease pores up to 1-3% in LATP technology for thermoplastic matrix, and increase mechanical properties to 60%.

It is assumed that, lower mechanical properties of specimens by FW and LATL are caused from fiber breach or void content in the final composite, which were analyzed in this research. Statistical analysis of the data showed some very significant results, which should be very helpful in improving the composite parts. Validity of this study lies in the expected results from the use of the different parameters in these technologies. Corresponding research made at this study, are in order to acquire full advantage of the quality of the composite products to avoid troubles when they are transformed into the final products from different parameters in these technologies. Mechanical, Aeronautical and Biomedical Engineering Department, University of Limerick, Limerick, Ireland

REFERENCES


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APPLICATION OF TAGUCHI METHODS WITH OPTIMIZATION OF FIBRE ORIENTATION ANGLE OF LAMINATED AL/ARAMID/EPOXY COMPOSITE CARDAN SHAFT

Jasmina BLAGOJEVIĆ
Zorica DORDEVIĆ
Sandra VELIČKOVIĆ

Abstract: Optimization of fibre orientation angle of the laminated Al/aramid/epoxy composite cardan shaft using Taguchi methods was carried out in this paper. The aim of the study is to obtain values of fibre orientation angle at which the lowest value of angle of twist of shaft is obtained. The analysis of the fibre orientation angle of the laminated composite shaft has been carried out using ANOVA analysis. The laminated composite shaft consists of a layer of aluminum and eight layers of aramid/epoxy composite whose fibre orientation angle taken into consideration is -45°, 0°, 45° and 90°. To model the cardan shaft, programmes like FEMAP and NeNASTRAN were used, and they helped obtain angles of twist of Al/aramid/epoxy composite cardan shaft at appropriate factor levels. Predicted value of the angle of twist deviated from the experimental one by 1.805%, whereas the value obtained by confirmation test deviated by 1.491% from the experimental value of the angle of twist.

Key words: Al/aramid/epoxy composite, cardan shaft, Taguchi method, fibre orientation angle, angle of twist.

1. INTRODUCTION

The basis of the study of this paper is to determine the fibre orientation angle of the laminated Al/aramid/epoxy composite cardan shaft, more precisely, to find the optimal variation of the angles of the layers where the lowest value of the angle of twist of the shaft is obtained. A review of the literature has shown that the two-piece steel cardan shafts are replaced by one-piece composite shafts due to the reduction of weight. A very large number of papers are referring to determining the fibre orientation angle of composite cardan shaft.

Rangaswamy and Vijayarangan performed the optimization of drive cardan shafts in the paper [1]. They used composite materials: E-glass/epoxy and HM carbon/epoxy. The weight savings for the composite E-glass/epoxy drive shaft is 48.36% compared to the steel shaft, while the weight savings of HM carbon/epoxy composites are 86.90% of the steel shaft. In this paper [2], Dinesh and Anand Raju replaced the conventional two-piece steel drive shaft with one-piece E-glass/epoxy, HS carbon/epoxy and HM carbon/epoxy composite drive shafts. The shafts are subjected to restrictions, such as transmission torque, torsional buckling capacity and natural bending frequency. The weight savings of E-glass/epoxy, HS carbon/epoxy and HM carbon/epoxy composites are 48.36%, 86.90% and 86.90% of the weight of the steel shaft respectively.
good properties and that it could be used as a replacement for steel.

In this paper, Taguchi methods were used to determine the optimal variant of the factors. The fiber orientation angles of the layers of laminar composite shaft are factors, and the angle of twist of shaft is a response. The laminar composite shaft consists of a layer of aluminum and eight layers of aramid/epoxy composites. The shaft model and the values of angle of twist for the combined factor levels were obtained in the FEMAP and NeNASTRAN programs. The Minitab 16 program was used for statistical processing of the results, and the confirmation of the experiment for determining the interval of the angle of twist of the composite shaft was used for the obtained optimal variant.

2. COMPOSITE CARDAN SHAFTS

The basic role of the cardan gears is transmission of the torque between shafts which are spatially at constantly variable angle, allowing their relative motion [6]. In modern aircrafts, airplanes, cars and boats, primarily in order to save the fuel and increase starting, intensive work is done to reduce the weight of the vehicle, by using aluminum or plastic materials in the construction of vehicles and engines or by using other lightweight materials of increased strength (light alloys, composite materials, etc.) [7, 8, 9]. The laminar composites have advantages due to their high specific stiffness. The composite drive shafts have a longer lifespan of the drive advantages (light alloys, composite materials, etc.) [7, 8, 9]. The laminar composites have materials of increased strength (light alloys, composite materials, etc.) [7, 8, 9].

The basic dimensions of the one-piece cardan shaft are: length of the shaft - 1.35 m, the mean radius of the shaft - 0.041 m, the thickness of the wall of the annular cross-section shaft - 0.003 m [11].

Table 1: Basic characteristics of aramid/epoxy composites

<table>
<thead>
<tr>
<th>Longitudinal modulus</th>
<th>E₁</th>
<th>81.8 GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse modulus</td>
<td>E₂</td>
<td>5.10 GPa</td>
</tr>
<tr>
<td>Shear modulus G₁₁</td>
<td>G₁₁</td>
<td>1.82 GPa</td>
</tr>
<tr>
<td>Shear modulus G₁₂</td>
<td>G₁₂</td>
<td>1.51 GPa</td>
</tr>
<tr>
<td>Poisson's ratio ν</td>
<td>ν</td>
<td>0.31</td>
</tr>
<tr>
<td>Density ρ</td>
<td>ρ</td>
<td>1380 kg/m³</td>
</tr>
<tr>
<td>Composite layer thickness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. TAGUCHI METHODS

Taguchi developed a method for designing experiments to examine how different parameters affect the mean value and variation of process performance characteristics that determine how well the process works. The experimental design that he proposed involves the use of orthogonal arrays for organization of parameters that affect the process and levels which are to be changed [12].

According to Taguchi, the selection of parameters is accomplished by methods of experiment planning, whereby Taguchi proposes using, along with ordinary indicators, a new quality indicator, the so-called signal/noise ratio (S/N). The Taguchi method uses the loss function to calculate the deviation between the experimental value and the desired values. This loss function is converted into a S/N ratio. There are three types of S/N ratio: smaller the better, larger the better, and nominal the best, which serve to measure quality characteristics [13, 14, 15]. The S/N ratio the smaller the better was used in this paper:

$$S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_{i}^{2} \right) \quad (1)$$

where n is the repetition number of each trial and $y_{i}$ is the result of the i-th experiment for each trial.

4. EXPERIMENTAL PART

The influence of the fibre orientation angle of aramid/epoxy composites on the angle of twist of the laminar combined Al/aramid/epoxy composite cardan shaft was tested in this paper. The aim of the paper is to obtain the values of the fibre orientation angle with the least torsion of the shaft.

The basic dimensions of the one-piece cardan shaft are:

- 252 quadrangular finite elements of the shells were used for modelling the shaft. The maximum value of the maximum torque, at which the cardan shaft was tested, was 5000 Nm.
- Table 3 shows the factors and levels of factors that are analysed. In this case, the factors are the fibre orientation angles of the composite laminar shaft. The first layer of the shaft is made of aluminum and the other layers are made of aramid/epoxy composites and the slopes of their fibres are on four levels (-45°, 0°, 45° and 90°).
Table 3: Factors and their levels

<table>
<thead>
<tr>
<th>Factors (The fibre orientation angle)</th>
<th>Unit</th>
<th>Level I</th>
<th>Level II</th>
<th>Level III</th>
<th>Level IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Layer 1</td>
<td>°</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(B) Layer 2</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(C) Layer 3</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(D) Layer 4</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(E) Layer 5</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(F) Layer 6</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(G) Layer 7</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(H) Layer 8</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>(J) Layer 9</td>
<td>°</td>
<td>-45</td>
<td>45</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

The first step in the application of Taguchi methods is to select the appropriate orthogonal array. Since a number of factors and levels are known, the appropriate orthogonal array L32 has been selected for determining the optimal values of the fiber orientation angles of the layers of composite cardan shaft [16]. Since the factor A has only one level, it can be ignored in further analysis. The model of cardan shaft was made in the FEMAP and NeNASTRAN programs and the angles of twist of the Al/aramid/epoxy composite shaft are obtained by using those programs at the corresponding factor levels and they are shown in Table 4.

4.1. Statistical processing of the results

Table 4 shows the obtained S/N ratio values. S/N ratios were obtained by the use of Minitab 16 using the equation (1). This equation is used when it tends to the minimum target value, and in this case it is the angle of twist of the laminar composite shaft.

Table 4: Orthogonal array L32 with experimental values of angle of twist and S/N values for Al/aramid/epoxy composite shaft

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
<th>Angle of twist [rad]</th>
<th>S/N ratio [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-45</td>
<td>-45</td>
<td>-45</td>
<td>-45</td>
<td>-45</td>
<td>-45</td>
<td>-45</td>
<td>0.187</td>
<td>14.5632</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.219</td>
<td>13.1911</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>-45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>0.185</td>
<td>14.6566</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-45</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>0.219</td>
<td>13.1911</td>
</tr>
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</tbody>
</table>

Based on the results of the S/N ratio, it can be determined which of the control factors has the greatest influence on the angle of twist of the one-piece composite shaft (Table 5). The optimal parameters of the angle of twist of these controlled factors can be determined based on the S/N ratios shown in Table 5 and Figure 2.
Parameter optimization of the angle of twist within the given factors and levels, considering the criterion “the smaller the better”, gives the combination of control factors: A1, B3, C3, D3, E3, F3, G3, H3 and J3. In other words, the combination of angles of aramid fiber slope is obtained in all layers of 45° for the lowest value of the angle of twist of Al/aramid/epoxy composite shaft.

Table 5: Response table for S/N ratio (for “the smaller the better” case)

<table>
<thead>
<tr>
<th>Level</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>14.01</td>
<td>14.00</td>
<td>14.00</td>
<td>14.00</td>
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<td>4</td>
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</table>

Experimental results are processed by applying the analysis of variance (ANOVA), which is used to identify the significance of the factors affecting the fibre orientation angles of the layers of composite shaft [17, 18]. The results of the ANOVA analysis are shown in Table 6.

Based on the ANOVA analysis of the S/N ratio, it can be concluded that all factors almost equally influence the angle of twist of the composite cardan shaft. Factor H has the greatest influence (14.46%), and factor B has the smallest influence (9.60%), while the influence of the error is almost negligible, amounting to 1.27%.

Table 6: Results of ANOVA analysis of the S/N ratio

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
<th>Pr</th>
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</thead>
<tbody>
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<td>B</td>
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<td>0.25900</td>
<td>0.25900</td>
<td>0.086333</td>
<td>17.63</td>
<td>0.001</td>
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<td>C</td>
<td>3</td>
<td>0.30876</td>
<td>0.30876</td>
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<td>21.01</td>
<td>0.001</td>
<td>11.44</td>
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<td>D</td>
<td>3</td>
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<td>0.108961</td>
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<td>E</td>
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<td>0.32737</td>
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<td>0.34503</td>
<td>0.115011</td>
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<td>G</td>
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<td>0.130094</td>
<td>26.56</td>
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<tr>
<td>J</td>
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<td>0.36207</td>
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<td>Residual Error</td>
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<td>0.004898</td>
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<tr>
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</table>

4.2. Confirmation of the experiment

Besides Taguchi optimization technique, the experiment confirmation is used to confirm the statistically obtained optimal factor variant. The predicted optimal value of the angle of twist is obtained by considering the individual effects of the factors and their levels (A1, B3, C3, D3, E3, F3, G3, H3 and J3). Estimated optimal value of the angle of twist may be obtained from the equation [17, 19]:

\[
\varphi_p = \tau_\varphi + (A1 - \varphi_\varphi) + (B3 - \varphi_\varphi) + (C3 - \varphi_\varphi) + \\
(D3 - \varphi_\varphi) + (E3 - \varphi_\varphi) + (F3 - \varphi_\varphi) + (G3 - \varphi_\varphi) + \\
(H3 - \varphi_\varphi) + (J3 - \varphi_\varphi)
\]

where \(\tau_\varphi\) is the mean value of the angle of twist, and A1, B3, C3, D3, E3, F3, G3, H3 and J3 are the S/N responses of the main factors at certain levels. The calculated optimal value of the angle of twist is 14.78333 dB. The confidence interval for the predicted optimal value is calculated by using the terms:

\[
CI = \sqrt{\frac{F_{\alpha, V_2} \cdot V_e \cdot \left[ \frac{1}{n_{\text{eff}}} + \frac{1}{r} \right]}{\alpha}}
\]

where \(F_{\alpha, V_2}\) is the table value F за ниво неизвестности for confidence level \(\alpha\), \(V_2\) is degree of freedom of pooled error, \(V_e\) is pooled error variance, \(r\) is the number of repetitions, and \(n_{\text{eff}}\) is the number of effective measured results defined as:

\[
n_{\text{eff}} = \frac{\text{total experimental trials}}{\text{total degree of freedom of factors for prediction}}
\]
One confirmation experiment was performed for the evaluation of the performances of experimental tests for the angle of twist under optimal conditions, and because of that $r=1$. For the level of reliability 95%, $\alpha = 0.05$ and $V_2 = 7$, value of $F_{\alpha, V_2} = 5.59$. A confidence interval $(\pm 0.221)$ was calculated based on the equations (3) and (4).

The experiment for the levels of factors $A1, B3, C3, D3, E3, F3, G3, H3$ and $J3$ was performed and the result is compared with the values obtained by the previous equations and with the predicted values obtained in Minitab 16 (Table 7).

The predicted value of the angle of twist of the shaft deviates from the experimental one by 1.805 %, while the value obtained by the confirmation of the experiment deviates by 1.491 % from the experimental value of the angle of twist.

### Table 7: Results of the angle of twist and S/N ratio

<table>
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<th></th>
<th>Predicted value</th>
<th>Experiment confirmation value</th>
<th>Experimental value</th>
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<td>The angle of twist of the Al/aramid/epoxy composite cardan shaft [rad]</td>
<td>0.181719</td>
<td>0.1823</td>
<td>0.18506</td>
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</table>

The optimal values of the fibre orientation angles are also obtained in the FEMAP and NeNASTRAN programs. The fibre orientation angle of the aramid / epoxy composite is Al$/\pm 45^{\circ}$. For these optimal fibre orientation angles, the value of the angle of twist of the Al/aramid/epoxy composite cardan shaft is 0.182 rad [12].

The deviation of the optimum value of the angle of twist of the composite shaft obtained by Taguchi method is 1.685 % of the optimal value obtained in the FEMAP and NeNASTRAN programs. The fibre orientation of the aramid / epoxy composite is Al$/\pm 45^{\circ}$.

#### 5. CONCLUSION

Based on the research in this paper, it can be concluded:

- ANOVA analysis of the S/N ratio shows that all factors have almost the same impact on the torsion of shaft and the error is 1.27 %.
- The lowest value of the angle of twist of the Al/aramid/epoxy composite cardan shaft by using the Taguchi method is obtained when the fibre orientation angles of aramid are in all layers of the aramide/epoxy composite + 45°.
- For optimal values of the fibre orientation in the FEMAP and NeNASTRAN programs, the obtained angle of twist of the shaft is 0.18506 rad (experimental value), and the obtained angle of twist in the Minitab 16 program is 0.181719 rad (predicted value), while the angle of twist is obtained by confirming the experiment by 0.1823 rad.
- The predicted value of the experimental one deviates by 1.805 %, and the value of the angle of twist obtained by the experiment confirmation deviates by 1.491 % from the experimental one.
- The angle of twist obtained for the optimal variation of the fibre orientation angles in FEMAP and NeNASTRAN programs deviates from the angle of twist obtained by using the Taguchi method (experimental value) by 1.685 %.
- Taguchi methods can be used to analyse and optimize the fibre orientation angle of the laminar composite shaft layers that affect the angle of twist of the shaft.

### REFERENCES


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RAPID PROTOTYPING AND MANUFACTURING FOR MODEL OF HUMAN HEAD

Saša ŽIVANOVIĆ

Abstract: Modeling of the human body has advanced in recent years with the rapid development of computer technology and the needs of the real digital and physical models. This paper describes an example of a rapid development of a model of a human head, on the basis of STL-format, which includes a digital information chain CAD / CAM / CNC, to a level which allows the successful realization of the physical models using new technology, by adding and subtracting material. In this paper is presented a photogrammetric method of obtaining STL model, where new technologies are applied for rapid prototyping. For several examples of 3D printing are shown and software for verification of programs and simulation of 3D printing.

Key words: rapid prototyping and manufacturing, STL, human head, 3D printing, verification, simulation

1. INTRODUCTION

Rapid prototyping has emerged as a key enabling technology, with its ability to shorten product design and development time. Rapid prototyping is a technology for quickly fabricating physical models, functional prototypes and small series of parts directly from CAD models. This technology has also been referred to as layer manufacturing, solid free-form fabrication, material addition manufacturing and 3D printing [1,2].

Rapid prototyping – an enabling technology for time compression engineering. If different design and manufacturing activities are carried out concurrently it is possible to compress the overall product development time, which will be shorter than in the serial activities, Fig.1. This can also allow engineers to be creative by providing more time for design, based on the time savings.

With the development of computers and software for the CAD product design and 3D modeling of the human body is rapidly progressed, including technology to produce realistic models adequate for the needs of simulations and animations, or physical models.

3D models of the human head can be obtained in several ways: (i) using specialized software for modeling; (ii) obtaining a 3D scanning point cloud data for the model, using the reverse engineering method for getting a CAD model; (iii) using photogrammetric method, which is based on 2D images on the basis of which the obtained 3D CAD model.

Application of new technologies rapid prototyping based on models in STL format. In the first case this may be the additive technology that is using adding material in the layers. Another approach involves rapid prototyping technology based on subtraction of materials layer by layer, that is also based on a model in STL format.

2. RAPID PROTOTYPING AND MANUFACTURING

Rapid prototyping of different products, which includes machine parts is no longer a novelty, but is a real resource that provides processes and tools for rapid prototyping by adding and/or subtracting material. Rapid Prototyping in the present time is related to the beginnings of 3D Systems Company from the United States [3].

One of the definitions of rapid prototyping says that is the method of making 3D parts of a given shape using their models, usually made in CAD system environment, using a fast, repeatable and flexible processing operations [4].

Rapid prototyping is a process of joining materials to make physical objects from 3D CAD model, usually layer upon layer, as opposed to subtractive manufacturing or molding/casting technologies [5].

Although for rapid prototyping usually associated adding materials technologies, this can include the subtracting materials technologies, and the combination of adding and subtracting materials. One possible classification of these technologies is shown in Fig.2.

Now there are already many manufacturers of equipment for rapid prototyping, so there is a lot of different
technologies. Classification of RP technologies can be made upon different criteria. The most frequently applied is classification based on model material. Using this criteria all RP methods can be divided into three groups: 0D, 1D and 2D (Fig.2). These dimensions of material are: 0D for liquid/gas, 1D for powder form, and 2D for sheet form. More detailed information on every specific RP method can be found in the references [1], [2], [6].

Fig.2: Basic classification of rapid prototyping

Methods of cutting, also one of the frequent method of rapid prototyping or rapid manufacturing. Some equipment manufacturers offer also systems for programming milling machines used for the first verification of the project mechanical parts for which there is already a model in STL format. These milling machines, also known as a desktop milling machine, are usually cheaper than other machines for rapid prototyping so their low price is recommended as an alternative [4].

There is a third possibility, which is combining the technology of adding and subtracting material. In this case, additive technology preparing layers of the preform, and after that followed technology of cutting using finishing milling.

Prototypes in general can be divided into three main groups: (i) Form, (ii) Fit and (iii) Function, Fig.3. The phrase Form-Fit-Function, also referred to as 3F, is used in rapid prototyping to describe the identifying characteristics of a prototypes.

Group Form, are mainly reliefs. This group of prototypes serves to reach a conclusion on the usability and/or benefits in the form of prototype. This group is characterized: design verification, marketing and communication tool, high dimensional accuracy is not required, non-technical people see how product looks and feels.

Group Form, are mainly geometry of prototype. This group of prototypes used for various checks conclusion, however in this case, dimensional accuracy of this prototype is important in order after checking was possible to continue further development. This group is characterized: fit verification of ability of a part to physically interface with, connect to, or become an integral part of another part, verification of manufacturability and assembly, required shape along with good dimensional tolerances, material choice is not important.

Fig.3: Prototype classifications (3F=FFF)

Group Function, are a prototypes that can be both relief and geometry. This group of prototypes used to test functionality of real part. Material should be similar to actual part. Function prototype should have same failure modes and levels as actual part. That is, should have similar characteristics to the real part.

Rapid prototyping is a typical additive technology, where models are formed layer by layer. Typical process stages for additive manufacturing is shown in Fig. 4 and includes the following stages: (i) CAD modeling of part, (ii) STL file is exported from CAD model and STL file is checked for defects, (iii) STL files are used as an input to slicing software, (iv) Machine setup, (v) simulation of 3D printing, (vi) building prototype, (vii) additional interventions on prototype (3D printed model) such as curing, surface polishing, finishing, etc.

Fig.4: Stages for additive manufacturing process from CAD model to 3D part

In the next section, this procedure is applied in the case of the realization of a human head physical model.
3. RAPID PROTOTYPING AND MANUFACTURING PHYSICAL MODELS OF HUMAN HEAD

This section presents examples of rapid prototyping of several models of the human head. The first example is the realization of a model of human head on the basis of the finished CAD model. Based on this model prepared STL file using export option of CAD system. For this example are applied both technologies by adding and subtracting material.

For example, realization of model of human head with additive technology has been used the software Autodesk 123D Make [7]. This software is licensed as Freeware for Windows operating system without restrictions. Software allows creation of low-tech LOM (Laminated Object Manufacturing) -style solid models. Autodesk 123D Make loaded STL model based on which work slicing and preparation of layers for additive construction. The software can be prepared by different layouts for the construction of the physical model based on STL file. As the output of layout layers are available in formats *.DXF, *.EPS and *.PDF. There is also the possibility of simulation the adding layer by layer. The illustration of this kind of additive manufacturing was shown in one example of making of the head model from cardboard of a layer thickness of 2 mm, Fig. 5a.

For the same model were applied technology for rapid manufacturing with subtracting material. For this purpose is used specialized software for the rapid manufacturing based on STL file, which allows pre-machining layer by layer and finally finishing. Such similar specialized softwares for machining based on STL file has many and some of them are CUT3D, DeskPROTO, MeshCAM, etc. Usually this kind of softwares are presented as CNC Software for Non-Machinists and working with them is very intuitive. These softwares enables the loading of the model in the STL format, orientate model for machining, tool selection, choosing machining strategies for roughing and finishing, simulation of material removal for machining cases from different materials, and finally postprocessing the tool path into G code. A sample of machining for the selected head model is shown in Fig. 5b. Machining is carried out on 3-axis vertical Parallel Kinematic Milling Machine LOLA pn101_4 V2, that is installed at the Faculty of Mechanical Engineering in Belgrade.

3.1. Autodesk 123D Catch and 123D Make

For the second example, is characteristic way of preparing model in STL format. In this case, the STL model obtained by the photogrammetric method based on 2D images using the software Autodesk 123D Catch [8].

Fig. 5a: An example of building model of a human head using additive and subtraction technologies

For the second example, is characteristic way of preparing model in STL format. In this case, the STL model obtained by the photogrammetric method based on 2D images using the software Autodesk 123D Catch [8].

Fig. 5b: Machining for the selected head model using 123D Catch and 123DMake
Autodesk 123D Catch is a handy, free Windows program, belonging to the category Design & photography software with subcategory 3D Design and has been published by Autodesk [8]. This software allows creating 3D models from series of photographs taken at various angles using photogrammetry method. After we get initial STL model, follow its completion in the CAD system and preparing corrected STL format for next step. This step is load STL file into the software Autodesk 123D Make [7] that makes it possible to obtain of layers layout, as well as simulate the adding of layers, and present how to build a prototype.

3.2. 3D printing of model of human head

Third example, is realized for the same model as in the second example, but in this case the applied technology is known under the name of Fused deposition modeling, Fig.7.

Based on the input of the STL file, the G code was postprocessed, and then the simulation of additive manufacturing was performed, in order to finally make a physical model on the 3D printer Stratasys uPrint SE. In order to send the STL model to the 3D print, the software Catalyst EX is used as an interface for communicating with the available printer and which is a recommendation, or basic communication software for printers produced by firm Stratasys.

4. PROGRAMMING, VERIFICATION AND SIMULATION OF 3D PRINTING

This section presents an examples of programming and program verification obtained for 3D printing. There are various specialized softwares for 3D printing, as already mentioned Catalyst EX (Fig8a), or Replicator G (Fig.8b), Repetier-Host (Fig.8c) and others.

Fig.7: Building the 3D model of the head using 3D printing

Fig.8: Specialized softwares for 3D printing
ReplicatorG [9] and Repetier-Host [10] are simple, open source 3D printing programs. These programs represent an interface for communication with additive manufacturing machines. The input into these programs is an STL file based on which additive layers are obtained and the required paths for adding materials. Such programs usually allow:

(i) 3D display of the model being created; (ii) scaling the model to the desired size; (iii) control of model orientation in the workspace; (iv) Automatic or manual basing of the model in the case of making several parts in one production process; (v) simulation of the addition of layers and display of each layer; (vi) generating G code for machine.

To verify the obtained G code for the addition of materials, may be used usual CNC editors and simulators, as well as the WEB CNC simulators. In addition, the standard CAD / CAM systems are starting to include Additive Manufacturing option, as is the case with the PTC Creo 4.0.

4.1. CNC simulators

The obtained G code based on STL file for Additive Manufacturing, it is possible to verify using commonly CNC editors for simulating the tool path, in this case, the deposit of materials. For example, for the created model from Fig.7, G code is verified by simulation path in two environments: (i) CNC editor CIMCO [11], Fig.9a, (ii) WEB CNC simulator [12], Fig.9b.

Although CIMCO editor is not intended for Additive technologies, it enables drawing tool path defined by G code thus enabling successful visualization of models and display simulations path, Fig.9a.

A standard characteristic of most CAD/CAM systems is the simulation of the virtual machine tool along a given tool path. For now, there is no possibility of direct simulation of the virtual machine for additive manufacturing, although this is possible in PTC Creo. This indirect method implies that the 3D printer is modeled in the same way as the milling machine with the same kinematics.

Machine tools for additive manufacturing, or as they are also called 3D printers, can be modeled as a CAD model that includes appropriate kinematic connections. The most common machine tool for additive manufacturing are machine with serial kinematics and three translatory axes. Each of the translatory axes is defined as kinematic connection type Slider in PTC Creo, Fig.11.

4.2. Machine simulation of 3D printing in CAD/CAM environment

Today and commercial CAD/CAM systems are beginning to integrate Additive technology into their CAM modules. For example, in a CAD/CAM system PTC Creo [13] from version 3.0 M040 have Additive Manufacturing functionality, Fig 10. 3D printing workflow using a User-Defined printer, or a supported printer Stratasys [5].
Only for opening the cabin door is defined rotary axis as kinematic connection type Pin, which has no influence on simulation process. Such a model is shown for the case of a 3D printer Stratasys uprint SE plus [14], Fig.11 and Fig.12. The design is very rigid and compact. During the simulation, the machine is treated as if the milling machine, that moves along a path of adding material.
To obtain the path of adding material, it is necessary to convert the path of the printing head into G code. Thus obtained path in G code can be converted to the DXF file that is loaded as a tool path into the CAM module by which the printer nozzle is run only for simulation purposes. During the simulation, CAD model of the machine can be loaded, which is made for better visualization, as shown in Fig. 12.

![Fig.12: 3D printing machine simulation in PTC Creo environment](image)

### 5. CONCLUSION

This paper provides an overview of rapid prototyping and manufacturing technology in brief and emphasizes on their ability to shorten the product design and development process. This paper described several examples of a rapid prototyping and manufacturing of a models of a human head, using new technology, by adding and subtracting material.
In this paper is explained a photogrammetric method of obtaining STL model, using appropriate software.
The paper analyzes the possibility of tool-path simulation by adding a material, as well as the simulation of the machine for additive manufacturing (“3D printers”).

### REFERENCES


### CORRESPONDANCE

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PREDICTION OF THE OPTIMAL MICRO HARDNESS AND CRYSTALLINE SIZE OF NANOSTRUCTURE VIA MACHINING AND NEURO-FUZZY TECHNIQUE

Dalibor PETKOVIĆ
Miloš MILOVANČEVIĆ

Abstract: Materials of nano crystalline are of great interest for the engineers due to its advances mechanical properties such as high strength and high hardness. The main drawback of these materials is high cost incurred during its production. In this paper the method of ANFIS (adaptive neuro fuzzy inference system) was applied to the data resulting from these measurements in order to predict the optimal machining parameters. The main goal is to minimize nanocrystalline structure via machining. The ANFIS process for variable selection was also implemented in order to detect the predominant variables affecting the prediction of micro hardness and crystalline size of the nanostructure via machining.

Key words: ANFIS; prediction; machining; nanostructure; crystalline

1. INTRODUCTION

Materials of nanocrystalline have the highest mechanical properties due to strength, hardness and ductility. Severe plastic deformation is one of the approach for the materials synthesizing. This approach breaks downs the microstructure into smaller grains since the ultra-fine grained materials exhibit significantly enhanced mechanical properties. Another approach is based on materials that have conventional crystalline microstructures. By this approach materials are built up atom by atom, molecule by molecule or cluster by cluster form bottom such as physical vapor deposition and chemical vapor deposition. It is crucial to develop a method for optimizing the nanocrystalline structure via machining process. To obtain optimal machining performance, the minimum crystalline size [1] and the maximum micro hardness [2] are desired. Therefore it is suitable to make a prediction method of the optimal crystalline size [3] and micro hardness [4]. In article [5] was carried out to develop a case depth hardness prediction model where the results indicated that the loss of case depth hardness uniformity was highly influenced by the tempering temperature and the change of cooling rate. The increase in indentation hardness within the plastic zones of macro-indents was experimentally determined by micro-Vickers indentation and then compared with that predicted by finite element modeling in article [6]. A three-layer backward propagation model was used in article [7] to predict the hardness of Ni–TiN nanocoatings fabricated by pulse electrodeposition where the effect of plating parameters, namely, TiN particle concentration, current density, pulse frequency, and duty ratio on the hardness of Ni–TiN nanocoatings was investigated. It was shown that the model, with a maximum error of approximately 1.03%, can effectively predict the hardness of Ni–TiN nanocoatings. In paper [8] a feed-forwarded multilayer perceptron artificial neural network framework was used to model the dependence of the grain size of nanocrystalline nickel coatings on the process parameters namely current density, saccharin concentration and bath temperature where the results showed that the current density has the most significant effect and the bath temperature has the smallest effect on the resulting grain size. In this paper the method of ANFIS (adaptive neuro fuzzy inference system) was applied to the data resulting from these measurements in order to predict the optimal machining parameters. The main goal is to minimize nanocrystalline structure via machining. The ANFIS was applied to select the most influential parameters affecting the prediction of micro hardness and crystalline size. The process, which is called variable selection, includes a number of ways to discover a subset of the total recorded parameters that show good capability of prediction. The ANFIS network was used to perform a variable search and thereafter, it was used to examine how 5 parameters influence prediction of micro hardness and crystalline size.

2. METHODOLOGY

2.1. Data collection

Data collection was achieved with CNC Fanuc lathe. The crystalline size of the machined chips are measured on a Rigaku Ultima X-ray diffractometer. The microharness of the samples was measured by indentation with a Vickers indenter with a 200 g load and 30 s dwell time on
a Mitutoyo micro hardness tester. Scherrer equation has been applied to estimate the size of crystallites [9]:

\[ T = \frac{k\lambda}{B\cos\theta} \]  

where \( T \) is the crystalline size, \( k \) is the constant that varies with the method of taking the breath, \( \lambda \) is the wavelength of incident X-rays, \( B \) is the width of the peak at half maximum intensity of a specific phase, \( \theta \) is a Bragg angle.

It is important to fix the parameters that influence the machining output to a greater extent. From the literature [10], the important machining parameters considered are: rake angle, depth of cut, heat treatment, feed and cutting velocity for which the output response used to measure the machinability is crystalline size and micro hardness. Different levels of machining parameters are chosen to determine the optimal machining parameters to get the desired output response: higher hardness and lower crystalline size. Table 1 shows the all the machining parameters and their corresponding levels.

2.2. Input and output variables

Table 2 shows the 5 input parameters selected for analysis. These parameters are considered potentially influential on prediction of the micro hardness and crystalline size parameters in Table 3.

<table>
<thead>
<tr>
<th>Table 1: Input parameters</th>
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<tbody>
<tr>
<td>Inputs</td>
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<td>input 1</td>
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<td>input 2</td>
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<td>input 3</td>
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<td>input 4</td>
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<td>input 5</td>
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<table>
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<th>Table 2: Input parameters</th>
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<tbody>
<tr>
<td>Inputs</td>
</tr>
<tr>
<td>input 1</td>
</tr>
<tr>
<td>input 2</td>
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<tr>
<td>input 3</td>
</tr>
<tr>
<td>input 4</td>
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<tr>
<td>input 5</td>
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</tbody>
</table>

Table 3: Output parameters

<table>
<thead>
<tr>
<th>Output</th>
<th>Parameters description</th>
<th>Min-Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>output 1</td>
<td>Micro hardness (VHN)</td>
<td>462-834.5</td>
</tr>
<tr>
<td>output 2</td>
<td>Crystalline size (nm)</td>
<td>28.52-73.39</td>
</tr>
</tbody>
</table>

To build a system with the best characteristics, it is necessary to identify the most relevant and influential subset of parameters and subject these to analysis. This process of selection is usually called variable selection. The purpose of this process is to find a subset of the total set of parameters that have been recorded that show good capability of prediction. Essentially, with neural network as the foundation, we modeled the complex system’s architecture in function of approximation and regression. Neural networks are an architecture which is made up of extremely parallel adaptive processing elements. These are interconnected through structured networks. Therefore, the accuracy of the neural network models which are created as a result of this data relies heavily on the accuracy of the chosen sensor data in the representation of the system. To achieve a successful generation and creation of a model which is capable to estimate a special process output, the selection process of the subset of parameters that are really pertinent is crucial. This is achieved in the process of variable selection. As mentioned before, the purpose of this procedure is to find a subset of the total set of parameters that have been recorded to show good capability of prediction [11, 12, 13, 14]. The problems faced in the process of the selection of parameters could possibly be resolved by integrating and applying prior knowledge to segregate and remove parameters that are irrelevant. Otherwise, a more sophisticated manner of approach to the above-mentioned problem is to view it as an optimization procedure through the use of genetic algorithms [15]. The objective here is to select the proper explanatory (input) parameters and thereby reduce and minimize the error that exists between the observed values and the model estimations of the explained variables. Amongst the many neural network system, one of the most used and powerful is the ANFIS; and the ANFIS was employed here, for the purposes of this study, in the variable selection part [16].

3. RESULTS

3.1. Evaluation criteria indices

Predictive performances of proposed model were presented as root means square error (RMSE), Coefficient of determination (R^2) and Pearson coefficient (r). These statistics are defined as follows:

1) root-mean-square error (RMSE)

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \]  

2) Pearson correlation coefficient (r)

\[ r = \frac{n\sum_{i=1}^{n}P_iO_i - (\sum_{i=1}^{n}P_i)(\sum_{i=1}^{n}O_i)}{\sqrt{n\sum_{i=1}^{n}P_i^2 - (\sum_{i=1}^{n}P_i)^2} \sqrt{n\sum_{i=1}^{n}O_i^2 - (\sum_{i=1}^{n}O_i)^2}} \]
3) coefficient of determination ($R^2$)

$$R^2 = \left[ \frac{\sum_{i=1}^{n} (O_i - \overline{O}) (P_i - \overline{P})}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \right]^2$$  \hspace{1cm} (3)

where $P_i$ and $O_i$ are known as the experimental and forecast values of, respectively, and $n$ is the total number of test data.

### 3.2. ANFIS prediction

Figure 1 shows scatter plots of ANFIS prediction of micro hardness (Figure 1(a)) and prediction of crystalline size (Figure 1(b)). The better prediction accuracy can be observed for micro hardness prediction than for the crystalline size prediction. This observation can be confirmed with very high value for coefficient of determination. The number of either overestimated or underestimated values produced is limited. Consequently, it is obvious that the predicted values enjoy high level precision.

In order to demonstrate the merits of the proposed models on a more definite and tangible basis, four models’ prediction accuracy was compared each other. Conventional error statistical indicators, RMSE, $r$ and $R^2$ were used for comparison. Table 4 summarize the prediction accuracy results.

<table>
<thead>
<tr>
<th>Micro hardness</th>
<th>$r$</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{O}$</td>
<td>0.969506</td>
<td>0.9399</td>
<td>26.58499</td>
</tr>
<tr>
<td>Crystalline size</td>
<td>$r$</td>
<td>$R^2$</td>
<td>RMSE</td>
</tr>
<tr>
<td>$\overline{O}$</td>
<td>0.857226</td>
<td>0.7348</td>
<td>6.307403</td>
</tr>
</tbody>
</table>

### 3.3. Sensitivity analysis

A comprehensive search was performed from the given inputs in order to choose the set of the ultimate optimal combination inputs (Table 1) which has the most impact and influence on the output parameters (micro hardness and crystalline size). Basically, an ANFIS model is built by the functions for each combination and they are then respectively trained for single epoch. Subsequently, the achieved performance is reported. From the outset, the most impactful input in the prediction of the output was identified and determined, as depicted in Table 5. The input variables with the lowest training errors have the most relevance in regards to the outcome.

As it can be clearly seen from the Table 5, the input variable 4 (feed (mm/rev)) is the most influential for the micro hardness prediction and the input variable 5 (cutting velocity (mm/min)) is the most influential for the crystalline size prediction.

![Fig. 1: ANFIS scatter plots for prediction of (a) micro hardness and for (b) crystalline size](image)

| Table 4: Statistical results for prediction of micro hardness and crystalline size |
|----------------------------------|-----|-------|-------|
| Micro hardness | $r$ | $R^2$ | RMSE |
| $\overline{O}$ | 0.969506 | 0.9399 | 26.58499 |
| Crystalline size | $r$ | $R^2$ | RMSE |
| $\overline{O}$ | 0.857226 | 0.7348 | 6.307403 |

| Table 5: Input parameters influence on micro hardness and crystalline size prediction |
|----------------------------------|-----|-------|
| Micro hardness | Crystalline size |
| ANFIS model 1: in1 --> trn=79.8795, chk=132.4067 | ANFIS model 1: in1 --> trn=7.9538, chk=14.0770 |
| ANFIS model 2: in2 --> trn=87.6742, chk=117.6481 | ANFIS model 2: in2 --> trn=10.1254, chk=16.9335 |
| **ANFIS model 4: in4 --> trn=45.9984, chk=174.5915** | **ANFIS model 4: in4 --> trn=8.3189, chk=14.5005** |
| ANFIS model 5: in5 --> trn=75.6704, chk=172.3097 | ANFIS model 5: in5 --> trn=7.9134, chk=18.0515 |
4. CONCLUSION

The study carried out a systematic approach to predict the optimal micro hardness and crystalline size by the ANFIS methodology. The simulations also employed MATLAB, and outcomes were checked on the corresponding output blocks. If further research is attempted we recommend polling users for deeper issues to obtain increased reliability. The ANFIS is used to eliminate the vagueness in the information and produces the best machining conditions. The proposed ANFIS model is used to convert the complicated multiple performance characteristics into the optimization of single multi response performance index. As a results, the optimization methodology developed in this research is useful for enhancing the multiple performances characterizing in the production of nanostructure. The ANFIS network was also used to perform a variable search to determine how 5 parameters influence prediction of the micro hardness and crystalline size.

There are many advantages in the use of the ANFIS scheme. Some of the main advantages are: it is adaptable to optimization and adaptive methods, as well as being computationally efficient. ANFIS can be integrated with professional systems and rough sets for use in other applications. Systems that handle more complex parameters can also employ the use of ANFIS, as it is much faster compared to other control strategies. And here is yet another favorable aspect of ANFIS, it conducts the tedious job of training membership functions.

REFERENCES


CORRESPONDANCE

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PREDICTION OF THE FLOW STRESS OF TITANIUM ALLOY LOADED WITH HIGH STRAIN AT VARIOUS TEMPERATURES BY ADAPTIVE NEURO-FUZZY TECHNIQUE

Miloš MILOVANČEVIĆ
Dalibor PETKOVIĆ

Abstract: In this study the flow stress of titanium alloy (Ti-6Al-4V) under strain and various temperature conditions are analyzed. The flow stresses are measured at mechanical tests for different strain rates at different temperatures. The method of ANFIS (adaptive neuro fuzzy inference system) was applied to the data resulting from these measurements in order to predict the flow stress of titanium alloy loaded with strain and various temperatures. The ANFIS process for variable selection was also implemented in order to detect the predominant variables affecting the prediction of flow stress of titanium alloy.

Key words: ANFIS; prediction; flow stress; titanium alloy

1. INTRODUCTION

Titanium alloy Ti-6Al-4V is very important in industrial applications. The main characteristics of this alloy is good deformability, low density, high specific strength, corrosion resistance and high temperature strength retention. Since the mechanical characteristics of the alloy is very complex and very sensitive to the processing parameters strain rate and temperature, it is need to make a model for the deformation models of the alloy in relation to the input parameters. There are several numerical, analytical and experimental studies about the loading rate on this material. To understand and evaluate the thermo mechanical property of the titanium alloy, a uniaxial compression test was performed in [1] where is was found significant tension/compression asymmetry in the mechanical response under high strain rate loading. The high strain rate fracturing is characterized by ductile fracture behavior. The plastic deformation behaviors of titanium alloy over wide ranges of strain rate and temperature were investigated in [2] by the quasi-static and dynamic uniaxial compression tests where it was calculated the average standard deviations between the experimental and calculated flow stresses range from 4% to 13%. The residual stress and microstructure in the different depth of titanium alloy have been investigated in article [3] where the results shown that the dislocation interaction dominates the grain refinement process. The surface modification is the main technique to maintain a relatively good mechanical properties and biocompatibility. In article [4], a surface modification using different ceramic shot was done on the titanium alloy microstructures. Investigation [5] was shown that the laser shock processing could repair the surface defects of titanium alloy structure effectively and reduce the surface roughness with lower laser pulse energy. The flow stress of the titanium alloy increases with increasing equiaxed alpha phase, but decreases with increasing alpha grain size [6]. The estimated value of plastic zone size at the periphery of rough area is close to the average diameter of the primary grains of the titanium alloy [7]. In article [8] was shown that the limit strain decreases with temperature lowering but strain-rate increasing of the titanium alloy.

The obtained results so far are insufficient and highly time challenging. The main problem is the high strain rate and high temperature properties of the alloy since the alloy is subjected to impact or shock loading in the most crucial structures and components [9]. In other words there are need to develop the deformation model of the alloy for the conditions which seems best suited for the alloy.

Even though a number of new mathematical functions have been proposed for modeling of the plastic deformation behavior of the alloy, in this investigation the main aim is to overcome high nonlinearity of the plastic behavior of the alloy by applying the soft computing method. Artificial neural networks (ANN) can be used as alternative to analytical approach as ANN offers advantages such as no required knowledge of internal system parameters, compact solution for multi-variable problems.

In this investigation adaptive neuro-fuzzy inference system (ANFIS), which is a specific type of the ANN family, was used to predict the dynamic plastic behavior of the alloy or flow stress for different strain rates and in the different temperature range. ANFIS was applied also to select the most influential parameters affecting the prediction of flow stress if the alloy. ANFIS shows very good learning and prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. ANFIS, as a hybrid intelligent system that enhances the ability to automatically learn and adapt, was used by researchers in various engineering systems [12, 13].
2. METHODOLOGY

2.1. Experimental measurement

Alloy bars Ti-6Al-4V was used in this investigation. The bars have the following chemical composition: 6% Al, 4% V, 0.2% Fe, 0.015% C, 0.008% N, 0.0057% H and 0.15% O. Compression tests are performed for different strain rates ranging from 500 to 5000 s\(^{-1}\) and for different temperatures ranging from room temperature to 1100°C. The experimental procedure is described in [26]. The stress in the specimen is obtained from the strain as the face of the transmitter bar in contact with the specimen. Since the bar is elastic the following equation can be stated:

\[
\sigma_s = E_\beta (\varepsilon_{TB} + \varepsilon_{TB}^p)
\]  

(1)

where \(\varepsilon_{TB}^p\) is a pulse which can be determined from strain pulses \(\varepsilon_{TA}\) and \(\varepsilon_{TB}\) which are recorded as the incident and transmitter bar gauge stations. The pulse changes are caused by transmission through the thermal gradient:

\[
\frac{\varepsilon_T}{\varepsilon_I} = \frac{2E_1}{E_1 + (E_1E_2)^{1/2}}
\]

(2)

where \(E_1\) and \(E_2\) are the moduli of elasticity on the two sides of the bars’ thermal gradient. For room temperature tests, the strain, strain rate and specimen stress:

\[
\varepsilon = \left(\frac{2C_0}{L_0}\right) \int_0^L \varepsilon_t \, dt
\]

(3)

\[
\dot{\varepsilon} = \frac{2C_0\varepsilon_t}{L_0}
\]

(4)

\[
\sigma = E \left(\frac{A}{A_0}\right) \varepsilon_t
\]

(5)

where \(C_0\) is the longitudinal wave velocity in the bar, \(L_0\) is the effective gage length of the specimen, \(E\) is the Young’s modulus of the bar, \(A\) and \(A_0\) are the cross sectional areas of the bar and the specimen, respectively. Table 1 shows three input and output parameters which are used in this investigation. Output parameter flow stress is determined by measurements and by calculation.

<table>
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<td>input 2</td>
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<tr>
<td>input 3</td>
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<tr>
<td>output</td>
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2.2. ANFIS

Fuzzy inference system in MATLAB software is employed in the whole process of the ANFIS training and evaluation. An ANFIS network for 2 input variables is depicted in Figure 1.

![Fig. 1: ANFIS structure.](image)

The fuzzy IF-THEN rules of Takagi and Sugeno’s class and two inputs for the first-order Sugeno is employed for the purposes of this study:

\[
\mu(x) = \text{bell} \left(x; a_i, b_i, c_i, d_i\right) = \frac{1}{1+\left[\left(\frac{x-c_i}{a_i}\right)^2\right]^b_i}
\]

(7)

where \(\{a_i, b_i, c_i, d_i\}\) is the set of parameters set. The parameters of this layer are designated as premise parameters. Here, \(x\) and \(y\) are the inputs to nodes. The membership layer is the second layer. It looks for the weights of every membership function. This layer gets the receiving signals from the preceding layer and then it acts as membership function to the representation of the fuzzy sets of each input variable, respectively. Second layer nodes are non-adaptive. The layer acts as a multiplier for the receiving signals and sends out the outcome in \(w_i = \mu_{AB}(x) * \mu_{CD}(y)\) form. Every output node exhibits the firing strength of a rule. The next layer, the third, is known as the rule layer. All neurons here act as the pre-condition matching the fuzzy rules i.e. each rule’s activation level is calculated whereby the number of fuzzy rules is equal to the quantity of layers. Every node computes the normalized weights. The nodes in the 3rd layer are also considered non-adaptive. Each of the node computes the value of the rule’s firing strength over the sum of all rules’ firing strengths in the form of \(w_i^+ = \frac{w_i}{w_i + w_j}, i = 1,2\). The outcomes are referred to as the normalized firing strengths.
The 4th layer is responsible for providing the output values as a result of the inference of rules. This layer is also known as the defuzzification layer. Every 4th layer node is an adaptive node having the node function $O_i^4 = w_i^x x f = w_i^x(p_i x + q_i y + r_i)$. In this layer, the $\{p_i, q_i, r_i\}$ is the variable set. The variable set is designated as the consequent parameters.

The 5th and final layer is known as the output layer. It adds up all the receiving inputs from the preceding layer. Thereafter, it converts the fuzzy classification outcomes into a binary (crisp). The single node of the 5th layer is considered non-adaptive. This node calculates the total output as the whole sum of all receiving signals,

$$O_i^5 = \sum_i w_i^x x f = \frac{\sum_i w_i f}{\sum_i w_i}$$ (8)

In the process of identification of variables in the ANFIS architectures, the hybrid learning algorithms were applied. The functional signals progress until the 4th layer whereby the hybrid learning algorithm passes. Further, the consequent variables are found by the least squares estimation. In the backward pass, the error rates circulate backwards and the premise variables are synchronized through the gradient decline order.

3. RESULTS

3.1. Evaluation criteria indices

Predictive performances of proposed model were presented as root means square error (RMSE), Coefficient of determination ($R^2$) and Pearson coefficient ($r$). These statistics are defined as follows:

1) root-mean-square error (RMSE)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2},$$ (9)

2) Pearson correlation coefficient ($r$)

$$r = \frac{\frac{1}{n} \sum_{i=1}^{n} O_i P_i - \left(\frac{\sum_{i=1}^{n} O_i}{n}\right) \left(\frac{\sum_{i=1}^{n} P_i}{n}\right)}{\sqrt{\left(\frac{1}{n} \sum_{i=1}^{n} O_i^2 - \left(\frac{\sum_{i=1}^{n} O_i}{n}\right)^2\right) \left(\frac{1}{n} \sum_{i=1}^{n} P_i^2 - \left(\frac{\sum_{i=1}^{n} P_i}{n}\right)^2\right)}}$$ (10)

3) coefficient of determination ($R^2$)

$$R^2 = \frac{\left(\frac{1}{n} \sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})\right)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sum_{i=1}^{n} (P_i - \bar{P})^2}$$ (11)

where $P_i$ and $O_i$ are known as the experimental and forecast values of, respectively, and $n$ is the total number of test data.

3.2. ANFIS prediction

Figure 2 shows scatter plots of ANFIS prediction of flow stress of titanium alloy. This observation can be confirmed with very high value for coefficient of determination. The number of either overestimated or underestimated values produced is limited. Consequently, it is obvious that the predicted values enjoy high level precision.

![Fig. 2: ANFIS scatter plots for prediction of flow stress of titanium alloy](image)

In order to demonstrate the merits of the proposed models on a more definite and tangible basis, four models’ prediction accuracy was compared each other. Conventional error statistical indicators, RMSE, $r$ and $R^2$ were used for comparison. Table 2 summarize the prediction accuracy results.

<table>
<thead>
<tr>
<th>Flow stress of titanium alloy prediction</th>
<th>$r$</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.999228</td>
<td>0.9985</td>
<td>11.20064</td>
</tr>
</tbody>
</table>

3.3. Sensitivity analysis

A comprehensive search was performed from the given inputs in order to choose the set of the ultimate optimal combination inputs (Table 1) which has the most impact and influence on the output parameter (flow stress of titanium alloy). Basically, an ANFIS model is built by the functions for each combination and they are then respectively trained for single epoch. Subsequently, the achieved performance is reported. From the outset, the most impactful input in the prediction of the output was identified and determined, as depicted in Table 3. The input variables with the lowest training errors have the most relevance in regards to the outcome.

As it can be clearly seen from the Table 3, the input variable 2 is the most influential for the flow stress of titanium alloy prediction and the optimal combination of input variable 2 and 3 is the most influential for the flow stress of titanium alloy prediction.
Table 3: Input parameters influence on flow stress of titanium alloy prediction

<table>
<thead>
<tr>
<th>One input</th>
<th>Two inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANFIS model 1: (\text{in1} \rightarrow \text{trn}=276.3501, \text{chk}=294.4293)</td>
<td>ANFIS model 1: (\text{in1} \rightarrow \text{trn}=16.7083, \text{chk}=18.3606)</td>
</tr>
<tr>
<td>ANFIS model 2: (\text{in2} \rightarrow \text{trn}=38.1348, \text{chk}=32.8575)</td>
<td>ANFIS model 2: (\text{in1} \rightarrow \text{trn}=210.0466, \text{chk}=391.6481)</td>
</tr>
<tr>
<td>ANFIS model 3: (\text{in3} \rightarrow \text{trn}=264.7179, \text{chk}=286.0212)</td>
<td>ANFIS model 3: (\text{in2} \rightarrow \text{trn}=29.0827, \text{chk}=131.6645)</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The study carried out a systematic approach to predict the flow stress of titanium alloy by the ANFIS methodology. The plastic deformation behavior of the alloy subjected to high strain rate and under different temperatures has been investigated. The ANFIS is used to eliminate the vagueness in the information and produces the best machining conditions. The proposed ANFIS model is used to convert the complicated multiple performance characteristics into the single multi response performance index. As a results, the prediction methodology developed in this research is useful for enhancing the multiple performances characterizing in the production of titanium alloy. The ANFIS network was also used to perform a variable search to determine how 3 parameters influence prediction of the flow stress of titanium alloy.

There are many advantages in the use of the ANFIS scheme. Some of the main advantages are: it is adaptable to optimization and adaptive methods, as well as being computationally efficient. ANFIS can be integrated with professional systems and rough sets for use in other applications. Systems that handle more complex parameters can also employ the use of ANFIS, as it is much faster compared to other control strategies. And here is yet another favorable aspect of ANFIS, it conducts the tedious job of training membership functions.

REFERENCES


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THE INFLUENCE OF THE INPUT PARAMETERS TO THE DIMENSIONAL ACCURACY OF THE 3D PRINTED PROTOTYPE

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Aleksandra KOPRIVICA
Mirjana JOKANOVIĆ
Srđan ĆURIĆ

Abstract: The key of a success, in making the physical prototypes of a good accuracy, is certainly a technology of a rapid prototyping (RP - Rapid Prototyping), by which are, relatively rapidly and inexpensive, produced different classes of a prototype. The RP technology implies a sequence of technological procedures which enable direct production of a complex of physical objects. The digital 3D geometric models are used as inputs. They may be prepared using a CAD program or a technology of a 3D scanning of the existing object and the subsequent treatment of the scanning results. One of the RP technologies, which is prepared by adding a physical model of the material, layer by layer, is 3D printing. Whereas, in 3D printing, the thickness of a layer is selected depending on the desired accuracy of the prototype, this paper analyses the influence of the thickness of the 3D printer to the dimensional accuracy of the prototype, in case when the prototyping is based on the CAD model.

Key words: 3D printer, dimensional accuracy, prototype.

1. INTRODUCTION

The increasing market globalization, as well as the constant acceleration of the technical - technological progress require from companies increased flexibility in product design. It is essential that companies are oriented to continuous innovation and the creation of new, or changes of the existing products. In the context of the product development, certainly the most important place takes a phase of the prototype production, where the model of the desired product is made, very representative, with high quality and the possibilities of testing the characteristics. Although the benefits of 3D printing are at a high level, one of the perceived flaws would be dimensional accuracy, that is, the deviation of the starting model, from the CAD software, to the produced prototype, which was analysed in this paper.

2. THE PROTOTYPE AND THE METHODS OF ITS PRODUCTION

Word prototype represent a derivative of the Greek words “protos” = first and “tipos” = impression of “prototipon” = primitive form. Accordingly, a general definition could be formed as follows: The prototype is the first or original copy of something that is or will be reproduced or developed. However, given the widespread use of the prototype concept in practice, the following comprehensive definition also could be used: A prototype is a first, the original shape, type, example of the product/system or of its part in an appropriate form, intended for various kinds of tests, testing and use, depending on the characteristics of the prototype and the areas of the implementation of the newly-developed products/systems [1].

For centuries it was thought that the design of a particular product is confirmed with the production of its physical model of the prototype. However, at the present time, fabrication of the prototype, as an important part of the product development process, comprise the activities of the design, optimization and simulation on the computer and also creating a real, tangible and functional part (physical prototype). On one side, there are virtual prototypes, which are studied and analyzed, while on the other hand, there is a physical model of the product, which is used for testing and experiments [2].

Methods for the production of a physical prototype can be classified into three groups [3]:

- traditional methods (manual and mechanical),
- rapid prototyping and
- others.

The greatest significance of the traditional method is the ability to create prototypes of the materials that will be used for the production. Traditional methods have some limitations, as for example: the time required for the production of the prototypes, the problems in making a complex object, a large amount of manual labor, a wide variety of technical and practical knowledge which are necessary for the prototypes' production [3].

Rapid prototyping is a general name for several similar technologies which produce physical prototypes directly, from CAD files or other digitized data by layered application of the building material [3].
2.1. Rapid Prototyping

The term rapid prototyping (RP) refers to a series of similar manufacturing processes by which are automatic, with successive application and with bonding layers of building materials, based on the control instruction created directly from CAD files or other digital data without the use of tools, equipment, without the need for additional machining operations, produced physical objects [1].

The process of applying the layers of the building material is commonly performed in a horizontal xy plane, while the process of interconnecting the layers of the building material is performed in a vertical z plane [1]. The overall process may be viewed through the 3 phase [3]:

- pre-processing,
- direct production of prototypes and
- post-processing.

Since the advantages of RP technology are extremely huge, it has resulted in the rapid development, so today we can speak about the tree of RP technologies. A common feature of all technologies is to use method of preparation of layer by layer, and depending on which material is used (liquid, solid, powder), they all may be divided into 2 groups [3]:

1. Techniques of materials addition, for building the physical model, layer by layer. Within this group there are a number of techniques but those that are commonly used in practice are: Stereolithography (SLA), Selective Laser Sintering (SLS), Modeling of the Deposit of Molten Material (FSM), 3D Printing (3DP).

2. The material removal processes, such as milling, which removes the excess material from the block of spatial model, thereby producing the desired physical model.

The characteristics of the previous mentioned technologies are given in the following table.

<table>
<thead>
<tr>
<th>RP TECHNOLOGY</th>
<th>SLA</th>
<th>SLS</th>
<th>FSM</th>
<th>3DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum size (mm)</td>
<td>510x510x610</td>
<td>380x330x460</td>
<td>610x510x610</td>
<td>510x610x410</td>
</tr>
<tr>
<td>Layer thickness (mm)</td>
<td>0.05-0.3</td>
<td>0.08-0.2</td>
<td>0.05</td>
<td>0.013-0.3</td>
</tr>
<tr>
<td>Accuracy (mm)</td>
<td>0.1-0.01</td>
<td>0.03-0.38</td>
<td>0.127-0.254</td>
<td>0.025-0.356</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Post-processing and liquid working materials</td>
<td>Size, weight and the price of the system</td>
<td>Speed</td>
<td>Stability of the model</td>
</tr>
</tbody>
</table>

2.1.1. 3D Printing

The work of these systems is based on chemical bonding, adhesive liquids - binder, powdered building materials, whereby physical objects are printed, directly from the 3D CAD environment [4].

The figure 1. illustrates the method of making one layer. The following sections should be noted on the schematic view: on the left side there is a dust storage and a piston for adding material. The roller is shown as a circle, along which is a moving bridge represented as a square. In the middle, there is a working chamber with a platform and on the right there is a hole for accepting the surplus of the material. The bridge can move in both directions and the head moves along the bridge. This makes the possibility for applying the binder in a horizontal plane [5].
In the first operation, the moving bridge, which carries the roller and the print head, moves from left to the right. The roller rotates in the direction shown in (1) and takes away a certain quantity of powder. Then, in the second step (2), this powder is drawn into a thin layer over the previously made layer on the platform of the working chamber. At the end of the walk to the right (3), the roller takes away the excess of the powder to the opening that accepts it and enters the repository. In the next step (4), the bridge moves from right to the left, and in the same time the nozzle on the print head of the syringe binds the appropriate points of the current cross-section and thus forms the liquid layer of the model. When the bridge arrives in the extremely left position (5), the piston for adding the material is raised by one step, while the platform is lowered by the thickness of the layer and everything is ready for the re-cycle [5].

Dust to which no binding agent is applied serves as a support. When the process is completed, the finished part is in unbound powder. The platform of the working volume is lifted and the part is removed from the excess powder. The excess material is sucked in and sifted and reused for the next model [5].

The produced prototype, removed from the machine working chamber can be applied for a limited use, while for the full use it is necessary to perform post-processing. Post-processing operations are reduced to the infiltration of the prototype by the appropriate means (wax, cyanoacrylate, two-component epoxy resin, etc.), blasting, painting, lacquering and metallizing for a better visual effect. By adding these agents, the prototype improves mechanical properties and ensures elasticity, all in accordance with the requirements and needs of the customer [5].

3. EXPERIMENTAL RESEARCH

3.1. The prototype production on the ZPrinter 450

The ZPrinter 450 features the latest features that automate and simplify the 3D color printing process. Pleasant design and simplicity, combined with high performance composite materials, have made it possible to use this printer widely. It is also important to emphasize that a precise 450 DPI 3D color prototype model is obtained, five to ten times faster than the others printer for the same purpose. The appearance of the printer is shown in the next figure 2 [6].

The ZPrinter 450 offers the ability to print prototypes of products of various designs, relief maps, human hearts, architectural models (in order for construction workers to have a cleaner picture of design plans, etc.), which puts it on the list of one of the most reliable and high quality printers. The biggest advantage is certainly the ability to print the prototypes in color [6].

The experiment was done in the laboratories at the Production and Management Faculty Trebinje. Workshop drawing of the object, i.e. the 2D model was developed using the AutoCad 2013 software (figure 3). Based on the 2D model, the 3D model, shown in the figure 4, was also created.

Since there are many factors that can have a different effect on achieving the accuracy of prototype production, it is important to emphasize that the printing was done in the function of varying the thickness of the layer. The constructed 3D model is converted into a STL file, after which the models, with the different layers’ thickness were made.
The size of the layers’ thicknesses and number of layers for each model is given in the table 2. Figure 5 shows produced models.

Table 2: The size of the layers’ thickness and number of layers

<table>
<thead>
<tr>
<th>MODEL</th>
<th>MODEL 2</th>
<th>MODEL 3</th>
<th>MODEL 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layers’ thickness</td>
<td>1.250</td>
<td>1.125</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of layers</td>
<td>78</td>
<td>87</td>
<td>98</td>
</tr>
</tbody>
</table>

Fig. 5: Produced models

Time, required, for all produced models is given in the following table 3.

Table 3: The total required time for models’ production

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>TIME [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
</tr>
<tr>
<td>Pre-processing</td>
<td>10</td>
</tr>
<tr>
<td>Direct production</td>
<td>35</td>
</tr>
<tr>
<td>Post-processing</td>
<td>50</td>
</tr>
<tr>
<td>TOTAL</td>
<td>95</td>
</tr>
</tbody>
</table>

After the models were made, they were accessed by measurement, i.e. their height (h=35 mm), length (l=40 mm) and thickness (s=10 mm). Positions, at which the measurement was done, are shown in the next figures (figure 6, figure 7, figure 8). At every position, the dimensions were measured three times and after that their average values were used for the analyses.

Using Microsoft Excel, while analyzing the data and layer’s thicknesses, certain dependences were made. The deviation of the workpieces’ thickness, depending on the thickness of the layer, is shown in the figure 9. From the diagram, it can be seen that, contrary to expectation, the deviation is greatest at the lowest value of the thickness of the layer and it decreases with the increasing the layer’s thickness.
Of all geometric dimensions, the slightest deviation from the nominal measure, depending on the layer’s thickness, is the angle deviation, which is shown in the diagram in the figure 12. The diagram shows that the deviation is minimum at the smallest value of the layer’s thickness and that it first grows and then decreases, with the increasing the layer’s thickness.

4. CONCLUSION

The emergence of 3D printing technologies has already been declared by many as the third industrial revolution, as well as the technologies that will surely mark the 21st century. 3D printing solutions offer the ability to produce very complicated shapes of products and tools in a relatively short period of time, only based on 3D model of the product or tool design. Geometric shapes, which can not be achieved with conventional production technologies, do not pose any problems for 3D printing. In addition, 3D printing also allows the creation of a whole assembly made of parts, which are actually made as one product, so that the installation operation is missing.

Based on 3D prints, future products can be analyzed more efficiently, as well as avoiding potential bugs on products, that, based on a 3D computer model, could not be spotted. Previously said saves both, time and money.

From the analyses carried out, it can be concluded that the deviations of the geometric values from the nominal measure significantly depend on the thickness of the powder’s layer. Thus, when creating work items on a 3D printer, the thickness of the powder’s layer should be selected depending on the required accuracy of the geometric dimensions.

REFERENCES


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Abstract: In this paper, the results of experiments for ultrasonic assisted turning of hard to machine material SPM10 will be presented. Cutting force values will be shown for various cutting parameters. Ultrasonic assisted turning allows many hard-to-machine materials to be machined with greater material removal rate, prolonged tool life and less affected surface microstructure. Its benefits are beyond dispute and many authors have tested it and graded it as a positive upgrade for conventional machining process. It is found out that while turning the workpiece made of SPM10, cutting forces are reduced when compared with conventional turning.

Key words: ultrasonic assisted turning, cutting forces

1. INTRODUCTION

While machining with ultrasonic vibration assisted turning (UAT), the cutting tool is induced with small vibrations, usually couple of microns, and high frequency, around 20 kHz. Intermittent contact between the cutting tool and the workpiece is the result of this movement which means that cutting forces are generated only during one half-period of vibration. This cutting force is usually higher than those during conventional turning (CT), but average forces in UAT are smaller than those in CT. Ultrasonic assisted turning is a potential technology suitable for machining hard-to-machine metallic and non-metallic materials. Result of ultrasonic assisted turning usage leads to better surface of the machined workpiece, prolonged tool life and more favourable microstructure of the workpiece surface layer. The ultrasonic vibrations can be applied along any of the three cutting directions or along any combinations of them [1]. The most positive effect has been found to be generated during applying vibrations in the tangential direction, which is in the direction of the cutting force.

Main condition for vibration assisted cutting which has to be met to make an effect, is the cutting speed to be less than $v < v_c = 2\pi Af$, where $v_c$ is critical cutting speed, $A$ is an amplitude and $f$ is the frequency of vibrations.

In this paper a short presentation on developed ultrasonic assisted turning device will be presented. Also a brief preview of cutting forces while turning hard-to-machine material SPM10 will be made. Comparison with cutting force values between conventional turning and ultrasonic assisted turning will also be shown.

Ultrasonic vibrational cutting is long known and one of the first papers were [2] and [3]. As the time went by, the topic started expanding and soon many authors accepted the idea. For example influence on surface roughness in turning with ultrasonic vibrating tool has been later done by [4]. But the idea hit its peak only recently, with the development of technical equipment, mostly electronic controllers and powerful personal computers for simulations and modeling. One of the things that brought novelty is finite element numerical analysis. Among many areas it was also used for research on influence of ultrasonic vibrational cutting on occurrence of chatter during turning [5]. The obtained results from the numerical analysis for some selected points of the stability lobe were compared and validated against the observed experimental results. It was shown that ultrasonic vibration can improve the stability for some cutting conditions, while degrading the stability in others. Hence, the proposed numerical analysis is a valuable tool to aid the designer to predict the effect of ultrasonic vibration on chatter stability [5]. Prior that, one paper analysed the influence of ultrasonic turning on chatter [6] and came to the conclusion that chatter is effectively suppressed irrespective of the tool geometry by vibration cutting. However, in the case of conventional cutting the occurrence of chatter was strongly influenced by the tool geometry. Obviously, vibration cutting achieved a higher cutting stability as compared with conventional cutting. By applying the vibration cutting method, the occurrence of chatter can be reduced significantly [6].

Regarding a theoretical basics of UAT, one of the most in depth paper which is dealing with this subject is [7]. A kinematics model has been developed in the mentioned study for the relative movement between the cutting tool and workpiece in UAT. Among the others, the model...
predicts that the cutting tool does not disengage from the workpiece during its cyclic motion and inevitably rubs and presses against the lateral surface remaining after each revolution of the workpiece. [7]. In the second part of this [8] study, a dynamics model has been developed for UAT. The model can theoretically estimate the instantaneous cutting mechanics parameters and forces at various vibration frequencies and amplitudes and for different turning parameters. It is found out that the cutting process is carried out easier at large rake angles due to the lower cutting forces in UAT [8]. Third part [9], which is the final part of this study, is experimentally investigating claims of hypothesis and models stated in two previous works. There was a close agreement between the theoretical and experimental. The development of new materials such as high-strength metals, composites and ceramics, which are very hard, brittle and abrasive, is demanding progress in the machining techniques. Ultrasonic assisted turning is one of the promising techniques for machining intractable materials. These new materials include Ni and Ti based super alloys, composites, ceramics, glass etc. [10]. Some everyday hard-to-machine materials have been studied and machined with UAT, for example hardened steel SCM440 [11], stainless steel [12], low alloy steel (DF2) [13] and Ti-64 [14]. Others researches are focused on more complex materials like Inconel 718 [15] [16] [17], Ti-15333 [18] [19] or shape memory alloy Nitanol [20] [19]. Some focused their research on materials specially developed for certain purposes, like for example Ti-676-0.9La [21] or Ti-15332Zr-0.9La [22]. Most above mentioned papers reported improvement in machinability of those hard to machine materials with ultrasonic assisted turning.

Regarding abovementioned remarks it is clear that SPM10 hasn’t been machined with ultrasonic assisted turning. Because of its acoustic properties, this material is heavily used for production of sonotrodes for ultrasonic welding. While having these optimal properties for usage, SPM10 has a big disadvantage which is a low tool life. To solve this problem a solution has been proposed to machine above mentioned material with ultrasonic assisted turning. By this time only partial experiments have been conducted and results are presented in this paper.

2. EXPERIMENTAL SETUP

At the Faculty of Technical Sciences, Department for Production Engineering a device has been developed for UAT. This project originated as cooperation with Telsonic company from Kac and the Faculty. Telsonic company, which is active in the field of ultrasonic welding, is using SPM10 for ultrasonic sonotrode manufacturing and had the need to improve the production process. The idea was to engage ultrasonic assisted turning and to try to extend tool life and to increase process parameters which would directly lead to shorter manufacturing time. Sonotrode, which is also the toolholder, is made from steel SPM10 and its dimensions are calculated with respect to acoustic properties given for frequency on which it will operate. Modeling of acoustic behavior of sonotrode has been performed in Solidworks and the snapshot of final result is shown on Fig. 1. Part of this equipment development has already been presented [23].

It can be seen that the ratio of input and output amplitude is 1:1, which is 20 µm on 20 kHz. Tool insert was VCGT 11 03 04-UM 1125 by Sandvik Coromant, two pieces which provided symmetric balance during oscillations. Through the brass ring the sonotrode was mounted on steel holder custom made to fit on Kistler 9257A dynamometer and onto the conventional lathe manufactured by Boehringer-Prvomajska. Classical piezo-electric ultrasonic transducer with 2kW power was used to drive the sonotrode. Telsonic ultrasonic generator type DHG2020 with auto tune option was used to drive the transducer. Position of ultrasonically assisted turning device mounted on the lathe is shown on Fig 2.

![Fig. 1: Acoustic properties of tool holder, modeled in Solidworks and result from acoustic analysis](image1)

![Fig. 2: Assembly of sonotrode on the lathe with Kistler dynamometer and ultrasonic transducer](image2)
### 3. EXPERIMENTAL RESULTS

As it was mentioned before workpiece material, used for this experiment, was tool steel SPM10. Chemical composition of this material is shown in Table 1. Tool insert used for this experiment was VCGT 11 03 04-UM 1125 made by Sandvik Coromant. Machining parameters which were varied are cutting speed $v$, feed rate $s$, depth of cut $a$ and the value of the amplitude $A$. They were all varied on three levels and values in each level are shown in Table 2. Average values of measured cutting forces are shown in Table 3, where $F_s$ is the feed (axial) force, $F_p$ is the passive (radial) force and $F_v$ is the main cutting (tangential) force.

For the experiment the Taguchi L$_{18}$ orthogonal array design was used. During experiments, at the beginning only conventional turning was employed. This phase lasted about 30 seconds and then the ultrasonic vibration was turned on for about the same time. With this kind of approach direct comparison of cutting forces can be made. Example of cutting forces variation is shown on graph in Fig 3. This example is for experiment number 7 in the Table 3.

![Fig. 3: Cutting forces for CT and UAT](image)

#### Table 1: Chemical composition of SPM10 tool steel

<table>
<thead>
<tr>
<th>Chemical element</th>
<th>Value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.45</td>
</tr>
<tr>
<td>Mn</td>
<td>0.5</td>
</tr>
<tr>
<td>Si</td>
<td>0.9</td>
</tr>
<tr>
<td>Cr</td>
<td>5.25</td>
</tr>
<tr>
<td>V</td>
<td>9.75</td>
</tr>
<tr>
<td>Mo</td>
<td>1.3</td>
</tr>
<tr>
<td>S</td>
<td>0.07</td>
</tr>
</tbody>
</table>

#### Table 2: Levels and values of machining parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cutting speed, $v$ [m/min]</td>
<td>10 20 30</td>
</tr>
<tr>
<td>B</td>
<td>Feed rate, $s$ [mm/rev]</td>
<td>0.1 0.15 0.2</td>
</tr>
<tr>
<td>C</td>
<td>Depth of cut, $a$ [mm]</td>
<td>0.2 0.4 0.6</td>
</tr>
<tr>
<td>D</td>
<td>Amplitude of oscillation, $A$ [$\mu$m]</td>
<td>10 15 20</td>
</tr>
</tbody>
</table>

#### Table 3: Experiment machining parameters and measured cutting forces for CT and UAT

|----------------|---------------------------|-------------------------|------------------------|-------------------------------------|-----------------------------------|---------|---------|-------------------------------------|---------|---------|
As can be noticed from measured cutting forces values, shown in Table 3, smaller values of cutting forces are generated during ultrasonic assisted turning. Figure 4 show the measured force components during conventional and ultrasonic assisted turning for experiment number 7. The average force is computed by performing a numerical average of the measured force component over time. The average tangential force reduces significantly from 100.85 N to 57.01 N, the radial force reduces significantly from 39.95 N to 21.18 N, the axial force reduces significantly from 20.6 N to 12.27 N, when the ultrasonic vibration is switched on.

Table 4 shows the results of ANOVA analysis for the main cutting force $F_v$, because the tangential force is traditionally referred to as primary cutting force. Results of this analysis is that main effect on cutting force has depth of cut with 40.6% of influence, the next in line is amplitude of oscillation with 23.2% and feed rate with 22.9%. It also suggest that the cutting speed has very little influence on main cutting force with only 6.7%.

![Fig. 4: Cutting forces for CT and UAT](image)

Table 4: ANOVA analysis for the main cutting force $F_v$

<table>
<thead>
<tr>
<th>Factor</th>
<th>DOF</th>
<th>Sum of squares</th>
<th>Variance</th>
<th>F-ratio</th>
<th>Pure Sum</th>
<th>Percent %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ($v$)</td>
<td>2</td>
<td>24,186</td>
<td>12,093</td>
<td>9.673</td>
<td>21,685</td>
<td>6,726</td>
</tr>
<tr>
<td>B ($s$)</td>
<td>2</td>
<td>76,339</td>
<td>38,169</td>
<td>30,534</td>
<td>73,839</td>
<td>22,904</td>
</tr>
<tr>
<td>C ($a$)</td>
<td>2</td>
<td>133,351</td>
<td>66,675</td>
<td>53,337</td>
<td>130,851</td>
<td>40,588</td>
</tr>
<tr>
<td>D (A)</td>
<td>2</td>
<td>77,254</td>
<td>38,627</td>
<td>30,9</td>
<td>74,754</td>
<td>23,188</td>
</tr>
<tr>
<td>Other</td>
<td>9</td>
<td>11,249</td>
<td>1,249</td>
<td></td>
<td>6,594</td>
<td>6,594</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>322,382</td>
<td>1,249</td>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The overall effectiveness of UAT in the cutting hard to machine material such as steel SPM10 is demonstrated. As can be seen from Table 3 a noticeable reduction in cutting forces has been observed while using ultrasonic assisted turning with comparison to conventional turning. The reduction in average tool force measured for UAT are a result of the intermittent contact between the tool and uncut material. In-depth investigation of process behaviour is suggested while ultrasonically assisted turning of SPM10. Tool wear is also one of the main parameters which is to be monitored to see if there is any influence of this technology in tool life duration.

Acknowledgements

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REFERENCES


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THE USE OF MODERN INFORMATION TECHNOLOGIES IN THE EDUCATIONAL PROCESS OF GRAPHIC ENGINEERS AND DESIGNERS

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Abstract: Graphic engineering and design is considered as rapidly growing and changing industry field. Complexity of education in this field may be reflected in understanding and learning structural design and operating ways of graphic equipment, if only conventional educational tools are used. Integration of wide variety of multimedia formats can be helpful supplement to conventional teaching method. With recent development of virtual and augmented reality, web, communication and mobile technologies it become possible to enrich education experience and augmented reality to be used to its full potential in education. The graphic industry equipment (printing presses, folding and cutting machines etc.) reproduced in a 3D virtual environment with ability to disassemble and analyze particles and animations of production processes can provide students with lifelike experiences, mimic the real-life usage scenarios, ensuring deeper immersion in learning process.

Thus, this paper aims to present possibilities for integration of augmented reality technology in education of graphic engineers and designers, which can lead to far better comprehension of the subject and improvement of learning process. The concept presented can be easily implemented in other engineering fields as well.

Key words: IT technologies, augmented reality, education, graphic engineering, graphic design

1. INTRODUCTION

Graphic engineering and design is rapidly growing and fast changing industry field. Complexity of education in this field may be reflected in understanding and learning structural design, operating ways of graphic equipment and training for successful organisation of production process. Having in mind that education is the process of facilitating learning, or the acquisition of knowledge, skills, values, beliefs, and habits related to the field the means and media by which the knowledge is conveyed, which may include the classroom, a variety of technologies, independent study, or a combination of approaches plays extremely significant role. Importance of face to face education cannot be underestimated but technological developments during past few decades offer new and exciting possibilities for supplement and further improve the education process [1]. Integration of wide variety of multimedia formats can be helpful supplement to conventional teaching method especially in fast changing fields such as graphic engineering. Recent development of virtual and augmented reality, web, communication and mobile technologies made possible to enrich education experience and to stay up to pace with dynamic changes with employment of these cost effective technologies. Some studies show that online and classroom learning are essentially equally effective, thus cost effectiveness is bonus [2].

3D virtual environment reproduction of graphic industry production systems (printing presses, folding and cutting machines etc.) offer possibilities to gain overview of production system functionality as a whole, and also to disassemble systems and individual machinery in order analyze subsystems detailed. This provides students with lifelike experiences, mimics the real-life usage scenarios, ensuring deeper immersion in learning process.

Besides higher education vocational training as life long process with aim to improve job performance is where new technologies prove their worth offering possibilities to learn in such a way that it does not interfere with the job: typically, outside work hours and not at a fixed place. The desire to make education less dependent on time and place is mainly related to the increasing number of people who combine study and work in order to stay well prepared for changes in job requirements, to improve career perspectives, and to realize personal growth [3].

There are some optical in adoption of E-learning. Prediction in 1998. was that 50 percent of all workplace training would be delivered online. Today actual percentage in developed countries is about to 15 to 20 percent and significantly less in undeveloped countries. Main advantage of E-learning so far has been eliminating training related travel costs in industry.
Advantages and disadvantages of E-learning must be considered carefully before making the decision of investing in such a system, some of them are given below [4]:

**Advantages of E-learning**
- Reduction of travel cost and time
- Class work can be scheduled around personal time table
- Students can study wherever and whenever they have access to a computer and internet
- Self-paced learning modules
- Flexibility to join discussions in chat rooms
- Different learning styles in one course
- Students have the option to select learning materials for their level of knowledge and interest

**Disadvantages of E-learning**
- Problems with motivation
- Isolation and lack of social interaction
- Instructor may not always be available on demand
- Some courses can be difficult to simulate
- Software usage can involve a learning curve
- This form of education may take getting used to
- Slow or unreliable Internet connections influences performance

2. INFORMATION TECHNOLOGIES IN THE EDUCATIONAL PROCESS

There are several different technologies that can be utilized for educational purposes. Basic approach would entail dissemination of the learning materials through electronic media in contrast to classical printed material. Electronic media offer significantly more possibilities for communication, through multimedia materials (sound, animation, interactivity, etc.). Presentation of the material is usually done on the screen of a computer or a mobile device. Latest technological advancements offer possibilities for reality augmentation or virtual reality utilization. Department for graphical engineering and design has so far developed a significant number of simulations presented in virtual laboratory. There are also mobile application based on augmented reality technology produced in order to help in the engineering field education.

2.1. Multimedia knowledge base with equipment presentation

Developed of knowledge base consists of numerous theoretical materials presented using up to date multimedia technologies. Special addition to the knowledge base is rich library of graphic equipment interactive presentations. These presentations are based on a virtual 3D visualization allows examination of all system elements with the insight into the knowledge base containing information about the theoretical and practical functioning of each element in virtual space. Figure 1 shows one of such presentations regarding the process of packaging prototyping for the particular case of graphic cutter Aristo Mat 1317 SL. The student is provided with unambiguous information about operation carried out by the device and its basic parts, which significantly facilitates the acquisition of knowledge about the system [5].

![Fig. 1. E-learning presentation of Aristo Mat 1317 SL](image1)

2.2. Equipment simulation

Different approach to the training is production of functional simulations of graphic equipment. Building on the previous concept of presentation, simulation offers full functionality reproduced in virtual environment.

![Fig. 2. Simulation operation algorithm](image2)
Functional simulation of paper cutting graphical system, which algorithm is shown in figure 2, is problem and project based learning tool. Simulating machine operation and JDF like programming for graphical equipment can prepare trainee for operating real machines by mimicking user interface of graphic equipment. Flash based animation supported by ActionScript programming language offers all the tools needed for creating such simulation [4].

Other simulation based learning tool is HP-200 colorimeter training application shown in figure 3. This application alongside theoretical knowledge regarding color measurements offers the functional simulation of the device with preprogrammed tasks for the trainee and appropriate corrections in case of mistake.

Fig. 3. Simulation of HP-200 colorimeter

Its functionality can prepare trainee for real world problems. Simulation program essentially allows the user to conduct an operations of the process through simulation without actually occupying device, leaving it free for other use. It mimics real world situations and problems to some extent depending on the complexity and versatility of possible problem solutions.

2.3. Augmented reality application for education

Augmented reality technology as an education tool achieved its full potential through advancements of the hardware performance in mobile devices. It made possible capturing the real world images in sufficient quality, processing them, simultaneously processing the virtual content and combining them into augmented reality displayed on the device’s screen. Augmented reality basically overlays computer-generated virtual elements onto the real-world images, thus enhancing their informative or entertainment value. Most important characteristic of this concept is that the overlay content is context-sensitive, which means that information displayed is triggered by the real world object in real time. For education field Vision-based tracking technique is especially interesting having in mind that augmented reality is usually used as an upgrade to existing printed learning materials.

Fig. 4. Interactive 3D model trigger

CADEDU application developed by the Department for graphical engineering and design uses Marker tracking technique, where the corresponding image descriptors are provided beforehand and stored into the database. Application offers integration of augmented reality into the cad modeling and engineering drawing training of designers and offers interactive 3D model augmentation and video augmentations, triggered by the figures 4 and 5. This application intended for Android platform and can be downloaded from the following address: www.grid.uns.ac.rs/symposium/download/cadedu.apk

When application is installed and run, interactive 3D model triggered by the image shown in figure 4 offers possibility to the user to manipulate the model and to get much better understanding of the object shape [6].

Fig. 5. Video augmentation trigger, placement and creation of the orthographic projections
3. CONCLUSION

This paper presented the possibility for usage of modern information technologies in the educational process of graphic engineers and designers through integration of multimedia material, interactivity and augmented reality technology. The basic approaches are explained followed with examples of applications utilizing that technology. Augmented reality technology as the most recent, offers exiting possibilities for integration with existing teaching materials and optimization of old material to fit better with future trends. Time needed for training on the real machine exploits production resources and by usage of the shown applications this can be changed, freeing up the equipment for other uses. Simulations of the machine operation can save expensive recourses and prevent injuries and equipment destruction by inexperienced trainee.

All the results shown are effort of the small group of authors, with evolvement of the experts in each of the fields mentioned. Future research will be focused on the exploitation of the other possibilities of the augmented reality technology and introduction of virtual reality technology in the educational process.

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REFERENCES


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LASERES WITH THE SOLID EASY AND THEIR APPLICATIONS FOR GRAVING ON TRANSPARENT MATERIALS

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Mileta JANJIĆ

Abstract: LASER is an acronym of English words “Light Amplification by Stimulated Emission of Radiation”, which in translation means an increase in light stimulated by radiation emission. In fact, the laser is a light oscillator, that is, a generator of monochromatic, coherent and directional light. The main feature of this light is the possibility of focusing on a small diameter point (<1 mm), which is impossible with natural light [2]. In this paper, the application of solid-core lasers Nd: YAG is shown for sub-surface engraving on transparent materials (crystals).

Key words: Nd: YAG laser, 3D crystal K9, modeling, sub-engraving

LASERI S ČVRSTIM JEZGROM I NJIHOVA PRIMJENA ZA GRAVIRANJE NA TRANSPARENTNIM MATERIJALIMA


Ključne riječi: Nd: YAG laser, 3D kristal K9, modeliranje, podpovršinsko graviranje

1. UVOD

Laser je uređaj za stvaranje i pojačavanje koherentnog elektromagnetnog najčešće monohromatskog, usko usmjerenog zračenja. Zasniva se na kvantnim pojavama prilikom prenosa energije zračenjem. Izmjena energije zračenja s atomima ili molekulima aktivnog medija u laseru (plin, kristal, plazma), odvija se stimulisanom emisijom. To se događa kada se na atom ili molekulu u pobuđenom stanju, to jest u stanju u kojem su elektroni na višem energetskom nivou, djeluje bijelom svjetlošću ili elektromagnetnim poljem. Laseri se razlikuju prema vrsti aktivnog materijala koji služi za pojačavanje svjetlosti. Za rezanje i graviranje se upotrebljavaju CO2 i Nd:YAG laseri, koji su dobili ime prema vrsti aktivnog materijala. Značaj svakog lasera je talasna dužina emitovane svjetlosti (λ). Ona je funkcija različite energetskih stanja atoma / molekula aktivnog medija. Uopšteno govoreći CO2 laseri rade odlično na materijalima koji su slabi provodnici toplote i elektriciteta. Čisti metal i druge refleksivne površine ne mogu da absorbiraju svjetlost generiranu u CO2 laserima tako dobro kako to mogu, svjetlost generiranu u YAG laserima. Lasersko markiranje ima svaki dan sve veću primjenu u različitim granama industrije. Primjenjuje se u elektronici, automobilskoj industriji, na polju široke potrošnje, a naročito je značajna njegova primjena u medicini. Svake godine se razvijaju nove osobine i poboljšavaju laserski sistemi. Laser proizvodi ekstremno intenzivni snop svjetlosne energije. Da bi gravirao snop se fokusira (kroz specijalno sočivo) u tačku veličine 0.01mm. Fokusirani snop je tako intenzivan da ustvari površinu materijala, i ostavlja trag ili prolazi kroz materijal i isjeca ga. U oblasti laserskog graviranja najčešće se koriste CO2 i YAG laseri. CO2 laser radi na principu podizanja energetskog stanja molekula mješavine gasova ugljen-doksida i obično nitrogena i helijuma, dok YAG laseri koriste diodnu pumpu. Predmet istraživanja ovog rada je nastanak, razvoj i primjena čvrstostelnog Nd: YAG lasera za podpovršinsko graviranje u 3D kristalima i drugim transparentnim materijalima.
2. OSNOVNA PODJELA LASERA

Poznato je na hiljade vrsta lasera, ali većina je samo za specijalne istraživačke svrhe. Osnovna podjela lasera je na:
- pulsné lasere, lasere sa čvrstim jezgrom, gasne lasere, poluvodičke lasere, hemijske lasere, lasere sa bojilima, lasere sa slobodnim elektronima [7].

3. OBLASTI PRIMJENE LASERA


4. DIJELOVI LASERA

Laser se sastoji od tri osnovna dijela (Sl. 1.):
- Energija za pobuđivanje medija ili laserska pumpa,
- Laserski medij ili laserski materijal,
- Dva ili više ogledala koji stvaraju rezonantnu šupljinu ili optički rezonator [5].

4.1. Laserska pumpa

Laserska pumpa (engl. pump source) je dio koji osigurava energiju za rad lasera. To može biti električno pražnjenje naboja, bljeskalica (engl. flashlamp) elektrolučna svjetiljka, svjetlo sa drugog lasera, hemijska reakcija ili čak eksplozivno sredstvo. Koja će se vrsta laserske pumpe upotrijebiti, zavisi o laserskom materijalu. Tako na primjer, Nd: YAG laser koristi lasersku diodu.

4.2. Laserski medij


4.3. Optički rezonator

Optički rezonator (engl. optical resonator) predstavlja dva paralelna ogledala, smještena oko laserskog medija,
koji omogućuje povratnu vezu svjetla. Na ogledala se stavljaju optički premazi, koji određuju stepen refleksije. Uglavnom, jedan je reflektor s visokim stepenom refleksije (engl. highly reflective mirror), dok je drugi reflektor s djelomičnim stepenom refleksije (engl. partially reflective mirror), koji se još naziva izlazni reflektor, zato što omogućuje da jedan dio svjetla napusti optički rezonator stvarajući izlazni snop lasera (engl. laser output) [5]. Svjetlo iz laserskog medija, stvoreno spontano emisijom usljed djelovanja laserske pumpe, se reflektuje na ogledalu i vraća u laserski medij, gdje može biti pojačana stimuliranim emisijom. Reflektovanje sa ogledala i prolazak kroz laserski medij, može se dogoditi i na stotine puta, prije nego svjetlost napusti optički rezonator. Kod složenijih lasersa, koristi se raspored sa 4 ili više ogledala. Konstrukcija i poravnanje ogledala, s obzirom na laserski složeni lasers, koristi se raspored sa 4 ili više ogledala. Konstrukcija i poravnanje ogledala, s obzirom na laserski medij, je od najveće važnosti za određivanje tačne radne talasne dužine i ostalih svojstava lasera.

5. Nd: YAG LASER


Sl. 2. Nd: YAG laser

6. SOFTWARE


7. SUB SURFACE LASER ENGRAVING (SSLE)

7.1. Istorija nastanka

Ova tehnika je gurnuta u drugi plan, tek nakon što je Kemin Du sa Instituta za lasersku tehnologiju u Ahenu-Njemačka, izmislio novi princip. Nova tehnologija je omogućila da se postigne 500 tačaka u sekundi. Nekoliko godina kasnije njegov sledeći izum, zasnovan na tzv. ploči lasera je dostigao astronomsku brzinu obilježava njega od 10 000 tačaka u sekundi. Ovim je drastično smanjena i krupnoća zrna, pa je finija struktura zrna omogućila ravnomjernije stvaranje 3D modela u optički čistom staklu K9 [10]. U stvari, ovako napravljena slika izgleda kao skulptura unutar bloka stakla. To je prva tehnika koja omogućava da se stvori "Skulptura" uz pomoć računara (CAD). Po prvi put se dešava da se 3D modeli iz unutrašnjosti računara transformišu u nešto što se pravi izvan njega [6].

**7.2. Princip rada**


**7.3. Kretanje laserskog snopa**

Kretanje laserskog zraka označava način na koji se laserski snop kreće da bi gravirao određenu sliku. Većina sistema podržava vektorsko i rastersko kretanje tj. isovremeno kretanje po X i Y osi. Rastersko kretanje, predstavlja kretanje laserske glave napred nazad. Za vrijeme graviranja, laserski snop se kreće od vrha prema dnu radne površine, dok snop oscilira lijevo i desno (Sl. 5.). Kako se snop kreće sa lijeva na desno, tako se uključuje i isključuje i gravira lik. Pored Watt-aže, ono što determiniše snagu lasera je i veličina tačke laserskog snopa. Kao što rečeno ranije, laserski snop je koncentrisan i fokusiran na veličinu "vrha igle" pomoću...
specijalnog sočiva, koje određuje kolika će količina svjetlosti biti prisutna u određenom polju. Treći tip kretanja je galvanometarski. Sa sistemom baziranom na galvanometru, laserski snop je usmjeren pomoću malih ogledala, koji se kontrolišu galvanometrom. Kako se napon dovede do galvanometra, u ogledalu se proizvodi lik, iznad gravure [1].

7.4. Pozicioniranje sočiva

Na koji način se sočivo podešava za fokusnu daljinu, je jedan od elemenata koji se razlikuju od proizvodjaca do proizvodjača. Fokusiranje predstavlja udaljavanje sočiva od materijala za graviranje na određenu distancu, da bi sočivo postiglo tačku na materijalu za graviranje. Ta distanca varira od tipa sočiva i od veličine tačke (spot size). Postoji ručno podešavanje fokusne distance, kada se oslobadaju zavrtnji na držaču sočiva i ono se fizički pomjerja na određenu distancu. Automatski način fokusiranja, podrazumijeva senzor za određivanje fokusne distance. Sve što trebate da uradite je da postavite materijal za graviranje na radnu ploču i mašina će automatski da postavi sočivo na korektnu fokusnu distancu. Ima različitih uredaja za automatsko fokusiranje, neki na primer imaju mogućnost određivanje fokusa na transparentnim materijalima, a neki čak i na konkavnim (oblim).

7.5. Prednosti i nedostaci galvanometarskog kretanja

Najveća prednost lasera baziranih na galvanometru je brzina. Brzina graviranja je termim koji se odnosi na brzinu kretanja laserske glave preko materijala za obradu i terminiše se kao inč na sekund (ips) ili cm na sekund (cps), i odnosi se na kretanje po pravoj liniji. Mnoge mašine imaju podešljivu brzinu, što je korisno za graviranje različitih materijala i različitih dubina graviranja. Ovaj tip lasersa ne prolazi horizontalnu putanju, koju mora da prođe mehanički sistem, nego se pojavljuje tamo gdje ima što radi tj. eliminira nepotrebno kretanje. Slednja prednost ove tehnologije je izuzetna mala potreba za održavanjem. Međutim, ovi sistemi imaju ograničenu radnu površinu, a i koštaju dosta više nego konvencionalni. Radna površina galvanometarskog lasera je reda veličine 300x400x100 mm. Pozicioniranje sočiva je automatizovano. Materijal (optički savršen stakleni blok) se postavlja na radnu ploču, i mašina automatski usmjerava laserski snop kroz transparentni blok na mjesto početka graviranja modela.

8. PRIMJENA GOTOVIH MODELA

Kao rezultat primjene Nd: YAG lasera, sofisticiranom tehnologijom, dobijaju se jako privlačne i nesvakidašnje skulpture oku posmatrača. Interesantno je da je moguće gravirati 3D modele u kristalu, po želji posmatrača i tako ih trajno ovjekovječiti. Dijapazon primjene ove tehnologije je zaista širok. Mogu poslužiti kao prigodni pokloni, kako za fizička tako i za pravna lica, sportske saveze, državne institucije, vjerska obilježja itd. Primjeri modela su prikazani na (Sl. 6.).
9. ZAKLJUČAK
Na kraju se može zaključiti da je ubrzan razvoj tehnike i tehnologije dovelo do prave laserske revolucije. Laser je našao svoju primjenu u gotovo svim oblastima ljudske djelatnosti. Posebno mjesto u industriji su našli laseri sa čvrstima jezgroma u koje spada i Nd: YAG laser. Zbog svojih karakteristika (emitovanja zelene svjetlosti 532 nm), našao je primjenu za podpovršinsko graviranje u 3D kristalima i ostalim transparentnim materijalima. Prednosti su mu: velika brzina rada, preciznost, tačnost, lako održavanje, dug vijek. Omogućeno je automatsko kretanje po X i Y osi, kao i podizanje radnog stola po Z osi. Međutim, ove laserske mašine imaju ograničenu radnu površinu 300x400x100 mm, zbog kretanja laserskog zraka, što je njihov nedostatak a i skuplji su od konvencionalnih.

LITERATURA

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HYDRO AND THERMAL POWER PLANTS
DESIGN OF WATER HAMMER CONTROL STRATEGIES IN HYDROPOWER PLANTS

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Abstract: Hydropower plants play an important role in the growth of the renewable energy sector. The main objective of the paper is to present, discuss and assess critical parameters which may cause unacceptable water hammer loads in hydropower plants. Water hammer is caused by flow disturbances in a conduit from one steady state to another. It induces pressure rise or drop in hydraulic systems, rotational speed variation in hydraulic turbomachinery and level fluctuation in surge tanks and air chambers. Design principles of water hammer control strategies (mitigation of excessive loads) are outlined including operational scenarios (closing and opening laws), surge control devices (flywheel, surge tank, regulating valve, air valve, etc.) or redesign of the pipeline components. Water hammer models and solutions are briefly discussed in the light of their capability. Case studies include hydropower plants with long fluid conveying systems (open channels, tunnels) and water hammer control devices (surge tank, regulating valve).

Key words: hydropower plant, water hammer control, surge tank, regulating valve

1. INTRODUCTION

Modern hydropower systems should be able to cover peak demands and to store surpluses of grid energy, in particular that coming from intermittent generators associated with wind and solar power. There are several key parameters associated with the design of a new or refurbishment of aging hydropower plant including safety, efficiency, availability and profitability of the plant. Refurbished plant by definition starts from old basic infrastructure which may raise issues not encountered with new plant: some ageing components cannot be refurbished adequately (in particular civil works), changes in the role of the plant in the energy system (increased operational flexibility), increase of plant output and changes in the environment of the plant. The objective of this paper is to present, discuss and assess the critical parameters which may cause unacceptable water hammer loads in hydropower plants. Flow-induced vibrations (draft-tube surge, rotor-stator interactions) [1] are beyond the scope of this paper. Water hammer [2] can be kept within the prescribed limits (e.g. pressure in the flow-passage system, turbine rotational speed, surge tank water level, etc.) with the following methods: (1) alteration of operational regimes, (2) installation of surge control devices in the system and (3) redesign of the flow-passage system layout.

2. DESIGN PRINCIPLES OF WATER HAMMER CONTROL STRATEGIES

Large transient loads may disturb overall operation of the hydropower plant and damage the system components. Water hammer [2] can be kept within the prescribed limits (e.g. pressure in the flow-passage system, turbine rotational speed, surge tank water level, etc.) with the following methods: (1) alteration of operational regimes, (2) installation of surge control devices in the system and (3) redesign of the flow-passage system layout.

2.1. Alteration of operational regimes

Alteration of operational regimes includes appropriate regulation of the wicket gate and runner blade maneuvers in reaction turbines, and turbine distributor (needle valve) and jet deflector maneuvers in impulse turbines. Typically a two-speed wicket gate closing time function (adding a cushioning stroke) significantly improves reaction turbine safe operation. Opening of runner blades during Kaplan or bulb turbine shutdown (normal, mechanical quick stop, emergency) results in favourable blade operation, improved over-speed performance and reduced negative axial hydraulic thrust. Appropriate setting of closing/opening times of the shutoff valves contributes to safer operation of these devices in emergency and exceptional operating conditions. A draft tube gate can be used to protect axial turbine against runaway. In addition, sluicing operation of the low-head axial turbines can attenuate open channel
waves during transient regimes. Limitation of operating regimes (reduced discharge) is yet another option. This measure may be considered as temporary one before more effective method is devised.

### 2.2. Installation of surge control devices

Installation of surge control devices in the system alter the system characteristics (shorten the active conduit length, reduce the liquid compressibility, increase the turbine unit inertia). The protective devices that may be installed along the inlet and outlet conduit or added to the hydropower system components include:

1. increased turbine unit inertia (adding flywheelATsmall units, increasing the generator inertia);
2. resistors (to absorb excessive power);
3. surge tank in headrace and/or tailrace (shortens the active conduit length, improves governing stability);
4. air cushion surge chamber (requires compressed air supply);
5. pressure-regulating valve (operates synchronously with the turbine wicket gates);
6. pressure-relief valve (opens at a set pressure, small units);
7. rupture disc (bursts at a set pressure, small units);
8. aeration pipe (attenuates water column separation);
9. air valve (attenuates water column separation, reduces negative axial hydraulic thrust).

### 2.3. Redesign of the flow-passage system layout

Redesign of the flow-passage system layout includes:

1. change of water conveyance profile (high point);
2. change of conduit dimensions (diameter, length);
3. different position of system components (valve).

Operational, safety and economic factors are decisive for selection of the type of protection against the undesirable water hammer effects. A number of alternatives should be investigated before the final design. The most convenient water hammer control method in the hydropower plant is the alteration of operational regimes. It is expensive to install additional surge control devices in the system except if this cannot be achieved by the first method. It is rarely feasible to redesign the proposed flow-passage system. Water hammer control devices should operate smoothly in normal operating conditions. These conditions include the turbine start-up, load acceptance, load reduction and total load rejection (mechanical quick stop, electrical emergency shutdown). Emergency conditions are load rejections in which the runner blades (axial and diagonal turbines) fail to operate or partial runaway occurs. The turbine runaway is considered as a catastrophic transient regime. Water hammer analysis should be performed for normal, emergency and catastrophic operating conditions [2].

### 3. WATER HAMMER ANALYSIS

Water hammer is the transmission of pressure waves along the pipeline resulting from a change in liquid flow velocity (discharge). It leads to higher dynamic loads on plant components during transient operating events (rapid load acceptance and reduction, unit shutdown). This requires a thorough transient analysis. Hydraulic transient analysis is traditionally undertaken with deterministic models [2], [3] that treat a number of transient regimes based on experience, guidelines and codes. In addition, parametric analysis accounts for uncertain parameters (e.g. friction, wave speed, turbine performance characteristics). These results form the basis for risk analysis to transients in hydropower plant that includes identification of critical regimes, evaluation of the risk (low, high) and risk management (modifications to reduce the risk) [4]. It is clear the scope of analysis is dependent on the type of the machine and complexity of the plant layout.

Water hammer in hydropower plants can be calculated using either elastic or rigid water hammer theory [2], [3]. The elastic liquid column model is used for the systems with relatively long tunnels and penstocks, and systems with rapid transients. Slightly compressible liquid and elastic pipe walls are assumed in the elastic column model. Unsteady flow in closed conduits is described by two one-dimensional equations; the continuity equation and the equation of motion. The hyperbolic set of equations is solved by the method of characteristics. For run-of-river power plants with relatively short inlet and outlet conduits the rigid column model is recommended. In this case the length of the conduit is of the same order as the cross-sectional dimensions. Incompressible liquid and rigid pipe walls are assumed in the rigid column model. Rigid water hammer is described by the one-dimensional equation of motion for unsteady pipe flow. The equation can be solved numerically by using the Runge-Kutta method. Elastic and rigid column equations are solved simultaneously with the boundary condition equations (turbine, valve, surge tank, reservoir, etc.) [2], [3]. The hydraulic turbomachine may undergo turbine, pump or pump-turbine operating modes. The governed turbine boundary condition is described by the turbine (head balance equation, dynamic equation of rotating masses) and the governor (dynamic equation which relates the pump-turbine rotational speed change to the position of the regulating mechanism(s)), and it is coupled with pipeline water hammer equations. The relationship among influential turbine variables is presented in the form of the experimentally predicted characteristics (head, torque, axial force). The complete set of the hydraulic turbomachine-governor-pipeline equations should be used for the case of load reduction in which the turbine speed is regulated by the governor. The governor equations are omitted in analysis for the case of turbine sudden load rejection in which the unit speed change is controlled by the turbine net torque only. The theoretical description of the actual hydropower system invariably introduces assumptions and approximations [5] which may have negligible influence in certain applications but introduce significant systematic errors in other circumstances. Field test cases are needed to verify water hammer models and adequacy of design strategies.

### 4. CASE STUDY 1: TURBINE EMERGENCY SHUTDOWN IN ZLATOLIČJE HPP

The Slovenian run-off river type Zlatoličje HPP has been recently refurbished. Two old Kaplan turbines were upgraded with new runners of larger output capacity each of 80 MW. Two Kaplan units are embedded into large-scale open channel system (Fig.1). The length of the inlet channel
is of 17,200 m and the outlet channel is 6,200 m long. The channels are of trapezoidal profile with its bottom and side walls concrete lined.

Each of the two Kaplan turbines (Fig. 2) is equipped with a pressure regulating valve (PRV). The PRV is comprised of five vertical vanes connected via the rod to servomotor and controlled by the turbine governor. The continuous measurement of the channel water level at the turbine inlet, and pressures in the turbine scroll case and draft tube indicates that water level oscillations in the two open channels are small and within the prescribed limits during water hammer events. The PRV attenuates free surface waves in both channels [6]. Therefore, the constant water levels at the turbine inlet and the turbine outlet are assumed in water hammer calculations. Analysis of free surface waves in both channels is beyond the scope of this paper. Fig. 3 shows action of the PRV during shutdown from full-load. The detailed plant layout used for water hammer calculations can be found in Bergant et al [6]. The length of the conduit is of the same order as the cross-sectional dimensions and the cross-sectional area is of complex shape. The standard one-dimensional elastic column water hammer model cannot accurately predict the physics of wave transmission and reflection in very short pipelines. The rigid column model is recommended to be used for this case. The dimensions of the inlet conduit, scroll-casing and draft tube used in the one-dimensional rigid water hammer model are expressed as geometrical characteristics $G_u = 0.876 \ m^{-1}$ and $G_d = 0.549 \ m^{-1}$, respectively ($G = \Sigma (L/A)$; $L =$ length, $A =$ area).

Emergency shutdown of the Kaplan turbine unit from 75 MW load is presented as the case of one of the most severe normal operating regimes with respect to large transient loads. The turbine is disconnected from the electrical grid followed by the complete closure of the wicket gates while the runner blades open to their fully open position (Fig. 4(a)). The PRV blades first open to about 90 % opening synchronously with the wicket gate closure (Fig. 4(a)) and then start to close at a very slow rate to its fully closed position. The PRV linear full-stroke closing time is twenty minutes.

The computed maximum momentary scroll case pressure head ($H_{sc}$) of 35 m practically coincides with the averaged measured one; there is a reasonable agreement between the calculated and measured draft tube pressure heads too (Fig. 4(b)). The agreement between the computed maximum rotational speed rise of 35 % and the measured one is good too (Fig. 4(c); $n_0 = 125 \ min^{-1}$). The maximum scroll case pressure head and the maximum speed rise are within the guaranteed limits (43.9 m and 45 %, respectively).
5. CASE STUDY 2: TURBINE EMERGENCY SHUTDOWN IN PERUĆICA HPP

Montenegrin Perućica HPP is comprised of a concrete tunnel (length 3335 m, diameter 4.8 m), surge tank (Fig. 5) and three parallel penstocks (Fig. 6) with horizontal-shaft Pelton turbines built at their downstream ends.

All seven turbine units are embedded in powerhouse (Fig. 7) with two tailrace tunnels (one for units A1 to A5, one for units A6 and A7). The runner diameter of twin type turbine units A1 to A5 is 2400 mm and for twin type turbine units A6 and A7 is 2100 mm. Two safety spherical valves are attached to each turbine unit. A detailed description of the Perućica HPP flow-passage system with its all main characteristics can be found in Karadžić et al [7]. Rehabilitation of turbine units has been performed in several stages. This includes supply of new distributors (needle valves) and refurbishment of the pertinent spherical valves (replacement of seals and actuating servomotors) for the first four turbine units, and finally, supply of six new Pelton wheels for 39 MW units and three wheels for 59 MW units.

The standard one-dimensional elastic column water hammer model is used for transient analysis because of long tunnel and penstocks. Method of characteristics based software package with a novel Pelton turbine boundary condition has been validated for a number of typical transient regimes [7] in Perućica HPP. Emergency shutdown of turbine unit A1 from initial power of 39.5 MW is presented in this paper. The corresponding discharge in the penstock I: 8.4 m$^3$/s, penstock II: no discharge and penstock III: 22 m$^3$/s.
Numerical and measured heads at the turbine inlet ($H$) for emergency shutdown of the unit A1 are compared in Fig. 8(b). The computed and the measured total needle closure times are the same (55.3 s - see Fig. 8(a)). Maximum measured head of 557.7 m occurs when the nozzle is fully closed. Head rise for this case is 24.5 m. Maximum calculated head is 556.4 m (two-speed closure; the cushioning stroke is 2.5%). The maximum calculated head matches the measured one. Calculated and measured heads are much lower than the maximum permissible head of 602 m. Fig. 8(c) shows comparison between computed and measured rotational speed. The maximum measured turbine rotational speed rise of 8.1% occurs at time of full deflection of the jet (at 1.6 s). The maximum computed turbine speed rise of 8.0% agrees well with the measured one. After jet deflector deflects all the water into the tailrace, the computed turbine speed decrease reasonably agrees with measured one. The maximum turbine inlet pressure head and the maximum speed rise are within the guaranteed limits.

6. CONCLUSIONS

Water hammer in hydropower plants is caused by turbine load acceptance and reduction, load rejection under governor control, emergency shutdown and unwanted runaway, and closure and opening of the safety shutoff valve. It induces pressure rise or drop in hydraulic systems, rotational speed variation in hydraulic turbomachinery (pumps and water turbines) and level fluctuation in surge tanks and air chambers.

The paper presents design principles of water hammer control strategies (mitigation of excessive loads) including operational scenarios (closing and opening laws), surge control devices (flywheel, surge tank, regulating valve, air valve, etc.) and redesign of the pipeline components. Classical theoretical water hammer models and solutions are briefly discussed in the light of their capability and availability. Case studies include hydropower plants with long fluid conveying systems (open channels, headrace and tailrace tunnels) and water hammer control devices (surge tank, regulating valve). Due to very long inflow and outflow open channels in Zlatoličje HPP a special vaned pressure regulating device attenuates extreme pressures in Kaplan turbine flow-passage system and controls unsteady flow in both open channels. Water hammer in inlet and outlet short conduits is controlled by appropriate adjustment of the wicket gates and runner blades closing/opening laws. Transients in long tunnel of Perućica HPP are controlled by cylindrical type surge tank with an expansion and overflow. Water hammer in the three penstocks that feed seven Pelton turbines is controlled by appropriate adjustment of the distributor needle valve closing/opening maneuvers.
The agreement between computed and measured results for emergency shutdown cases in both hydropower plants is reasonable. Most important, water hammer control means keep transient pressure heads and turbine rotational speed rise within the prescribed limits.

REFERENCES


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THE NUMERICAL CALCULATION BIFURCATION A6 OF PIPELINE C3 AT HPP “PERUCICA”

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Abstract: This paper presents the results of numerical calculation bifurcation A6 of pipeline C3 at HPP “Perucica”, which was realized in the summer of 2007 and spring of 2008, from the team of experts led by Dr. Milorad Miso Buric, the full professor of the Faculty of Mechanical Engineering in Podgorica and Head of the Center for transport machines and metal constructions (CETIM). The calculations were obtained at the critical points of the internal wall of the bifurcation that is the tension greater than the boundary of the large elongations for Nioval 47 steel, so it was concluded that there were cracks in these places. And indeed, when the protective paint was removed in these places, a large number of cracks were discovered. These cracks were then testing by the Institute of Black Metallurgy from Niksic and performed their analysis. The aforementioned expert team gave a written recommendation to the management of HPP “Perucica” to perform reconstruction of the bifurcation, emphasizing that the situation is very critical. In April 2016, Lahmeyer International GmbH, Germany, in Study of measures and works during Phase II of reconstruction for HPP “Perucica”, explicitly requires the reconstruction of the A6 bifurcation to be carried out, and additional surveys include other parts of the pipeline.

Key words: Numerical calculation of the tension state, critical tension, pipeline, cracks, reconstruction

THE NUMERICAL CALCULATION BIFURCATION A6 OF PIPELINE C3 AT HPP “PERUCICA”


Ključne riječi: numerički proračun naponskog stanja, kritični naponi, cjevovod, pukotine, rekonstrukcija.

1. UVOD

Na slici 1 je prikazan prostorni model cjevovoda C3 HE "Perućica".Na njemu se nalazi račva A6 (slika 2.) koja usmjerava vodu na agregate A6 i A7 i predstavlja jedno od najslожнојih i najosjetljivijih mjesta u cjevovodu C3. Ta složenost račve je bila jedan od razloga zašto smo veoma odgovorno i studiozno pristupili njenom ispitivanju. U okviru Elaborata(1) ekspertski tim pod rukovodstvom dr Milorada Miša Burića, redovnog profesora Mašinskog fakulteta u Podgorici i rukovodioca Centra za Transportne mašine i Metalne konstrukcije (CETIM) je izvršio numerički proračun račve A6 cjevovoda C3 HE "Perućica"[1].

2. NUMERIČKI PRORAČUN RAČVE A6 CJEVOVODA C3

2.1. Granični uslovi
Da bi se uradio detaljan proračun račve napravljen je kompletan prostorni model cjevovoda C3 od temelja T9 do agregata, dužine oko 200 m sa svim postojećim račvama (Slika 1.). Model je urađen veoma precizno i postavljen su korektno granični uslovi. Ovakav posao je podrazumijevao pravljenje izuzetno velikog geometrijskog modela, postavljanje mreže i romnog broja konačnih elemenata, postavljanje velikog broja oslonaca a zatim nanošenje opterećenja od pritiska vode i težine konstrukcije. Ukupan broj konačnih elemenata je 2.429.397 tipa tetraedar i 680 GAP elemenata upotrijebljenih za modeliranje oslonaca. Rezultati dobijeni ovakvim postupkom su opravdali veliki trud, znanje i uloženo vrijeme.

Karakteristike materijala od kojih je napravljen cjevovod C3 smo uzeli iz „Dokumentacije o kontroli materijala i kvaliteta izrade cjevovoda pod pritiskom za HE Perućica - treća faza“ koju je uradio Institut za ispitivanje materijala, Beograd 1975 godine. Slika 3 prikazuje fotografiju atesta, a Tabela 1 mehaničke karakteristike mikrolegiranog konstruktivnog čelika NIOVAL 47 od kojeg je izrađen cjevovod C3.

**Slika 3.**

Za potrebe korišćenog softvera materijal račve A6 je modeliran aproksimativnom krivom očvršćavanja čelika NIOVAL 47. Pošto je kriva nelinearna, u programu je korišćena njena aproksimacija u obliku bilinearne krive napon–deformacija sa uslovnom granicom razvlačenja \( R_{0.2} \) i zateznom čvrstoćom \( R_m \) koja je prikazana na slici 4.

**Table 1: Mehaničke karakteristike NIOVAL 47**

<table>
<thead>
<tr>
<th></th>
<th>Jedinice</th>
<th>Vrijednost</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIOVAL 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modul elastičnosti:</td>
<td>daN/cm²</td>
<td>( E = 1.95 \cdot 10^6 )</td>
</tr>
<tr>
<td>Modul klizanja</td>
<td>daN/cm²</td>
<td>( G = 0.75 \cdot 10^6 )</td>
</tr>
<tr>
<td>Uslovna granica razvlačenja</td>
<td>daN/cm²</td>
<td>( R_{0.2} = 4700 )</td>
</tr>
<tr>
<td>Zatezna čvrstoća</td>
<td>daN/cm²</td>
<td>( R_m = 6500 )</td>
</tr>
<tr>
<td>Izduženje</td>
<td>%</td>
<td>( A_{10} = 30 )</td>
</tr>
<tr>
<td>Poasson-ov koeficijent</td>
<td></td>
<td>( \mu = 0.3 )</td>
</tr>
</tbody>
</table>

Na slici 5 je prikazana mreža konačnih elemenata u zoni račve A6. Kao osnovno opterećenje račve se pojavljuje pritisak vode, koji za horizontalnu ravan koja prolazi kroz osu cjevovoda iznosi \( p = \frac{5099400 + 1000 \cdot 9.81 \cdot (0.99003 - z)}{2} \). (1) Takođe je uzeta u obzir i težina samog cjevovoda.

**Slika 4.**

**Slika 5.**

2.2. **Analiza pomjeranja cjevovoda**

U prvom koraku smo dobili napone i pomjeranja bez uticaja sila trenja u osloncima. U drugom koraku smo vertikalne reakcije oslonaca množili sa koeficijentom trenja \( k = 0.05 \) koji odgovara ležištu izrađenom od teflona i nerđajućeg čelika. Zatim smo horizontalne reakcije usmjerili u suprotnom smjeru od rezultante pomjeranja cjevovoda C3 u tačkama ležišta. Na taj način smo dobili nove rezultate napona i pomjeranja koji su bili realniji od dobijenih u prethodnom koraku. Dobijeni rezultat pomjeranja račve A6 u pravcu X-ose je iznosio 16 – 17 mm. Upoređivanje ovog pomjeranja sa stvarnim (izmjenjenim) je pokazalo da je stvarno pomjeranje znatno manje i iznosi 10.3 mm. U sledećim koracima smo povećavali prosječni koeficijent trenja u osloncima sve dok nismo dobili pomjeranje koje je jako blizu izmjerenoj vrijednosti (10 – 10.5 mm). Na ovaj način smo se maksimalno približili stvarnim (izmjenjenim) uslovima rada ovog dijela cjevovoda C3, i na taj način dobili napone i pomjeranja u njemu. Na slikama 6, 7 i 8 su prikazana pomjeranja u X pravcu kako posmatranoj dijelu cjevovoda C3 tako i same račve A6.
Sa slike 6 se može zaključiti da su maksimalna računska pomjeranja posmatranog cjevovoda 15.3 mm i ostvaruju sa na krivini šeste odvodne cijevi cjevovoda C3.

Sa slike 7 se vidi da su značajna pomjeranja i na račvi A6 tj. na krivini prve odvodne cijevi cjevovoda C3. Na tom mjestu maksimalna pomjeranja iznose oko 14 mm.

Na slici 8 se može vidjeti da su računska pomjeranja račve A6 u pravcu X ose, na mjestu mjerenja približna izmjerenim ($\Delta_1 = 10.3 \text{ mm}$), tj.:

$$\Delta_1 \in (10\text{mm};10.5\text{mm})$$

(2)

Sa slike 7 se može zaključiti da su maksimalna računska pomjeranja posmatranog cjevovoda 15.3 mm i ostvaruju sa na krivini šeste odvodne cijevi cjevovoda C3.

Slika 7. Pomjeranja u X pravcu u zoni račve A6

Na slici 8 se može vidjeti da su računska pomjeranja račve A6 u pravcu X ose, na mjestu mjerenja približna izmjerenim ($\Delta_1 = 10.3 \text{ mm}$), tj.

$$\Delta_1 \in (10\text{mm};10.5\text{mm})$$

(2)

Sa slike 7 se vidi da su značajna pomjeranja i na račvi A6 tj. na krivini prve odvodne cijevi cjevovoda C3. Na tom mjestu maksimalna pomjeranja iznose oko 14 mm.

Slika 8. Pomjeranja u X pravcu u zoni račve A6

Slika 9. Von – Misesovi naponi na cjevovodu C3
2.3. Analiza naponskog stanja

Globalna slika Von – Misesovih napona posmatranog dijela sistema cjevovoda C3 (slika 9) pokazuje da je u najvećem dijelu, za statička opterećenja, cjevovod dobro dimenzionisan. Međutim, detaljnom analizom naponskog stanja račve A6, dolazi se do zaključka da na njoj postoje opasne zone za čvrstoću posmatranog cjevovoda. Prije svega treba istaći činjenicu da se maksimalni Von – Misesov napon \( \sigma_{\text{max}} = 4293.8 \text{ daN/cm}^2 \) nalazi upravo na račvi A6, na mjestu skretanja prve cijevi (slika 11, 12,) i to na njoj unutrašnjoj površini.

Slika 10. Von–Misesovi naponi u zoni račve A6 (pogled I)

Sa slike 12 se vidi da je mjesto najvećeg napona u zoni uticaja toplote (ZUT) zavarenog šava koji vezuje lim debljine 36 mm za elipsu. Njegova vrijednost je daleko veća od vrijednosti dozvoljenog napona, tj.:

\[
\sigma_{\text{max}} = 4293.8 \text{ daN/cm}^2 > \sigma_d = 2250 \text{ daN/cm}^2 \quad (3)
\]

Ovo je svakako kritično mjesto na račvi A6 pa ga treba detaljnije analizirati.

Slika 11. Von–Misesovi naponi u zoni račve A6 (pogled II)

Ako znamo da su dozvoljena dinamička opterećenja u cjevovodu za 10 % veća od statičkih [1], onda možemo pretpostaviti da u dinamičkim režimima rada napon iz izraza (1.3) može postati:

\[
\sigma_{\text{din}} = 1.1 \cdot 4293.8 \text{ daN/cm}^2 = 4723.18 \text{ daN/cm}^2 \quad (4)
\]

Ovaj napon je veći od napona na granici velikih izduženja za NIOVAL 47, tj.:

\[
\sigma_{\text{din}} = 4723.18 \text{ daN/cm}^2 > \sigma_v = 4700 \text{ daN/cm}^2 \quad (5)
\]

Na slikama 13 i 14 su prikazane fotografije pronađenih pukotina koje su analizirane od strane Instituta za crnu metalurgiju iz Nikšića[2].

Slika 12. Von–Misesovi naponi u zoni račve A6 (pogled III)

REFERENCE
[1] Elaborat o ispitivanju naponskog stanja u karakterističnim presjecima cjevovoda C3 HE „PERUĆICA”. UNIVERZITET CRNE GORE, MAŠINSKI FAKULTET PODGORICA, CETIM, maj 2009. god
[2] Izvještaj br. 020000-08/09 o ispitivanju bez razaranja i strukturnoj analizi materijala cjevovoda br.3 (račve A6 i A7), INSTITUT ZA CRNU METALURGIJU „NIKŠIĆ” 30.09.2009. godine

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ANALYSIS OF ECONOMIC JUSTIFICATION OF CONSTRUCTING A SMALL HYDRO POWER PLANT

Darko SKUPNJAK
Milan VUKČEVIĆ

Abstract: This Work presents economic analysis of the project: SMALL HYDRO POWER PLANT: small hydro power plant "Murino" “Dos’s river- Neno’s spring" of power 1,5 MW. To have this project economically treated related to technical elements emerged from technical analysis of the project, it is necessary to determine costs of constructing a small hydro power plant, which are versatile, by their nature. Costs, as one of elements of engineering economy, have provided the required amount of investments. In the work, static and dynamic indicators of economic-financial analysis have been used, based on which an evaluation of economic justification of constructing a small hydro-power plant is given. The analysis is treating reduced production volume for 20% and 30% as possible risk due to change of hydrologic conditions.

Key words: Small hydro power plant, investments, economic-financial analysis, production volume.

1. INTRODUCTION

Engineering economy is an engineering discipline which has developed techniques which simplify comparison of alternatives on economic base. Engineering projects, which in addition to technical solutions based on scientific knowledge equally need to meet certain economic validities in order to be economically sustainable from one side and payable in overall from the other side, for the one (investor) for who such project is realized with acceptable cost.

In Engineering Economy, the principles and methods which help in precisely defined scientific manner defining and analyzing economic alternatives of project realization have been developed. Based on these analyses, an evaluation is given regarding acceptable solutions no matter they are done by an individual or the team. It is quite difficult to find a balance between technical and economic project feasibility. In particular, a project may be feasible in technical sense, but difficult to be realized in economic sense, or vice versa.

2. PROJECT DESCRIPTION

Small hydro power plant - small hydro power plant "Murino" is placed on the water flow of the Murino river. The Murino river is made of Dos’s River and Neno’s spring. One tank of water is placed on Dos’s river, while the other is placed on Neno’s spring on position 1224 m.n.m. From there, water is transported by free fall to compensation tank for both water flows. The compensation tank of small hydro power plant "Murino" is placed on the position 1220 m. n. m. Water is transported from both water tanks to compensation tank by derivation pipes. The compensation tank is designed to be on the place where water flow is moved to the pipes by free fall and falling under pressure. From the compensation tank to the place of small hydro power plant which is placed on the position 965 m. n. m., water is transported through the pipes under the pressure.

The analysis of hydro potential and technical calculations has provided selection of the best technical solution in terms of positioning the power plant on the water fall, calculations related to gross, net fall, losses in the pipeline, selection of the turbine type, calculation of required turbine strength, degree of usefulness, strength of generator and the transformer, including elements required for connection to distribution grid.

The investor decided to make the investment of 30% from his own resources and 70% from the loan. Using the methods of the engineering economy, an analysis of economic justifiability of capital invested in the project of small hydropower plant is made. The economic analysis should show whether the project is sustainable, i.e. to determine interdependency between all economic phenomena and the processes based on economic principles and logics, to explain their generation, former flow and predict future period, to determine optimum direction of the project development, as well as measures which will direct development of the project to desirable, optimal flow. The economic analysis should also show possibility of changing economic parameters no matter they are desirable or undesirable considering their consequences.
3. APPLICATION OF MONEY-TIME RELATION

The term ‘capital’ presents an economic value which is invested in production or some other economic activity aiming to enlarge, i.e. may be used to generate more fortune. Most of engineering economic studies include investment of capital in longer period of time, therefore, the impact of time needs to be taken in consideration. In that sense, it is understandable that one euro values more today than one euro after one or more years, because of the interest (or profit) which can make. Accordingly, the money has higher value over the time [4].

The capital in terms of money, machine, power, material and other elements required for operation of some company may be divided into two basic categories. Equity is capital owned by individuals or the companies that invested their money or the property in some business project or venture hoping to get profit. Loaned capital got from the creditor to invest in projects. The goal of researches of the engineering economy is the income required to be generated. It researches if the investment with all depending costs emerging over the time, may be covered by the income (saving) of the capital and if this income is acceptable in terms of risk and potential alternative solutions. The key element of this research is time-money relation [1].

3.1. Method of present value

Method of present value PW or net present value (PW) is based on the concept of equivalent value of all cash flows related to some base or initial spot in time. In order to find a present value in function of interest rate and %, for series of money inflows and outflows, it is necessary to discount future values to present one, using the interest rate in certain period, as follows [1]:

\[
PW(i\%) = F_0(1 + i)^0 + F_1(1 + i)^{-1} + F_2(1 + i)^{-2} + \cdots + F_N(1 + i)^{-N} = \sum_{k=0}^{N} F_k(1 + i)^{-k}
\]

where:
- \( i \) - effective interest rate or MARR, for calculation period,
- \( k \) - index for each period of consideration (0≤k≤N)
- \( F_k \) - future cash flows at the end of period k.
- \( N \) - number of periods of interest (for example, years).

The Minimum Acceptable Rate of Return (MARR) is the strategic goal of the company and it is defined by top management. Net present value is a sum of discounted net inflows (from economic flow) realized during the project exploitation. Actually, net inflows from economic flow (by years) are multiplied with proper discount factor, and then the sums got like this are added. The result got is an amount of means for reproduction realized in the project in its economic period, from the present point of view. Realization of the investment project is justifiable if PW is positive, i.e. higher than zero. One of the problems when applying this criterion might be choosing a real discount rate. From this reason an interest rate corresponding to the interest rate of loan is taken for calculation [1].

\[
PW (NPV) = \sum_{t=1}^{N} \frac{F_t}{(1 + i)^t}
\]

where:
- PW - net present value
- N - project duration
- \( F_t \) - net cash flow in the year t
- \( i \) - required interest

It refers to an integral and absolute indicator for evaluation of economic profitability and project acceptability. In order to make this project acceptable, net present value needs to be higher than zero, which means that positive project effects exceed the investment costs.

3.2. Method of future value

Future value, FW, is based on equivalent value of all money inflows and outflows at the end of period of consideration by the interest rate which equals to minimum acceptable profit rate [1].

\[
FW(%) = F_0(1 + i)^N + F_1(1 + i)^{N-1} + F_2(1 + i)^{N-2} + \cdots + F_N(1 + i)^0 = \sum_{k=0}^{N} F_k(1 + i)^{N-k}
\]

3.3. Method of internal rate of return IRR

Method of internal rate is a method which is mostly used in engineering economic analysis. The method requires the interest rate which equals equivalent value of alternative money inflows (incomes and savings) with equivalent value of money outflows (expenditures or costs, including the investment costs). For this method, other names are also used: Investment method, method of cash flows discounts, index of profitability [1].

\[
\sum_{k=0}^{N} R_k(\frac{P/F}{i\%,k}) = \sum_{k=0}^{N} E_k(\frac{P/F}{i\%,k})
\]

where:
- \( R_k \) = net inflows or saving for k years
- \( E_k \) = net costs that include any investment cost for k years,
- \( N \) = period of project duration

Another method for determining internal profit rate for alternative is to determine \( i \) in way that present value equals to zero.

Then IRR is determined from the expression [1]:

\[
PW = \sum_{k=0}^{N} R_k(\frac{P/F}{i\%,k}) - \sum_{k=0}^{N} E_k(\frac{P/F}{i\%,k}) = 0
\]

It can be said that the internal rate of return is a discount rate which equals present value of negative net inflows (by years) from economic flow to present value of positive inflows, i.e. a discount rate for which PW of project is equal to zero. It indicates the lowest discount rate at which realization of the investment project is justifiable. The internal profitability rate is compared to individual discount rate and must be equal or higher than it.

4. STATIC AND DYNAMIC INDICATORS OF INVESTMENT PROGRAM

The valuation of the investment program means application of certain methods aiming to consider justifiability and acceptability of the project.
It relates to the essential information of the investment project stated in the investment-technical documentation [6].

4.1. Static indicators

This evaluation is done based on data related to one year of full capacity use and maximum use of credit burden. Method of determining profitability rate only uses representative years of the project lifetime which makes it logically static. The minimum rate of profitability means the minimum selling price acceptable, ie, minimum volume of production in the future, with which the project is still capable to settle all duties. Or more simply, the minimum profitability rate indicates what amount of income you need to receive in order to cover the costs you incurred for the purpose of getting income.

Investments per employee as relation between total investments and number of employees show how much credit and personal resources every employee spends.

Accumulations as relation between accumulation and the investments in assets and turnover show capability of the programme to realize certain accumulation burdened by costs for assets and turnover.

Cost-effectiveness as relation between total income and total expenses shows if a good company meets essential economic postulate in achieving possible results with as less investments as possible, i.e. it shows how much income is realized for 1€ of expenditure...

Long-term loan as relation between the long-term credits and total liabilities is an indicator of a financial structure. This indicator shows how much means from the loan is spent on every euro of liability and in dependence on other indicators and parameters leads to a conclusion weather the company considers impact of financial leverage as a model of realization of a high rate of income to personal resources or it refers to unrealistic evaluation which may question program realization.

4.2. Dynamic indicators

Dynamic indicators are determined based on consideration of certain period of time in which their effects are analyzed.

Dynamic evaluation includes:
- Method of net present value PW,
- Method of internal rate of return IRR,
- Period of financial investment return.

Relative project effectiveness - In addition to net present value as an indicator of the absolute investment income, relative effectiveness is also calculated compared to the investor and relative project efficiency compared to number of employed workers. Relative efficiency of the project compared to the investor is a relation between PW of investment and pre-calculation value. This value, also, has to be positive indicating the amount of material base return of the investor’s work against euro investment, while expressed in percentage shows an accumulation rate. Relative efficiency of the project against number of employees shows the amount of contribution provided by every employee to increase material base of the project.

Time frame of the investment return is a period expressed in years during which the discounted annual net inflows of investment (from economic flow) will regain total discounted investment. Realization of the project is justifiable if the deadline for returning the invested means is less or equal to the period of time determined by the credit provider.

5. ECONOMIC-FINANCIAL ANALYSIS

5.1. Investments

Total investment consists of four groups of investments, such as: A. Costs of building object for power generation (construction works and equipment); B. Costs of making technical documentation (research works, designing equipment, designing construction objects); C. Costs of professional services (expert supervision, monitoring); D. Costs of acquiring property rights (lots for power plants, switchyards). Project of small hydro power plant includes small hydro power plant "Murino" (Dos's River - Neno's spring) and separately a switchyard for purpose of connecting this hydropower plant to electric-distribution grid, this will be provided further in the study through their costs with exact values of share in the investment.

Table 1: Structure of investment

<table>
<thead>
<tr>
<th>STRUCTURE OF INVESTMENT</th>
<th>EURO (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Costs of object building</td>
<td>1,869,279.74</td>
</tr>
<tr>
<td>B. Costs of technical documentation</td>
<td>110,578.64</td>
</tr>
<tr>
<td>C. Costs of professional services</td>
<td>112,156.78</td>
</tr>
<tr>
<td>D. Costs of acquiring property rights</td>
<td>13,084.96</td>
</tr>
<tr>
<td><strong>TOTAL INVESTMENT</strong></td>
<td><strong>2,105,100.12</strong></td>
</tr>
</tbody>
</table>

Table 2: Calculation of operation costs

<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>EURO (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation</td>
<td>109,099.83</td>
</tr>
<tr>
<td>Investment maintenance</td>
<td>16,611.73</td>
</tr>
<tr>
<td>Calculation of insurance premium</td>
<td>10,746.60</td>
</tr>
<tr>
<td>Labor force</td>
<td>14,328.00</td>
</tr>
<tr>
<td>Other non-material costs</td>
<td>3,960.00</td>
</tr>
<tr>
<td><strong>TOTAL OPERATION COSTS</strong></td>
<td><strong>154,746.16</strong></td>
</tr>
</tbody>
</table>

Table 3: Projected total annual income

<table>
<thead>
<tr>
<th>Power supply plant</th>
<th>Small Hydro Power Plant &quot;Murino&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power on plant exit Ppe (MW)</td>
<td>1,42862</td>
</tr>
<tr>
<td>Annual power production (kWh)</td>
<td>4,200,000.00</td>
</tr>
<tr>
<td>Incentive price (Group 1) Ppe ≤ 1MW [€/kWh]</td>
<td>10.44</td>
</tr>
<tr>
<td>Incentive price (Group 2) 1 ≤ Ppe ≤ 3 MW [€/kWh]</td>
<td>9,35570 (10.44-7xPpe)</td>
</tr>
<tr>
<td>Total power plant (€)</td>
<td>392,939.40</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>392,939.40 €</strong></td>
</tr>
</tbody>
</table>
5.3. Projection of total income during period of ten years

In conformity with the Investor’s intentions, production of small hydro power plant will participate in meeting need for power sources in Montenegro. As a concept, hydro power plant converts power of the water flow to electric power, therefore, hydro power plan operates using current inflows. The fact is that it is not possible to manage production (i.e. production adjusts to current inflow) which indicates that it is necessary to analyze current inflows as precise as possible, i.e. a curve of distribution of average daily flows. Based on that curve, annual production is projected and determined.

5.4. Economic - financial indicators

The table shows economic-financial indicators of the project of constructing a small hydro power plant for different production volumes.

### Table 4: Calculation of operation costs (volume 100%)

<table>
<thead>
<tr>
<th>No</th>
<th>Element of Analysis</th>
<th>Production Volume 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Income/year</td>
<td>392.939,40 €</td>
</tr>
<tr>
<td>2.</td>
<td>Total investment</td>
<td>2.105.100,12 €</td>
</tr>
<tr>
<td>3.</td>
<td>Deadline to return investment</td>
<td>7god.</td>
</tr>
<tr>
<td>4.</td>
<td>Cost-effectiveness</td>
<td>1.52</td>
</tr>
<tr>
<td>5.</td>
<td>Accumulation rate</td>
<td>16%</td>
</tr>
<tr>
<td>6.</td>
<td>Net present value (PW)</td>
<td>1.697.684,96 €</td>
</tr>
<tr>
<td>7.</td>
<td>Internal rate of return (IRR)</td>
<td>14%</td>
</tr>
</tbody>
</table>

### Table 5: Calculation of operation costs (volume -20%)

<table>
<thead>
<tr>
<th>No</th>
<th>Element of Analysis</th>
<th>Production Volume -20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Income/year</td>
<td>314.351,52 €</td>
</tr>
<tr>
<td>2.</td>
<td>Total investment</td>
<td>2.105.100,12 €</td>
</tr>
<tr>
<td>3.</td>
<td>Deadline to return investment</td>
<td>8 god.</td>
</tr>
<tr>
<td>4.</td>
<td>Cost-effectiveness</td>
<td>1.26</td>
</tr>
<tr>
<td>5.</td>
<td>Accumulation rate</td>
<td>12%</td>
</tr>
<tr>
<td>6.</td>
<td>Net present value (PW)</td>
<td>554.146,13 €</td>
</tr>
<tr>
<td>7.</td>
<td>Internal rate of return (IRR)</td>
<td>8%</td>
</tr>
</tbody>
</table>

### Table 6: Calculation of operation costs (volume -30%)

<table>
<thead>
<tr>
<th>No</th>
<th>Element of Analysis</th>
<th>Production Volume -30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Income/year</td>
<td>275.057,58 €</td>
</tr>
<tr>
<td>2.</td>
<td>Total investment</td>
<td>2.105.100,12 €</td>
</tr>
<tr>
<td>3.</td>
<td>Deadline to return investment</td>
<td>10 god.</td>
</tr>
<tr>
<td>5.</td>
<td>Accumulation rate</td>
<td>10%</td>
</tr>
<tr>
<td>6.</td>
<td>Net present value (PW)</td>
<td>-17.623,28 €</td>
</tr>
<tr>
<td>7.</td>
<td>Internal rate of return (IRR)</td>
<td>3%</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Using static and dynamic indicators of economic-financial analysis, an objective evaluation of investment is provided based on financial benefits when making a final decision. If all presumed conditions are realized for 100% of realized production volume used as a base for analyzing economic-financial aspects of the investment, construction of small hydro power plant small hydro power plant "Murino" is economically HIGHLY JUSTIFIABLE.

The work is analyzing unfavorable possibilities of operation of small hydro power plant "Murino" for the case of reduction of the production volume due to change of hydrologic conditions. Production volumes have been analyzed for 100% (projected), as well as reduced for 20% and 30%.

The risk which objectively exists in case the production of small hydro power plant "Murino" operates with 30% reduced capacity (i.e. negative net inflows) for certain year or years, the investor might, in agreement with the loan provider, overcome problem by using some financial derivate.

Considering overall economic-financial project, it is highly FAVORABLE FOR THE INVESTOR.

REFERENCES


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APPLICATION OF PROMETHEE METHOD AS SUPPORT IN THE PLANNING PROCESS OF SMALL HYDROPOWER PLANTS

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Budimirka MARINOVIĆ
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Željko ĐURIĆ

Abstract: During the planning of small hydropower plants, besides the energy performances of the possible alternatives, it is necessary to valorize all the other effects of projects construction. This paper gives an insight into the application of multi-criteria decision analysis (MCDA) methods in the planning of small hydropower plants through the creation of the model using the Promethee method.

Key words: Multi-criteria decision analysis, Promethee method, small-hydropower plant.

1. INTRODUCTION

Energy has become one of the most discussed issues in economical, political, social and environmental aspects. Industrialization and technological developments resulted in major environmental concerns. Current and future possible environmental, economical, political and social negative consequences also force the countries to incline towards to renewable energy resources. In this respect, renewable energy has become the answer for sustainable energy planning [1]. Renewable energy decision-making can be viewed as a multi criteria decision-making problem with correlating criteria and alternatives. This task should take into consideration several conflicting aspects because of the increasing complexity of the social, technological, environmental and economic factors [2]. This all because renewable energy alternatives are emerging as a solution for a sustainable, environmentally friendly, cost-effective source of energy.

This work aims to evaluate applicability of multi-criteria decision analysis (MCDA) in order to provide a technical-scientific decision making support. The study propose suitable model for indentifying the most pereferable solution for regional energy planning by creating classifications of alternative of small hydropower plants. Small hydropower plant is a clean source of power, but also small hydropower plans are site specific and need careful planning for project formulation and implementation. Therefore using effective techniques as MCDA tools may become helpful to produce better understanding and results.

The results from the analysis lead to the conclusion that MCDA can be recommended as a decision support tool along with the development of relevant databases to be incorporated into policy and program development procedures [3].

2. MULTICRITERIA DECISION ANALYSIS METHODS IN ENERGY PLANNING

MCDA method is form of integrated sustainability evaluation. MCDA method deal with process of making decisions in the presence of multiple objectives. The objectives are usually conflicting, the solution is highly dependent on the preferences of the decision-maker and must be a compromise [4]. Nowadays, the focus on global environmental protection drives MCDA aid in energy systems [5].

MCDA techniques are being successfully used in many different planning processes: energy resource allocation, energy planning problems, environmental problems. Polatidis et al. [6] developed methodological framework to provide insights regarding the suitability of multi-criteria in the context of renewable energy planning. Loken, 2007 [7] described various MCDA methods for energy planning problems. MCDA method can provide better understanding and better analysis of decision problems, also. Supriyasilp et al., [8] used MCDA analysis to determinate the advantages and disadvantages of hydropower plant plants in the Ping River Basin. Mladineo et al. [9] used Promethee method to rank locations in order to make the unit costs as low as possible.

2.1. Promethee metod

MCDA with Promethee (Preference Ranking Organisation Method for Enrichment Evaluation) method was used in this paper to anlize the adventage and disadvantage for eight project, based on seven criteria, including technical, socio-economic and environmental aspects. Promethee method uses the outranking principle to rank the alternatives. Basis of this metod is decision matrix:
where $a_{ij}$ is the performance of $j$-th criteria of $i$-th alternative, $w_j$ is the weight of criteria $j$, $n$ is number of criteria $i$ and $m$ is number of alternatives.

The different alternatives are compared pairwise by considering the deviation between the evaluations of two alternatives on a particular criterion. Based on this deviation, the decision-maker assigns a preference to the best alternative (under that given criteria) expressed by a number between 0 (indicating no preference or indifference) and 1 (indicating outright preference). For small deviations, a small preference to the best alternative is allocated (or possibly even no preference if the deviation is considered negligible), while larger preferences are assigned to larger deviations.

The preference of alternative $a_1$ over alternative $a_2$ for a particular criteria $C_j$ can be determined by means of a preference function $P_j(a_1,a_2)$, which expresses the preference as a function of the deviation $d_j(a_1,a_2)$ between $a_1$ and $a_2$ on that particular criterion:

$$P_j(a_1,a_2) = F_j\left(d_j(a_1,a_2)\right) = F_j\left(c_j(a_1) - c_j(a_2)\right)$$

where $F_j$ is a function of the deviation and ensures that $0 < P_j(a_1,a_2) < 1$ [12].

An overall or global preference index

$$\Pi(a_1,a_2) = \frac{\sum_{j=1}^{P} P_j(a_1,a_2)w_j}{\sum_{j=1}^{P} w_j}$$

represents the intensity of preference of $a_1$ over $a_2$. Outranking flows are then calculated in order to rank one alternative against all the other alternatives. The outranking flows for alternative $a_i$ are given by

$$\phi^+(a_i) = \frac{1}{N-1} \sum_{b \neq a_i} \Pi(a_i,b) - \text{positive outranking flow}$$

$$\phi^-(a_i) = \frac{1}{N-1} \sum_{b \neq a_i} \Pi(b,a_i) - \text{negative outranking flow}$$

and they express how the alternative outranks all the others - positive flow, while negative flow expresses how the alternative is outranked by all the others.

Net outranking flow for each alternative

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i)$$

give a complete ranking for the alternatives. The alternatives with the highest net outranking flow value are given the highest rank [12].

Figure 1 presents a flowchart of steps for ranking the proposed solutions of small hydropower plants using the Promethee method of MCDA.

![Flowchart](image)

**2.2. Multicriteria analysis for small hydro plants using Promethee method**

This example deals with eight small-scale hydropower plants on Vrbas river. The main advantage of small-scale hydropower plants is that they could be easily developed in a short time based on local community participation. In addition, the small-scale hydropower could be used as a main energy resource for rural area as well as a supplementary for the country level. Accordingly, it is important to discover a potential area where is able to develop the small-scale hydropower plant. [11]. Also, small hydropower plants are recognized as a renewable and environmentally sustainable energy source.

MCDA has been applied in order to determine advantages and disadvantages of the hydropower plants in seven criteria (Table 1.). The criteria enable the alternatives to be compared from a specific viewpoint. The number of criteria to use depends on the availability of both quantitative and qualitative information and data relating to the potential criteria [12].

Important step in MCDA analysis is criteria weighting [3]. The weights determine how heavily a criteria contributes to the overall score. In this paper criteria weights have been discussed by experts and then the weights were calculated with the AHP (Analytic Hierarchy Process) method. As a consequence of weight assignment, the investment safety and legal abstract are the most important criteria in the view of the experts.

The analysis was facilitated by the Visual Promethee software.
Table 1: Overview of used criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Type</th>
<th>Expert weight</th>
<th>Description</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed capacity</td>
<td>Quantitative</td>
<td>0.08</td>
<td>Indicates the potential for generating electrical power</td>
<td>[8]; [11]</td>
</tr>
<tr>
<td>Annual energy production</td>
<td>Quantitative</td>
<td>0.11</td>
<td>High annual energy production means high potential [8]</td>
<td>[1]; [8]; [11]; [12]</td>
</tr>
<tr>
<td>Flow pattern and amount of flow</td>
<td>Qualitative</td>
<td>0.2</td>
<td>Sites are ranked from the least impact to the most impact on flow pattern and amount of flow as: 1 – sites with an existing infrastructure and reservoir, 2- the sites currently in water resource development plan, 3 – the sites with low head Q based type, 4 – the warweway type and 5 – site that is not n the water resorce development plan.</td>
<td>[8]; [11]</td>
</tr>
<tr>
<td>Investment cost</td>
<td>Quantitative</td>
<td>0.06</td>
<td>Cost rendered from purchasing the equipment, installation and construction</td>
<td>[1]; [5]; [8]; [10]; [11]</td>
</tr>
<tr>
<td>Investment safety</td>
<td>Qualitative</td>
<td>0.25</td>
<td>Plants are ranked from the least impact on flow pattern and amount of flow [8]</td>
<td>[1]; [8]</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>Qualitative</td>
<td>0.05</td>
<td>Acceptance by the local population regarding the plant</td>
<td>[1]; [5]; [10]; [12]</td>
</tr>
<tr>
<td>Legal abstracle</td>
<td>Qualitative</td>
<td>0.25</td>
<td>If plant is in conservation area or if there are ancient remains in the area project can not be developed.</td>
<td>[8]</td>
</tr>
</tbody>
</table>

2.3. Results and discussion

Figure 2. present the resulting ranking. By MCDA analysis the alternative ranked highest is option MHE 3. The criteria that mostly affected on this result is that it has highest installed capacity, and highest annual energy production and lowest investment cost.

A sensitivity analysis of the results determined the robustness of the model and the responsiveness of the rankings to change in the weights assigned to the criteria. The sensitivity analysis (Table 2) show that the two highest ranked options, MHE 3 and MHE 2, do not change their rank as a result of the change in weights.

Table 2: Stability intervals

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight [%]</th>
<th>Stability intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Installed capacity</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Annual energy production</td>
<td>11</td>
<td>9.08</td>
</tr>
<tr>
<td>Flow pattern and amount of flow</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Investment cost</td>
<td>6</td>
<td>5.87</td>
</tr>
<tr>
<td>Investment safety</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Legal abstracle</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>
3. CONCLUSION

Hydropower plant depends on several conditions, and energy planning processes should take into account not only technical but also environmental, economical and social dimension.

The present work proposed MCDA approach to select the best compromise alternative of hydro-power plant, in order to assist policy making for hydropower development. In this way the complexity of a multi-actor energy system can be an asset in planning when using MCDA.

The selection is based on comparaison of eight alternatives according to their performances with respect to relevant technical, environmental social and financial criteria. The application the Promethee method of MCDA analysis proved to be a valuable tool to assess and evaluate alternatives.

Analysis of the weight stability intervals, the limits within which its weight can be modified without changing ranking, are very large, except in criteria investment cost and annual energy production.

REFERENCES


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Abstract: In order to maintain the high reliability of the HPP Pirot, special attention is paid to maintenance of the system, which consists in the planning of maintenance, maintenance, monitoring of the maintenance process and continual improvement of the maintenance process. In order to improve the maintenance process of the penstock HPP Pirot, a work platform was developed for the maintenance of the penstock. Since the diameter of the pipeline is 3.5, 3.3 and 3.0 m, the conditions for maintaining of the penstock are difficult. For this reason, is development work platform for the transportation of the necessary maintenance equipment, the needs of the upper part of the pipeline. The paper presents the development of a working platform for the maintenance of the penstock of the hydroelectric power plant Pirot.

Key words: product development, work platform for maintenance of penstock, HPP Pirot

1. INTRODUCTION

Hydroelectric power plant "Pirot" is located on the territory of southeastern Serbia, between Pirot and the Bulgarian border, and uses the water of the river Visočica on the profile of the dam "Zavoj". It is a storage (reservoir) type hydropower plants with a tunnel and a pressure pipeline. Hydroelectric power plant "Pirot" started construction in 1983, while the first aggregate was put into operation in 1990. The accumulation "Zavoj" was created naturally. Big landslide closed the valley of Visočica, turning it into a lake. At the bottom of the lake, the village of Zavoj remained, and the natural dam was used to build an artificial dam with 1.5 million cubic meters of stone, clay and filter material. The accumulation itself is multipurpose. Its waters are used for:

• electricity production
• acceptance of the flood wave
• water supply
• preventing of water borne deposition
• refining small waters.

Powerhouse of hydroelectric power plant is overhead with 2 vertical aggregates with Francis turbines with power of 80 MW, with command and distribution facilities. Operating time of the plant is 1400 hours per year (4.5-5 hours per day).

Pirot Hydroelectric Power Plant has an inlet tunnel with an entrance building and a tunnel of the control gate. Length of tunnel 9093m, diameter 4.5m. Surge tank height of 97m, variable diameter from 8 to 15m. Steel pipeline with tunnel section of pipeline of 400 m, total length 2030 m, diameter 3.5 m, 3.3 m and 3.0 m. In front of the power plant it is divided into two branches d = 1.70 m.

Preventive maintenance of the HPP Pirot plant is carried out once a year. During this period, the inspection of the penstock is carried out and the necessary work is carried out for the maintenance of the pipeline. Since the diameter of the pipeline is 3 m, these maintenance conditions are difficult. The need for the transport of the necessary maintenance equipment for reaching the upper part of the penstock, required the development of the work platform for the maintenance of the penstock.

The paper presents a new innovative solution for the developed working platform for penstock maintenance based on the defined requirements:

• Launch the work platform with its own weight platform and a winch with a steering wheel and support rollers;
• All platform elements should be so dimensioned that it is possible to smoothly enter the pipeline through the inspection holes, and to quickly assembly;
• The work platform should enable the safe transport of cargo and persons working on the maintenance of the penstock;
• Maximum platform speed of 0.5 m / sec;
• Platform length 3000 mm;
• The width of the work platform should be as high as possible, but so as not to interfere with the movement through the penstock;
• Maximum platform load of 5 kN;
• The work platform should provide a simple and efficient placement system in a horizontal position;
• It is necessary for the winch and the work platform to have a braking system for the effective positioning of the work platform in the desired position along the penstock;
• An integral part of the work platform should include ladders for safe entry-exit onto the platform;
• The winch should be portable and provide easy transport and installation on a horizontal basis;
• The winch drive should be a motor with frequency speed control.

In addition to the above requirements, the following requirements are added:
• The maximum mass of one part of the structure is max 30 kg.
• The solution should ensure efficient positioning of the work platform so as to prevent possible rotation of the platform around the axis of the pipeline.
• High flexibility of the work platform in relation to the change in the slope of the pipeline.
• Achieving a good relationship between quality and price of the construction of the work platform.
• High durability of all elements of the work platform and low maintenance costs.
• High efficiency and reliability of the work platform's functioning.

In order to fully meet the defined requirements, and especially because the penstock changes the diameter and direction, both vertically and horizontally, an penstock analysis has begun. This analysis was also necessary due to the requirement that the work platform be as wide as possible and not interfere with the movement through the penstock.

2. ANALYSIS OF THE PENSTOCK OF HPP PIROT

The objective of the analysis of the penstock of the HPP Pirot is to generate relevant data necessary for the design of a work platform intended for operation on the maintenance of the penstock of the HPP Pirot.

The length of penstock the pipeline changes the direction (in the vertical and horizontal plane), the diameter and the thickness of the sheet metal. The general appearance of the penstock is given in Fig. 1.

1. The minimum diameter of the penstock through which the moving work platform must move is 3000 mm.
2. The maximum diameter of the penstock through which the moving work platform is moving is 3500 mm.
3. The maximum distance between the two inspection openings on the penstock is 701 m.
4. The minimum slope of the penstock is 0° in the control gate and at the branch in the front of the machine hall. In both cases, there are extremely short relationships of maximum 10 m.
5. The maximum slope of the inlet pipeline is 11.922055°, which starts at about 294 m in front of the branch. This slope of the pipeline retains at 189 m of its length. The maximum change in the slope of the pipeline is 8.383248 ° in front of the machine hall.
6. The maximum change in the direction of the pipeline in the horizontal plane is 26.633810 °.

3. CONSTRUCTION OF THE TRANSPORT SYSTEM OF WORK PLATFORM

The work platform, the winch and the accompanying equipment is intended for operation on the maintenance of the penstock of the HPP Pirot. Platform capacity is 5 kN. Down of pipelines work platform moves its own weight. The withdrawal of the platform along the pipeline is realized by a winch. The main parts of the transport system within the pipeline of the HPP Pirot are:

1. Winch,
2. Work platform trolley,
3. Work platform,
4. Support (horizontal) and directional (vertical) rollers,
5. Boundary L profiles, which are mounted along the pipeline.

The work platform consists of the supporting trolleys and the working part of the platform, which are connected with the pin joint that allow the rotation of the platform's workpiece by the angle < 14°. This rotation is required to bring the working part of the platform to a horizontal position independent of the inclination of the pipeline. The change of the angle of the workpiece of the platform is achieved by means of hydraulic cylinders, manual pumps and three-stage distribution valve.

The diameter of the pipeline is from 3300 to 3500 mm and the slope of the pipeline is from 2° to 12°. In the pipeline at the control gate, the diameter is 3000 mm. In order to provide a smooth passage of the work platform with a width of 2300 mm and through this narrowest part of the pipeline it is necessary that the height of the stroller be lower than 2142 mm (Fig. 2).
The penstock changes the slope in relation to the horizontal, and the platform should maintain a horizontal position. This leads to a change in the height of the work platform while moving through the penstock. The change of the fictive height of the work platform (Fig. 3) is given by the expression (1):

\[ H_f = H_k + \frac{L_p}{2} \cdot \sin \alpha + H_p \cdot \sin \alpha \]  

Based on the conducted analysis of the penstock of the HPP Pirot, the projected solution of the platform meets the necessary conditions for smooth passage along the entire route of the penstock with a diameter of 3300 to 3500 mm. It is possible to pass through the penstock with a diameter of 3000 mm, but only if it is straight-line without changing the direction, which is also the case in the control gate.

In order to secure the position of the platform in the transverse plane of the penstock and to prevent the rotation of the platform around the axis of the pipeline, the boundaries along the penstock are placed.

Figure 4 shows the model of the work platform in the penstock.

The launching of the platform is achieved by the own weight of the work platform and the winch with a directional and support rollers.

The platform with two cables is connected to the winch, where one cable is powered and the other one is safety. For the axial positioning of the platform, besides the cable, all the wheels are placed so-called. complete brakes.

In order to prevent possible rotation of the work platform around the axis of the penstock, there are welded screws for mounting the L profile along the entire pipeline as the stops for the work platform wheels.

The work platform is made the basis of the panel-framing combined system made of stainless steel welded, which can be inserted into the penstock through the inspection holes 600 mm in diameter.

The work platform is prefabricated. Connecting parts is done with the screwed and cotter joint. Assembly is simple and quick. All platform elements have a maximum weight of 300 N.

Technical solution the work platform intended for maintenance of penstock of the HPP Pirot (Figures 5, 6 and 7) is fully realized (projected and implemented) by the Faculty of Mechanical Engineering in Niš.
4. CONCLUSION

HPP Pirot belongs to the system of peaking hydroelectric power plants. In order to maintain the high efficiency of the system, ie the high availability and reliability of the system, special attention has been paid to the maintenance of the system in the HPP Pirot, which consists in the planning of maintenance, maintenance, monitoring of the maintenance process and continuous improvement of the maintenance process. In order to improve the maintenance process of the penstock HPP Pirot, a work platform was developed for the maintenance of the penstock.

User of the technical solution of work platforms for operation on the maintenance of the penstock is the Public Enterprise of the Electric Power Industry of Serbia Branch of HPP ĐERDAP - Hydroelectric Power Plant Pirot.

Certain results of the technical solution can be applied with similar hydroelectric power plants.

REFERENCES


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NUMERICAL ANALYSES OF TRASH RACKS CHARACTERISTICS UNDER DIFFERENT EXPLOITATION CONDITIONS IN HYDROPOWER PLANTS

Miloš KRUNIĆ
Ivan BOŽIĆ

Abstract: This paper represents a research about the influence of different operational conditions on trash racks characteristics. The main goal of the research was to find how the specific parameters of the trash racks (flow velocity, head loss and head loss coefficient) change in the various exploitation situations. The comparison was done by looking at the cases of the normal flow (flow is perpendicular to the trash rack’s frontal area) and inclined flow (flow takes different angles). All of the mentioned cases were analysed by running simulations based on the branch of fluid dynamics called computational fluid dynamics (CFD). In both cases simulations were based on the steady flow, while the normal flow case was analysed with both steady and unsteady flow simulations.

Key words: trash racks, simulations, conditions, comparison.

1. INTRODUCTION

Trash racks (often called bar screens) are one of the most common and most responsible parts of mechanical equipment in hydropower plants. Their role is highly important, as they need to prevent water debris from passing through them. This is vital because any form of debris can make working parameters of the facility worse, while bigger pieces can do serious damage not only to turbomachines (water turbines), but also to the plant or building itself. They need to be reliable and resistant, because if they get deformed or broken due to accumulation of debris, the process of electricity generation has to stop. Trash racks are located at the intake of the hydropower plant and they can be totally or partially submerged, which depends on the size of the plant and depth of the inlet reservoir.

One of the most important geometric parameters of trash rack is clean span opening, which represents an open area between the bars, and it is usually square or rectangle.

There are different tips on choosing the right dimensions for the opening, but the most important rule is that clean span opening must be smaller than the smallest opening of the water distribution pipe or the inlet of the water turbine. Clean span dimensions also depend on the type of the water turbine and the origin/structure of water debris.

2. HEAD LOSS CALCULATION

One of the most important hydraulic parameters of the trash rack is the head loss. It is defined as the drop of water level after water flow passes through the bars. If the surface of the trash rack is cleaned and maintained regularly (and all previously mentioned dimensions are well chosen), head loss has the value equal to few centimeters. Head loss can be influenced by the amount of debris, flow velocity in front of the trash, angle of the water flow, and by the hydraulic shape and characteristics of the trash rack. Value can be calculated by using the equation below [2]:

\[ h_R = \frac{v_R^2}{2g} \]  

In the equation above, “\( h_R \)” represents the head loss, “\( \zeta_R \)” represents head loss coefficient, “\( v_R \)” represents stream velocity in front of the trash rack, and “\( g \)” stands for gravitational acceleration. For the purpose of research other equations were also used for calculating the head loss value. First equation was developed by Kirschmer and it is based on the geometry of both horizontal and vertical bars of the trash rack [3]:

\[ h_R = K \left( \frac{t}{b} \right)^{\frac{5}{6}} v_R^2 \]  

Fig.1: Trash rack at the intake of the hydropower plant (wilcoxdiving.com).

One of the most important geometric parameters of trash rack is clean span opening, which represents an open area between the bars, and it is usually square or rectangle.
In this equation, factor “K” depends on the cross section shape of trash rack’s bar (see figure 2), “t” stands for bar thickness, while “b” represents the distance between the two bars. Angle “α” is the angle between the trash rack and the river bottom.

Next equation was developed by Beresinsky and it also takes geometry of the trash rack into consideration, while the expression is a bit more complex than those mentioned before [2]:

\[ h_R = \zeta_{fr} \cdot K_5 \]  

(3)

Where “K_5” is the factor of flow angle (if the flow is normal then \(K_5 = 1\), otherwise, it depends on the flow angle). “\(\zeta_{fr}\)” is the normal flow head loss coefficients and it is calculated as [2]:

\[ \zeta_{fr} = \beta_{OR} \cdot \left( \frac{A_{B} - A_{Z}}{A} \right)^{1.4} \cdot \left( 2.3 \frac{1}{b} + 8 + 2.4 \frac{1}{b} \right) \sin \alpha \]  

(4)

Where “\(\beta_{OR}\)” represents factor that depends on cross section shape of the bar, “\(A_{B}\)” is the area of the trash rack which is occupied by the rack’s elements (bars, frame and mounting guides), “\(A_{Z}\)” is clogged area of the trash rack, while “\(A\)” represents the total area of the trash rack, and finally “l” represents length of the bar’s profile.

Finally, the third equation used in this paper was developed by Idel’chik. It can be described as only geometry based since all of the variables (\(\beta_2\) and \(\zeta\)) are dependent on trash rack’s bar dimensions [4]:

\[ h_R = \zeta_{fr} \cdot \frac{\sqrt{\frac{v^2}{2g}}}{\beta_2} = \beta_1 \cdot \zeta \cdot \sin \alpha \cdot \frac{\sqrt{\frac{v^2}{2g}}}{\beta_2} \]  

(5)

As it was mentioned in the abstract of the paper, results of these calculations were compared to the results obtained by running CFD based analyses. Head loss was calculated as pressure drop (pressure difference in front and behind the trash rack).

3. MODEL USED FOR THE RESEARCH

For the purpose of the research, 3 different trash rack models were made by using the modeling software. The only difference between them is the cross section of the vertical bars – the first model has vertical bars with rectangular shaped cross section, the second model has rectangular cross section with rounded edges, while the third one has round (circular) cross section. The thickness of the bars has the same value (15 mm), cross sections are 30 mm long, and the distance between the bars (clean span opening) is 200 mm.

Each of the trash racks is 10m high and 6m wide. Also, each one has 23 vertical bars and 7 horizontal bars. By looking at figure 4, it is clear that model consists of three-dimensional trash rack and the volume that represents the river. Channel behind the trash rack is mostly made of concrete, so it was defined as “wall”, while the “side walls” of the water volume in front of the trash rack were defined as “symmetry” (wall which doesn’t affect any of the analyzed parameters). Also, the entrance to the trash rack’s area is rounded, because it is the most common case since it balances negative flow effects (especially in the case of inclined flow). Dimensioned model with red-coloured rounded entrance can be seen in figure 5:
Every simulation had several different stream velocities (from 0.4 m/s to 2 m/s). In every simulation there was an assumption that the trash rack was clean.

4. NORMAL FLOW SIMULATION

The first analysed case was the case of normal flow through the trash rack. All of the three available trash rack models were used, while 7 different stream velocities were selected as input values for CFD based software. Head loss was calculated by using CFD value, and by using equations developed by Kirschmer (2), Berezinsky (3 and 4) and Idel’chik (5).

4.1. Steady flow simulation

Steady flow is theoretical form of fluid flow which is based on assumption that parameters of the flow don’t change during the time (they have constant values). When it comes to the simulation setup, it should be noted that unstructured mesh was used (with around 3 million elements) and that SST model (Shear Stress Transport) was used as the turbulence model (because the trash rack was defined as wall). Velocity changes during normal flow can be seen in figure 6:

![Fig.6: Stream velocity changes for different input velocities during steady normal flow simulations [1].](image)

Results of the simulation are shown as in the following tables and diagrams (the abscissa represents square value of stream velocity while the ordinate represents head loss):

**Table 1: Head loss during normal flow through the trash rack with rectangular shaped cross section of vertical bars [1].**

<table>
<thead>
<tr>
<th>(v_R)</th>
<th>CFD</th>
<th>Kirschmer</th>
<th>Berezin.</th>
<th>Idel’chik</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>(h_R)</td>
<td>0.103</td>
<td>0.093</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>1.5</td>
<td>(h_R)</td>
<td>0.058</td>
<td>0.052</td>
<td>0.084</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>1</td>
<td>(h_R)</td>
<td>0.037</td>
<td>0.033</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>1</td>
<td>(h_R)</td>
<td>0.026</td>
<td>0.023</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>1.2</td>
<td>(h_R)</td>
<td>0.016</td>
<td>0.015</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>1</td>
<td>(h_R)</td>
<td>0.009</td>
<td>0.008</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
<tr>
<td>0.8</td>
<td>(h_R)</td>
<td>0.004</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.506</td>
<td>0.46</td>
<td>0.74</td>
</tr>
</tbody>
</table>

![Fig.7: Comparison of head loss values for the case of steady normal flow through the trash rack with vertical bars with rectangular shaped cross section [1].](image)

**Table 2: Head loss during normal flow through the trash rack with rectangular cross section of vertical bars (with rounded edges) [1].**

<table>
<thead>
<tr>
<th>(v_R)</th>
<th>CFD</th>
<th>Kirschmer</th>
<th>Berezin.</th>
<th>Idel’chik</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>(h_R)</td>
<td>0.103</td>
<td>0.088</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>1.5</td>
<td>(h_R)</td>
<td>0.058</td>
<td>0.049</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>1</td>
<td>(h_R)</td>
<td>0.037</td>
<td>0.031</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>1</td>
<td>(h_R)</td>
<td>0.026</td>
<td>0.022</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>0.8</td>
<td>(h_R)</td>
<td>0.016</td>
<td>0.014</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>0.6</td>
<td>(h_R)</td>
<td>0.009</td>
<td>0.008</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>0.4</td>
<td>(h_R)</td>
<td>0.004</td>
<td>0.0035</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>(\zeta_R)</td>
<td>0.505</td>
<td>0.43</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Fig. 8: Comparison of head loss values for the case of steady normal flow through the trash rack with vertical bars with rectangular cross section (with rounded edges) [1].

Table 3: Head loss during normal flow through the trash rack with circular cross section of vertical bars [1].

<table>
<thead>
<tr>
<th>$v_R$</th>
<th>$h_R$, CFD</th>
<th>$h_R$, Kirschmer</th>
<th>$h_R$, Berezin.</th>
<th>$h_R$, Idelchik</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.108</td>
<td>0.089</td>
<td>0.078</td>
<td>0.079</td>
</tr>
<tr>
<td>1.5</td>
<td>0.061</td>
<td>0.050</td>
<td>0.044</td>
<td>0.044</td>
</tr>
<tr>
<td>1.2</td>
<td>0.039</td>
<td>0.032</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>1</td>
<td>0.027</td>
<td>0.022</td>
<td>0.019</td>
<td>0.020</td>
</tr>
<tr>
<td>0.8</td>
<td>0.017</td>
<td>0.014</td>
<td>0.012</td>
<td>0.013</td>
</tr>
<tr>
<td>0.6</td>
<td>0.009</td>
<td>0.008</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>0.4</td>
<td>0.004</td>
<td>0.004</td>
<td>0.003</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Fig. 9: Comparison of head loss values for the case of steady normal flow through the trash rack with vertical bars with circular cross section [1].

As it can be concluded from the obtained results, CFD simulation can be successfully used for determining the value of the head loss caused by the flow parameters and trash rack itself. However, it is highly recommended that those results should be checked by comparing them to the equations and expressions from the literature.

4.2 Unsteady flow simulation

Unsteady (transient) flow is natural case of water flow when all of the flow parameters have different values over the time (unsteady flow can be described as vortical, unstable, chaotic, nonlinear and dissipative). The idea was to compare results of the steady and unsteady simulations of normal flow through the trash rack, so it can be seen whether or not the steady flow simulations are suitable to be used for this level of research (since unsteady simulation needs a far better computer for calculations, more time and memory). It should be noted that 20 seconds of flow simulation took around 15 hours to complete and around 50 GB of hard disk storage room. For that reason, only trash rack with rectangular cross section of the bars was used.

Since the results of unsteady simulations are almost identical to the results of steady simulations presented in Table 1 and Figure 7, only the tabular results are given:

Table 4: Comparison of head loss values from steady and unsteady CFD simulation of the river flow through the trash rack with vertical bars with rectangular shaped cross section [1].

<table>
<thead>
<tr>
<th>Flow velocity</th>
<th>$h_R$, steady</th>
<th>$h_R$, unsteady</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.103</td>
<td>0.104</td>
</tr>
<tr>
<td>1.5</td>
<td>0.058</td>
<td>0.059</td>
</tr>
<tr>
<td>1.2</td>
<td>0.037</td>
<td>0.038</td>
</tr>
<tr>
<td>1</td>
<td>0.026</td>
<td>0.026</td>
</tr>
<tr>
<td>0.8</td>
<td>0.016</td>
<td>0.017</td>
</tr>
<tr>
<td>0.6</td>
<td>0.009</td>
<td>0.0094</td>
</tr>
<tr>
<td>0.4</td>
<td>0.004</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

Table 5: Comparison of head loss coefficient values from steady and unsteady CFD simulation of the river flow through the trash rack with vertical bars with rectangular shaped cross section [1].

<table>
<thead>
<tr>
<th>Flow velocity</th>
<th>$h_R$, steady</th>
<th>$h_R$, unsteady</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.103</td>
<td>0.104</td>
</tr>
<tr>
<td>1.5</td>
<td>0.058</td>
<td>0.059</td>
</tr>
<tr>
<td>1.2</td>
<td>0.037</td>
<td>0.038</td>
</tr>
<tr>
<td>1</td>
<td>0.026</td>
<td>0.026</td>
</tr>
<tr>
<td>0.8</td>
<td>0.016</td>
<td>0.017</td>
</tr>
<tr>
<td>0.6</td>
<td>0.009</td>
<td>0.0094</td>
</tr>
<tr>
<td>0.4</td>
<td>0.004</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

It can be concluded that steady simulation is suitable for usage when it comes to this type of research/simulation. For more complex situations and specific phenomena which could possibly occur, it is recommended to use the unsteady setup of the simulation and run it for a far longer period (measured in days or even weeks).

5. STEADY INCLINED FLOW SIMULATION

It is vital to find out what happens with the flow parameters when river flow is not perpendicular to the trash rack. The case of inclined flow is very common, and
the interesting fact is that the angle of the flow (δ) has different values at different water depth level (this fact was not part of research).

For the purpose of the simulation, 4 value of flow angle were analysed (15°, 30°, 45°, 60°). In CFD simulation’s setup 2 intakes were chosen and only trash rack with vertical bars with rectangular cross section was taken into consideration. Inclined flow is presented in figure 10:

![Inclined Flow Direction](image)

**Fig.10: Inclined flow direction at the entrance of analysed model.**

Since the entrance to the trash rack’s area is rounded, it tends to rectify the flow which means that flow angle does not have that big influence on head loss value. However, after the simulations were done it was clear that flow angle at the entrance of the model (δ) is different than the actual flow angle in front of the trash rack (δR). Same applies to the velocity. Like in the case of normal flow (figure 6), velocity change for different flow angles is represented in the following figure (vR=2 m/s):

![Stream Velocity Change](image)

**Fig.11: Stream velocity change in case of the inclined flow for different flow angles [1].**

As it can be seen, head loss values merely change compared to the case of normal flow (when the entrance to the trash rack’s area is rounded). However, values of flow velocity are different (lower), so inclined flow can affect parameters behind the trash rack which are, in case of the hydropower plant, the intake parameters of the water turbine.

### 6. CONCLUSION

Trash racks are very responsible and important parts of hydropower systems. They are exposed not only to the accumulation of water debris, but also to stream velocity and flow angle variations. The purpose of this paper is to represent analyses of different exploitation conditions of the flow through different types of trash racks, and to determine how those conditions change flow and energy parameters.

**Table 6: Flow parameters in case of inclined flow through the trash rack when the angle is equal to 15° [1].**

<table>
<thead>
<tr>
<th>δ = 15°</th>
<th>VR, entr  → VR, trash rack</th>
<th>δR</th>
<th>vZ</th>
<th>ζR</th>
<th>hR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vR,entr = 1.646</td>
<td>0.8</td>
<td>1.676</td>
<td>0.461</td>
<td>0.0657</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.987</td>
<td>1.08</td>
<td>1.005</td>
<td>0.459</td>
<td>0.0236</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.786</td>
<td>0.672</td>
<td>0.457</td>
<td>0.0105</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.393</td>
<td>0.336</td>
<td>0.460</td>
<td>0.0026</td>
<td></td>
</tr>
</tbody>
</table>

**Table 7: Flow parameters in case of inclined flow through the trash rack when the angle is equal to 30° [1].**

<table>
<thead>
<tr>
<th>δ = 30°</th>
<th>VR, entr  → VR, trash rack</th>
<th>δR</th>
<th>vZ</th>
<th>ζR</th>
<th>hR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vR,entr = 1.746</td>
<td>13.9</td>
<td>1.799</td>
<td>0.463</td>
<td>0.0764</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 1.047</td>
<td>13.9</td>
<td>1.079</td>
<td>0.463</td>
<td>0.0275</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.698</td>
<td>13.9</td>
<td>0.719</td>
<td>0.463</td>
<td>0.0122</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.388</td>
<td>14</td>
<td>0.359</td>
<td>0.465</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

**Table 8: Flow parameters in case of inclined flow through the trash rack when the angle is equal to 45° [1].**

<table>
<thead>
<tr>
<th>δ = 45°</th>
<th>VR, entr  → VR, trash rack</th>
<th>δR</th>
<th>vZ</th>
<th>ζR</th>
<th>hR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vR,entr = 1.728</td>
<td>17.51</td>
<td>1.812</td>
<td>0.473</td>
<td>0.0792</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 1.037</td>
<td>17.38</td>
<td>1.087</td>
<td>0.473</td>
<td>0.0285</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.690</td>
<td>17.47</td>
<td>0.724</td>
<td>0.475</td>
<td>0.0127</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.346</td>
<td>17.22</td>
<td>0.362</td>
<td>0.479</td>
<td>0.0032</td>
</tr>
</tbody>
</table>

**Table 9: Flow parameters in case of inclined flow through the trash rack when the angle is equal to 60° [1].**

<table>
<thead>
<tr>
<th>δ = 60°</th>
<th>VR, entr  → VR, trash rack</th>
<th>δR</th>
<th>vZ</th>
<th>ζR</th>
<th>hR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vR,entr = 1.549</td>
<td>24.53</td>
<td>1.703</td>
<td>0.521</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.928</td>
<td>24.61</td>
<td>1.021</td>
<td>0.523</td>
<td>0.0278</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.618</td>
<td>24.60</td>
<td>0.680</td>
<td>0.522</td>
<td>0.0123</td>
</tr>
<tr>
<td></td>
<td>vR,entr = 0.308</td>
<td>24.65</td>
<td>0.339</td>
<td>0.523</td>
<td>0.0031</td>
</tr>
</tbody>
</table>
After all analyses were done, a list of conclusions can be written as the summary of the research:

- CFD simulations can be used for calculation of head loss and head loss coefficient in case of the normal flow through the trash rack. However, it is also recommended to calculate those parameters by using different equations, so the results obtained from simulations can be both checked and compared to the calculated ones.
- When it comes to the selection of the cross section shape of trash rack’s bars, the head loss value cannot be primary criteria, since the shape barely affects head loss as a parameter. However, economic aspect can be used as criteria since the more complex shape of bar requires more detailed and precise production – so it is more expensive.
- Although real flow is always unsteady (transient), the results show that both steady and unsteady setup of simulation can be used, since in both cases results are almost identical. However, unsteady simulations take way more time to complete, and they require a very powerful computer for running the simulations.
- Building the rounded entrance to the trash rack area is highly recommended since it is shown that the geometry of the entrance rectifies the inclined flow and reduces head loss values variations. It should be noted that rounded entrance also lowers stream velocity, so the inclined flow can still affect the intake parameters of the water turbine, which is behind the trash rack.
- For the future researches, it is recommended to run simulations on supercomputer, so the CFD mesh can be denser (it could be made from tens or hundreds of millions of elements compared to the mesh used in this research which consists of 3 millions of elements).

REFERENCES

[2] BENIŠEK, M. (academic year 2015/16) Hydropower plants and equipment; Part two (lectures), (in serbian: Hidroenergetska postrojenja i oprema; Drugi deo), University of Belgrade Mechanical Engineering Faculty, pp 12-13

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ANALYSIS OF TRANSIENTS IN HYDROELECTRIC POWER PLANTS FOR SPECIFICIED OPERATIONAL REGIMES

Jovan ILIĆ
Ivan BOŽIĆ

Abstract: In this paper one of possible working regimes of a hydroelectric power plant is investigated. Analysis of sequential turbine starts and their implementation is one of modern approaches that should be taken into account during building of a new energetic system. In this paper results of simulations and analyses of sequential turbine starts in a hydroelectric power plant “Pirot” are presented. Those results are compared to a regimes that are currently used in that system. Equations that describes simulations are shortly presented along with method that is used for their implementation.

Key words: water-mass oscillations, transients, sequential starts, hydropower plant working regimes.

1. INTRODUCTION

Hydropower plants, as very flexible systems, occupy top area on electro-energy diagram of a country. Every change in required power is successfully balanced by these power production systems. Power manipulation is done by closing/opening turbine gate and this process has an effect on all elements in a Plant. Various turbine operations such as start-up, shut down, load acceptance or rejection produce transients in hydroelectric power system. Calculation of hydro-mechanic transients during normal, special or emergency working regimes is very important during construction and exploitation of hydropower plant. This phenomenon requires serious approach taking into account possible consequences like human lives and expensive equipment loss. Intense pressure oscillations, during transient state, represent major problem for penstock, turbine regulation and other equipment and that pressure can be several times higher than normal. There are six groups of transient analysis that should be taken into account during construction of a hydropower plant (HPP) and they are represented in table 1. Which analysis needs to be done depends on the elements that hydropower plant possesses. The basis of this paper are water-mass oscillations analyses, although equations that are used for water hammer research are the same. Turbine shut-down, especially in emergency situations, is followed by large pressure oscillations in water supply system. It is of great importance to have precise information on extreme pressure values in system. Analyses of water-mass oscillations are followed by low frequency, but long term oscillations, and by analyzing them designer chooses pipe dimensions and dimensions of the surge tank. In this paper, those analyses are done for a specific HPP, named “Pirot”. With already defined construction and operating modes, there is a better chance of synchronizing equations for simulations of transient regimes in a hydroelectric power system. HPP “Pirot” as a well-equipped hydropower plant is a good example for

<table>
<thead>
<tr>
<th>No</th>
<th>Analysis</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WMO</td>
<td>Water-mass oscillations. These analyses are done if there is a surge tank in HPP. These transients are followed by low frequency pressure oscillations in a tunnel (reservoir – tunnel – surge tank).</td>
</tr>
<tr>
<td>2</td>
<td>WH</td>
<td>Water hammer analyses are important for the calculation of pressure oscillations in a penstock (reservoir – pipe – turbine).</td>
</tr>
<tr>
<td>3</td>
<td>TGOV</td>
<td>Turbine governing. These analyses are used to define turbine gate maneuvering while HPP is working and needs power change.</td>
</tr>
<tr>
<td>4</td>
<td>HOCH</td>
<td>Hydraulic oscillations. These researches are done to define possible resonance between quasi-settled oscillations of every element in a HPP.</td>
</tr>
<tr>
<td>5</td>
<td>OPCH</td>
<td>Open channel. This research is done if s HPP has open channel as an element.</td>
</tr>
<tr>
<td>6</td>
<td>LGOV</td>
<td>Level governing. These analyses are most often required if there is more than one HPP on the same flow - cascade.</td>
</tr>
</tbody>
</table>
analysis so the further on presented results are neither a part of previous design activities nor a part of existing project documents. Therefore, mathematical models were developed and necessary numerical simulations were performed.

2. HPP “PIROT” TRANSIENTS SIMULATION

Hydroelectric power plant “Pirot” is located in the south-east of Serbia. This facility is using potential energy from “Zavojsko” lake which has an altitude of 600 m above sea level and presents upper reservoir. Level of the lower water is around 370 m. HPP “Pirot” is equipped with two Francis turbines of 40 MW each, rotational speed of 500 rpm, and maximum flow up to 45.6 m$^3$/s. Considering gross head and field topology, this plant has more than eight kilometres of tunnels and around two kilometres penstock of derivation systems. At the end of the tunnel part there is a surge tank placed as one of security elements. Another security element of the plant is synchronous valve which is placed directly on spiral casing. HPP scheme is presented in figure 1 with its main parts.

![Fig.1: Hydro power plant “Pirot” scheme [5]](image)

Equations that are included in this paper along with the ones given in the literature made it possible to form a program for numerical simulations of transients in HPP.

3. EQUATIONS WHICH DESCRIBE TRANSIENTS IN HPP

Analysis of transients in hydro power plants is done through mathematical model that is formed for numerical simulation. Equations that are used are basic equations of fluid mechanics – continuity equation and dynamic equation. These equations were adjusted so they could be successfully implemented in mathematical model. Most of them can be found in literature [1], but for some cases [3] and [4] are recommended. The method of characteristics is used in numerical simulations. The purpose of this method is to convert partial differential equations into solvable normal differential equations. In the researched case, there are two matrices of coefficients and two familiar lines that are defined as Characteristics. These equations of characteristics are:

$$Q_f = C_p - C_a \Pi_f$$  \hspace{1cm} (1)

$$Q_s = C_n + C_a \Pi_s$$  \hspace{1cm} (2)

where “P” is an index for the next time step, Q is discharge and $\Pi$ is piezometric head. Coefficients $C_p$ and $C_n$ are defined as:

$$C_p = Q_A + \frac{\lambda}{a} \Pi_A - \frac{\lambda \Delta t}{a^2} Q_A |_{Q_A}$$  \hspace{1cm} (3)

$$C_n = Q_A - \frac{\lambda}{a} \Pi_A - \frac{\lambda \Delta t}{a^2} Q_s |_{Q_S}$$  \hspace{1cm} (4)

where “A” is cross-section area of the pipe, “a” is wave velocity, “D” is diameter of the pipe, $\lambda$ is friction coefficient and $\Delta t$ is time step which is needed to fulfill criteria of numerical stability. Indices “A” and “B” are defined in previous time step as shown in figure 2.

![Fig.2: Principle for calculation of next time step by method of characteristics [5]](image)

This method is most commonly used in engineering practice and it is recommended in literature [2]. For this method to be used, boundary conditions must be defined at the beginning and at the end of the pipe in all internal points. Boundary conditions that are used for mathematical modeling of hydroelectric power plant are defined in master thesis [5] and they are not subject of this paper.

4. STABILITY CRITERIA FOR NUMERICAL CALCULATION

Certain conditions must be fulfilled so that method of characteristics can give proper results. Rapidly growing error during calculation indicates numerical instability. Analysis of stability criteria is very complex and there were many recommendations about conditions that should be fulfilled. Recommendation by Perkins is:

$$\frac{\Delta \Pi}{\Delta a} < \frac{1}{a}$$  \hspace{1cm} (5)

In addition, Courtan’s researches present that equality in previous equation is also acceptable and recommended. Chaudhry recommends equation (6) which is related to more complex systems [1].

$$\Delta t = \frac{L}{a^2 n}$$  \hspace{1cm} (6)

where “L” is pipe length and “n” is number of sections into which pipe is divided.
5. SEQUENTIAL STARTS IN HPP “Pirot”

Series of researches were made during analyses of transients in HPP “Pirot”. Analyses considering water-mass oscillations and water hammer were investigated and part of water-mass oscillations analyses is represented here. One of operating regimes that is investigated is sequential turbine starts. Sequential starts are usually investigated during construction of HPP when low investment is needed. Main feature of these regimes is that minimal time difference between starts of turbine generator units is defined. By doing this restriction it is possible to build up a system with less material and cheaper security elements. Main effect during simultaneous turbine starts is pressure drop, this effect can be mitigated by doing sequential starts. These operation regimes are compared to the simultaneous turbine starts. Change of characteristic parameters during start of both turbines at the same time is shown in figure 3.

![Fig.3: Simultaneous turbine start of two turbine generator units [5]](image)

Change of the height of the liquid surface in the surge tank, change of flow rate in the stand pipe and change of flow before the surge tank are presented. Values of the main parameters that define hydroelectric power plant are: reservoir height \( H_{res} = 576 \) m, discharge at the start \( Q_{start} = 5.8 \) m\(^3\)/s and turbine gate opening duration of 90 seconds. It is shown that minimal height of the liquid surface in the surge tank is 531 m. This value defines bottom of the surge tank as it must not be higher than this. Improper construction of the surge tank, in the way that it is higher than it should be, can make catastrophic consequences during air suction in pipe system. In this paper two cases are taken into account. The first is with a delay of 90 s and the second is with a delay of 180 s between starts. In both cases turbine gates were opening to full load in 90 seconds. The opening way of turbine valves gates open is shown in figure 4 for the first case.

![Fig.4: Turbine gates of two turbine generator units during sequential start with 90 s delay [5]](image)

The values of characteristic parameters are shown in figure 5.

![Fig.5: Sequential turbine start of two turbine generator units with a delay of 90 sec [5]](image)

Figure 5 shows that there is no noticeable change in height of the liquid surface of the surge tank during sequential start with delay of 90 s with comparison to the simultaneous start. Further on, in case two, analysis of sequential turbine start with delay of 180 seconds is performed. For the second case where both turbines are also started to full load, the opening way of turbine gates is shown in figure 6.

![Fig.6: Turbine gates of two turbine generator units during sequential start with 180 sec delay [5]](image)
The values of characteristic parameters for case two are shown in figure 7.

In this case there are visible changes in pressure drop which is defined through height of the liquid surface in surge tank and decreases to 553 m. There is a 2 m difference in height. This difference is not enough for this working regime to be adopted so it would be useful to continue research of this regime on a hydroelectric power plant “Pirot”.

6. CONCLUSION

Calculation of fluid transients presents one of the greatest problems and challenges during construction of a hydroelectric power system. Extreme values of parameters that follow these phenomena are investigated and the results are used for the construction of basic elements. Wrong calculation may cause serious casualties and expensive damages of every part of the plant. Analyses of transients are necessary and they are done whenever a new energy system is built. Sequential starts give possibility for HPP building to become cheaper through operating limits and procedures. Sequential turbine starts were part of the master thesis [5] and the level of their examination is shown in this paper. Although it is already clear that these analyses are not very useful for the existing hydroelectric power plants, the idea is to present them and to show the way of their implementation. The more turbine generator units in hydroelectric power plant, the greater the requirement for this type of regime. This paper presents a comparison between simultaneous and sequential turbine starts. Numerical simulations were performed using original software developed within master thesis [5]. This software gave unlimited possibilities for performing tests of any working regimes in a hydroelectric power plant considering water-mass oscillations and water hammer oscillations. Results are showing that these working regimes are useful and should be implemented in a system if needed. Further investigation should be placed in projects for new hydroelectric power plants and in that way these analyses may become valuable.

REFERENCES


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THE FIRST FLUE GAS DESULPHURIZATION PLANT FOR THE COAL-BURNING THERMAL POWER PLANTS IN SERBIA

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Abstract: The primary goal of environmental protection in the field of energetics in the Republic of Serbia is the reduction of sulphur oxide emission from the large boilers of the thermal power plants. Pursuant to the valid legislation in the Republic of Serbia (Environmental Protection Law – Official Gazette of RS, no 135/04) and with the purpose of complying with the requirements of the EU directive for large combustion plants (EU Directive no. 2001/80/EC), the first flue gas desulphurization plant, which burns lignite from the Kostolac mine, was built and put into trial operation at TPP Kostolac B (2 x 350MW). This study shows the design and technical solutions, performed works, installed equipment and results received from the guarantee testing of this plant.

Key words: environmental protection, sulphur oxide, limestone, gypsum

1. INTRODUCTION

The necessity for building the flue gas desulphurization plant (FGD plant) at TPP Kostolac B came from the obligation to apply the national and international regulation in the field of the environmental protection. Meeting these requirements should provide obtaining the ecology licence, mandatory for the TPP Kostolac B further operation. Relatively high content of the total sulphur in the Kostolac coal basin (approx. 1,3%) and the access emission of sulphur oxides in flue gasses at TPP Kostolac (5,000 – 7,000 mg/m3), were the reason that the first flue gas desulphurization plant in thermal power plants in Serbia was designed and constructed in TPP Kostolac B. Pursuant to the valid Environmental Law (Official Gazette of the Republic of Serbia no.135/04) and the National Environmental Programme of the Republic of Serbia, and within the measures of substantial development and environmental management, as one of the primary goals was protecting the environment from the access emission of sulphur oxides from the big burners (EU Directive no.2001/08/EC). Public Enterprise ELECTRIC POWER INDUSTRY OF SERBIA – Belgrade, has concluded the contract with the Chinese company CMEC- Beijing, China for designing, delivery of the required equipment and construction of the flue gas desulphurization plant, created by coal combustion in the boilers of the TPP Kostolac B two units, both having the power of 2 x 348,5 MW. Based on the Investor's Design Task (PE EPS Belgrade) for preparing the Detailed Design, and the basis for designing and offered and contracted equipment, the Detailed Design was prepared by the designing company ENERGOPROJEKT Entel-Belgrade. After expert's control of this design and technical documentation, and based on the Report by the Republic Revision Committee and the Design Task, the Building Permit Design was done by the consortium consisted of the companies: ‘Kirilo Savic’ Institute, Belgrade and Designing company NDC, Belgrade.
2. DESIGN BASIS

The design basis are provided in the Design Task and shown in the following tables.

Table 1: Flue Gas Characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas temperature</td>
<td>°C</td>
<td>175</td>
</tr>
<tr>
<td>Flue gas flow (S.T.P., dry base, Oxygen)</td>
<td>m³/h</td>
<td>1469000</td>
</tr>
<tr>
<td>Flue gas flow (S.T.P., wet base, Oxygen)</td>
<td>m³/h</td>
<td>1830530</td>
</tr>
<tr>
<td>Flue gas flow (170°C, wet base, real oxygen)</td>
<td>m³/h</td>
<td>2970000</td>
</tr>
<tr>
<td>H₂O (S.T.P., wet base, Oxygen)</td>
<td>vol. %</td>
<td>19.75</td>
</tr>
<tr>
<td>O₂ (S.T.P., wet base, Oxygen)</td>
<td>vol. %</td>
<td>8</td>
</tr>
<tr>
<td>CO₂ (S.T.P., wet base, Oxygen)</td>
<td>vol. %</td>
<td>11.46</td>
</tr>
<tr>
<td>Concentration of SO₂ (S.T.P., dry base, 6%O₂)</td>
<td>mg/Nm³</td>
<td>7661</td>
</tr>
<tr>
<td>Concentration of ash (S.T.P., dry base, 6%O₂)</td>
<td>mg/Nm³</td>
<td>50</td>
</tr>
<tr>
<td>Concentration of SO₃ (S.T.P., dry base, 6%O₂)</td>
<td>mg/Nm³</td>
<td>50</td>
</tr>
<tr>
<td>Concentration of HCL (S.T.P., dry base, 6%O₂)</td>
<td>mg/Nm³</td>
<td>50</td>
</tr>
<tr>
<td>Concentration of HF (S.T.P., dry base, 6%O₂)</td>
<td>mg/Nm³</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 2: Limestone characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Base</th>
<th>Gypsum for disposal</th>
<th>Gypsum for the plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free moisture</td>
<td>%</td>
<td>dry</td>
<td>≤ 5.0</td>
<td>≤ 5.0</td>
</tr>
<tr>
<td>Calcium Carbonate CaCO₃</td>
<td>%</td>
<td>dry</td>
<td>≥ 89.0</td>
<td>≥ 94.0</td>
</tr>
<tr>
<td>Magnesium carbonate MgCO₃</td>
<td>%</td>
<td>dry</td>
<td>≤ 4.0</td>
<td>≤ 3.0</td>
</tr>
<tr>
<td>Sillicone dioxide SiO₂</td>
<td>%</td>
<td>dry</td>
<td>≤ 5.0</td>
<td>≤ 3.0</td>
</tr>
<tr>
<td>Iron oxide Fe₂O₂</td>
<td>%</td>
<td>dry</td>
<td>----</td>
<td>≤ 0.8</td>
</tr>
<tr>
<td>Total inert (incl. MgCO₃)</td>
<td>%</td>
<td>dry</td>
<td>≤ 11.0</td>
<td>≤ 6.0</td>
</tr>
<tr>
<td>Particles size analysis</td>
<td>mm</td>
<td>dry</td>
<td>19.05 x 0</td>
<td>19.05 x 0</td>
</tr>
<tr>
<td>Bond index (BW1)</td>
<td>KWh/T</td>
<td>as received</td>
<td>≤ 12.0</td>
<td>≤ 12.0</td>
</tr>
</tbody>
</table>

3. DESCRIPTION OF FGD PLANT

3.1. Location of the plant

FGD Plant is located on the vacant area behind the Units B1 and B2 within the TPP Kostolac B. The proposed location has enough space for placing the FGD Plant. The arrangement of the mentioned systems of the plant for flue gas desulphurization using the wet procedure was agreed with the TPP Drmno Urban Plans (TPP Kostolac B) and OCM Drmno, established in the year 1982 and with the arrangement of the new ash and slag transportation system. The requirements for the area needed for building one or two more Units for the TPP Kostolac B were also considered. The by-product of the flue gas desulphurization process is gypsum. Gypsum disposal area, which cannot be used commercially at time being, will be located in the available area of the closed part of the open cast mine Drmno.

Placing the gypsum disposal site in the exploited part of the open cast mine Drmno is favourable solution in respect of the environmental protection, since it does not require additional space, and provides possible re-usage of the material disposed in such manner. On the area in question a protective foil was put thus preventing the surface waters to reach the ground and the underground waters, figure no.2.

3.2. The designed technology of the plant operation

The TPP Kostolac B FGD Plant designing principles were the following:
1. The proces uses the moist-wet procedure 'from limestone to gypsum',
2. One absorber was designed and installed from each boiler,
3. The designed efficiency of the flue gas desulphurization, being min.97.5%, meets the boiler operation with maximum capacity while burning the designed coal of the lowest quality,
4. CO₂ emission does not goes over 200 mg/Nm3 in designed conditions,
5. One bypass channel for the flue gas was designed for safe functioning of the process with the load up to 100% of the FGD Plant operation,
6. FGD Plant is min.95% disposable,
7. Working life of the Plant is 15 years.

3.3. FGD plant consists of the following systems:
- Limestone storage and limestone slurry preparation system - sorbent,
- Absorber system,
- Flue gas system,
- FGD Plant process building,
- Dewatering system and gypsum transportation system,
- FGD Plant pipe bridges,
- Transportation system,
- Chimney, and
- Electrical installations.
3.4. Limestone storage and limestone slurry preparation system - sorbent

Limestone slurry preparation system (including limestone storage, grinding and delivery systems) includes:
- Limestone storage with the capacity of about 5040 t, 75m long, 26m wide and 9m high. The limestone is stored up to 4m in height. Limestone storage provides the supplies for approx. 7 working days for both Units,
- Limestone is delivered from the warehouse by the wheel loaders to the underground hopper-bunker to the adjacent object for limestone slurry preparation,
- The limestone is transported to the limestone silos via vibration doser and the elevator. Limestone silos, with the effective volume of 2,200 m³, provides the necessary supply of limestone for the continuous operation of both units for 72 hours. The limestone is carried from the silos via belt conveyor to the mill grinders (wet ball mills),
- The limestone is being ground by the two wet balls mills that provide the needed granulation of the limestone particles. Limestone particles cannot be larger than 44 microns,
- The preparation of the limestone slurry is joint for the both Units, B1 and B2 and the necessary slurry is being provided (30% of limestone and 70% of water) until meeting the requirements for the limestone particles size. Limestone slurry is pumped into the hydrocyclone and separated. The sediment (including also the larger particles) is then returned into the grinder and the upper flow automatically goes into the limestone slurry tank,
- Limestone slurry preparation system is apart from the absorber system.

A large limestone slurry tank is placed near the absorber system. The slurry is being delivered into the absorbers via limestone slurry pumps.

3.5. Absorber system

One absorber was designed for each Unit. Absorber diameter is 15,3m and reaction basin diameter is 16,9m. Flue gasses from the boilers enter the absorbers above the liquid level in the absorber reaction basin and they flow upwards with the designed speed of 3,8m/s.

Inside the absorber at the certain levels there are nozzles (sprinklers) for making the limestone slurry fog. Flue gas pass through the spreaded limestone slurry fog thus activating the chemical reaction of purifying the flue gas from the sulphur oxides and forming the gypsum slurry. Through the two lines of droplets eliminators installed above the line of nozzles, the flue gas pass through and exit the flue gas outlet located at the top of the absorber and move into the clean flue gas channels (fig.3).

Dimensioning of the absorber circulation pump used in the process, must be determined depending on the boiler load and the actual needs for the absorption slurry. The slurry that circulates and that has absorbed $SO_2$, falls into the absorber reaction basin. On the absorber walls in the absorber reaction basin, the four sets of gypsum slurry mixer were installed.

Air Fan (air blower) for oxidation provides the oxygen for the oxidation in the reaction basin. The oxidation air distribution system applies the "air eruption" principle. The system for intervening cooling of the flue gas was installed at the flue gas inlet channel into the absorber, for the case of flue gas temperature rising. Each absorber has one emergency water tank located above the gas input into the absorber.
Gypsum slurry is transported from the absorber via discharge pump from to the system for gypsum dewatering.

Two sets of liquid level gauges, two sets of pH gauges and one aerometer were designed for each absorber, for measuring and controlling the liquid level, pH measuring and measuring the gypsum slurry thickness. In the absorber zone, one drainage pit with the mixer and the drainage pump was designed for each unit. The function of the drainage pit is to collect the slurry from absorber discharge and the water used for flushing the equipment and the pipeline and then transport it in the absorber or in the intervent slurry tank.

3.6. Flue gas system

A complete flue gas channels system was provided for each Unit. Into the flue gas system channels for each Unit booster up fans (BUF) were installed in the dry flue gas zone before entering the flue gas into the absorber.

Flue gas system channels mostly consist of the following 4 parts:
- Channel from the FGD fan output to the chimney, including the output bypass channel to the old chimney for the tour around the FGD Plant.
- Input channel into the BUF fan,
- Channel between BUF output and absorber input,
- Channel between the absorber output and the new chimney.

The hot flue gas from the suction fan, under pressure, created by the BUF fan, flows towards the absorber. The flue gas at the absorber input goes through the emergency cooling up to the temperature of <1800°C.

Flue gas emergency cooling system was designed at the gas input into the absorber and consists of the water tank, nozzles and the flushing pipeline, water pump, valves and the auxilliary equipment. The pumps are located in the process building of the FGD Plant. Finally, the flue gas goes into the chimney. Temperature of the flue gas at the chimney output is 60 °C.

- The stopples, installed in the flue gas system, provide the normal operation of the FGD Plant, as well as some emergency operations, via bypass line.

3.7. Gypsum drainage and transportation system

It consists of the subsystem for drainage (thickening) and gypsum transportation sub-system.

- **Gypsum drainage subsystem** consists of the two-phased drainage process. The first phase is realized in the gypsum slurry hydrocyclone and the second phase is realized in the vacuum belt filter. Water content in the gypsum after the drainage is approximately < 10%. Gypsum slurry from the absorber is transported to the gypsum slurry hydrocyclone via absorber discharge pump. In the case of damage or during the overhaul of the absorber, the same pump delivers the gypsum slurry into the emergency tank.

Overflow from the gypsum slurry hydrocyclone automatically enters the waste water hydrocyclone supply tank. After that, it is transported to the waste water hydrocyclone via waste water hydrocyclone supply pump. Outflow of the gypsum slurry hydrocyclone enters the vacuum belt filter for drainage.

Overflow of the gypsum slurry hydrocyclone is transported out the FGD system and the outflow automatically enters the filtrate water tank. The design implies two vacuum belt gypsum filters. After the dewatering the gypsum falls into the gypsum storage facility and then is transported via wheel loader from the storage facility to the gypsum discharge bunker.

- **Gypsum belt conveyors subsystem** is equipped with all the necessary equipment between the underground basket to the disposal area and/or further gas distribution.

Gypsum transportation sub-system consists of the following:
- Underground basket for the gypsum,
- Other equipment for supplying the belt conveyors,
- Belt conveyors C1 to C4 with relay points,
- Remaining equipment (fans, controls, fire protection etc).

Below the underground basket – hopper, a belt feeder/doser was provided, for transporting the gypsum to the one-way belt conveyor. Via four in-line one-way belt conveyors the gypsum will be transported to the disposal area.
Gypsum conveyors consist of the 4 transporters (Cg-1,Cg-2, Cg-3, Cg-4) and 3 towers as the relay points (Tg-1, Tg-2, Tg-3). These towers are armoured concrete and steel constructions supplied with the manual chain cranes and infusion channels (hoppers).

3.8. The subsystems arranged in the process building of the FGD plant are:

- Process-technical water subsystem,
- Compressed air subsystems,
- Limestone slurry tank and the auxiliary equipment.

The subsystems for gypsum dewatering, process water and compressed air subsystem were designed to be used jointly between the Units B1 and B2.

- Process and technology water subsystem

This is the water used from the ash and slag pump station and via underground pipeline transported to the FGD Plant. One process water tank is installed in FGD system and its effective volume is sufficient for the water consumption.

Process water provides the complete FGD system with water, more precisely:
- flue gas and equipment cooling water,
- water for recharging (make-up) the absorber water,
- water for flushing the droplets eliminator,
- water for oxidation air moisture,
- water for flushing the gypsum from the drainage system,
- water for flushing the pipes of the FGD system and emergency fire water for FGD system.

- Discharge and drainage subsystem

This subsystem consists of the following equipment:
- two absorber drainage channels,
- one drainage channel in the limestone slurry preparation zone,
- one drainage channel in the gypsum thickening zone,
- one drainage channel in the emergency storage tank zone,
- one drainage channel in the chimney zone.

The mixer on the top and the submerged pump are installed on every drainage channel except the channel located in the chimney zone, where only the pump is installed, without the mixer.

- Compressed air subsystem in the FGD Plant consists of the instrumental air and service air used solely for maintainance purposes.

Two new compressors were installed (operating and standby) with the filters, air dryers and necessary armour.

3.9. Transportation system

The system for transportation, storage and mechanical constructions and technology includes:
- Solid materials storage with adequate equipment for transportation and disposal,
- Mechanical construction for transportation means – belt measuring limestone transporter to the grinder; bucket elevators for transporting limestone to the limestone silos; infusion basket and steel bar with the steel separator and vibro doser for the limestone transportation,
- Silo with the deduster on the top for limestone storage,
- Wet balls mills – grinders, as part of the main equipment of the limestone slurry preparation system,
- Mechanical construction for transportation means – belt conveyors for gypsum with adequate subsystems:
  - System for gypsum thickening/dewatering,
  - Process water system and
  - Limestone slurry tank and the auxiliary equipment.

3.10. Chimney

After the detailed technical and economical consideration of the possible design and technical solutions, it was desicced to design and construct a new chimney. Since there is a necessary area near the existing chimney 250m high, a new concrete chimney 177m tall was built and equipped with two cylindric steel pipes, with the diameter of 6,7m and 180m high, with titanium alloy in order to prevent condensate corrosion appearing on the pipe walls. The condensate which appered and is collected is transported via drainage channel into the chimney drainage pit and then via pump into the absorber or the emergency tank.

3.11. Electrical installations

The main supply for the FGD Plant was realized by building the separate 110kV voltage adapter and installing the two redundant transformers with the power of 2x25 MVA and the voltage of 110/6.6kV. For supplying the users of the voltage levels 6,3; 0,4 and 0,23 kV, the necessary number of necessary transformers and substations which are connected via required energy cables.

Safety supply of the priority uses was provided in three manners: double from the network and single from the diesel electric accumulator (DEA).

Supplying the single-current with the power of 30 kW was provided by installing the two lead storage batteries with the capacity of 2x400Ah and the voltage of 220V, which provide the 3 hours of operation for the JSS user with the total power of 30 kVA.

The supply voltage for the FGD Plant control system was provided using the necessary number of adequate apparatus for continuous supply – UPS, supplied from the network from the busbars 0,4/0,23 kV, from the emergency system or storage batteries.

Distribution and Control System (DCS) and Systems for continuous monitoring of gas emission (CEMS) are connected to central control of Units.

The installation of the lights, grounding, lightning protection, video surveillance and telecommunications were done pursuant to the needs of the FGD Plant as a whole.

4. GUARANTEE TESTING RESULTS

The following table shows the results of the conducted guarantee testing:
5. CONCLUSIONS

The results of performed guarantee testing, conducted by the independent and accredited laboratories of the Mining Institute – Zemun and Electrotechnical Institute Nikola Tesla, Belgrade, have shown the adequacy of the selected technology for the plant's operation (wet procedure 'from limestone to gypsum') and proved that TPP Kostolac B FGD Plant including the applied technical solutions and installed equipment, have met the guaranteed technical parameters. Based on previously performed retrofit of the Units, confirmed guarantee parameters for FGD Plant operation and the installed system for continuous monitoring of gas emissions (CEMS), and after completion of construction and commissioning of new waste water treatment plant, TPP Kostolac B shall meet conditions for obtaining the ecology permission for operation. TPP Kostolac B FGD Plant has been constructed and commissioned as the first such plant in Serbian thermal power plants and may be used as model for obtaining the experience in developing, designing and construction the other similar plants.

REFERENCES


CORRESPONDANCE

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Fig.4: Gypsum dump location in the excavated area of the open cast mine Drmino

Statements:
Guarantee testing measured values provided within the previous table show that the values are in accordance with the contracted guaranteed values. The results of the FGD Plan operation reliability must be monitored during the first year of operation of the Units' B1 and B2 FGD Plant. The contracted guaranteed values for the FGD Plant's operation must be exactly or better that 90% x 8.760 h.
THERMODYNAMIC ANALYSIS OF SYSTEM OF LOW-PRESSURE HEATERS
THERMO-ENERGY PLANT

Ivana KEĆMAN
Mirko DOBRNJAC

Abstract: The objective of this paper is an exergy analysis of a system of low-pressure heaters. Low-pressure heaters for which the calculations were made are recuperative heat exchangers. The calculations were made on the basis of data onto the technology scheme for thermal power plant. Using values which are given in a scheme and taking into account that the calculations were made for water, steam, or their mixture, the values of unknown parameters were calculated. After determining the following parameters: temperature, pressure, enthalpy and entropy of water and steam, on the inlet and outlet of all heat exchangers by using the formula for exergy matter flow the values of exergies on the inlet and outlet of low-pressure heat exchangers were calculated. By using the exergy method of thermodynamics analysis exergy efficiency was obtained, and later checked by using entropy method of thermodynamics analysis.

Key words: exergy, water and steam, exergy efficiency, low pressure heater, recuperative heat exchanger

1. UVOD

Na osnovu drugog zakona termodinamike, svaki oblik energije sastoji se od eksergije i anergije. Eksergija predstavlja onaj oblik energije koji se može neograničeno transformisati u rad, dok anergija predstavlja oblik energije koji se ne može prevesti u eksergiju.

2. EKSERGETSKO I ENERGETSKO PROCEJNIJAVANJE TERMODINAMIČKOG SAVRŠENSTVA- UPOREDNA ANALIZA

Kao primjer upoređenog energetskog i eksergetske procjenjivanja termodinamičkog savršenstva možemo uzeti parni kotao i kondenzator. Prema energetskoj analizi najveće gubitke ima kondenzator, skoro dvije trećine, jer se u njemu energija koja je dobijena od goriva odvodi u okolinu. Termodinamički stupeni korisnosti kondenzatora prema energetskoj analizi je oko 33%. Dok se u parnom kotlu gubi samo oko 10% od energije unešene u ciklus, sa izlaznim dimnim gasovima i zbog nesavršenosti izolacije. Potpuno drugačiju sliku dobijamo ako iste elemente posmatramo eksergetskom analizom. Naime kotao ima najveću nepovratnost, jer se toplota sa dimnih gasova na vodu i vodenu paru prenosi sa velikim razlikama temperature što dovodi do značajnih gubitaka eksergije. Za razliku od kotla, sa eksergetske analize, kondenzator je u velikoj mjeri termodinamički savršeniji, jer se toplota odvodi u okolinu pri znatno manjoj razlici temperature. Energetska analiza pokazuje da bi se trebali smanjiti gubici u kondenzatoru, dok eksergetska analiza pokazuje da bi se veća pažnja trebala posvetiti smanjivanju gubitaka u kotlu.

3. EKSERGETSKI STEPEN KORISNOSTI

Termodinamička analiza procesa koji se realizuje u nekom postrojenju se vrši na sledeći način:
1. postrojenje se kontrolnom granicom odvoji od okoline,
2. odrede se eksergije tokova materije i energije koje ulaze i izlaze kroz kontrolnu granicu (figura 1),
3. uporedi se odnos ulaznih i izlaznih eksergija. U realnim postrojenjima sumu izlaznih eksergija je manja od sume ulaznih za iznos gubitaka eksergije. Do gubitaka dolazi usljed nepovratnosti realnih procesa.

![Fig.1: Postrojenje odvojeno od okoline kontrolnom granicom](image)

Odnos izlaznih i ulaznih eksergija naziva se eksergetskim stepenom korisnosti:

$$\eta_e = \frac{\Sigma Ex_{ul}}{\Sigma Ex_{ul} - D},$$

gdje su: $\eta_e$ - eksergijski koeficijent korisnosti, $Ex_{ul}$ - ulazne eksergije, $Ex_{ul}$ - izlazne eksergije i $D$ - gubici eksergije. Kod eksergijske metode eksergetske stepen korisnog dejstva računamo na osnovu ulaznih i izlaznih eksergija, dok ga kod entropijske metode računamo na osnovu ulaznih eksergija i gubitaka eksergije.

4. EKSERGETSKA ANALIZA

Tradicionalne metode analize i proračuna složenih termoenergetskih sistema zasnivaju se na prvom zakonu termodinamike. Te metode koriste energetske bilanse za sistem. U principu, energetski bilansi ne daju nikakvu informaciju o internim gibodima. Nasuprot tome, drugi zakon termodinamike uvodi pojam eksergije, koji je koristan u analizi termoenergetskih sistema. Eksergija je mera za ocenu kvaliteta energije, i omogućava određivanje lokacije, uzroka, realnih veličina nastalih gubitaka kao i ostataka u nekom termičkom procesu.

Sistem zagrijača niskog pritiska čiju analizu vršimo (figura 2) za zagrijavanje osnovnog kondenzata koristi 4 zagrijača niskog pritiska (ZNP 1, ZNP 2, ZNP 3 i ZNP 4). Imamo dva radna medijuma voda koja se zagrijava u kondenzatora ZNP 4, a dio se odvodi u hladnjak šljake. Para između ZNP 1 i ZNP 2 se uvodi zagrijana voda iz zagrijača nižeg pritiska ZNP 2 i tako do ZNP 4. Kondenzat iz ZNP 4 se odvodi u kondenzator.

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Fig. 2: Tehnološka šema zagrijača niskog pritiska u sklopu termoenergetskog postrojenja

Legenda uz Fig. 2: \( G \) – protok [\( \text{kg/h} \)]; \( P \) - pritisak [\( \text{MPa} \)]; \( T \) – temperatura [\( \text{o} \)C]; \( H \) – entalpija [\( \text{kJ/kg} \)].

Jako bitan faktor pri procesu eksergetske analize jeste i usvajanje parametara okoline. Pod parametrima okoline podrazumevaju se referentna temperatura i pritisak. U literaturi se sreće nekoliko modela, ali najčešće se kao referentna temperatura i referentni pritisak usvajaju vrednosti: \( T_0 = 298.15[\text{K}] \), \( p_0 = 1013 \text{ mbar} \).

Na osnovu podataka dati na Figuri 2, koristeći se proračunom i programom za računanje parametara vode i pare dobijamo podatke u Tabeli 1.

Tabela 1: Pregled parametara ZNP 1

<table>
<thead>
<tr>
<th></th>
<th>Temperatura [K]</th>
<th>Entalpija [kJ/kg]</th>
<th>Protok [kg/s]</th>
<th>Entropija [kJ/kgK]</th>
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</thead>
<tbody>
<tr>
<td>Voda ulaz</td>
<td>371.3</td>
<td>414.1</td>
<td>213.333</td>
<td>1.294</td>
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<td>Voda izlaz</td>
<td>415.8</td>
<td>602.8</td>
<td>213.333</td>
<td>1.772</td>
</tr>
<tr>
<td>Para ulaz</td>
<td>521.4</td>
<td>2959.8</td>
<td>15.943</td>
<td>7.328</td>
</tr>
<tr>
<td>Para izlaz</td>
<td>376.9</td>
<td>435.8</td>
<td>15.943</td>
<td>1.352</td>
</tr>
<tr>
<td>Voda na ( T_s )</td>
<td>298</td>
<td>104.92</td>
<td>-</td>
<td>0.3672</td>
</tr>
</tbody>
</table>

Tabela 2 dobijena je korištenjem izraza za eksergiju toka materije u slučaju kada se potencijalna i kinetička energija struje fluida mogu zanemariti:

\[
Ex = W_{\text{max}} = H_1 - H_0 - T_0 \left( S_1 - S_0 \right) \quad (2)
\]

gdje su: \( H \), \( S \) - entalpija i entropija toka materije u stanju neravnoveža sa okolinom; \( H, S \) - entalpija i entropija toka materije u stanju ravnoteže sa okolinom.

Odnos izlaznih i ulaznih eksergija naziva se eksergetskim stepenom korisnosti ili koeficijentom termodinamičkog savršenstva pokazujemo proračun na ZNP 1:

\[
\eta_e = \frac{\Sigma Ex_{\text{ul}}}{\Sigma Ex_{\text{ul}}} = \frac{16906.55 + 596.42}{7038.62 + 12444.49} = 0.898366 = 89.84\% \quad (3)
\]

Oznaka: \( \eta_e \) – eksergetski stepen korisnosti

Na osnovu podataka dati na Figuri 2, koristeći se proračunom i programom za računanje parametara vode i pare dobijamo podatke u Tabeli 1.

Tabela 2: Vrijednosti eksergija ZNP 1

<table>
<thead>
<tr>
<th></th>
<th>Eksergija [kJ/kg]</th>
<th>Eksergija [kJ/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voda ulaz</td>
<td>32.9936</td>
<td>7038.62</td>
</tr>
<tr>
<td>Voda izlaz</td>
<td>79.2496</td>
<td>16906.55</td>
</tr>
<tr>
<td>Para ulaz</td>
<td>780.5616</td>
<td>12444.49</td>
</tr>
<tr>
<td>Para izlaz</td>
<td>37.4096</td>
<td>596.42</td>
</tr>
</tbody>
</table>

Provjeravamo dobijene podatke korištenjem entropijske metode:

\[
D = T_0 \cdot \Delta S_s = 298 \cdot (101,973 - 95,275) = 1966,004[\text{kJ/s}] \quad (4)
\]

Gdje su:

\[
\Delta S_s = m \left( s_{v,iz} - s_{v,ul} \right) = 213,333(1,772 - 1,294) = 101,973[\text{kJ/sK}] \quad (5)
\]

\[
\Delta S_p = m \left( s_{p,iz} - s_{p,ul} \right) = 15,943(1,352 - 7,328) = -95,275[\text{kJ/sK}] \quad (6)
\]

351
\[\eta_e = \frac{\Sigma E_{x_d} - D}{\Sigma E_{x_i}} = \frac{19483,11 - 1996,00}{19483,11} = 0,89755\]
\[\eta_e = 89,75\%\]

Tabela 3: Vrijednosti eksergija ZNP 2, ZNP 3 i ZNP 4

<table>
<thead>
<tr>
<th>Broj ZNP</th>
<th>Ulazna Eksergija ([kJ/s])</th>
<th>Izlazna Eksergija ([kJ/s])</th>
<th>Eckergetska stepen korisnosti (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1168,10</td>
<td>1132,81</td>
<td>96,98</td>
</tr>
<tr>
<td>3</td>
<td>4042,78</td>
<td>3470,95</td>
<td>85,85</td>
</tr>
<tr>
<td>4</td>
<td>1816,30</td>
<td>1112,72</td>
<td>61,26</td>
</tr>
</tbody>
</table>

Ulazne i izlazne eksergije za ZNP 2, ZNP 3 i ZNP 4 su određene na isti način kao i za ZNP 1. Nakon određivanja vrijednosti eksergija dobijen je stepen korisnog dejstva eksergijskom metodom koji iznosi:

\[\eta_e = 87,59\%\]

5. ZAKLJUČAK

Proračun stepena korisnog dejstva za zagrijač niskog pritiska (ZNP) 1 rađen je eksergijskom metodom, nakon čega je provjeren entropijskom metodom. Korištenjem eksergijeske metode dobijeno je da je stepen korisnog dejstva 89,94%, odnosno da su gubici 10,16%. Pri provjeravanju rezultata entropijskom metodom dobijeno je da je stepen korisnog dejstva 89,75%, odnosno da su gubici 10,25%. Razlika između dobijenih rezultata je manja od 1% na osnovu čega možemo zaključiti da je proračun sproveden ispravno i da su mala odstupanja pri korištenju različitih metoda. Za ostale ZNP i za ukupan sistem ZNP korištena je samo eksergijska metoda pri proračunu stepena korisnog dejstva. ZNP 4 ima najveće gubitke 38,74%, a ZNP 2 ima najmanje gubitke 3,02%, dok ZNP 3 ima gubitke 14,15%. Ukupan sistem zagrijača niskog pritiska ima gubitke 12,41%, odnosno stepen korisnog dejstva od 87,59%. ZNP 4 ima prevelike gubitke, zbog toga bi ga trebalo zamijeniti zagrijačem niskog pritiska koji bolje provodi toplotu ili primijeniti neke od ostalih mjera za povećanje stepena korisnog dejstva izmjenjivača toplote. Kao na primjer povećanje koeficijenta prolaza toplote u vidu izmjene konstrukcije zagrijača ili promjene režima srušanja kroz zagrijač.

REFERENCE

[5] CHEMICAL LOGIC, ChemicalLogic Steam Tab Companion, Thermodynamic and transport properties of water and steam, version 2.0

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MECHANICAL SYSTEMS
MONITORING AND
MAINTENANCE
DETERMINATION OF CRITICAL SIZE OF CORROSION PIT ON MECHANICAL ELEMENTS IN HYDRO POWER PLANTS

Radivoje M. MITROVIĆ
Dejan B. MOMČILOVIĆ
Ivana D. ATANASOVSKA

Abstract: Researchers in the field of fracture mechanics, predominantly developing appropriate solution algorithms for problems of solid bodies with cracks. Problems in mechanics generally, related with fracture and fatigue for solid bodies with various geometries of sharp notches, are studied to a much lesser extent. This situation can be explained by analytical difficulties arising in solving problems of elasticity theory for bodies with rounded notches. To solve problems of such class, starting from data on stress concentration in the rounded notch tip with a significant radius of curvature, simplified solutions with are therefore of great importance. Recent years, due to constant rise of computing power and development of numerical methods, re-evaluation of stress concentration factors from a viewpoint of theory of elasticity is present. This is mainly as a feedback from industry, which have requirements toward mega and nanostructures.

Corrosion represents an important limitation to the safe and reliable use of many alloys in various industries. Pitting corrosion is a form of serious damage on metals surface such as high-strength aluminum alloys and stainless steel, which are susceptible to pitting when exposed to a corrosive attack in aggressive environments. This is particularly valid for dynamic loaded structures.

The basic idea behind this paper is finding links between different scientific and engineering disciplines, which will enable useful level of applicability of existing knowledge. The subject of this paper is application of new method of determine length scale parameter for estimating the mechanistic aspect of corrosion pit under uniaxial/multiaxial high-cycle fatigue loading.

Key words: stress concentration, fatigue, multiaxial fatigue, corrosion pit, critical distance

1. INTRODUCTION

The variation of complex geometries on real mechanical components is in direct relation with local stress concentration phenomena. During recent years different theories have been developed to particularly perform the high-cycle fatigue assessment of notched components without missing the undoubted advantages of linear-elastic finite element solutions. The magnitude of fatigue damage can be quantified also in terms of linear-elastic notch tip stresses, taking into consideration the high-cycle fatigue only. The advantage of this simplification is that linear-elastic notch root stresses can easily be determined via conventional linear-elastic finite element (FE) models. The main drawback is that this methodology is very straightforward, the resulting level of conservatism is seen to increase as the sharpness of the geometrical feature being assessed increases. Consequently, under relatively large values of the stress concentration factors, this leads to components and structures which are heavier and bigger than necessary, with an end result of inefficient usage of materials and energy efficiency. Further, this simplified approach cannot be used to design against fatigue cracks and sharp notches, because the resulting linear-elastic local stress fields become singular when crack/notch tip radii are taken equal to zero. The problem increase with complex three dimensional geometries on components subjected with uniaxial/multiaxial loading [1]. Some of the answers for noted problems are solved by Theory of Critical Distances (TCD). TCD represents a family of methods that are all characterized by two main common features: (i) the relevant stress fields are determined by adopting a simple linear-elastic constitutive law to model the mechanical behavior of the material being assessed; (ii) the extent of damage is assessed via an effective stress whose value depends not only on the entire linear-elastic stress fields acting on the material in the vicinity of the crack initiation locations, but also on a material characteristic length [2-4].

The TCD can be applied solely to notches subjected to in-service Mode I fatigue loading. In order to extend its use to those situations involving complex multiaxial load histories, this approach has to be applied along with an appropriate multiaxial fatigue damage model. Researchers [1] has been proven that the highest level of accuracy is obtained by applying the PM along with the so-called Modified Wöhler Curve Method (MWCM) [5,6] and gradient elasticity [7-10], through length scale parameter
ℓ (1). The MWCM is a bi-parametrical critical plane approach, the critical plane being that material plane experiencing the maximum shear stress amplitude \( \tau_a \). The MWCM quantifies the extent of fatigue damage not only via \( \tau_a \), but also via the mean value, \( \sigma_{n,m} \), and the amplitude, \( \sigma_{n,a} \), of the stress perpendicular to the critical plane. Recent efforts [7–10] in the mechanics, materials science, and applied physics communities have introduced internal length in phenomenological gradient models to account for internal micro/nanostructures and derive, among other things, non-singular analytical expressions for dislocation/crack fields, as well as to interpret deformation localization phenomena (shear bands, dislocation patterns) along with size effects. As a result further development can be expected by combining gradient elasticity with TCD and MWCM. As to a possible way to determine length scale parameter \( \ell \), it is evident that gradient elasticity and the TCD share some important features. In particular, both approaches post-process the relevant stress fields by coupling linear-elasticity with an internal length scale parameter which is assumed to be an intrinsic material property. By taking as a starting point these similarities, recently it was proven that length \( \ell \) can directly be estimated from the TCD’s critical distance \( L \) as follows (1):

\[
\ell \approx \frac{L}{2\sqrt{2}} = \frac{1}{2\sqrt{2\pi}} \left( \frac{\Delta K_{th}}{\Delta \sigma_0} \right)^2
\]

Previous equation points that length scale parameter \( \ell \) can directly be estimated from the material plain fatigue limit, \( \sigma_0 \), and the threshold value of the stress intensity factor range, \( K_{th} \), or through known value of critical distance \( L \). Because both \( \sigma_0 \) and \( K_{th} \) are material properties, \( \ell \) is in turn an intrinsic characteristic length which is different for different materials and different load ratios.

The results in this field open field of application on corrosion fatigue damage assessment. Example for this application is given in [12, 13] which is good example of real component subjected to both uniaxial and multiaxial fatigue loading, with stress concentration – corrosion pit on transition radius, Fig 1. Detail of damage caused by corrosion on transition zone is shown on Fig 2.

2. DESCRIPTION OF APPLIED METHODOLOGY

The theory of critical distances (TCD) has named by Taylor [2] attempts to predict the effect of notches and other stress concentration features by considering the stress field in the region close to the notch tip. This theory requires two parameters, a characteristic distance and a critical stress or strain characterizing failure. In one version of the critical distance theory, termed as the Point Method, the failure occurs when the stress becomes equal to the failure stress at a given distance from the notch root. In the other version of the critical distance theory, termed as the Line Method, the failure is assumed to occur when the stress becomes equal to the failure stress when computed as an average value over a line of given length. The background philosophy lying behind the TCD is described as wish to observe engineering components rather than to test specimens. In practice this meant that we only considered predictive methods which could be applied to bodies of arbitrary shape and size, subjected to arbitrary loadings, containing stress concentration features of arbitrary geometry. This is achieved by measuring material behavior using test specimens containing notches rather than cracks (fatigue threshold \( \Delta K_{th} \) and toughness \( K_c \) using sharp notches rather than pre-cracks) which avoids the difficulties and uncertainties of carrying out standard fracture mechanics tests. The second presumption of successful application of TCD is the existence of an accurate stress analysis of the machine part.

Published results show that gradient elasticity was seen to be capable of accurately modeling, in the fatigue limit condition, the transition from the short to the long-crack regime [11]. Moreover, gradient elasticity applied along with the MWCM was successful in assessing the high cycle fatigue strength of specimens, the estimates falling within an error interval of ±20%.

The analysis and assessment of influence of corrosion pit depth on crack initiation was discussed [12–15]. The analysis of the stresses on various dimensions of pits on numerical model, Fig 3 and Fig 4a) was used to evaluate a critical depth of pit for this particular case, Fig 4b).
3. CONCLUSIONS

From the presented and promising results, the general conclusions from gradient elasticity point of view are:

Identification and determination length scale parameter through solid physics arguments from phenomena like fatigue, mechanism-based microscopic models, multiscale simulations, and
experiments, presents the way of enhancing present knowledge of stress concentration. This is important due fact that coupling gradient elasticity applied along with the MWCM is highly accurate in estimating high-cycle fatigue strength of notched components subjected to both uniaxial and multiaxial fatigue loading. It is also important to underline that application on real components require further research in this area to extend the use of the proposed methodology to the finite lifetime regime.

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REFERENCES


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METHODOLOGY FOR THE REPAIR OF DAMAGES THAT OCCURRED ON THE WELDED JOINTS AT THE BODY OF GUIDE VANE APPARATUS VANES OF THE VERTICAL KAPLAN TURBINE

Miodrag ARSIĆ
Srđan BOŠNJAK
Mladen MLADENOVIĆ
Zoranka MALEŠEVIĆ
Zoran SAVIĆ

Abstract: Vertical Kaplan turbines, with nominal power of 178 MW and manufactured in Russia, have been installed in 6 hydroelectric generating units of hydro power plant 'Djerdap 1'. Experimental tests were carried out by non-destructive methods in order to determine the turbine condition during the rehabilitation of the hydro power plant. Lack of root penetration was detected in V40 welded joints between upper and lower sleeves and bodies of guide vane apparatus vanes. Height of the lack of root penetration was in the range between 5 and 15 mm, while the allowable height of the lack of root penetration is 3 mm, according to the technical conditions. The upper sleeves were made of cast steel 25L (in accordance with GOST 977), while lower sleeves were made of steel forging St 25 (in accordance with standards GOST 1050 for chemical composition and GOST 8479 for forgings).

Methodology for the repair of non-penetrated welded joints between the sleeves and body of the guide vane apparatus vane was composed taking into account the results of ultrasonic testing. By repair methodology it is necessary to, due to the structural solution and service function of guide vane apparatus vanes, specify a large number of details, consider them carefully and carry them out in order to improve safety, because if some of them get overlooked, underestimated or incorrectly perceived, significant problems in turbine operation may occur.

This methodology refers solely to the repair of damaged welded joints between sleeves and bodies of guide vane apparatus vanes.

Key words: sleeve, guide vane apparatus vane, welded joint, lack of root penetration, repair methodology

1. INTRODUCTION

Vertical Kaplan turbines, with nominal power of 178 MW and manufactured in Russia, have been installed in 6 hydroelectric generating units of hydro power plant 'Djerdap 1' [1]. They were designed for the service life of 40 years due to the structural solution, or in other words due to the impossibility to perform periodic inspections and condition analyses. In figure 1 the guide vane apparatus vane is shown. In figure 2 welded joints V40 between the upper or lower sleeve and body of the vane are displayed, while in figure 3 the dimensions of the vane are represented. The repair methodology for non-penetrated welded joints was composed on the basis of ultrasonic testing results.

2. CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF PARENT MATERIAL

Chemical compositions and mechanical properties of cast steel 25L, steel forging St 25 and sheet metal MSt 3 of which the shaft sleeves and bodies of guide vane apparatus vanes were made are presented in tables 1 and 2, according to standards GOST 977 [2], GOST 8479 [3], GOST 1050 [4] and GOST 380-60 [5].
Fig. 1: Appearance of a vertical Kaplan turbine with nominal power of 178 MW

Fig. 2: Appearance of a guide vane apparatus vane with marked V40 welded joints

Fig. 3: Dimensions of a guide vane

Table 1: Chemical composition, values in [%]

<table>
<thead>
<tr>
<th>Material</th>
<th>GOST</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>25L</td>
<td>997</td>
<td>0.22-0.30</td>
<td>0.20-0.52</td>
<td>0.35-0.80</td>
<td>≤ 0.040</td>
<td>≤ 0.045</td>
<td>≤ 0.30</td>
<td>&lt; 0.30</td>
<td>&lt; 0.30</td>
</tr>
<tr>
<td>St 25</td>
<td>1050</td>
<td>0.22-0.30</td>
<td>0.17-0.37</td>
<td>0.50-0.80</td>
<td>≤ 0.035</td>
<td>≤ 0.04</td>
<td>&lt; 0.25</td>
<td>&lt; 0.25</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>MSt3</td>
<td>380-60</td>
<td>0.14-0.22</td>
<td>0.12-0.30</td>
<td>0.40-0.65</td>
<td>≤ 0.045</td>
<td>&lt; 0.055</td>
<td>&lt; 0.30</td>
<td>&lt; 0.30</td>
<td>&lt; 0.30</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of normalized and annealed material

<table>
<thead>
<tr>
<th>Material</th>
<th>GOST</th>
<th>YS [N/mm²]</th>
<th>TS [N/mm²]</th>
<th>Elongation A [%]</th>
<th>Contraction Z [%]</th>
<th>Impact energy KCU [KJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25L</td>
<td>997</td>
<td>305-315</td>
<td>520-530</td>
<td>21-23</td>
<td>27-28</td>
<td>62-64</td>
</tr>
<tr>
<td>St 25</td>
<td>8479</td>
<td>min 195</td>
<td>min 390</td>
<td>20</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>MSt3</td>
<td>380-60</td>
<td>min 206</td>
<td>min 509</td>
<td>43</td>
<td>-</td>
<td>54</td>
</tr>
</tbody>
</table>

3. WELDABILITY ANALYSIS OF PARENT MATERIALS

Weldability of parent materials is limited. Taking into account that cast steel 25L is 60 mm thick, as well as that sheet metal MSt 3 is 36 mm thick, it is recommended to perform preheating and post weld heat treatment even when welding / surface welding is being performed with use of filler material of the same type.

According to Sepherian, preheating temperature for thicknesses up to 200 mm is being calculated on the basis of the chemical composition, table 1. For thicknesses up to 200 mm and chemical composition of cast steel 25L, necessary preheating temperature during welding calculated according to Sepherian is

\[ T_p = \frac{360C + 40(Mn + Cr) + 20Ni + 28Mo}{h} = 360 \cdot 0.3 + 40(0.80 + 0.3) + 20 \cdot 0.3 = 158 \]

\[ h = \frac{158}{360} = 0.438 \]
\[ T_p = 350 \sqrt{C - 0.25} = 350 \sqrt{0.876 - 0.25} = 276^\circ C \]

\[ [C] = [C]_b + [C]_d = 0.438 + 0.438 = 0.876 \]

\[ [C]_d = 0.005 \cdot d \cdot [C]_b = 0.005 \cdot 200 \cdot 0.438 = 0.438 \]

3.1. Selection of welding procedure

Based on experience, the welding / surface welding process carried out through the use of filler wire (procedure 136) was selected due to the fact that significantly lower residual stresses compared to other welding procedures that are based on the use of filled welding electrodes occur.

3.2. Selection of filler material

Repair of non-penetrated welded joints between the sleeves and bodies of guide vane apparatus vanes by welding / surface welding was carried out through the use of filler wire Ø 1.2 mm [6]. Chemical composition and mechanical properties of weld metal formed through the use of filler wire OK E71T-1 are presented in tables 3 and 4.

**Table 3: Chemical composition of weld metal, values in [%]**

<table>
<thead>
<tr>
<th>Filler wire</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK E71T-1</td>
<td>0.06</td>
<td>0.50</td>
<td>1.30</td>
</tr>
</tbody>
</table>

**Table 4: Mechanical properties of weld metal**

<table>
<thead>
<tr>
<th>Filler wire</th>
<th>Yield strength YS [N/mm²]</th>
<th>Tensile strength TS [N/mm²]</th>
<th>Elongation A [%]</th>
<th>Impact energy KV [KJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK E71T-1</td>
<td>&gt; 420</td>
<td>510-590</td>
<td>&gt; 22</td>
<td>&gt; 54 (-20 °C)</td>
</tr>
</tbody>
</table>

4. METHODOLOGY OF REPAIR OF NON-PENETRATED WELDED JOINTS

This methodology refers to works carried out during the repair of non-penetrated welded joints between the sleeves and bodies of guide vane apparatus vanes by welding / surface welding.

4.1. Removal of non-penetrated areas in welded joints

Appearance of a non-penetrated area in welded joint V40 is shown in figure 4. Grinding of the section with lowered weld metal thickness should be carried out until reaching the depth which allows easier welding of 2-2.5 mm of sheet metal thickness in root area. Multiple openings with 3 mm in diameter should be drilled in order to check this measure. Length of the section which is being repaired is restricted to 200 mm in one passage in order to reduce the level of deformations. When it comes to longer sections, the repair should be carried out in several passages. Grinded spots should not have sharp edges and should enable accessibility for deposition of layers by welding. Grinded area should be degreased, dry and clean.

![Fig.4: Appearance of welded joints with the lack of root penetration on the side of the upper sleeve of a guide vane apparatus vane](image)

![Fig.5: Appearance of the grinded area at the side of the upper sleeve of a guide vane apparatus vane](image)
5. METHODOLOGY OF WELDING PROCESS PERFORMED IN ORDER TO REPAIR AREAS WHERE LACK OF ROOT PENETRATION WAS DETECTED

Preheating at max 150°C was performed by using the inductors located 300 mm around the area where grinding was performed, in compliance with Russian literature for cast steel 25L. Preheating temperature was checked by IC thermometers.

Welding was performed in PA position in grinded areas that were located on the same side of the vane, while welding in areas that were located symmetrically on both sides of the vane was carried out by 2 welders in PF position [7].

Welding was performed at ambient temperature greater than 5°C, with no significant air streaming. Weld reinforcement was removed by grinding after the finish of the welding process.

5.1. Parameters of repair welding performed in areas of welded joints where lack of root penetration was detected

Parameters that were used during the welding through the use of filler wire OK E71T-1 are as follows:

- Wire diameter: 1.2 mm;
- Current source:
  - direct,
  - polarity +,
  - voltage 25-28V,
  - current intensity 215-225 A;
- Protective gas:
  - Ar mixture,
  - composition of gas mixture in accordance with EN 439: M3-1 [8],
  - gas consumption 12-15 l/min;
- Welding speed in horizontal position: 0.35-0.45 m/min;
- Wire feed speed in horizontal position: 9.5 m/min;
- Length of the free end of the wire: 10-12 mm;
- Distance between the nozzle and the welding position: 12 mm.
5.2. Procedures that cause decrease of stresses and deformations that occur during repair welding

Following procedures were applied for the decrease of stresses and deformations that occur during repair welding:

- During the deposition of weld beads system that included overlaying of groove edges, with the finish layer for annealing, which was removed by grinding the face of the weld in order to even it with parent material (figure 8) was applied;
- Every layer was treated by pneumatic hammer with rounded top with diameter of 3 mm;
- After grinding was performed wide area (weld metal, heat affected zone and 10 mm of parent material on every side) of the repair weld was treated by pneumatic hammer with rounded top with diameter of 3-5 mm, during which overlapping of prints was required. After hammering the surface had to be polished.

6. HEAT TREATMENT OF REPAIR WELDS AT GUIDE VANE APPARATUS VANES

Heat treatment was carried out only for guide vane apparatus vanes with the volume of repair welds that exceeds 3000 cm³.

Applied parameters that refer to heat treatment, shown in figure 9, are as follows:

- Heating until reaching $T = 300^\circ C \pm 25^\circ C$ was carried out in 1 hour;
- Heating until reaching $T = 590 \pm 15^\circ C$ was carried out with rate less than 70 °C/h;
- Keeping the temperature at $590 \pm 15^\circ C$ was carried out in 5h;
- Cooling until reaching 250 °C was carried out with rate less than 50 °C/h;
- Cooling below 250 °C in still air.

![Fig. 8: Appearance of the order of deposition of weld beads along the cross-section of the guide vane apparatus vane](image)

![Fig. 9: Diagram that refers to heat treatment of repair welds of guide vane apparatus vanes](image)
7. TESTING OF REPAIR WELDS BY NON-DESTRUCTIVE METHODS

Testing of repair welds by non-destructive methods was carried out after the machining of the weld face and heat treatment were finished.

7.1. Visual testing

Visual testing (VT) of repair welds was carried out before, during and after welding in compliance with standard [9] and acceptability criteria from standard [10] for quality level B.

7.2. Magnetic particle testing

Magnetic particle testing (MT) of repair welds was carried out after the machining of the weld face and heat treatment were finished, in compliance with standard [11] and acceptability criteria from standard [12] for acceptance level 2.

7.3. Ultrasonic testing

Ultrasonic testing (UT) of repair welds was carried out after the machining of the weld face and heat treatment were finished, in compliance with standard [13] and acceptability criteria from standard [14] for acceptance level 3.

8. CONCLUSION

Successfulness of applied methodology for repair of areas of welded joints where lack of root penetration was detected between sleeves and bodies of turbine guide vane apparatus vanes by welding / surface welding at hydro power plant 'Djerdap 1' was confirmed by equipment manufacturer 'Power Machines' from Saint Petersburg, because they gave the guarantee for their use until next rehabilitation of the turbine.

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REFERENCES


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REPAIR WELDING OF GEAR SHAFTS OF SERVICE ROLLERS AT THE ŽELEZARA SMEDEREVO

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Uroš TATIĆ
Aleksandar SEDMAK
Mirjana OPAČIĆ

Abstract: Presented in this paper are two methods for repair welding of a total of 8 gear shafts (toothed shafts) of service rollers in the “Topla valjaonica” rolling mill within Železara Smederevo. Damage that occurs in these shafts is a consequence of exploitation conditions, which lead to lateral wear of the tooth up to one half of its thickness, due to adhesion and surface fatigue. Shown in the following text are the procedures for repair welding of gear shafts, including manual arc welding (MAW procedure) and the automatic welding procedure (FCAW). In addition, the requirements that need to be fulfilled in order to successfully perform the repair welding, so that the repaired parts can be exploited again, are presented. The techno-economic analysis had confirmed the technological and economical justifiability of applying this repair welding methods, compared to purchasing of new parts.

Key words: repair welding, gear shaft, wear, techno-economic analysis

1. INTRODUCTION

Material loss represents one of the main causes for applying of repair weld procedures. In the case of contact between two or more coupled machine parts, the following mechanisms of material loss can be distinguished: wear, abrasion, erosion. Damages caused by these mechanisms occur on the machine part surface. In addition to these damages, machine part damage can occur along the volume, due to material fatigue [1-4], usually caused by dynamic loads.

In order to make the proper decision about the need for repair welding and the corresponding procedure, it is necessary to develop the requirements and algorithm of the repair welding technology [5, 6]. Each technological procedure for repair welding of a machine part has its own specificities. The general algorithm for repairing of machine parts consists from a series of activities, which should be performed in the following order: disassembling, specimen cleaning, damage analysis, selection of the repair method, techno-economic analysis, development of technical documentation, development of the technological procedure, specimen preparation, repairing, tests and control, machining to the final dimensions, assembly, running in of the repaired parts.

Shafts made coupled with the gear, i.e. toothed shafts, are typically manufactured from materials used for the manufacturing of gears. These materials include cementation steel or enhanced materials, in accordance with the technical requirements. Finishing of the teeth is performed by milling or grinding, whereas other functional surfaces are always finished by grinding. In addition, shafts to which toothed elements are attached are made of high quality enhanced materials. Shaft samples are made of forgings or rolled material. The model of one such toothed shaft is shown in Figure 1.

Fig. 1: Model of gear shaft
Presented in this paper is the welding technology used on eight toothed shafts, i.e. the repairing of damaged teeth of driving shafts. Damage was caused by the exploitation conditions, and were reflected in form of worn teeth along the lateral profile, until one half of the thickness, due to adhesion and surface fatigue, which affects the connection between the shaft and the coupling. These gear shafts are parts of service rollers of "Topla valjaonica" rolling mill within Železara Smederevo. Železara Smederevo has 6 facilities with 2 service rollers and 2 support rollers. These driving shafts were manufactured by the German company "Siemag". During exploitation, gear shafts were subjected to variable loads and difficult working conditions at elevated temperatures. In Figure 2, the appearance of the teeth after exploitation and their damage can be seen.

Fig.2: Appearance of some of the gear shafts in the rolling mill „Topla valjaonica“ in Steelwork Smederevo

2. BASE MATERIAL OF GEAR SHAFT

Gear shaft, which were repaired due to damage, were made of steel 42CrMo4. This is an enhancing steel used for machine parts in engines and vehicles, subjected to high levels of load, at elevated temperatures. 42CrMo4 is an alloyed heat treatable steel with a typical tensile strength of 900 - 1200 N/mm². The 42CrMo4 alloy material also has high fatigue strength and good low-temperature impact toughness and low temper brittleness. The chemical composition of 42CrMo4 is given in Table 1, whereas its mechanical properties are given in Table 2.

Table 1: Chemical composition of steel 42CrMo4 [7]

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage [%]</td>
<td>0.38-0.45</td>
<td>Max 0.4</td>
<td>0.6-0.9</td>
<td>0.9-1.2</td>
<td>0.15-0.3</td>
<td>&lt;0.025</td>
<td>&lt;0.035</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of steel 42CrMo4 [7]

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Re [N/mm²]</th>
<th>Rm [N/mm²]</th>
<th>As %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>780</td>
<td>1000</td>
<td>10-14</td>
</tr>
</tbody>
</table>

Taking into account significant probability of residual stresses occurring after welding of parts whose thickness is greater than 30 mm, preheating and tempering after welding are required in order to remove these stresses. In addition, it is recommended to preheat in order to reduce the cooling rate, thus avoiding unwanted micro-structural changes [8-10].

3. REPAIR TECHNOLOGY FOR TOOTHED SHAFTS

During exploitation, gear shafts were subjected to variable loads and difficult working conditions at elevated temperatures. After the load analysis was performed, the development of the welding plan was initiated.

The welding plan begins by determining the reasons for repairing, and for this purpose the following activities are undertaken [5, 6, 11]:

- Selection of the repair procedure
- Calculation of the preheating temperature (if needed)
- Selection of additional materials
- Determining of the number of passes (layers)
- Determining of technological welding parameters
- Determining of the eventual need for additional heat treatment (if necessary)
3.1. Selection of the repair procedure

Repair welding was performed on eight gear shafts of service rollers. Based on the geometry and size of a gear shaft, the possibility of welding and the quality of the base material, as well as on rational welding procedures, two repair welding procedures were selected:

1) Flux core arc welding (FCAW procedure)

Seven of the shafts were repaired using the EPP procedure, and one was repaired using the E procedure.

3.2. Selection of additional materials

The chemical composition and mechanical properties of the electrode used for manual arc welding differs from the one used in the FCAW procedure. Based on the map shown in Figure 3, the selection of additional materials for repair welding is made. This selection is made in accordance with the percentage of carbon and other alloying elements, as well as in accordance with damage mechanisms.

Fig.3: Map of iron based hard repair welding [5]

Taking into account the selected repair procedures, base material quality, geometry and dimensions of the welded surface, geometry after machining, as well as the conditions under which the toothed shaft is working, the following additional materials for each procedure were selected:

1) For the flux core arc welding (FCAW), the WLDC 3 Ø 3.2 mm wire was used, along with the universal Weldclad powder. WLDC 3 wires are used for general purposes and are characterized by exceptional wear resistance at higher temperatures [12].

2) For manual arc welding (E), the following two electrodes were used:
   - Electrode Piva 29/9 R Ø 3.25 mm for the applying of the intermediate layer. This is an austenite-ferrite rutile electrode, used for welding of appropriate types of corrosion resistant steels and steel moulds, and for welding of heterogeneous steels, hard manganese steels and steels with poor weldability. It is suitable for repair welding and welding of intermediate layers [13].
   - Electrode Piva 430 B R Ø 5 mm for the finishing layers. This is a coated base electrode, used for repair welding of worn elements such as gears, axles, crushers, shafts and other machine elements [13]. Welded layers are characterized by high wear resistance and can be machined. Welded layers are pure, without porosity and material toughness is high at low temperatures as well. Hydrogen content in the welded layer is less than m1/100g of metal.

Electrode Piva 430 B and wire WLDC 3 are located in the adhesion resistant area, according to the map shown in figure 3, which partially corresponds to the requirements of the welded layer on the shaft. These electrodes are commercially available, economical and completely meet the welded layer requirements. Commercial designations, electrode manufacturers, chemical composition and mechanical properties of pure weld metal for the electrodes available on the market are presented in table 3 [12, 13].
Table 3: Electrodes used for repair welding procedure: chemical composition and mechanical characteristics

<table>
<thead>
<tr>
<th>No.</th>
<th>Commercial designation</th>
<th>Manufacturer</th>
<th>Chemical composition %</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>1</td>
<td>PIVA 430 B</td>
<td>FEP Plužine</td>
<td>0.15</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>PIVA 29/9 R</td>
<td>FEP Plužine</td>
<td>0.15</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>WLDC 3</td>
<td>Weldclad</td>
<td>0.12</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Before use, these electrodes were dried for two hours at a temperature of 300°C, and were then stored at a temperature of 150°C. On site, the electrodes are kept in accessory driers (quivers).

**3.3. Repairing of the toothed shaft**

After the additional materials have been selected, the repair welding of damaged gear shafts took place. In the following section of the paper, the activity flow during the repairing is presented, for both procedures.

The first step is the removal of worn-out teeth on one, as well as on both sides (depending on the damage) of the shaft, by machining. Shown in Figure 4 are the shaft dimension before and after preparation, i.e. machining. In this way, the damaged parts of the shaft (teeth) were removed, until the shaft diameter of $\Phi 380$ mm was achieved. In addition, machining also removed the material along the length until the non-damaged part of the shaft is reached.

![Fig.4: Left) Shaft dimensions before, and Right) after repair welding preparations](image)

The next step involved the testing of the prepared surface for repair welding via magneto-flux in order to detect cracks and other defects which can affect the bond between the parent material and the welded layer. Taking into account the workpiece thickness, as well as the properties of the base material, heat treatment of the welded joint represents the key position for the successful repairing of the gear shaft. Prior to welding, the shaft is locally preheated to a minimum of 200 mm to the left/right of the welding location to temperatures of 300 ±10°C. Preheating temperature was determined according to the Seferian procedure [14, 15].

Repair welding in accordance with the selected procedure and the corresponding additional material (in the case of repair welding using the MAW procedure, a puffer layer is first applied, using the Piva 29/9 R electrode, whereas welding continues with the use of Piva 430 B electrode). In order to overcome the differences in the mechanical properties, an intermediate layer made of a "softer" material is applied, which is common practice in engineering [6, 16, 17]. Parameters of the repair welding process are given in table 4.

Table 4: Welding parameters

<table>
<thead>
<tr>
<th>Manual arc welding (MAW procedure)</th>
<th>Flux core arc welding (FCAW procedure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Welding currency</td>
<td>190 - 230 A</td>
</tr>
<tr>
<td>Welding arc length</td>
<td>4 - 5 mm</td>
</tr>
<tr>
<td>Electrode angle relative to the application line</td>
<td>70 - 80°</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Powder - granulation (Tyler)</td>
<td>8 x 48</td>
</tr>
<tr>
<td>Current type and amperage</td>
<td>(+) do 800 A</td>
</tr>
</tbody>
</table>
Temperature during the repair welding was locally maintained within the range between 280 °C and 300 °C, for its full duration. The welding process lasted until the removed material was filled (i.e. until the pre-treatment shaft diameter was achieved), with added 3 mm along the generatrix for machining - tooth manufacturing. Welding was performed until a shaft diameter of 415 mm was achieved.

After welding, the repaired shaft is tempered in order to reduce residual stresses. The shaft is heated locally to a temperature of 620 °C/h at the rate of 50 °C/h and this temperature is maintain for a period of 3 hours. After 3h, the shaft is subjected to controlled cooling at the rate of 50 °C/h, until the temperature of 150 °C is reached, and at this point the machine is turned off and heat isolation is removed. After that, cooling continues at room temperature.

For the purpose of welded layer quality control, hardness was measured for both cases of repairing (MAW and FCAW procedures). Measured hardness of surfaces welded by the E procedure after heat treatment ranged from 280 to 310 HB, which entirely corresponds to the hardness of the tooth surface before repairing. The hardness of the welded layer on one of the shafts welded using the FCAW procedure is slightly higher and ranged from 320 to 340 HB.

3.4. Techno-economic analysis

Repair welding of working parts can help in achieving significant savings. All repaired shafts from the "Topla valjaciona" rolling mill have been in exploitation for over two years and there are still no signs of damage. The costs of repairing a single shaft, including the manufacturing of all necessary tools were around 1,500 €. The price of manufacturing a new shaft is around 25,000 €. Savings achieved with the use of repair welding in this case was around 200,000 € for all eight shafts, compared to the purchase of new ones. It should be mentioned, that due to their dimensions, delivering and assembling of new shafts would require several months, whereas repair welding can be performed in one week. Production downtime of several month in this facility would cause considerably higher financial losses. Thus it can be concluded that the indirect savings achieved by the use of repair welding is significantly higher than the aforementioned amount.

The conceptual solution for repair welding of machine parts was developed within the Železara Smederevo. A detailed techno-economic analysis determined that a bit over 800,000 € could be saved on an annual level, i.e. that repair welding of spare parts would make up 53% of the price of new parts. Costs mentioned previously also include the purchasing of necessary equipment, adaptation of the industrial hall, additional materials, etc.

4. DISCUSSION AND CONCLUSION

The problem of repair welding cannot and should not be observed purely as compensation of lost dimensions. Significant issues in repair welding occur within the domain of working parts dimension preservation. Enhancing the work surfaces quality is a particular technological problem whose solving needs to include extensive material science, the metallurgical nature of both base and added materials, which are dictated by the requirements which the applied welded layer must meet. In the example presented here, providing of a high quality weld in the case of toothed shaft repair welding requires the controlling of the following:

- preparation of the shaft for welding
- electrode drying process
- preheating and tempering temperatures
- the repair procedure itself, including the work done by welders or operators.

A high quality welded layer can be expected only in the case that all these elements are in accordance with the prescribed technology. After repair welding, the welded surface is machined, and after that, it needs to be examined in detail, using a non-destructive test method. It should also be noted that repairing of a single machine part cannot be performed an unlimited number of times. Practice had shown that a machine part can be repaired up to 3 or 4 times, thus it would be useful to introduce records about the repair history of any given machine parts, as a form of its "passport", which would contain information about its previous repairs.

In the example presented in this paper, both repair welding procedures that were performed (manual arc welding - MAW procedure, and flux core arc welding - FCAW procedure) were determined as favorable solutions for compensation of materials lost due to wear. Of all the requirements that need to be fulfilled, the most important ones are related to the absence of cracks and notches from the welded layer. In the case defects are detected after the repairing was completed (insufficiently welded surface for the MAW procedure and surface cracks for both procedures), these defects are removed by grinding the surface, or grooving in the case of significant depth of defects, followed by repeated welding in accordance with the technology.

All eight of the repaired shafts were put into back into exploitation and have been working for over two years, still showing no signs of damage, which confirms the justifiability of this technical solution for repairing. Direct financial savings achieved by applying repair welding, compared to the purchase of new shafts can be seen from these examples. Techno-economical analysis had determined that the total amount of around 200.000 € was saved, for all eight shafts, whereas the indirect saving were even greater.

ACKNOWLEDGEMENT

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REFERENCES


[7] Material data sheet, Dr. Sommer Material Technology, Dr. Sommer Werkstofftechnik GmbH


[12] Weldclad Roll welding technology, Material Data Sheet, Doc. No. DS024


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THE CASE OF UNSUCCESSFUL REPAIR WELDING OF A TREIBER ROLL

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Marko GAJIN

Abstract: Presented in this paper is the case of unsuccessfully performed repair welding of the upper treiber roll in the „Topla Valjaonica“ facility within the Železara Smederevo, currently known today as Hesteel ltd. Inadequate and improperly performed welding technology resulted in the occurrence of a large number of cracks, with the possibility of their propagation to the parent material. The upper and lower treiber roll are parts of the installation whose purpose is to fold the rolled strip and then send it to be further machined. The parent material used for the upper treiber roll was the structural steel S235JO. Repair welding was the consequence of damage that occurred during the exploitation of the roll. Shown in the paper are some of the cracks detected on the welded surface of the upper treiber roll. The analysis of the reasons behind the occurrence of these cracks is presented, and machining was recommended for the purpose of removing of these cracks, along with the use of certain NDT methods.

Key words: repair welding, cracks, preheating, welding

1. INTRODUCTION

Welding and activities related to it represent a process which requires special attention, starting from the design stage, through the development and performing of the technology and up to welded joint control stage, for the purpose of putting the welded or repaired machine part in exploitation. Deviations that occur during each of these stages may result in defects, cracks and deformation due to rapid cooling, along with the occurrence of unwanted metallurgical structures. Welding should be performed entirely in accordance with the welding technology. Presented in this paper is the case of repair welding of the upper treiber roll in the „Topla Valjaonica“ facility within the Železara Smederevo. The upper and lower treiber roll are the driving rolls which are placed in front of each strip coiler. These rolls are used to fold the strip supplied by the output rollers and direct it towards the coiling mandrel. The upper treiber roll is supported by the driver switch cradle. In addition, the treiber roll serves the purpose of providing sufficient tensile force to the strip between the rolls and the coiling mandrel. The diameter of the upper treiber roll is 900 mm, its calibrated length is 2280 mm, whereas the lower roll diameter is 400 mm. The geometry and position of the treiber rolls is shown in figure 1.

Due to exploitation conditions and wear, it was necessary to repair weld the upper treiber roll, as was predicted by the manufacturer. The roll was pre-machined in the mechanical workshop at the Železara Smederevo, to a diameter of 870 mm. After machining, magnetic flux testing of the whole roll was performed (including the branch and the work surface). The thickness of the welded hard layer should be up to 40 mm, including the intermediary layer, i.e. the diameter of the roll should be 910 mm. After welding and applying of hard weld layer, the upper roll have to be machined to a diameter of 900 mm. The following section of this paper contains a detailed overview of all activities performed during welding, as well as the activities performed in order to remove cracks. Repair welding was unsuccessful, resulting in the occurrence of cracks after cooling.
2. PROPERTIES OF THE UPPER TREIBER ROLL PARENT MATERIAL

The parent material of the treiber roll was steel S235JO, a general purpose structural steel with good weldability. Depending on the manufacturing process, chemical composition and relevant application, further letters and classifications might be used to reference particular grades/products of structural steel. This structural steels are used in many ways and their application can be diverse. They are particularly useful because they offer the unique combination of good welding properties with guaranteed strengths. Structural Steel is an extremely adaptable product and is often favored by the engineer trying to maximize strength or structure while minimizing its weight [1, 2]. The chemical composition of the roll parent material is given in table 1, whereas table 2 shows its mechanical properties.

Table 1: Chemical composition of the roll parent material

<table>
<thead>
<tr>
<th>Chemical Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>P max</th>
<th>S max</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.17</td>
<td>0.3</td>
<td>1.4</td>
<td>/</td>
<td>/</td>
<td>Max 0.55</td>
<td>0.045</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of the roll parent material

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Tensile strength Rm [N/mm²]</th>
<th>Yield strength Rf [N/mm²]</th>
<th>Elongation</th>
<th>Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>400-490</td>
<td>245</td>
<td>22</td>
<td>27</td>
</tr>
</tbody>
</table>

It should be noted that steel S235JO does not have the tendency towards neither hot nor cold cracks.

3. WELDING TECHNOLOGY

Repair welding was performed using automated FCAW procedure, with the following additional materials.

- WLDC 9 wire, along with the universal Weldclad powder was used for the puffer layer. This wire is low alloyed flux-cored wire, used for submerged-arc welding for build-up, maintenance and repair. WLDC 9 has excellent hot slag release, especially suitable for continuous welding operations.

- Universal Flux is suitable for single and multi-pass welding using single or twin wire technique [3].

- For the hard weld, WLDC 17 wire was used. This wire is fully basic, all mineral, non-alloying agglomerate flux for submerged arc welding wire, used for multilayer surfacing of hot strip mill process rolls including wrapper rolls and has a martensitic matrix [3].

First two layers formed the intermediary layer (puffer), whereas the following three layers represent the hard weld. Layers were applied using the oscillation technique, with weld overlap of 30-35%. Welding parameters are given in table 3. The diameter of the roll after surfacing is Ø 910-912 mm.

Table 3: Welding parameters

<table>
<thead>
<tr>
<th>Layer</th>
<th>Wire</th>
<th>Temperature max</th>
<th>Amperage</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WLDC 9</td>
<td>420 °C</td>
<td>500 – 550 A</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>WLDC 9</td>
<td>420 °C</td>
<td>500 – 550 A</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>WLDC 17</td>
<td>420 °C</td>
<td>500 – 550 A</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>WLDC 17</td>
<td>420 °C</td>
<td>500 – 550 A</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>WLDC 17</td>
<td>420 °C</td>
<td>500 – 550 A</td>
<td>+</td>
</tr>
</tbody>
</table>

The roll was not annealed after the repair welding was complete. Cracks have occurred in certain zones. These cracks where grooved by a grinder after surfacing, and it was determined that they cannot be eliminated, along with the assumption that they propagated into the pre-machined parent material. Shown in figure 2 are some of the cracks (along with the grooved ones), with designated fields (A to G).
4. INSPECTION AND CRACK IDENTIFICATION

A total of 46 cracks were detected in the treiber roll after applied repair welding procedure. In addition to these cracks, a number of small mesh cracks were observed in field A, along the full circumference. For the purpose of easier identification, cracks were divided into zones, denoted A to G. Some of these cracks are shown in figure 3.

Field A was ground with a width of 300 mm along the circumference. Small mesh cracks were detected by magnetic flux testing in this field. Field B was 200 mm wide and grooved along the circumference. A total of 19 cracks were detected in this field. Two of the cracks were eliminated by grooving, to a depth of 20 mm. The depth to which the cracks have propagated could not be accurately determined, since there is no documentation about it. Field D, with a width of 300 mm, contained 13 cracks along its circumference. One of the cracks shown in this field was eliminated by grooving to the depth of 25 mm. The depth to which the cracks have propagated could not be accurately determined. Field F was 200 mm wide, and 14 cracks were detected along the circumference, some of which were eliminated by additional grooving, whereas some were not. No cracks were detected in fields C, E and G.

Fig.2: Appearance of treiber roll after repair welding

Fig.3: Some of the cracks on the treiber rolls after the surfacing
5. DISCUSSION AND CONCLUSIONS

Cracks have occurred as the result of a lack of preheating, i.e. due to cold surfacing of grooved locations. The cracks are caused by applying the hard weld to an insufficiently preheated, or completely cold surface, even though the welding technology specified that preheating is mandatory. Most of the cracks were located in the reinforced part of the roll, as well as its vicinity. It is well known that parts with thickness greater than 20 mm must be preheated and this is recommended for properly performing welding procedure [4-6].

The treiber roll with defects shown in the previous parts of this paper could not be put back into exploitation. Thus, it is recommended to develop the plan for machining of the welded roll for the purpose of removing of cracks and defects. Due to welded layer thickness, it can be concluded that the operation of removing the whole weld for the purpose of determining of the extent of crack propagation, must be performed in several passes. It is recommended to perform testing using NDT methods on the surface following the removal of each layer, for the purpose of determining the crack depth. It cannot be claimed with certainty that the cracks have propagated into the parent material, since additional crack grooving was performed in order to eliminate them. In this paper, the significance of preheating prior to repair welding for the purpose of avoiding crack initiation and other types of deformation can be seen. Preheating reduces the cooling rate, which in turn reduces the temperature difference between the cold parent material and the welded layer (which transforms from molten hot phase to a solid phase during the cooling, until the environment temperature is reached).

In addition to technical consequences, this also resulted in economic losses due to additional machining of the treiber roll after welding for the purpose of removing of defects, along with the need for repeated welding.

ACKNOWLEDGEMENT

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REFERENCES


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MAINTENANCE OF AXIAL BEARING OF KAPLAN TURBINE

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Mensud DIDEVIJA

Abstract: Axial slide bearing of vertical Kaplan turbines is main bearing element supporting up to several hundreds tones of turbine elements self weights and water column. Because if that, exact assembling and maintenance is of vital significance for turbine correct operating. Problems which could appear in long term operations are damages of segments basements or “white metal” and change of position of bearing housing due to long term loading and subsidence of concrete foundations. This paper presents examples of testing and maintenance of segments of axial bearing and correction of bearing housing position. Effects of corrections and their indicators are also presented.

Key words: Caplan turbine, axial bearing, maintenance.

1. INTRODUCTION

During the planned reconstruction and revitalization of a hydro-aggregate, replacement of all of damaged and worn individual parts and solution of all defects recorded during the exploitation should be done. If possible, application of new constructive solutions could be used, which will improve the operation of certain mechanical assemblies. Axial bearing of hydro aggregate is a very important assembly for reliable and functional work of hydro aggregates. It is loaded by a large scale axial force consisting of the weight of the rotating parts of the hydro-aggregate - a runner with blades, a turbine shaft, a rotor of a generator and a pressure force of the water column above blades of a runner.

Correction of defects on the axial bearing takes significant time needed for preparation due to the design of the hydro-aggregate (Fig. 1), the purchase of spare parts, the execution of the works and commissioning. In this paper the analysis of previous exploitation work, preparation for reconstruction and revitalization, installation and reconstruction, and analysis of work after the reconstruction of the axial bearing of aggregate no. 1 of HPP Grabovica, designed to carry axial load of 1060 tons are presented.

2. AN OVERVIEW OF EXPLOATATION HISTORY OF AXIAL BEARING

During the 33 years of exploitation, aggregate no. 1 of HPP Grabovica achieved 104,000 operating hours with 9,600 start-ups. In starting and stopping process, when aggregate rotates with rotation speed greater of 80% of the nominal (150 rpm), the oil is fed by high pressure pumps between the sliding surface of the segment and the sliding plate of the axial bearing, to ensure a necessary thickness of the oil film and improve the lubrication and protection of the sliding surfaces of the segment and sliding plate. Regularly, every hour of the aggregate operation, the temperature of the metals base of the four segments and oil are recorded. Capillary-mercury thermometers for measuring the temperature of the metal are placed in openings of 13 mm diameter and length of 400 mm, with an opening axis at the 30 mm from the upper sliding surface of the segment. Temperature value of peace metal base is measured at the distance of 23.5 mm from the contact surface of the segment and sliding plate. To measure the oil temperature, or more precisely – temperature of the oil film, the capillary thermometer is placed in a “wiper”, which is attached to the exit side of the segment and used to remove the oil film from the sliding plate immediately after the termination of the contact with the segment. The base of axial bearing segment is made of cast iron ČL. 0401. The maximum achieved temperatures in the previous exploitation of the hydro-aggregates at these five measuring points are shown in the table 1.
Table 1: Maximum temperature of axial bearing.

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Temperature (°C)</th>
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<tbody>
<tr>
<td>Metal segment 1</td>
<td>62</td>
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<tr>
<td>Metal segment 2</td>
<td>59</td>
</tr>
<tr>
<td>Metal segment 3</td>
<td>54</td>
</tr>
<tr>
<td>Metal segment 4</td>
<td>54</td>
</tr>
<tr>
<td>Oil</td>
<td>62</td>
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</table>

The values of the temperature were taken after a long operation of an aggregate on a power slightly less than the nominal value of 57.5 MW, when the stationary temperature distribution from the upper sliding surface of the segment (having an approximate temperature of the oil film of 62 °C) to the segment steel base in contact with the outer surface of the capillary probe at the distance of 23.5 mm, is established. Daily oil level in the tank of the axial bearing is controlled. Regularly, annual oil analysis was carried out to verify the physical and chemical characteristics of the oil and preventive detection of the beginning of the wearing process of the sliding surfaces and other surfaces of the axial bearings that are in mutual contact. During the operation of the aggregate, through the glass opening on the bearing housing, it was observed that the oil was foaming, which sometimes caused, at the normal operating level of the oil, a pronounced overflow of the created foam above the inner side of the tank housing and a loss of oil from the tank. In exploitation of the hydro-aggregate, and the axial bearing also, until the reconstruction, there were no defects requiring bigger maintenance, so the axial bearing assembly worked with the equipment installed during the commissioning in 1982.

4. EQUIPMENT DISASSEMBLY

During the dismounting of the axial bearing equipment, it was visually confirmed that, due to incorrect centering, the oil flow through some routing pipes up to 30% ended on the forehead of the oil wiper. Measurements were made of the horizontal support of the support ring plate and ring plate by a precision digital level Sokkia SDLIX and the mechanical level of resolution of 0.02 mm/m. Measuring the bearing plate horizontality by the digital level, a total difference of 0.31 mm between the highest and lowest measuring positions was measured. Measuring points were placed on the inner and outer diameter of each of the sixteen segments (32 measurement values). Tangential and radial slope were measured on the middle of the bearing segments (16 measured values). Tangential slope was ranged from -0.06 to +0.06 mm/m, and the radial slope was ranged from -0.10 to +0.04 mm/m. Measurement of the horizontal bearing height of the bearing bed - the top surface of the turbine cover - digital level cover was a total loss of 0.41 mm between the highest and lowest point positions measured on the inner and outer diameter of the hoisting rim (32 measurements), while the tangential slope of the midline of the support rim was -0.12 to +0.14 mm / m, and the radial slope of the center of the holding of the supporting ob Dressed from -0.20 to +0.04 mm/m (16 measured values), where at four measuring points it was not possible to measure the slope because the value was outside the measuring range of the machine gauze. It is important to note that between the support bearing segment and the bearing plate are the bottom bearing bottom mounts and 5 mm height, as well as between the support plate and the bearing base of 16 circular rubber girders and 5 mm in height. The NDT tests of the bearing segments showed as well, there were no rebuilding due to the very demanding and time consuming works for repairing possible malfunctions. It is considered the white metal replacement on the all segments, the replacement of the conic support g bolts, the replacement of the bolts for the connection of the conic support to the sliding plate and replacement of the white metal in the oil collector. In the previous solution, the oil collector pushes oil from the tank through eight coolers located around the bearing housing firstly, and then through a routing tube at a diameter of 1400 mm. They are directed to the segment sliding surface between the oil wiper and the beginning part of the sliding plate and the axial bearing segment, applying fresh oil, just after the wiper removed the hot oil film. By analyzing the constructive solution of the bearing, it has been concluded that the routing pipes, due to their position and the low bandwidth of action only partially apply oil to the sliding surface because of segment length of 650 mm. In addition, the processing of the support bearing and bearing ring plate is planned to achieve the required structural horizontality of 0.02 mm/m. This processing is planned because of machining of a horizontal flange of the turbine barrel at which the turbine cap is placed (its upper surface is in fact the support of axial bearing base) which is done because of obtaining structural horizontality.

3. PREPARATION FOR RECONSTRUCTION

Taking into account the facts stated in the previous chapter, that there were no failures of the axial bearing due to number of working hours and years of exploitation
presence of a no acceptable indications in white metal surface.

Fig.3: Results of horizontality measurement of the base

5. INSTALLATION AND EQUIPMENT RENEWAL

By measuring of the horizontality of the flange in the turbine barrel at which the turbine cover is located, a deviation of 1.7 mm in height has been established. The machining by a special machine mounted on the turbine bolt has been provided to obtain flange horizontality. The machining of the surface of the turbine cover which is is attached to this flange in the turbine barrel has also been carried out. The aim of the machining of these two flanges is to achieve the best horizontal position of the axial bearing base. These machining also affected horizontality of the bearing base and bearing ring plate, which also should be processed. With manual processing on the bearing base, the horizontality was reached at 29 measuring points with a deviation of 0.06 mm, while at three measuring points the height was increased by 0.03 mm. Tangential and radial slope of the center of the seating surface were from -0.03 to +0.02 mm/m (16 measured values). The actual horizontality of this surface is probably even better because, due to the manual processing, small local recesses and protrusions on the surfaces have been made.

Directional pipes are extended between the oil wiper blade and segment to the outer diameter of the 650 mm segment with openings on the upper surface through which fresh oil is applied to sliding plate. White metal (White Metal WM 80 with 80% tin, 12% antimony, 6% copper and 2% lead) was replaced on the bearing segments. The total thickness of the white metal is 10 mm, with the height of the "cargo tail" in the steel section of the segment of 6 mm. The construction of new capillary-mercury thermometers in four segments (metal segment 1 to metal segment 4) has been arranged in the mutually normal axes. A capillary thermometer with a shorter length is mounted for oil temperature measurement. Cleaning of the system for oil cooling is done before filling of new oil. The new oil of the same viscosity but another producer, with improved physical and chemical characteristics is used. New oil has specially increased oxidative stability, a reduced foaming tendency and high air separation capacity. In the process of the aggregate testing after renewal and revitalization, as well as by monitoring in the real work conditions with power near the nominal, it was found that the metal temperatures of the four segments of the bearing segments and the oil measurement points were increased by 0.02 mm or 0.05 mm. Tangential slope of the middle of the segment area had the values from 0.00 mm/m to 0.02 mm/m (at a single measured position +0.03 mm/m), while radial slope of the middle of the segment area was from 0.00 to +0.04 mm/m (at two measuring positions to +0.06 mm/m among 16 measured values).

Fig.6: Horizontality of bearing plate before and after machining
were significantly less than before the reconstruction, as shown in the table 2.

Table 2: Maximum temperature of axial bearing before and after maintenance i revitalization.

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Temperature before (°C)</th>
<th>Temperature after (°C)</th>
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<tbody>
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<tr>
<td>Metal segment 3</td>
<td>54</td>
<td>39</td>
</tr>
<tr>
<td>Metal segment 4</td>
<td>54</td>
<td>41</td>
</tr>
<tr>
<td>Oil</td>
<td>62</td>
<td>37</td>
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</tbody>
</table>

The average temperature of segment base metal is lower by 14.25 °C. The oil temperature is considerably lower because it is now the value of the oil in the bearing reservoir and before it was the temperature of the oil film in the wiper. After that, it should be noted that measuring of the absolute and relative vibration of the aggregates as well as the noise level in the turbine area, showed that the condition of aggregate 1 of HPP Grabovica can be classified as new equipment.

6. CONCLUSION

For the planned renewal and revitalization of the hydro-aggregate, as well as its individual assembly plants, it is necessary to:
- analyze all possible failures and causes of their occurrence that have been recorded since commissioning,
- analyze daily operating reports with all relevant data on aggregate work,
- implement constructive improvement and modernize existing technical solutions,
- make optimum selection of parts for replacement and revitalization,
- optimize the assembly time of all individual assemblies-planted by compromising the required functionality and reliable future work of the aggregate.

The application of all the above mentioned activities in the mainenance of the axial bearing of unit 1 of HPP Grabovica has been resulted in:
- the average lowering segment base metal temperature of the bearing for 14.25 °C, which will considerably prolong the service life of the bearing segments,
- Reduction of the oil film temperature, which will considerably prolong the working life of the bearing oil,
- Reduced oil spillage to prevent oil leakage from the bearing bed reservoir.

These improvements in operation are achieved primarily by:
- modifying the routing pipes which direct cooled oil on a substantially larger sliding surface,
- using oils of better physical and chemical characteristics, and
- achieving the designed horizontality of the base and bearing plate at 90% of area, while two sets of 5 mm thick rubber pads successfully amortize local unbalances (recesses and bulges).

REFERENCES


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CHALLENGES OF ROLLING ELEMENT BEARINGS FAULT DETECTION BASED ON VIBRATION SIGNAL MEASUREMENT AND ANALYSIS

Ninoslav ZUBER

Abstract: This paper addresses the suitability of vibration monitoring and analysis to detect different types of faults in roller element bearings and presents the result of an industrial evaluation of different vibration signal processing techniques as a method for condition monitoring of roller elements bearings condition monitoring. Different processing techniques are presented and demonstrated on signals acquired from real life industrial applications. Advantages and disadvantages of different techniques having in mind specific limitation have been shown.

Keywords: bearing faults, vibration signal processing, condition monitoring

1. INTRODUCTION AND LITERATURE REVIEW

Roller elements bearings (REB) are the most common components in rotating machines and they are claimed to be one the most responsible elements for machine’s unplanned stoppages and failures. Unplanned stops leads to loss of production, high maintenance costs and sometimes to losses of human lives. As a result, development of methods of vibration signal processing, together with the analysis of their applicability in REB diagnostics is very important and attractive. It is essential to detect REB defects as early as possible to avoid fatal breakdowns of machines and to reduce the secondary damage caused by failures.

In the last three decades many papers have been published that deal with methods of REB faults identification. In [9] authors gave a very detailed review of different methods of vibration signals analysis in time and frequency domains, analysis of noise pressure and intensity, shock waves and measurement and analysis of acoustic emission. In [2] some alternative techniques are presented such as shock pulse measurement, oil analysis and particle counting. In [4], [5] and [3] a review of techniques of analysis in time and frequency domains is given. There are many studies that investigate the mechanism of noise and vibration generation in REB ([8], [10], [6], [1], [7]). According to these papers the main cause of noise and vibration inside the REB is a non–uniform stiffness due to the fact that we have a finite number of rolling elements. The number of rolling elements that make a contact with inner and outer race of the bearing and the influence of the bearing loading zone are the parameters that influence the level and frequency content of noise and vibration signals ([8] and [10]). Even if the geometry of the bearing is perfect and if we treat both races as continuous the change of direction of contact forces generate unwanted noise and vibration.

We can define two types of REB faults: localized and distributed. Distributed faults are result of bearing production, improper mounting technique or abrasive wear ([7]). Localized faults are in the form of discrete cracks on contact surfaces of races and rolling elements. The most common cause of localized faults is a fatigue crack where the crack occurs bellow the contact surface and over the time propagates to the contact surface. Fatigue crack is the result of bearing overload or improper mounting.

2. SIGNAL PROCESSING TECHNIQUES IN REB FAULT DETECTION

In general REB has four components, two races, rolling elements and a cage. When we analyze localized REB fault we seek for discrete faults on these components. Characteristic REB fault frequencies are as follows:

\[
FTF = \frac{f_o}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) 
\]

\[
BPFO = \frac{f_o N_r}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) 
\]

\[
BPFI = \frac{f_o N_r}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) 
\]

\[
BSF = \frac{f_o}{2} \frac{D}{d} \left( 1 - \frac{d^2 \cos^2 \alpha}{D^2} \right) 
\]

where: FTF (cage frequency), BPFO (ball pass defect frequency at the outer race), BPFI (ball pass defect frequency at the inner race), BSF (defect frequency at the rolling element), d (diameter of the rolling element), D (REB pitch diameter), N_r (number of rolling elements)
and $\alpha$ (contact angle). These equations define REB defect frequencies in the units of harmonic orders (frequency divided by the shaft speed). In general case these frequencies are asynchronous. Also it is worth to mention that these equations assume that there is rolling movement inside the bearings. In real REBs there is always some slip so there is always some difference between calculated and measured REB’s bearing frequencies.

In case of existence of indentation or external particle inside a REB, every time the roller element passes over the indentation on a race, a decrease of internal strain will be produced. When a roller element passes over the metal particle that is on the race due to the flaking of the components, there will be an increase of REB internal stresses. These transient forces result in rapid change of accelerations of REB components and as a result shock phenomena are present in the vibration signal. If the size of the fault is large enough, these stress waves can excite the natural frequencies of the REB structure and the REB is “ringing”.

Due to the nature of this mechanism, techniques of applied vibration signal processing used in REB diagnostics should be adequate to identify transient components in acquired signal. These low amplitude high frequency components from the faulty bearings are superimposed with the high amplitude low frequency components from low frequency defects (such as residual imbalance).

Vibration measurement and signal processing for REB fault identification have three different challenges to face with:

1. **Low amplitude.** Amplitudes of stress waves are very low. A machine generates a high volume of vibration which far exceeds the amplitude of stress wave. Vibration transducer and vibration analyzer may have an excellent dynamic range (for example 90 dB), however this may not be sufficient. Even if it could be measured it would be quite hard to analyze the raw data. Therefore we need a method that removes the low frequency high amplitude components and focus on the area of interest (high frequency domain).

2. **Short duration.** The frequency of the stress wave is very high – typically greater than 5 kHz (1-50 kHz). Bearing faults generate repetitive impacts. If we could measure them directly we could calculate the periodicity of impact and relate it to the bearing component.

3. **Measurement issues.** Since we are interested in high frequency components of the signal, it is highly recommended to measure and analyze acceleration due to its sensitivity in high frequency region. Also for the purpose of having an adequate transfer function of the system care must be taken when choosing transducer mounting technique (mounting with the stud is preferred).

To cope with these challenges there are basically four different approaches:

1. Use of accelerometer to amplify high frequency components.
2. Use of high speed data acquisition to directly capture stress waves.
3. Use demodulation techniques for capturing high frequency vibration.
4. Use ultrasound measurements to capture high frequency components.

The most common used methods of vibration signals analysis applied to identification of defected REB are: time waveform analysis, analysis in the frequency domain, techniques of spectral enveloping and demodulation and time-frequency transformations. Techniques of time waveform analysis are focused on extraction of statistical parameters of raw or filtered time waveform signals in order to quantify the transient phenomena. The most common universal parameters are: root mean square - RMS, peak-peak value - PP, Crest factor – CF and Kurtosis – Kurt. Crest factor is a ratio of peak and RMS values of the signal while the Kurtosis parameter is the kurtosis is a measure of the "tailedness" of the probability distribution. Kurtosis is also a measure of impulsiveness of the time waveform and is independent of amplitude of the signal. Figure 2 shows a Kurtosis parameter (blue curve) with a time window of 20 msec over a time waveform of a REB with a defect on the inner race.

Transformation of time waveform into frequency domain using the FFT algorithm enables identification of possible typical REB defect frequencies in the signal (BPFO, BPFI, BS and FTF).
Demodulation / enveloping technique is the advanced signal processing method with its wide application in REB condition monitoring in the early stages of defect development. Repetitive impulses caused by roller elements passage over the indentation could excite REB housing natural frequencies. As a result, frequency spectrum contains peak at the natural frequency modulated by the REB defect frequency. After band pass filtering and signal rectification, envelope spectrum is generated with the sidebands shown as harmonic family. The success of REB fault detection using envelope spectra is highly dependent on filter cut off frequencies. The center frequency of the band pass filter should be near the resonance frequency of the bearing structure which is in general case unknown. This is the main culprit of enveloping in its use for everyday condition monitoring of machines. With faulty REB in case of its localized fault its envelope spectrum should contain sideband components of the REB fault frequency that periodically excited the REB’s natural frequency. The envelope spectrum is always analyzed in decibels and if the harmonics of REB’s fault frequencies are raised more than 20 dB (power ratio of 1:100) over the carpet noise the bearing is ready to be replaced.

Methods of time-frequency transformations are widely used in REB’s diagnostics due to the nonstationary nature of the impact phenomena. As a result, time-frequency transformations result in signal presentation in both domains – time and frequency. This makes possible to analyze frequency contents nonstationarity over the time. 

The most common used methods for time-frequency transformations in REB diagnostics are: short time frequency transform - STFT, Wigner – Ville distribution – WVD and wavelet analysis - WA.

3. EVOLUTION OF FREQUENCY SPECTRA COMPONENTS WITH THE REB’S DEFECT GROWTH

In order to get a reliable information from a defective bearing, as is the case in other fields of vibrodiagnostisc too, it is necessary to known how fault development affects the recorded vibration signal in time and frequency domain.

Initial stage of fault development begins with the occurrence of fatigue microcrack just bellow the contact surface of the faulty component. It is necessary to note that the level of degradation is small. Components of the vibration signals that come from a bearing are results of small impacts (shock impulses) and friction that occurs due to the abnormal lubrication. These components are located in the high frequency region (from 20kHz and above).

The reliability analysis of the existing detection methods gives the following conclusions:

1. High frequency methods (SPM, SpikeEnergy, PeakVue) in this stage are very reliable and their scalar representatives will grow together with the fault development.
2. Enveloping / demodulation of acceleration vibration signal, in assumption that the cutoff frequencies are well defined, will, despite the bad signal to noise ratio, detect the existence of fault inside the bearing.
3. Frequency spectra – FFT of the vibration velocity will not detect the bearing fault due to the fact that vibration components are in high frequency region. FFT of acceleration signal could give a very limited information on the bearing fault.
4. Time waveform analysis – generally, for this stage is not useful.

In the second stage of fault development, cracks on the faulty components become larger and wider and therefore the generated impulses could have enough energy to excite the bearing natural frequencies. In this stage the acceleration envelope should give a very clear information on the present defect in the bearing. The reliability analysis of the existing detection methods gives the following conclusions:

1. High frequency methods – their scalar parameters will still grow together with the fault development.
2. Enveloping / demodulation of acceleration vibration signal will clearly detect the existence of fault inside the bearing.
3. Frequency spectra – FFT of the vibration velocity will not detect the bearing. FFT of acceleration signal will give a very reliable and clear information on the bearing fault.
4. Time waveform analysis – generally, for this stage is not useful.

In the third stage, bearing faults are larger and there could be more of them in comparison with a previous stage. In this phase it is possible to get the bearing seizure. Typical for this stage is a strong excitement of bearing’s natural frequencies. Generally the wideband noise will be raised, both, in FFT and envelope spectra.

The reliability analysis of the existing detection methods gives the following conclusions:

1. High frequency methods – their scalar parameters will still grow together with the fault development.
2. Enveloping / demodulation of acceleration vibration signal will detect the existence of fault inside the bearing but the raised noise will start to mask the bearing frequencies.
3. Frequency spectra – FFT of the vibration velocity and acceleration will give a very reliable and clear information on the bearing fault.

1 These methods are not considered as universal since they require using vibration acquisition devices and softwares from specific vendors. Therefore, they are not analyzed in this paper.
4. Time waveform analysis – generally, is very useful for this stage. The third stage is generally a point where the bearing should be replaced, if possible. If not the vibration analyst should monitor the vibration parameters of the bearing on weekly basis.

If the bearing is still left in operation, initial faults on one bearing's component will damage the other bearing's components. Due to the indentations smearing, it is possible to get lower high frequency components, compared to the previous stage.

Due to the material flaking loosenes in the bearing grows. This directly affects the bearing geometry and this results in noisy operation and changing the bearing defect frequencies.

The reliability analysis of the existing detection methods gives the following conclusions:

1. High frequency methods – they are very unreliable in this stage due to the lowering of high frequency components. The bearing faults develops while the high frequency parameters are decreasing.
2. Enveloping / demodulation of acceleration vibration signal could detect the existence of fault inside the bearing but the raised noise very often mask the useful components.
3. Frequency spectra – FFT of the vibration velocity and acceleration will give a very reliable and clear information on the bearing fault.
4. Time waveform analysis – generally, is very useful for this stage since the impacts and amplitude modulation are visible.

The bearing in the forth stage must be immediately replaced.

4. EXPERIMENTAL PART AND RESULTS

Case presented in the paper deals with the REB fault on a recirculation fan (Figure 5, REB number 4) in the local can manufacture plant. Machine consists of one 30 [kW] motor that drives the fan using a belt transmission. This machine has been monitored once per year in the last 7 years. The trend of overall acceleration in last three measurements shows the fan REB fault development (Fig. 7). On the other hand, trend of overall values of vibration velocities doesn’t show much information that an ongoing REB fault development is present.

The REB type is 2218 (manufacturer SKF), so using formulae (1)-(4) and REB dimension data the characteristic defect frequencies in terms of rotating orders are: BS=7.02, BPFO=8.19, BPFI=10.81 and FT=0.43. A detailed analysis of time waveforms and frequency spectra reveals the nature of a fault (Fig. 7). The overall amplitude of last acquired time waveform compared to the time waveform acquired at the same location three years ago is much higher. The unit of time waveform is acceleration so this indicates a presence of strong metal to metal impacts in the signal. Comparison of frequency spectra shows two typical symptoms of a faulty REB:

1. Frequency spectrum is raised by the wide frequency noise which comes from the excessive looseness in the bearing caused by the REB with local faults left in operation.

2. Frequency spectrum shows the nature of the localized fault – there is a modulation around 3998 [Hz] (REB housing natural frequency) with the frequency of 187.5 [Hz]. Since the fan is rotating at 22.9 [Hz], this is the BPFO component of the bearing. Therefore, the nature of the initial localized fault of the REB is the defective outer race of the bearing.

Figure 5. Recirculation fan under the test

Figure 6. Trend lines for overall acceleration (top) and overall vibration velocity (bottom)
According to the REB fault development stages explained in the previous section, this REB is considered to work in the last 4th stage of the REB life. As a result of leaving this faulty REB in operation, a failure of frequency inverter and a failure of drive occurred 6 months before the last measurement!

5. CONCLUSION

Vibration analysis is the proven and the most reliable method for identification of faults inside the REB. The success and the content of the information we get from the measurement are highly dependent on the signal processing methods that were applied. The paper demonstrated that there is no unique universal method for monitoring the development of a fault inside the bearing from its mounting up to bearing’s wreck. The default measurement setup should include all the explained signal processing techniques in order to identify the REB fault in all developing stages.

REFERENCES


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SELECTION OF RELIABLE VBRODIAGNOSTIC MODEL ROTATION MACHINES

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Abstract: The control parameters of rotary machines are indirect individual sizes associated with structural parameters (vibrations, temperatures, bedding, oil pressure, etc.) and bearers are accurate information about the technical condition of the system. The parameters that bring the most information about the state of the technical system are surely the parameters of vibration, in addition to them, parameters of displacement, temperature, noise, current parameters, oil parameters for lubrication, etc. are also important.

This paper presents the vibrational diagnostic model for the control of rotary machines of large rotary machines, which, with two selected vibrational diagnostic displays, was confirmed as a very reliable diagnostic tool for diagnostic analyzes that were performed in power plants on aggregates during their exploitation. Research has shown that it is possible to carry out the selection and grouping of problems in the operation of rotary machines as well as the vibrodygnostic methods itself, and thus develop a reliable vibrodiagnostic model for controlling the operation of rotary machines, depending on the class of the machine, or the specificity of the controlled machines themselves.

Key words: Rotary machines, Vibration, Monitoring, Diagnostics

1. INTRODUCTION

Correct measurement, monitoring and analysis of diagnostic parameters relevant to the operation of the machine, especially those that describe the dynamic state and behavior is obtained at any time insight into the mechanical and procedural status of the machine, which is the goal of condition based maintenance. Occurrence of certain faults on the machine produce a stable excitation which generates a specific oscillatory motion. The outcome of the vibration response analysis reveals the character of the excitation force and determine the cause of machine malfunction Fig. 1.

Fig. 1: Dependence of system response to the excitation force

The vibrodiagnostics approach itself lies in the fact that any malfunction in the machine's operation produces a precisely determined vibration. By analyzing the signal from the vibration response we can determine the character of the stimulus force, or identify the cause of the vibrations.

The most common malfunction of rotating machines that we can promptly identify and monitor their further growth, using control-diagnostic systems are: imbalance (asymmetry of weight and rotor geometry changes), misalignment, malfunction roller bearings, failure to recline, resonance phenomena, fault slip beds, malfunctioning electrical origin, failure resulted from an act of aerodynamic and hydraulic power, a malfunction in the belt gears, gear failure, looseness of rotating parts, malfunction due to pulsations, touching (scraping) of the rotor stator, rotor anisotropy etc.

Commonly used vibrodiagnostic methods are: the overall level of vibration analysis, spectral analysis, phase analysis, real-time vector analysis, orbit, DC analysis, the impact impulse method (SPM method), energy analysis, Zoom FFT analysis, CPB analysis, cepstral analysis, SED detection, detection of HFD, LFD detection, SEE technology, modal analysis. It is possible to extract vibrodijagnostičke methods used for early detection of causes dynamic problems.

There are some other methods which contribute to a proper identifying of real causes of malfunction. They are: Monitoring and analysis of air gap, analysis of the magnetic flux, analysis of partial discharge, monitoring of parts wear, detection of combustion products, monitoring of system fluids (oil and lubricants, gases, coolants...).
corrosion monitoring (visual methods, gravimetric and electrochemical methods) [1..8].

2. SELECTION OF PROBLEMS AND SELECTION OF THE VIBRODIAGNOSTIC MODEL

Dynamic problem is typical for certain group of machines, depending on their power, rotation, construction, base etc. Using standard ISO 10816 all machines are classified in 4 classes and each class of machines has its recommended and allowed level of vibration, measuring points for vibration, the way of measurement and the selection of parameters for measurement, as shown in Fig. 2.

Analyzing certain causes of dynamic problems, we can conclude that the certain causes are typical for two types of machines:
- **GROUP 1**
  - Machines classes I – in according ISO 10816, Electric machines up to 15 kW
  - Machines classes II - in according ISO 10816, Medium machines, electric motors with power of 15 to 75 kW without special foundation and rotary machines with a special basis of power up to 300 kW
  Characteristics of this group machines has owning rolling-element bearings. The most common causes of the dynamic problem of this group of machines are: imbalance, rolling bearings defects, lack of susceptibility and leakage errors (soft foot, change in stiffness of the foot, relative resonance). Rarely, there are errors of electrical origin, damage to gears, mistakes caused by the action of aerodynamic and hydraulic forces, defects in belt drives, defects caused by pulsation, and the touch of the rotor from the stator
- **GROUP 2**
  - Machines classes III - in according ISO 10816, Large machines (over 300 kW) with high frequency and heavy foundations
  - Machines classes IV - in according ISO 10816, Large machines with low frequency bases (eg turbochargers)
  Characteristics of these group machines has owning journal bearings. The most common causes of the dynamic problem on these machines are: imbalance, insensitivity, slide bearings defects, reliance errors and resonant phenomena (as a consequence of low frequency bases and inadequate stiffness). Rarely, there are errors of electrical origin, mistakes caused by the action of aerodynamic and hydraulic forces, stator rotor coupling and anisotropy of the rotor.

During research, we came to conclusion that optimal model could be seen when using four valuable functions:
1. Identifying the cause of dynamic problem
2. Simplicity for use and performance
3. Early detection cause of dynamic problem
4. Economic aspect

The optimal set vibrodiagnostičkih method chosen by this criterion, in addition to the basic set includes: overall level of vibration, spectrum display, signal and image time polar trend, for machines to be used in Group 1 HFD vibration analysis, machine for Group 2: Bode presentation and analysis orbit. [9,10]

In order to have available the necessary data for the diagnostic evaluation and analysis of the technical system must be a system for the collection of all relevant data. The system must allow the display of data in the relevant form (format) in which decisions about the state of the machine, and take appropriate actions to maintain. With the existence of a system for the collection and analysis of relevant data must be a system of management and organizational machinery that clearly defines who gets access to what information, and who on the basis of them take the appropriate decisions.
2.1. Vibro-diagnostic model monitoring

For the purpose of selecting the necessary vibrodiagnostic formats necessary for reliable diagnostic analysis of machines Group 2, machines with sliding bearings, here is presented the setting of one vibrodygnostic control model, ie the necessary vibrodiagnostic displays that need to be monitored and analyzed in different operating modes, correlated with Process and other diagnostic parameters allow a robust diagnostic evaluation of the condition of controlled machines.

- The machine is not in operation

Absolute vibration: total vibrational velocity levels $V_{rms}$ with absolute vibration measurements, spectral display of absolute vibrations.

Rotor vibrations: Position the rotor axis (polar display)

- **RunUp and CostDown**

Absolute vibrations: the total level of vibration velocity $V_{rms}$, spectral display (cascade spectrum dependent on the number of rotations), Bode displays of 1X and 2X vibration harmonics (or polar).

Rotary vibration: Total vibrational displacement levels of $A_{p-p}$, spectral display (cascade spectrum dependent on the number of rotations), Bode displays of 1X and 2X vibration harmonics (or polar). Polar display of the position of the rotor axis (DC component of the vibration)

- **Synchronization and low loading of hydroelectric power plants**

Absolute vibrations: Total vibrational velocity levels $V_{rms}$, spectral vibration display, Polar displays of the 1X and 2X vibration harmonics

Rotor vibrations: Total vibrational displacement levels of $A_{p-p}$, spectral vibration display, Polar displays of the 1X and 2X vibration harmonics. Polar display of the position of the rotor axis (DC component of the vibration)

- **Operating mode**

Absolute vibrations: Total vibrational velocity levels $V_{rms}$, spectral vibration display, Polar displays of the 1X and 2X vibration harmonics.

Rotor vibrations: Total vibrational displacement levels of $A_{p-p}$, $S_{max}$, spectral vibration display, Polar displays of the 1X and 2X vibration harmonics, Polar display of the position of the rotor axis (DC component of the vibration). Display Orbit

- **Stop the machine**

Absolute vibrations: the total level of vibration velocity $V_{rms}$, spectral display (cascade spectrum dependent on the number of rotations), Bode displays of 1X and 2X vibration harmonics (or polar)

Rotary vibration: Total vibrational displacement levels of $A_{p-p}$, spectral display (cascade spectrum dependent on the number of rotations), Bode displays of 1X and 2X vibration harmonics (or polar). Polar display of the position of the rotor axis (DC component of the vibration)

It should also be noted that for reliable diagnostics it is necessary to observe multiple vibrato-diagnostic formats at the same time. Research has shown that the vibrodygnostic model, which at the same time shows on all bearings the position of the axis of the rotor, the orbit, the spectrum and the polar 1X vibration display, provides reliable diagnosis of the greatest possible number of possible malfunctions that can arise in the operation of the Group 2 machine. Of course, To be observed in correlation with the process parameters (the number of rings, forces, etc.) and the total level of vibration, which should also be the second vibrodiagnostic display. These two mixes of vibrodiagnostic representations actually represent an optimal model of vibrodyagnostics for rotary machines of large rotational masses.

3. VIBRODIAGNOSTIC ANALYSIS - CASE STUDY

Vibrodiagnostic analyzes performed on machines of GROUP 2 in real conditions of exploitation with previously shown vibro-diagnostic model are shown here.

3.1. Vibro- diagnostics of hydroaggregate

The vibrodiagnostic diagnostic analysis of the hydroaggregate was performed in HPP Višegrad, where the control diagnostic system of the manufacturer Bently Nevada - GE System1 was installed, shown in Fig. 5.

![Fig. 5. Display of the installed monitoring and diagnostic system in HPP Višegrad and the location of the vibration sensor installation](image-url)
The most unfavorable dynamic condition of the hydroaggregate is when the hydroaggregate is overturned and stopped in the range of the rotational speed of 50-70 rpm, where sudden vibration jumps occur, shown in the following figure. This can be characterized as a resonant frequency, most likely it is the lowest critical speed of the rotating circuit or the resonant frequency of the implement because at that moment the blades of the watering device are completely closed, but a deeper correlation analysis of the injection of the hydroelectric power plant should be done and the possibility of installation Stabilizer of the EE system. From the spectral vibrations, the dominance of the imbalance on the base tone is clearly noticed, and low-frequency vibrations and a slight presence of the 2X harmonics of vibrations are noticed. On the turbine part there is a slight presence of fluid forces, characterized as turbulence of flow and vortex in a diffuser, which mainly occurs with less power and its changes (a detectable frequency of 0.25 Hz and the threshold of high frequency components). From the spectral vibrations during the deposition of the hydro-aggregate, the presence of oil vortex in the generator bearing, on the small forces of the hydro-aggregate 20-30 MW, is observed, and a significant short-term sudden jump of rotor vibrations develops, this may be due to inadequate bearing clearance. This turbine part shows a small presence of turbulence flow on turbine blades and vortex in diffuser.

By analysis the position of the sleeve in the GVL it is clearly noticed that the one-way magnetic field force returns the axis of the rotor to the initial position and thus reduces the displacement of the geometric and inertial axes and the total value of the vibration of the fall. With the increase in load, further shifting of the axis of the sleeve in the bearing occurs, which causes the phase change of the vibration vector 1X, but the overall level of vibration remains the same. By analysing the polar diagrams, it can be clearly seen that the vectors of mechanical and electrical imbalances are in the protuberances, and that this is the reason for reducing the overall level of vibration. It is noted that phase 1X of the vibration vector changes with increasing power of the hydro-aggregate. There is also the presence of a force of electrical origin (at a frequency of 100 Hz).

From the previous pictures it can be clearly seen that there is a one-way force during the rocking of the hydro-aggregate which moves the rotor of the rotor opposite to the two adjacent bearings, that is, the verticality of the axis of the hydroaggregate is lost, there is obviously a certain degree of clarity in the system.
Also, when the ignition is switched on, the action of the one-way electrical force is clearly seen as a consequence of the magnetic field asymmetry, which further shifts the axis of the generator rotor. If we analyse the displacement of the sleeve in the bearing and taking into account the direction of rotation, the most probable direction and direction of this one-way force, which is perpendicular to the direction of movement of the sleeve in the case of small unidirectional forces, is obtained.

3.2. Vibro-diagnostic of turboaggregate

Vibro-diagnostic analysis of the turboaggregate was performed in TE Gacko based on the diagnostic system COMPASS, which is a product of the company Bruel & Kjaer, Vibro, which serves to monitor the turbine generator's state of mind in the on-line diagnostics and other rotary machines in the off-line Diagnostics and is integrated into the computer control and control system of the production process "OVATION" - the product of the American company Westinghouse. The measurement structure of the diagnostic system is shown. Fig. 8.

![Fig.8. Structure of COMPASS Diagnostic System in TE Gacko](image)

It should be noted that the system measures absolute and rotor vibrations on all turboaggregate bearings, and for the purpose of this analysis, the overall levels and spectral vibrations of those bearings where increased vibration levels are determined are shown.

As a result of the vibrodiagnostics of the turbo-generator, Fig. 9 and Fig.10. The odds are selected two vibrodiagnostic displays.

**Table 1.**

<table>
<thead>
<tr>
<th>Bearing s</th>
<th>HOR $\sum V_{RMS}$ [mm/s]</th>
<th>VER $\sum V_{RMS}$ [mm/s]</th>
<th>AX $\sum V_{RMS}$ [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>1.8</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>3.6</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
<td>3.3</td>
<td>4.6</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>3.8</td>
<td>5.8</td>
<td>9.3</td>
</tr>
<tr>
<td>8</td>
<td>6.4</td>
<td>5.2</td>
<td>4.1</td>
</tr>
</tbody>
</table>

With spectral display is clearly evident that the causes of the problem dinamičkih generator of unbalance and misalignment. In addition, spectrum display with 8 beds indicates that there is slack in this bed. The spectrum on the bearing 7 in the axial direction, there is a lack of stiffness of the bearing in the axial direction.

**Spectral analysis**

With spectral display is clearly evident that the causes of the problem dinamičkih generator of unbalance and misalignment. In addition, spectrum display with 8 beds indicates that there is slack in this bed. The spectrum on the bearing 7 in the axial direction, there is a lack of stiffness of the bearing in the axial direction.

**Fig.9. The first vibrodiagnostic display from the turboaggregate**

The analysis of spectral display is clearly evident that the problem dinamičkih generator of unbalance and misalignment. In addition, spectrum display with 8 beds indicates that there is slack in this bed. The spectrum on the bearing 7 in the axial direction, there is a lack of stiffness of the bearing in the axial direction.

**Polar trend display**

With polar display clearly shows that there is a change of amplitude and phase of the harmonic vibrations 1X with increasing load. This suggests that in addition to the mass asymmetry of the rotor comes up to change the rotor geometry, which may be due to thermal deformation or impact of asymmetric magnetic field. The analysis of polar trend 1X harmonic vibrations in these stages, you can clearly see these effects of these defects:

- Vector of A1-1X harmonic in cold conditions, the number of working without excitation,
- Vector of A2-1X harmonic on full load
- Vector A3 - 1X harmonic after power cuts.
It is observed that the B1-vector thermal imbalance, little influence on the dynamic state (overall vibration level is slightly changed) and C1-asymmetric magnetic field vector, which significantly affects the dynamic state of the machine, therefore it is in phase with the residual mass asymmetry of the rotor in response to the seventh beds.

It is apparent that the thermal imbalance at the reactance power of 91 Mvar, by the intensity is the same as the residual mechanical imbalance on the rotor, but that it is phase-difference by 45 °. By monitoring the trend further changes of the thermal imbalance vector, it can be concluded that by increasing the reactive power, the total vector of the imbalance (vector 1X of the rotor vibrations) would be inadmissible for the further operation of the turbocharger (especially expressed on bearing 7) [12].

4. CONCLUSION

Today, there are a large number of developed and implemented surveillance diagnostic systems in the world, whose software tools give a great opportunity to process and analyze signals, which allow the operator to provide a wide range of possible diagnostic displays that illustrate the existence of a problem and thus provide a diagnostic interpretation of malfunctioning in controlled machines. This is particularly true for a large number of developed and implemented vibrodiagnostic methods. The analysis carried out on aggregates under the conditions of their exploitation, Chapter 3, showed that the set vibrodiagnostic model, shown in Chapter 2.1, provides a reliable and clear analysis of the cause of malfunction in the operation of the controlled aggregates. It should be noted that the developed diagnostic systems do not provide vibrational images in this presented form, which confirms the fact that the knowledge and experience of the diagnostician working with these systems is of crucial importance, which is necessary for this type of diagnostic analysis. Also, the presented vibrodiagnostic model can serve to develop application software that would be tailored to the needs of the operators themselves. It should also be expected that the development of automated diagnostic systems will enable the entire diagnostic process to be automated and accelerated.

This type of machine monitoring in the production process enables us to have an insight into the “health” of the machine at any time, so that we can “control the machines”, which is one of the key preconditions for optimizing the production process as a whole.

The development of communications enables the development of remote monitoring (telemonitoring), which enables the appearance of expert consulting firms for the provision of services through remote monitoring. Of course, it would be interesting for the ERS to form a unique diagnostic center, considering energy facilities and built-in surveillance systems.

REFERENCES


CORRESPONDANCE

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VIBRATION ANALYSIS AND REPAIR PROCESS FOR THE VENTILATION SYSTEM FOR SMOKE DRAIN IN THE THERMAL POWER PLANT

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Safet ISIĆ
Edin DŽIHO

Abstract: Vibrations are common phenomenon in the rotating machinery, which could carry important information about condition of the rotating machinery. All specific failures in rotating machinery have their own characteristics of the vibrations. By measuring and analysis of vibrations cause of increased vibrations could be determined. Since misalignment and rotating looseness have similar frequency spectrum characteristics, it is difficult to determine which one of the failures is present. When cause of increased vibrations is determined, it is possible to plan the future steps for the repairing and neutralising present cause of the possible failure. Process of vibration analysis followed by present cause of increased vibration in rotating machinery repairing is presented in this paper through example on the ventilation system for smoke drain in the thermal power plant.

Key words: vibration analysis, thermal power plant, ventilation system

1. INTRODUCTION

Reliability of the thermal power plant as one of the mechanical systems is main goal of power producing companies, which causing continuous electricity production. Reliability is achieved when there are no unexpected failures of machines and when it is possible to predict time and cause of machine failure. With those predictions it is possible to plan a future stoppage and possible repairs in the machine system.

Most commonly used method for condition monitoring of the machines in the thermal power plant system is vibration analysis. By measuring frequency and amplitude of the machine vibrations it is possible to determine what is causing that vibration with frequency analysis and how much is machine moving with amplitude analysis. After determination of main cause of increased vibrations, it is needed to plan future repairs and removal of vibration cause. Since the most loaded elements of rotating machines are the bearings and the couplings, repairs are mostly consisted of replacing those machine parts. Those repairs are mostly time-consuming and the power production is process of high importance, so sometimes it is needed to do some quick repairs to habilitate machine for short-time usage, until repairing process is suitable to carry out.

Process of vibration analysis followed by present cause of increased vibration in rotating machinery repairing is presented in this paper through the example on the ventilation system for smoke drain in the coal-heated thermal power plant Kakanj, Bosnia & Herzegovina.

2. VIBRATION ANALYSIS

Vibrations are common phenomenon in rotating machinery, which could carry important information about condition of the rotating machinery. All specific failures in rotating machinery have their own characteristics of vibrations. Measurements and analysis of the vibratory behavior of the system and vibration changes leads to the detection of problems and faults [1][2].

Most common failure of rotating machinery is misalignment of shafts connected by couplings [1]. Misalignment could be parallel or angular. In practice, misalignment is usually combination of parallel and angular misalignment [1][3][4]. In frequency spectrum of severe misalignment are present orders of rotational frequency (1X, 2X...) even up to 10X in radial and axial direction.

Other failure with similar characteristics is rotational looseness who could be described as appearance of the clearance between rotating shaft, bearing or housing. Frequency spectrum also contain orders of rotational frequency (1X, 2X, ..) which could also go above 10X [5].

If it is impossible to determine which failure is causing the increased vibrations using frequency spectrum only, sometimes it is necessary to confirm present failure by some other characteristic (waveform, orbit, phase, etc.), by optical observing (opening bearing or coupling) or by physical measurement (misalignment by dials or laser, housing-foundation gap, etc.).
3. VIBRATION MEASUREMENTS ON THE VENTILATION SYSTEM

Vibration analysis and repair process for the ventilation system in thermal power plant is shown below. Ventilation system equipment have properties shown in table 1.

Table 1: Ventilation system equipment properties

<table>
<thead>
<tr>
<th>System name</th>
<th>Smoke drain ventilator (right)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>“Vemos” Ltd., M. Bistrica, Croatia</td>
</tr>
<tr>
<td>Motor serial no.</td>
<td>D-CV-09-100-1</td>
</tr>
<tr>
<td>Power</td>
<td>1080 kW</td>
</tr>
<tr>
<td>RPM</td>
<td>990 RPM</td>
</tr>
<tr>
<td>No. of vanes</td>
<td>8</td>
</tr>
<tr>
<td>Ventilator diameter</td>
<td>2500 mm</td>
</tr>
<tr>
<td>Shaft length</td>
<td>5400 mm</td>
</tr>
<tr>
<td>Shaft diameter</td>
<td>440 mm</td>
</tr>
<tr>
<td>Journal diameter</td>
<td>160 mm</td>
</tr>
<tr>
<td>Type of bearing</td>
<td>Double row cylindrical roller bearing</td>
</tr>
</tbody>
</table>

Ventilation system is shown in fig 1.

Vibrations are measured on the housings of the motor and the ventilator bearings in three perpendicular directions: horizontal, vertical and axial. Measurements are marked with L1 and L2 for ventilator bearings, and L3 and L4 for motor bearings. Accelerometers of type KD 37V and KD 41V are used for measurements. Accelerometers are connected to Spider 8 device for data acquisition through M28 power supply. Spider 8 is then connected to the computer, which is used for data recording. Magnetic stands with screws are used for accelerometer mounting on housings, so it is easy to detach them after measuring. Locations of bearings where measurements are done are shown on fig 2.

On fig. 5. is shown one of the bearing housings with accelerometers attached to the measuring spots.
3.2. Operating modes of ventilation system used for vibration measurements

Vibration testing program is planned to be done with different operating modes of the ventilation system. Operation modes for testing are chosen to be different number of rotations per minute of the ventilator shaft. Operation modes for vibration measurements are shown in table 2.

Table 2: Operation modes for vibration testing

<table>
<thead>
<tr>
<th>Measurement number</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>410</td>
</tr>
<tr>
<td>M2</td>
<td>481</td>
</tr>
<tr>
<td>M3</td>
<td>547</td>
</tr>
<tr>
<td>M4</td>
<td>705</td>
</tr>
</tbody>
</table>

3.3. Results of vibration measurement

Recorded acceleration data is integrated to obtain velocity records, which is used to calculate RMS of velocity. Results of the calculated RMS of velocity of ventilator bearings are shown in table 3., and RMS of velocity of motor bearings are shown in table 4.

Table 3: RMS of velocity on ventilator bearings

<table>
<thead>
<tr>
<th>RPM</th>
<th>L1 RMS [mm/s]</th>
<th>L2 RMS [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>V</td>
</tr>
<tr>
<td>410</td>
<td>1.7</td>
<td>0.5</td>
</tr>
<tr>
<td>481</td>
<td>2.1</td>
<td>0.7</td>
</tr>
<tr>
<td>547</td>
<td>4.7</td>
<td>3.0</td>
</tr>
<tr>
<td>705</td>
<td>6.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4: RMS of velocity on motor bearings

<table>
<thead>
<tr>
<th>RPM</th>
<th>L3 RMS [mm/s]</th>
<th>L4 RMS [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>V</td>
</tr>
<tr>
<td>705</td>
<td>5.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

As it could be seen, levels of velocity RMS is high on all of measuring points. According to ISO 10816, with 705 rpm machine is graded as class D (vibration could cause damage), since its 11.2 mm/s for horizontal and 9.3 mm/s for vertical measurement on L2 (bearing closer to coupling). Rest of the RMS values are graded as class C (short term operation allowable) according to ISO 10816, since its values are exceed 4.5 mm/s which is lower limit for this class. It is required to determine what is the main cause of this increased vibrations.

4. VIBRATION ANALYSIS

4.1. Waveform analysis

Recorded acceleration data is analyzed by its waveform characteristics. On figs. 6. and 7. Are shown waveforms for bearings L1 and L2 on the ventilator.

![Fig.6: Waveform of acceleration for L2 (H and V)](image)

![Fig.7: Waveform of acceleration for L1 (H, V and A)](image)

On the waveform for horizontal and vertical direction on bearing L1 some impacts could be noticed, which also transfers to horizontal direction on bearing L2. The shape of letter M and W could be also noticed on the waveform for horizontal direction of bearing L2. Those characteristics could suggest that combination of misalignment and looseness could be main faults of this system.
4.2. Frequency spectrum analysis

From the recorded accelerograms, frequency spectrums are created. On Fig. 8. and Fig. 9. are shown accelerograms for measurements done on ventilator bearings L1 and L2 in range from 0 Hz to 800 Hz when ventilator had 705 rpm.

![Frequency spectrum](image)

**Fig. 8: Frequency spectrum of L1 acceleration (0-800 Hz)**

On frequency spectrums rotating frequency and its multiple orders are noticeable. It could be also noticed some nonsynchronous frequencies (226 Hz, 346 Hz) where some of them could be bearing frequencies. Some floor noise is raised for frequency spectrum measured on the L1 bearing.

Frequency spectrum characteristics shown on Figs. 8. and 9. are suggesting that possible cause of high vibrations is misalignment and looseness, which already caused bearing failure.

5. REPAIR PROCESS

After main failure is determined, repair process is planned to be done as soon as there is no request for the continuous machine operation. Since that stopping is planned in a few weeks, it is needed to decrease level of vibrations so operation of ventilation system is possible.

First step was to decrease misalignment level. During misalignment measurement, it is noticed that the ventilator shaft journal is radially moving inside bearing closer to the coupling. By measuring radial movement of shaft on both sides of bearing it is concluded that ventilator shaft journal is bent.

![Misalignment measurement on coupling](image)

**Fig. 10: Misalignment measurement on coupling**

On the coupling of ventilator shaft side is measured that shaft journal is 1 mm bent on that end of shaft. It is concluded that best solution is to distribute that 1 mm of bent shaft journal on 0.5 mm on each sides of motor shaft.

Aligning procedure is done with radial and angular measurement (edge – face), where angular misalignment is reduced to <0.05 mm per 100 mm length, and radial misalignment is distributed horizontally and vertically by 0.5 mm.

5.1. Vibration measurement after the quick repair process

After alignment is done, ventilator and motor shafts are coupled. Vibrations on same locations are measured and compared with previous results. Velocity RMS values of vibrations after repair process are shown in table 5.

![Table 5: RMS of velocity on ventilator bearings after the quick repair process](image)

<table>
<thead>
<tr>
<th>RPM</th>
<th>L1 RMS [mm/s]</th>
<th>L2 RMS [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H V A</td>
<td>H V A</td>
</tr>
<tr>
<td>200</td>
<td>0.8 0.2 0.2</td>
<td>0.7 0.3 0.5</td>
</tr>
<tr>
<td>273</td>
<td>1.4 0.2 0.5</td>
<td>1.8 0.4 1.1</td>
</tr>
<tr>
<td>365</td>
<td>1.8 0.4 0.5</td>
<td>1.5 0.6 1.9</td>
</tr>
<tr>
<td>456</td>
<td>4.1 0.5 1.5</td>
<td>3.6 0.7 2.6</td>
</tr>
<tr>
<td>548</td>
<td>2.4 0.4 0.8</td>
<td>2.5 3.2 3.9</td>
</tr>
<tr>
<td>640</td>
<td>4.6 1.0 1.3</td>
<td>2.4 1.3 1.3</td>
</tr>
<tr>
<td>686</td>
<td>4.4 1.1 1.4</td>
<td>2.3 1.3 1.8</td>
</tr>
</tbody>
</table>
As it could be seen, highest value of vibrations on bearing L1 is decreased from 6.1 mm/s (705 rpm) to 4.6 mm/s (686 rpm), and for bearing L2 is decreased from 11.2 mm/s (705 rpm) to 3.6 mm/s (456 rpm). This drastic reduce of the vibration levels are due to distribution of ventilator bent shaft on both sides of motor shaft.

On Fig. 11 are shown levels of measured vibrations before and after the repair process. This ventilation system belongs to group 1 of machines with nominal power greater than 300 kW and with rigid foundations.

Similar traces are visible also on journal where this bearing was mounted. Most possible scenario in this case was that shaft mounted on ventilation system was already bent. Because of that, bearing was loaded over its maximum force and journal grinded inside inner ring of bearing and made some gap, so journal could skid inside the bearing. Since shaft was bent, it acted similar as misalignment. And since it made some gap between journal and bearing inner circle, it also had some frequency spectrum characteristics similar to misalignment frequency spectrum. Velocity RMS values after the main reparation process is shown in table 6.

Table 6: RMS of velocity on ventilator bearings after main repair process

<table>
<thead>
<tr>
<th>RPM</th>
<th>L1 RMS [mm/s]</th>
<th>L2 RMS [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>V</td>
</tr>
<tr>
<td>200</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>273</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>365</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>456</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>548</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>640</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>731</td>
<td>1.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

After the main reparation process where shaft and bearings are changed with new parts, vibrations are measured. It is shown that all vibration levels are classified as A, which is stated as a new machine condition.

6. CONCLUSION

In this paper is shown diagnosing and repairing process of ventilation system in thermal power plant. After this presented analysis, some conclusions could be stated as follows:
- If there are characteristics of vibrations which are similar for some different faults, it is sometimes required to take physical measurements of some possible faults to have full picture of what is happening in the machine.
- It is possible to reduce vibrations on the machine by reducing one of the faults which caused vibrations.
- Reducing machine vibrations could extend its working life, at least until it is possible to fully repair the machine.
- Bearing damage as possible fault in rotational machine could be present with other faults which are probably the cause of bearing failure.
- According to ISO 10816 levels, after the quick repair it is recommended to work with 60% capacity (550 rpm) until the main reparation process is possible, so vibration levels are lower than class C. This is only applied to this ventilation system.
- The main repair process has removed sources of the increased vibrations, so there are no restrictions for operating with this system after the main repair process.
REFERENCES


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SUSTAINABLE DEVELOPMENT IN THE ENERGY INDUSTRY
CONTEMPORARY APPROACH TO AUXILIARY MECHANIZATION OPERATIONS AND MAINTENANCE AT AN OPEN-PIT COAL MINE

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Dragan STEVIĆ

Abstract: This paper presents results of a project aimed at improving auxiliary mechanization (“AM”) (bulldozers, excavators, pipelayers, vehicles, etc.) operations and maintenance at the open-pit coal mine Drmno of the TE-KO Kostolac, a subsidiary of Electric Power Industry of Serbia (“EPS”). Business processes supported by ICT (GPS/GPRS system, IS/IT system) were designed and implemented for the needs of the department of auxiliary mechanization. In that way AM managing is provided from the point of readiness and availability at real-time. A basic organizational and technological platform is provided as infrastructure for further enhancements of the GPS/GPRS system of AM and its integration into ecosystem (e.g. open-pit coal mine maps, optimization of the machine paths at open-pit mine, Google maps, sensors for air quality parameters).

Key words: auxiliary mechanization, processes, ICT, operations, maintenance, open-pit coal mine

1. INTRODUCTION

An analysis of current state of an auxiliary mechanization (further AM) management system was conducted for the purpose of design, development, implementation and application of modern business processes, information systems (further IS) and information-communication technologies (further ICT) in the AM management sector, (bulldozers, pipe layers, dump trucks, vehicles....) at open-pit coal mine Drmno of the TE-KO Kostolac, a subsidiary of Electric Power Industry of Serbia (“EPS”), Fig.1. It was concluded that AM management does not apply modern business such as "end to end" business processes, IS and ICT. Then, basic business goals are defined:

- Readiness increasement,
- Availability increasement,
- Improvement of operational work and maintenance,
- Development and implementation of modern IS/ICT,
- Management and making decision based on data,
- Costs reduction: operational work, maintenance and spare parts.

For example, Fig.2 shows transport system disposition of tailing and coal, Figures 3, 4, 5 and 6 show paper documents that were used for management of exploitation and maintenance of machines and vehicles (further machines) at the AM.

Starting from the current state and business goals, the design, development, implementation and application of business processes with IS/ICT support with appropriate software solutions and GPS/GPRS system were carried out, which is given in further text.

Fig.1: The open-pit coal mine "Drmno", Serbia

Fig.2: Transport system disposition (year 2011)
2. CONTEMPORARY MANAGEMENT OF AM AT OPEN-PIT COAL MINE

The design, development, implementation and application of modern approach of AM management at open-pit coal mine "Drmno" are based on improved “end to end” business processes - BP (activities, responsibilities, business events, key performance indicators - KPI and documents), with ICT support (IS/IT, GPS/GPRS). Basic BP are:

- BPM - Maintenance, Fig. 7: BPM1 - Corrective; BPM2- Preventive; BPM3-Combined and BPM4 - According to the sub-process condition: Submission for maintenance, Reception (for maintenance), Diagnostics, Work order and Worksheets (Preparation and maintenance execution), Control, Report out (notification from exploitation), Handover.

Fig. 3: Job request for maintenance of machines/vehicles

Fig. 4: Work order for maintenance

Fig. 5: Machines/vehicles Work Schedule at the AM

Fig. 6: Monitoring of fuel consumption

Fig. 7: Business process "Technical maintenance of machines and vehicles"
BP-Exploitation: BP1- Updating of general and technical characteristics of machines and other general facilities; BP2- Support to annual work schedule by shifts and employee groups; BP3- Daily machines and operations schedule; BP4- Support to fuel management; BP5- Support to lubricant and technical fluids management; BP6- Solving fails of machines on site/service; BP7- Information for operational and top management.

For business processes and sub-processes, appropriate software solutions, i.e. IS for exploitation and maintenance of AM and GPS/GPRS system have been developed and implemented. This provides monitoring of all “end to end” business processes and sub-processes, as well as data and information for AM management. For instance business sub-processes are given for BP3- Daily machines and workers schedule: BP3.1- Machine status; BP3.2- Daily schedule of machines and BP3.3 - Daily schedule of the operator and for them software solutions have been developed. By activating, in the Main menu, Fig.8, the drop-down menu "Exploitation" (Daily) Schedule is activated, Fig.9.

Included activities of machine maintenance are: from submission for maintenance (document Q.Z.EK.10) to delivery of fixed machine/vehicle (document Q.OD.10), using necessary resources (workshops, qualified personnel, spare parts, engine for devices and machines testing, maintenance, technical documentation, information system for system maintenance management).

By activating, in the Main menu, Fig.10, the "Maintenance" drop-down menu, maintenance activities with software support is activated, Fig.10. For example, the documents forms BP-“ maintenance” which occur in the maintenance process are listed, Figures 11, 12, 13 and 14. Electronic documents can be printed.

Fig.8: Main menu ICT (ISPM, GPS/GPRS)

Fig.9: (Daily) Machine and operator schedule

Fig.10: Drop-down menu "Maintenance"

Fig.11: Submission for maintenance (see Fig.3)

Fig.12: Review of reported failure

Fig.13: Menu for definition of Work order and Worksheets (after diagnostics)
GPS/GPRS system has been developed and implemented for tracking machines and vehicles work at open-pit mine. The scheme of the system is shown in Figure 15.

**3. RESULT - MANAGEMENT INFORMATION**

The business process Exploitation and Maintenance generates documents (with data and information) for managing these processes, in real time. Data and information are available to operational and top management. Choosing the "Reports" option, Fig.9, reports are generated, Fig.16.

For example, Figure 17 shows **readiness**, and Figure 18 shows **availability** of machines and vehicles at open-pit coal mine "Drmno" which are generated currently.

**Readiness** (which includes working time and failure-maintenance time) is one of the key measures of successful operation and maintenance of machines on coal mines. Based on readiness, it is possible to plan operation of machines for next year, as well as assessment of new machines purchase, or maintenance system improvement.
Availability, in %, represents an overview of the correct and canceled machines / vehicles in the current time. Based on the availability, it can be concluded is it possible to carry out daily tasks at open-pit mine or is it necessary to make special efforts to maintain in order to realize daily tasks. From BPM-Maintenance in Fig. 19, the document Q.OD.33 is shown: The register of work orders generated based on: Q.Z.EK.10-Submission for maintenance, Q.OD.01-Diagnostics, Q.OD.2- Work Order and Q.OD.03- Maintenance lists.

An overview of regular services, spare parts costs, as well as other indicators of exploitation and maintenance of machines and vehicles, are obtained by activating the options shown in Fig.16.

Fuel. One of the main indicators of operation of machines at open-pit mine is fuel consumption. Every machine/vehicle has its own card, as well as operators and drivers. Through a mobile computer which is installed on the tank (fuel dispensing at open-pit mine) and using the appropriate communication structure, the data on tank injection and fuel dispensing machines in the field are sent to the server. It is pointed out that the implementation of "BP-fuel consumption" with software support has contributed to the savings that are measured in hundreds of thousands euros. Figure 21 shows one of the fuel-review reports: monitoring average, total, and average consumption according to normative in %. These values are monitored by machine operators and vehicle drivers.

Application of GPS/GPRS provides an overview of all AM machines and BASIC MECHANIZATION machines location by activating option "All" with symbol √ in the Control Display, Fig.20. It is possible to display only one type of machine by activating the symbol √ (for chosen machines). Choosing-clicking on certain - one machine at open-pit mine in the field “Machine/vehicle data” machine parameters are displayed: positions (GPS coordinates, ID device, time, amount of fuel in the tank). Also, notice about non-announcement of machine at open-pit mine at certain time intervals is given.

It is pointed out that it is possible to see the movement of machines in the mine for any previous period, even for the previous years by activating the "Map" option and entering the period for which an overview of the movement in this field is desired, Fig.20.

Fig.19: "Register of work orders" of the performed maintenance in the workshop

Fig.20: Position of machines at the "Drmno" with disposition of conveyor belts tailings and coal (see Figure 2.)
4. CONCLUSIONS

Paper presents basics of development, design and implementation of improved management of exploitation and maintenance system of AM machines and vehicles.

Some of the presented documents, that were used for management of the PM (as it is not possible to display all documents due to the space) were shown before the implementation of the modern approach with business processes and the support of ICT (IS/IT, GPS/GPRS) at open-pit mine "Drmno". Business processes of exploitation and maintenance with developed ISPM with adequate software support developed by Business processes and sub-processes as well as developed GPS/GPRS system were exposed. A basic organizational and technological platform is provided as infrastructure for further enhancements of the GPS/GPRS system of AM and its integration into ecosystem (e.g. open-pit coal mine maps, optimization of the machine paths at open-pit mine, Google maps, sensors for air quality parameters).

Some of the results, i.e. REVIEWS and REPORTS, are presented which enable management of AM in real time. All reviews and reports are generated from these processes of AM, in current time.

Developed and implemented processes with software support at the open-pit coal mine "Drmno" can be applied in other mines of various ores (minerals) with possible adjustment.

REFERENCES


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Abstract: A software application has been developed and integrated within modern ICT environment to support a fuel management process for Auxiliary Mechanization (“AM”) at the open-pit coal mine Drmno of the TE-KO Kostolac, a subsidiary of Electric Power Industry of Serbia (“EPS”). The fuel management process activities are automated as follows: (i) obtaining fuel from the local pump; and (ii) delivering the fuel to vehicles, machinery and fuel storage-tanks at the open-pit mine. To support fueling at open-pit mines software application named “Field Fuel-issuing” was developed and implemented on mobile computers. Data collected for fuel ‘in charge’ and supplied fuel are transmitted to the Auxiliary Mechanization Information System (in Serbian, ISPM) data base via the contemporary communication infrastructure of the TE-KO Kostolac. This data enables fuel management of AM. This approach to fuel management is based on fuel consumption monitoring results expressed by different technical parameters in an on-line data queries and reports, which are discussed in this paper.

Key words: auxiliary mechanization, fuel management data collecting, open-pit coal mine, software application for mobile computers

1. INTRODUCTION

Reduction of fuel consumption of machines/vehicles of Auxiliary Mechanization (AM) is one of the Key Performance Indicators (KPI) of the fuel management process and Auxiliary Mechanization management as a whole [1].

The first update of monitoring, ordering, issuing and reporting modes on fuel consumption of AM at the open-pit coal mine Drmno within the TE-KO Kostolac (henceforth: TE-KO) - a subsidiary of Electric Power Industry of Serbia (“EPS”) was undertaken during the period of 2010-2011 [1, 2]. A contemporary process approach and applied Information and Communications Technologies (ICT) were embedded in the foundations of design, development and implementation solutions. A “Fuel Management Support” process was conceived and a software solution developed and implemented within the Auxiliary Mechanization Information System (ISPM) (for the process and software, henceforth: “Fuel”). From that point on, the ISPM secured the daily insight of fuel consumption (per machine and vehicle, model and type), comparison of issued and registered items within the Work order, as well as monthly, quarterly, semiannual and annual insights in electronic form, which before 2011 was not possible.

Further improvement of the “Fuel” business process was sparked by the global ICT advances (for example: Cloud computing, Internet of Things, GPS/GPRS, [3]). Ongoing improvements were furthermore instigated by new technologies in the field of refueling, machine and vehicle identification, mobile computer’s data input and system and communications infrastructure updates at the TE-KO, as well as by improved mobile operator’s services and networks. This was acknowledged by the design teams of TE-KO Auxiliary Mechanization, Faculty of Mechanical Engineering and Institute „Mihajlo Pupin”.

In Chapter 2, this paper first presents the “Field Fuel-issuing” Application for mobile computer as a base for further improvement of the “Fuel” business process, with integration into ISPM. Yet, a more ample context of this business process improvement lies in contemporary perception of sustainable mining founded on five supporting pillars: economy, security, environment pollution, productivity and community [4]). Further on, in Chapter 3, the Application in question is described and viewed through its goals, specification of requirements, realization and description of the infrastructure where the Application is running. Chapter 4 presents and views some of the development and implementation of the Application in question related to management and decision-making support. Conclusion underlines the results related to planning improvements and diminishing of expenditures based on improved data quality of issued fuel to machines in the field obtained in real-time.
2. BUSINESS PROCESS IMPROVEMENT

According to current perception, sustainable mining is founded on five supporting pillars: economy, security, environment pollution, productivity and community. Taking these pillars for goals, the principle of a multi-goal optimization can be applied to sustainable mining, where all of the goals, opposing each other from immemorial times, are being simultaneously optimized. Furthermore, the optimization process in mining can be conducted in continuity so that the process parameters may adapt to changeable circumstances, such as climate conditions or situations of partial system failures, diminishing thus its functionality [4].

The use of modern information and communication technologies (ICT), as well as of multi-goal optimization in geology, mining engineering, mechanical engineering, ecology and economy may accomplish the goal of creating a frame for a complex mining factory of the future. Such a system would be of use to the superior management of mining organizations enabling them to obtain real-time information and make right decisions.

In contemporary business conditions activities within the fuel management process are mainly automated: refueling from storage-tanks, that is, fuel-issuing to vehicles, machines and fueling-trucks (for further field fuel-issuing). “Field Fuel-issuing” Application for mobile computer was developed and implemented for field refueling at open-pit mines (bulldozers, pipelayers, dump trucks…) which supports automatic identification of machines/vehicles and their operators/drivers through identification cards [1]. The referred Application was developed for industrial mobile computer Psion 8585 which has an option to substitute the keyboard with a screen. This means that the communication between the Application and its user is conducted through the touch screen – by the means of fields on the screen user choses available options or makes data entries. Training for the Psion Application use is thus greatly simplified, since contemporary smart phones and tablets use the very same functionality.

Via contemporary TE-KO communications infrastructure, data on fuel ‘in charge’ and issued fuel is transmitted to the ISPM data base. This data gives rise to a more efficient fuel management at the AM Sector. This is related to planning and control of fuel consumption on daily or, for example, monthly bases.

3. MOBILE COMPUTER APPLICATION FOR FIELD FUEL-ISSUING

3.1. The goals of Application development and implementation

The main goals of “Field Fuel-issuing” Application development and implementation are to avoid mistakes and accelerate data input on field fuel-issuing, as well as making such event information available as fast as possible to the ISPM.

The ultimate goal of building an application that monitors field fuel-issuing on mobile computer is to completely substitute paper documents (Q.EK.12 - Record-keeping form for event registration of field fuel-issuing at the open-pit mine, Fig.1). Entering of such an event is made directly through the mobile computer’s screen, whereas such data is further on transferred through communication channels to the data base, that is, to ISPM. Thus, the writing of documents in paper form is avoided, as well as the repeated entry of same data to ISPM. This eliminates mistakes during repeated entry and secures faster input, precision and system data availability. To attain this ultimate goal it is necessary to fulfill prior requirements, that is, certified digital signatures, a matter related to the whole of EPS. In this phase, data input is electronic while, instead of a certification body, a responsible person verifies the data in a still faster and easier way rather than by repeated entry of the same in ISPM.

![Fig.1: Q.EK.12 - Record-keeping form for field fuel-issuing at the open-pit mine](image-url)
3.2. Specification of Application requirements

As already stated, the main goal for development and implementation of the “Field Fuel-issuing” Application was to avoid mistakes and accelerate the data input on field fuel-issuing, as well as to secure that such information is rapidly forwarded to ISPM data base. The Application uses Identification Cards (ID) for machines and vehicles, for operators and drivers, as well as for the field fuel-issuer. Activities of “Field Fuel-issuing” are comprised out of three units:

- Fueling of fuel trucks at the fuel storage-tank,
- Field fueling of the machines,
- System’s functions as an Application support.

Last to units will be describe below.

Worker charged with field fuel-issuing (Fuel-issuer), logs into the system (identifies himself) through his ID card. After logging, he has a choice of two functionalities: refueling the fueling-truck or field fuel-issuing. Fig.2 depicts the Fuel-issuer’s scenario of field activities. All the data entered through this Application is forwarded to the central data base, further used to control field work and to obtain fuel consumption reports.

<table>
<thead>
<tr>
<th>Field Fuel-issuing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Enter the machine/vehicle card</td>
</tr>
<tr>
<td>2. Enter the operator/driver card</td>
</tr>
<tr>
<td>3. Enter the fuel quantity (touch screen numeric input)</td>
</tr>
<tr>
<td>4. Enter KM (kilometers) or MČ (machine working hours) (touch screen numeric input)</td>
</tr>
<tr>
<td>5. Enter the number of the Travel or Work order (touch screen numeric input)</td>
</tr>
<tr>
<td>6. Enter the Fuel-issuers card (fueling-truck driver’s card) for confirmation of data input</td>
</tr>
</tbody>
</table>

Fig.2: Activities during Field Fuel-issuing

Aside from the Fuel-issuer, the Application has an administrative user whose role is to maintain the ID card codes of machines and vehicles, as well as of the operators and drivers. Administrator is also the only one who can enter data into the system on technical parameters of fueling-trucks (fueling-truck’s internal number, current fuel quantity, fuel type, fueling-truck’s volume) and the initial totalizer value (totalizer – cumulative fuel quantity in liters dispensed from the fueling-trucks). Fig.3 depicts the choice of activities permitted to the Application Administrator for the adjustment of Application parameters. Fueling truck parameters (current system quantity value of fuel) may differ from the actual quantity of fuel in the fueling-truck due to the fuel technological working process (volume changes due to the temperature) or due to the fueling pistol’s precision and fuel issuing. In case of a difference between the real fuel quantity and the system quantity value, obtained from the Application, a Commission for leveling-out the state of fuel quantity in fueling-trucks, determines the real state according to the procedure for technological control, while, through the Administrator’s input console, the Administrator will introduce that data as a fueling-truck’s system parameter.

3.3. Application realization

According to given specification, a system for data recording of field fueling was developed and implemented, as well as for control and report-issuing on fuel consumption of machines and vehicles. Real-time field information significantly contributes to quality decision-making in fuel management (planning and purchasing), as well as in accompanying each units fuel consumption (machine or vehicle), on daily, monthly or annual basis.

The “Field Fuel-issuing” Application accompanies the fuel-issuer’s working process. Fuel-issuer signs-up in the system by introducing his ID card to the reader (screen shot at Fig.4).

Fig.4: Fuel-issuer’s system logging

Next step is the choice of activity: fueling of the fueling-truck or field fuel-issuing (Fig.5).

Fig.5: Fuel-issuers choice of activities

The refueling process of fueling-trucks involves the entry of issue-slip’s number and the fuel quantity if refueled system forwards this data (on refueling from a storage-tank) to ISPM through GPRS modem.
According to the field refueling plan and a Fuel-issuer’s Work order, fueling-truck’s driver and a Fuel-issuer are dispatched to the open-pit mine where, on field locations of the machines, refueling is conducted until completely filling up their tank. The Application provides data input of all of the relevant refueling information:
- Machine/vehicle’s ID card;
- Operator/driver’s ID card;
- Number of the operator/driver’s Work order;
- Quantity of issued fuel;
- Number of machine working hours (MČ) or vehicle kilometers (KM);
- Fuel-issuer’s ID card as conformation that all of the data has been entered.

Figures 6, 7 and 8 depict Application’s screens as an example of the working process unfolding during a refueling, to be entered by a Fuel-issuer.

End of shift
When a Fuel-issuer ends his shift, next step is the “Work ending” where, based on the shift data input, on the mobile computer screen the Application presents a review of activities during that shift. Summing up, the following is being presented (Fig.9):
- Fuel state at the beginning of the shift,
- Fueled quantity during the shift,
- Number of fuel storage-tank issuing’s during the shift,
- Issued fuel quantity,
- Number of field fuel-issuings,
- Fuel quantity at the end of the shift,
- Totalizer state at the beginning of the shift and
- Totalizer state at the end of the shift.

Input of system parameters
According to the requirements specification, the function of system parameters input has been executed. Administrator’s role within the system is to enter/delete/update all of the ID cards (operators/drivers and machines/vehicles) and to enter all of the technical fueling-truck parameters as described in Chapter 3.2.

3.4 Infrastructure
Fig.10 depicts the lay-out of the physical architecture of the designed and implemented “Field Fuel-issuing” Application with its major components. TE-KO data center hosts the ISPM application servers (data base, web server and communications server), while the TE-KO communications infrastructure provides for the ISPM accessibility from all of the TE-KO Kostolac locations. Equipment installed in fueling-trucks cabins or in tractors cabins pulling fueling-tanks, is comprised of (Fig.11):
- Mobile computer (Psion company),
- ID card reader, and
- GPRS modem.

Mobile computer (an industrial Psion company PC has been used) works under Windows XP operation system, while the Application itself has been executed in Java development settings. Data from ID cards is stored in data base, while all the information on refueling and fueling is stored in form of xml messages kept in “for sending” and “sent” folders, depending on the message’s status.
4. MANAGEMENT AND DECISION SUPPORT

One of the key indicators of the machine/vehicle performance in open-pit mines is the fuel consumption. Each machine/vehicle has its own ID card, as well as their operators/drivers. By the means of mobile computers installed on fueling-trucks (open-pit mine field fuel-issuing) and the use of adequate communications infrastructure, data related to the fueling of fueling-trucks and to the fuel-issuing of field machines (refueling from fueling-trucks) is sent to the server.

Fig.12 depicts fuel consumption. This review is generated in real-time and through the use of filters reports can be generated for any required period time since all of the data is stored in ISPM. Reports give the possibility of monitoring the fuel consumption of each the machines, or vehicles, as follows:
- Total consumption for a determined period of machine’s activity,
- Average consumption,
- Average consumption as related to the normative consumption in %.

The referred values are accompanied per machine operator and vehicle driver.

For the control purposes of issued and consumed fuel, a comparison of fuel issued from the fueling-trucks is made by entering data into ISPM from the Q.EK.12 document for registration of field refueling and fuel-issuing events, thus instead of “0.00” in the last column (Fig.13) issued fuel quantities are entered and compared with the automatically entered data from the “Field Fuel-issuing” Application (Fig.13 - Screen form for data verification of field fuel-issuing.)

5. CONCLUSION

Having in mind that AM fuel consumption is one of the key performance indicators of AM management in TE-KO, it is natural for the business process of fuel consumption management to be constantly improving based on the use of latest technologies. “Field Fuel-issuing” Application, developed and implemented on mobile computers, forms part of a system that integrates the identification equipment of machines/vehicles and operators/drivers on contemporary bases. Furthermore, an integration of ISPM data base was undertaken with the contemporary TE-KO communications infrastructure. Thus, the goal of improving data quality was achieved in the sense of precision and faster data accessibility from the sum total of data for decision-making in the process of fuel consumption management. This was accomplished due to the improvement of data quality on machine field fuel-issuing obtained in real-time, presented in action through reviews and reports important for planning fuel provisions.

It is to be noted that, due to the implementation of the up-to-date business process “Fuel Management Support” with developed and implemented software support, great savings have been made in TE-KO.

For further improvement of the business process of fuel consumption management one has to consider that this process is an important model of sustainable mining where the open-pit mines of TE-KO are viewed as a modern future factory.
REFERENCES


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CONTRIBUTION OF THERMAL POWER PLANT TO THE IMMISION OF PM10 IN THE CENTER OF PLJEVLJA

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Abstract: Pljevlja is one of the most polluted cities in Montenegro. All the basic elements of the environment in Pljevlja are endangered, and the indicators of the state of their quality are outside the limits permitted by law. The main sources of pollutant emissions in Pljevlja are numerous: the coal mine, power plant, industrial and non-industrial boilers, individual furnaces, road traffic, landfill, etc. Combustion processes have the greatest contribution to emissions - power plant boiler, road traffic, city boiler rooms and individual furnaces. This paper presents the influence of the operation of a nearby thermal power plant on the level of pollution by PM10 particles in the city.

Key words: pollution, emissions, TPP Pljevlja

1. INTRODUCTION

Pljevlja is one of the most polluted cities in Montenegro. The main sources of pollutant emissions in Pljevlja are numerous: the coal mine, power plant, industrial and non-industrial boilers, individual furnaces, road traffic, landfill, etc.

It should be noted that there is a long list of air pollutants in Pljevlja that are systematically monitored in a way that gives a detailed insight into the air pollution situation in Pljevlja. All the basic elements of the environment in Pljevlja are endangered, and the indicators of the state of their quality are outside of the law limits. Air quality in Pljevlja is continuously monitored since mid-2009, in line with European air quality standards transposed into Montenegrin legislation.

However, in accordance with the contemporary view on this issue, information on PM10 particles, which are recently treated as one of the critical components of pollution in terms of its impact on the health of residents, will be used as a reference pollutant indicator in this paper. Moreover, the measurements show that the level of concentration of this pollutant, in comparison to the others, is convincingly leading in exceeding allowed limit values. The measured PM10 concentrations in Pljevlja, averaged over the months, are given in [1] and are shown in Fig. 1.

Figure 1. PM10 concentrations in Pljevlja [1]
The average daily values of PM10 concentrations in Pljevlja for the year 2013 [1] exceeded the prescribed limit of 50 μg/m$^3$ during 177 days (out of 337 days of valid measurements), with the limit of tolerance exceeded during 85 days. The allowed number of exceeding days is 35 (10%). The average annual concentration of 79.51 μg/m$^3$ was above the prescribed limit value (40 μg/m$^3$) and the tolerance limit for 2013 (50 μg/m$^3$). Short-term concentrations exceeding 1000 μg/m$^3$ were measured several times.

There were 332 days of valid measurements of PM2.5. The average annual concentration was 45.69 μg/m$^3$, which is above the limit value of 25 μg/m$^3$ and the tolerance limit for 2013.

Similar values were measured in 2014 and 2015 [1]. Therefore, air pollution by PM10 in Pljevlja is significant, not only because of the measured concentrations, but also because of the large number of days with overruns of allowed values.

From Fig. 1 it can be seen that the concentrations of PM10 in the air during the heating season were significantly higher than the concentrations measured in the period from April to October.

In order to obtain a wider picture of the pollution situation in Pljevlja (and in Montenegro), Podgorica, Nikšić and Pljevlja are compared with several regions in the World in terms of PM10 concentrations in major cities. The comparison is given on Fig. 2. Year-round averaged data on worldwide PM10 concentrations is a result of analysis of 1600 cities [2].

![Figure 2. PM10 pollution worldwide](image)

It is clear that other major cities are also highly endangered and that the PM10 contamination problem is present throughout the world, both in developing and developed countries.

2. LOCATION OF TPP IN PLJEVLJA VALLEY

The town of Pljevlja is situated in Pljevlja valley located in the far north of Montenegro. The valley is of irregular shape, approximately 6 km wide and 9 km long. The hills of Maljevac, Velika and Mala Plješ and Stražica are elevations in the valley itself, with the heights of up to 900 m above sea level. Elevations that directly surround the valley reach the height of 1100 to 1400 m above sea level.

The valley in which the town of Pljevlja is located is at the altitude of 760 to 770 m above sea. The valley is irregular in shape and extends in the northwest-southwest direction and covers an area of 16 km$^2$. The city is located in an area that is approximately 2.5 km in length and 1 km wide. There are several hills in the valley, and the highest is Stražica (840 m altitude). The valley is surrounded by the hills on all sides: Golubinja, Maljevac, Glavica, Bogiševac and Balibeg hill.

The thermal power plant Pljevlja is located in the southwest part of the valley. Its distance from the centre of the town is about 4 km. The objects are deployed in a circle that occupies an area of 35.8 ha. The following facilities are located in this area: main building with boiler room and control room, transformers, workshop and warehouse, administrative building, electro-filters with dumper station and rectifier station, 250 m high chimney, pump station with two storage tanks of 2000 m$^3$ each, chemical water treatment with two reservoirs of demineralized water, auxiliary boiler room, electrolysis station, coal depot with transitional buildings and combined units, cooling tower with pump station, 35/0.4 KV substation and clean water treatment plant.

Coal is transported by dumpers between the mine and the crushing plant, and then by strip conveyors to the coal dump. Coal is then transported by strip conveyors between the coal dump and boiler bunkers in the main object. The capacity of the coal dump is approximately 100,000-120,000 tons.

A pulverized coal-fired boiler of TPP Pljevlja is equipped with a system for preparation of pulverized coal with direct incineration in the furnace. Due to the high moisture and ash content in coal, its grinding in pulverized coal is carried out in ventilation mills. The mixture of powdered coal and air is blown in the furnace at three levels, together with the heated combustion air.

The boiler is of a single drum type, with forced circulation of water and with membrane walls of the furnace. The flue gas tract of the boiler has the shape of Cyrillic letter „П“ - (P). The boiler operates with subsequent reheating of steam. The capacity is 194.4 kg/s, (pressure 13.73 MPa, temperature 540/540 °C).

3. CLIMATIC CHARACTERISTICS OF PLJEVLJA

The shape of the valley itself and the characteristic shape of the relief favour longer stay of accumulated cold air, so that the temperature inversions are common. Pljevlja has pronounced local inversions in lower atmospheric layers, in the colder part of the year, especially in the evenings, when the sky is clear. Their height is up to 50 m. Above this height, a layer with weaker inverse temperature gradients gradually forms, which rises to different heights. In the second half of the night, ground level gradient decreases, in higher layers it increases, and the development of the raised inversion is possible.
The ecological burden of the city area is compounded by the adverse climatic characteristics that prevail in the area of Pljevlja: a large number of silent days, with the frequent occurrences of “cold air lakes” and radiation fogs, especially in the winter months, which reflect on the long-term retention of pollutants and precipitating particles in the atmosphere.

Pljevlja is the city with the highest cloudiness in Montenegro. Cloudiness is increased in the cold part of the year, while in the summer period it reaches a minimum. The fog period in Pljevlja lasts 200 days a year. According to the available data, the number of foggy days has been rising since 1974, which can be related to the time of construction and opening of industrial facilities, which is especially valid for the discharge of water vapour from the cooling tower of the thermal power plant [3]. Natural conditions cause poor ventilation of Pljevlja basin, which causes fogs to appear and remain for a long time (Fig. 3). Fogs are characteristic in autumn and in winter days, they last long and are very low. In such conditions, the concentration of pollutants in the air increases.

Due to this geographical position, meteorological silence prevails in Pljevlja basin. In the annual distribution of silence, they account for 67%, which means that air currents from all directions amount to 33%. By frequency, the southern and north winds point out, and the eastern wind is the least frequent.

The data [4] obtained from the Hydro-meteorological Institute of Montenegro about the rose of the wind (Figure 4) and silence show that the medium silence lasts 46% of the winter time, and during the summer it lasts 5% of the time, which at the level of the year gives the duration of silence for 29% of the time. In this consideration, the year is divided into winter lasting from October to April and summer that lasts from May to September.

If the silence data for months during the year are presented graphically, it is obvious that the shape of the curve of PM10 concentration in Pljevlja (Fig. 1) has the character of the silence graph shown in Fig. 5.

For this reason, it would be important to monitor and record relevant weather data simultaneously with concentrations of pollutants.
4. ENVIRONMENTAL IMPACT OF THERMAL POWER PLANT

All thermal power plants have a major impact on the environment, causing soil, water and air pollution, resulting in excessive noise as well as in large electromagnetic radiation.

The soil is directly polluted by dust from the coal depot, ash blasted by the wind from the ash depot, and by solid particles that are emitted with the flue gas through the chimney and then deposited from the air.

Indirectly, the soil is polluted by precipitations that deposit all the harmful substances from the air (sulphur, nitrogen and carbon oxides and heavy metals) as well as process waste waters coming to the soil.

Air pollution in the vicinity of the thermal power plant is physical, chemical or radioactive. Physical pollution represents any colour change, blur, temperature or conductivity change. The typical physical pollution of water is due to the insoluble matters (oil, heavy oil, etc.) Chemical pollution of water is caused by ash, wastewater from chemical preparation of water, faecal waters and waters that rinses all the harmful substances from the surrounding surfaces.

Air pollution in the vicinity of the thermal power plant is the result of the combustion of coal in the boiler. There is primary and secondary air pollution by combustion products. Primary sources of pollution are oxides of combustible elements of coal (carbon, sulphur, hydrogen), than heavy metals, dust and aerosols. Secondary pollutants arise as a result of the reaction of primary pollutants with air under the influence of the solar spectrum, where more destructive pollutants can occur. An example is the conversion of NO that occurs in the boiler to NO₂ which is significantly more aggressive.

TPP Pljevlja directly or indirectly affects the quality of air, the watercourse of Vezišnica river and its tributaries, the watercourse of Paleški potok and further on to the water stream of Čehotina downstream of Pljevlja. Also, the impact of the coal mine which inevitably follows the operation of the thermal power plant should not be neglected. The most pronounced impacts on the environment are through [5]:

- Air pollution with particulate materials, SO₂, NOx, CO₂;
- The contribution of greenhouse effect by CO₂ emission;
- Pollution of water and air from ash and slime dump;
- Drying of vegetation caused by acid rain;
- Deposition of sediments and degradation of water in natural streams due to discharge of water from the thermal power plant;
- Soil degradation in the vicinity of the thermal power plant by deposition of fly ash and heavy metals as well.

Lignite from the surface coal mines Borovica and Potrlica with lower calorific value ranging from 6,782 kJ/kg to 12,016 kJ/kg is used as a fuel for TPP Pljevlja. TPP Pljevlja has been in operation since 1982. The total amount of coal burning in Pljevlja is over 1,800,000 tons a year, of which 1,700,000 burns in TPP, which, in addition to coal, annually consumes about 3,500 tons of oil and 660 tons of chemicals. Based on available data [3], TPP Pljevlja hourly consumes 225 tons of coal, 200 tons of oxygen and emits 230 tons of carbon oxides, 3,57 tons of sulphur oxides, 120 tons of water vapour and 0,36 tons of suspended particles per hour. Also, 44 tons of ash and 5 tons of slag per hour result as the products of combustion.

The height of the chimney of the thermal power plant is 252 m, so that its outlet exceeds 1000 meters above the sea level. Despite the relatively high thermal power plant chimney, increased concentrations of suspended particles are registered during the adverse meteorological conditions in the heating season.

Continuous emission monitoring system is installed on the chimney before the outlet of the gas to the atmosphere. The measuring site is located at the height of the existing platform (67 m).

In addition, continuous measurement of emission concentrations of suspended particles, carbon oxides and sulphur oxides are performed on the chimney. The average values of concentrations measured by the system for flue gas monitoring for the last few years are given in Table 1.

From the above data, it is clear that the thermal power plant invest considerable efforts in reducing the emissions of solid particles. Those efforts have been remarkably successful in recent years, primarily thanks to the reconstruction of the electro filters. Further reduction of sulphur oxide emissions from flue gases from the current approximately 5000 mg/nm³ to less than 150 mg/nm³ is possible only by the construction of a flue gas desulphurisation plant (DeSOX). The reduction of nitrogen oxide emissions from flue gases from the current cca 600 mg/nm³ to less than 200 mg/nm³ is possible by reconstructing/building a nitrogen oxide reduction plant in outlet flue gases (DeNOX) with the application of primary and secondary reduction measures.

Table 1. Average emissions from TPP Pljevlja

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Unit</th>
<th>2010</th>
<th>2011</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>MAC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid particles</td>
<td>mg/nm³</td>
<td>82</td>
<td>171</td>
<td>45</td>
<td>35</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>SO₂</td>
<td>mg/nm³</td>
<td>3229</td>
<td>4729</td>
<td>5610</td>
<td>5308</td>
<td>5384</td>
<td>150</td>
</tr>
<tr>
<td>NOx</td>
<td>mg/nm³</td>
<td>480</td>
<td>473,7</td>
<td>571</td>
<td>668</td>
<td>661</td>
<td>200</td>
</tr>
<tr>
<td>CO₂</td>
<td>%</td>
<td>11,46</td>
<td>10,74</td>
<td>12,5</td>
<td>11,93</td>
<td>11,7</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>mg/nm³</td>
<td>38</td>
<td>32,5</td>
<td>32</td>
<td>28</td>
<td>23</td>
<td>100</td>
</tr>
</tbody>
</table>

* maximum allowable concentration
5. IMMISIONS EMANATING FROM THE THERMAL POWER PLANT

Pursuant to Article 21 of the Law on air protection [6], the Ministry, in cooperation with the Agency and the local government bodies in whose territory the environment is endangered by pollution, issues an Air quality plan. The aim of the plan is to achieve as soon as possible the concentration values established by the Decree on determination of pollutants, limit values and other air quality standards.

To this end, for the purposes of air quality plan, TECHNE Consulting has completed a study on the impact of air pollution in the municipality of Pljevlja [3]. According to this study, the total emission of pollutants will increase in the coming years (observed by 2020) unless measures are taken to reduce pollution. By implementing a series of proposed measures, by 2020, pollution reduction will be achieved, especially in terms of PM10 suspended particles.

One of the main conclusions is that the influence of thermal power plant is minimal, i.e. among other things that, due to the high chimney, the emission of PM10 from the thermal power plant, does not compromise the air quality in the city. The impact of the emissions from the thermal power plant on the urban area of Pljevlja was estimated using the Calpuff model. Due to the height of the chimney (252 m), the emissions are dispersed in a large area, overtaking the city and settling away from it (Fig. 6).

This Study, although based on the use of sophisticated CFD technology, has a shortage for which it is hard to blame anyone. Input data of pollutant emissions were taken from the literature, i.e. exact data was not measured. On the other hand, when comparing the PM10 concentrations measured over a longer period of time (data from the Environmental Protection Agency of Montenegro) with interruptions in the operation of the thermal power plant (data on interruptions obtained by the courtesy of the thermal power plant operator), no correlation is obtained, which confirms the conclusion in the abovementioned study. This comparison for the year 2013 is graphically shown in Figure 7.
6. CONCLUSION

All the basic elements of the environment in Pljevlja are endangered, and the indicators of the state of their quality are outside the limits permitted by law. Waste materials emanating from the exploitation of coal, forests, clay, marlstone, electricity generation, etc. results in increased pollution of air, surface and groundwater, as well as in soil degradation and pollution, in accumulation of municipal and hazardous waste, deterioration of the health status of the population, destroying flora and fauna etc.

Combustion processes have the greatest contribution to emissions of pollutants – boiler of thermal power plant, industrial boilers, road traffic, non-industrial boilers in the household and service sector (city boiler rooms and individual furnaces) as well as processes related to extraction, refining and solid fuel transport.

However, the main culprit for excessive PM10 pollution in the winter months (heating season) is not the thermal power plant, but rather small boilers and furnaces in the city itself. Their fuel is primarily lignite, primarily because of its availability and low price. Because of the small height of the chimneys, those boilers and furnaces, in conjunction with adverse weather conditions, fail to disperse the flue gasses out of the city [8].

Solid fuel combustion in households is one of the leading sources of suspended particles in which a high percentage of benzene and benzo(a) pyrene is found. Among solid fuels, combustion of lignite produces the highest amount of pollutants per unit of calorific value. In addition to wood and coal, it is common to use packaging waste in household furnaces, which sometimes results in emission of carcinogenic pollutants such as dioxins and furans.

REFERENCES


[6] Law on air protection, Official Gazette of the republic of Montenegro 025/10, 040/11, 043/15, Podgorica, Montenegro (in Serbian)


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APPLICATION OF NEW TECHNOLOGIES IN THE DEVELOPMENT AND INCREASE OF WIND POWER PLANT CAPACITY

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Abstract: Energy stability and security have become an important issue for each country over the last few years, and the reason for this depends on the economic and social development of each country. Energy and energy systems, in addition to their well-being for the society as a whole, also have negative consequences such as release into the atmosphere of greenhouse gases and carbon dioxide. The world's tendency is to reduce the percentage of carbon dioxide and greenhouse gases which are result as a use of fossil fuels for energy production and this reduction is achieved through the use of renewable energy sources. Renewable energy sources include: biomass, solar energy, geothermal, hydroelectric power and wind. The paper presents a trend of energy production from renewable energy sources over the past ten years, with a special focus on wind power. The trend of development and modernization of the wind power plant from the beginning to the present, the influence of modern-new technologies on the development and implementation of wind power plants as well as the increase in electricity generation capacity has been demonstrated. A review of various design solutions for wind use as renewable energy sources is presented. In the end, a review of the future development of the wind power is utilized by using advanced technologies, i.e. technologies that establish the fourth industrial revolution.

Key words: energy, renewable energy sources, new technologies, wind, wind power plants.

1. INTRODUCTION

The use of fossil fuels in the world has for years caused global climate changes that humanity is now facing. Their use increased carbon dioxide and other greenhouse gases, which caused climate changes. The effects of climate change are already noticeable, such as melting of glaciers, disintegration of the polar ice, melting of permafrost, rising of sea level, which results in the change of the ecosystem. In addition, when nuclear energy is concerned, it has been shown that its production is insecure for the humanity, examples of which are large nuclear accidents such as Fukushima in Japan (March, 2011) and Chernobyl in former Soviet Union [1,2,3, 4,5,6,7,8,11,12]. This has forced the governments of almost all countries in the world to turn towards renewable energy sources.

Renewable energy sources play an increasing role in the energy system. Energy evolution is the most ambitious, because it introduces the production of energy from the renewable energy sources, as well as rigorous energy efficiency measures, so that by 2050 the largest share of energy production would be placed on renewable energy sources. Renewable energy sources can be divided into two main categories: traditional renewable energy sources such as biomass and large hydroelectric power plants, and so-called ‘‘new renewable energy’’ such as biomass (bio-fuel, bio-gas), small hydroelectric power plants, solar photovoltaic energy, solar thermal energy, wind power energy, geothermal energy[6,7,21,43,45], and sea energy (tidal energy, waves, and currents). Renewable energy sources are considered to be the future of the energy or clean energy that will replace fossil fuels and their harmful impact on the environment. In regard to the wind power energy, the development of wind power plants is increasing annually, thus increasing the height of the wind power plants and generator power. In 1980 the height of wind power plant amounted to 15 meters and generator power to 1 MW, while in 2015 with the application and implementation of new technologies in the development of wind power plants, their height reached 178 meters and generator power to 9.0 MW. There is an ongoing research in new technologies, especially nanotechnology, whose implementation in wind power plants will increase the height of wind power plants and wind generator power in the future.

2. ENERGY PRODUCTION IN THE WIND POWER PLANTS WORLDWIDE

The production of wind energy recorded the fastest growth of all renewable energy sources at the beginning of 21st century, so that the capacity increased about seven times in the period 2005-2015. The estimates are that renewable wind energy will have the growth tendency of 21% annually. The long-term technical potential of wind as a renewable energy source will increase, followed by the solution of the structural problems of wind power plants, because wind turbines are currently produced up to 178 meters and 9.0 MW. With future development of new technology, wind power plants will achieve height to 300 meters and 20 MWth [1-3,14]. Installation of wind power plants will occur on large areas and high altitudes, as well as in the oceans where wind resources are rather high.
Constructive solutions of wind power plants will be such that they will be mobile, and will be installed in the areas where the intensity of the wind is very large. The global production capacity of wind energy in the world for the period 2005-2015 is shown in Figure 1. [3-8]

![Figure 1: World production of electricity from wind power plants worldwide for the period 2005-2015](image)

The analysis of the Figure 1 indicates that the production of electrical energy from wind power plants in the world has the growing tendency every year. In 2005, total production was 59 GWh, while in 2015 total production was 433 GWh. We can conclude that in ten years the production of electricity increased about seven times. In order to get a complete picture of the production of electricity from wind power plants we need to conduct an analysis of electricity production by countries in the world. Top ten countries that produce highest percentage of electricity from wind power plants is shown in Figure 2.

![Figure 2: The produced electricity from wind power plants in ten top countries in the world in 2015](image)

The leading role in the production of electricity from wind power plants in the world belongs to China which produced 148 GWh in 2015, followed by USA with 72 GWh, and Germany with 47 GWh, and other countries: India, Spain, England, Canada, France, Italy, and Brazil with capacities shown in Figure 2.

In regard to global investment in renewable energy sources, investment are constantly increasing since 2005. In 2005 about 73 billion USD were invested worldwide, and in 2015 the tendency of investment has grown to about 286 billion USD [REN 21 RENEWABLES 2016 Global Report]. The largest investments are directed towards the solar energy, Figure 3 a), in which developed countries invested about 81 billion USD and developing countries about 80 billion USD in 2015. The second place in investment in renewable energy in the world is held by wind energy utilization, Figure 3b), where investment are increasing continuously every year. In ten years investment in this renewable energy source has increased from about 30 billion USD in 2005 to about 110 billion USD in 2015, and it can be concluded that the investment increased 3.6 times. Predictions are that this tendency of investment in renewable energy sources will continue in the future. The investment in renewable energy has led to the creation of new jobs and employment of workers in renewable energy sector in the world. In 2015 the RES employed 8.1 million workers [REN 21 Renewables 2016 Global Report], and the tendency of hiring workers in regard to wind energy usage is shown in Figure 4.

![Figure 3: Global new investments in RES technology and wind energy in the developed countries and developing countries in 2015](image)

![Figure 4: Employment in the world, China and Europe in technology and wind power plant production for the period 2010-2015](image)
Figure 4 indicates that the tendency of employment in the wind power plants is growing worldwide in the last five years. In 2015 there were approximately 1.081,000 workers in the world. Based on the Figure 4a) we can conclude that more is invested in wind energy by the developing countries in 2015, which is confirmed by Figure 4. We see that China is in the first place in the number of workers in this renewable energy source in last three years. In 2015 there were about 507,000 workers in the use of wind energy (technology and production) which is far more than in Europe. The estimates are that this tendency of employment will continue in the future.

3. THE APPLICATION OF NEW TECHNOLOGIES IN THE DEVELOPMENT AND INCREASE OF CAPACITY OF WIND POWER PLANTS

The world is undergoing the fourth industrial revolution “Industry 4.0”, so that the development of new technologies, such as digital technology, sensor technology and nanotechnology, contribute to the increase of boundaries in use of wind as renewable energy source. Figure 5 shows historical development of wind power plants in the world. Based on Figure 5 we see the past and the future development of wind power plants in the world. In 1980 the height of wind power plants was only 15 meters, and in 2000 wind power plants reached the height of 112 meters with 1.5 MW generators. The development of new technologies has favored the development of wind power plants so that in 2015 the largest wind power plant reached the height of 178 meters with 9.0MW generator. The development of new technologies and nanotechnology and its further application in wind power (nanomaterials and machines have already been introduced in the wind industry) aims to improve the durability of components of wind power plants critical elements. One of the element is the blade of turbine where the application of nanotechnology and new materials targets to improve their properties, Figure 6. The basic characteristic of the wind power plants blades that needs to be increased is the resistance and stiffness of the blades. New materials should ensure safe operation and long life operation of wind power plants.

Fig. 5: Former and future development of wind power plants in the world [1,2,11]

Fig. 6: New generation blades of wind power plants [2]
As is well known, the blades of wind power plants are made of polymer matrix composites. These materials dominate the market for several reasons: low price, smaller ratio of the weight and strength, excellent characteristics of material fatigue, high elastic modulus, high specific strength, as well as the possibility of making very complex geometric shapes that are very important in order to create greater resistance. High quality nanomaterials allow huge challenges and progress in the field of polymer matrix composites that will affect the characteristics of the blades in wind power plants, but also make them easier and rougher. Nanoparticles that are used for coating of blades of wind power plants have good diffusion barrier properties and excellent resistance to water, which is very important in the wind power plants blades. Use of nanoparticles in composite polymers have advantages and increase in: tensile strength up to 40%, modulus of elasticity up to 68%, bending stiffness up to 60%, and improves the fire retarding properties. They also have disadvantages, such as: improper ratio of price and their impact, difficulty in recycling, brittleness, etc. Revolutionary idea for long-term operation of blades of wind power plants is the development of super-hydrophobic and ice-phobic materials, since coating of blades, sensors and measuring equipment with these materials prevents the formation and accumulation of ice on these elements. The same situation is with the carbon nanotubes (Figure 7 show carbon nanotubes with cylindrical nanostructures) that are 50-110 times stronger and six times lighter than steel, whose coating on blades prevents icing.

Use of nanotechnology (nanoparticles, nanomaterials, and polymer matrix composites) enables the improvement of length of wind power plant blades, Figure 5. The objective is to increase the blades, so as to increase the power produced by wind power plants, because it is proportional to the square of the bladelength. Nanocomposite materials are used in order to develop new generation of blades that will have high performances. Considering the fact that during the operation of wind power plants, wind gusts can impact the blades, all elements of the generator are exposed to static and dynamic loads. Many companies in the world produce generators for wind power plants. In an effort to remain competitive in the market they need to develop and apply new technologies in the production of generators for wind power plants. Figure 8 shows the market share of ten manufacturers of wind power plants in the world in 2015.

Fig. 7: Carbon nanotubes used in wind power plants [14,15]

Fig.8: The market share of the ten top manufacturers of wind power plants in the world in 2015 [3]
The analysis of the involvement of the largest manufacturers of wind power plants in the world in 2015 provides us with the conclusion that companies from China are the largest manufacturers of wind power plants and cover 30% of the market. This conclusion confirms the fact that in 2015 China was the biggest producer of electrical energy with 148 GWh.

Due to unstable working conditions, all rotating elements in wind turbines are loaded statically and dynamically, and cracks can occur due to cyclic stress. In addition, it may cause wearing of rotating parts and the creation of localized corrosion. Nanotechnology has developed nano-lubricants with very low friction which coat the rotating elements in order to reduce the energy loss in them (gears, bearings). Nano-lubricant is the geometric structure of the nanoparticles, which acts as small ball bearings, and is convenient for the protection of the rotating elements against wearing. Wind power plants installed at sea are subject to moisture and water. In order to protect them, new seals based on nanocomponent elastomer have been developed, that protect and prevent the penetration of moisture and water.

### 4. CONCLUSION

The use of fossil fuels in the world has led to global climate change, and many strategies were made to replace fossil fuels with renewable energy sources. One of the renewable energy sources is wind. The use of wind for energy production in the world is increasing every year, and in 2015 it reached 433 GWh, with China becoming the largest producer with 148 GWh. Investment in the utilization of wind power energy is constantly increasing and in 2015 it reached about 110 billion USD. In addition, the number of jobs in the use of wind energy in 2015 increased to approximately 1.081 million workers. Investments have been made in technology which uses the wind as a renewable energy source, so that the height of wind power plants and power generators is continuously increasing. The largest contribution to the increase of the capacity of wind power plants is attributed to the new technologies, which include new materials, nanotechnology and sensor technology. The use of nanoparticles and nanotubes increase the wind power plants blades and their working life. In terms of rotating elements, they increase wear resistance, reduce friction and reduce the formation of localized corrosion and cracking, and thus increase the efficiency of wind power plants. Maintenance and replacement of parts of wind power plants are very expensive, as they contribute to significant delays in installations of wind power plants. The development of new technologies, especially nanotechnology, will provide a greater blade length of which the capacity of wind turbines depends, as well as the production of high power generators in the future.
REFERENCES


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APPLICATION OF RENEWABLE ENERGY SOURCES IN TERMS OF ECONOMIC, ENVIRONMENTAL AND SOCIAL SUSTAINABILITY

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Blagoje ŠUPIĆ
Aleksandra KOPRIVICA

Abstract: We are witnesses of everyday changes, which can bring the world into the question of survival. On the other hand, the progress and the speed of changes are the keys of success. What is important is that we have to change the human being’s life, due to the concept of the sustainable development, which includes three dimensions: ecology, economy and social aspect. This paper gives the analysis of using the renewable energy, through the production of the electricity, including the sustainable development.

Through research, attention was paid to analyzing the growth in the share of renewable energy in electricity production, as well as incentives to use renewable energy sources, in the area of Republic of Srpska.

Key words: electricity, renewable energy, sustainable development.

1. INTRODUCTION

Modern life style means much more energy, with the goal to achieve higher effectiveness and comfort. Nowadays, most energy needs are settled using extremely harmful fossil fuels, which, in the future, should be replaced with cleaner energy resources, like renewables or nuclear energy.

Sustainable development is a dominant philosophy which must be respected by every human in a global world, if he/she wants to settle nowadays needs without compromising the ability of future generations to meet theirs [1].

Also, sustainable development means maintaining a balance between use, saving and restoring all resources, and understanding that the generations who are coming will largely depend on our present actions [2].

The paper’s topic is very current due to the fact that the development of the renewable energy sources is a major challenge for the future of the whole world.

2. RENEWABLE ENERGY SOURCES

Renewable or inexhaustible sources of energy are those on the Earth, which are available in unlimited quantities. Although, the process of conversion and transformation temporarily spends their quantities, i.e. they can always be restored. Also, they are called alternative energy sources [3]. Renewable energy sources can be divided into several groups, based on similarities, which illustrates figure 1 [3]:

- Solar energy,
- wind energy,
- hydropower,
- earth energy,
- energy from biomass and
- other renewable energy.

Fig. 1: Renewable energy sources
Knowledge of the relative limitations and exhaustion of conventional, non-renewable energy resources and limited capacity of energy supply from renewable energy sources, have an impact on energy and economic development, forcing all users to rationality and maximum savings [3]. Energy of the future, but not only it, completely should turn to renewable energy sources, which will stop any unreasonable and irreversible exploitation of non-renewable fossil fuels. It is, for sure, Solar energy, created millions of years ago, which humanity consumes in the most unreasonable and the most possible damaging way, often destroying their own environment, which is increasingly becoming a prerequisite for the survival of the civilization. Non-renewable energy sources, such as coal, oil and nuclear energy, by the end of the 21st century will have been replaces with new, renewable, environmentally clean, natural energy sources, especially Solar, wind, water, biomass and geothermal energy [4]. Solar energy can be used actively and passively. The active use of energy means the conversion of solar radiation, directly, into heat or electricity. On the other hand, passive use of energy refers to energy efficiency, in the use of Solar energy, for heating homes and other buildings [3].

Like most of the renewables, wind energy is also derived from solar radiation. Wind energy occurs like a circumstance of a complex process of weather, various soil heating and evaporation of weather, which leads to differences in atmospheric pressure, at different geographical position and movements of air masses from a higher to a lower pressure position [3]. Hydropower power plants are plants in which the potential energy of water is first converter into kinetic energy of its flow, then into mechanical energy of the rotation of the turbine shaft and finally into electrical energy, in the generator [5].

Geothermal energy, in a narrow sense, includes only that part of the energy from the ground, which in the form of hot or warm geothermal media (water or steam) passes through the surface of the earth and is suitable for utilization in the original format (for bathing, treatments, etc.) or conversion to other forms (electricity, heat in thermal systems, etc.) [5]. Biomass is a biodegradable part of product, waste product from agriculture, forestry and forest industry, plant and animal origin, which use of energy is allowed in accordance with the regulations of environmental protection [6].

In the world, there are attempts to beneficial use of other renewable energy sources. This mainly refers to the energy of seas and oceans [3].

3. SUSTAINABLE DEVELOPMENT

Establishing a balance between economic development and higher standards of living, with the population growth and depletion of natural resources, creates a conceptual basis for a entirely new approach to the development of humanity - sustainable development [1]. According to one of the most commonly used definition, sustainable development is one that meets the needs of humanity in the present, taking care not to jeopardize meeting the needs of those who will live in the future [2].

Sustainable development implies a balance between meeting basic needs and achieving a certain standard of living, with the available natural resources and preservation of the environment. In essence, sustainable development is a process in which there is a harmony between the exploitation of resources, direction of investments, orientation of technological development and institutional change, in order to improve the potential for the satisfaction of human needs, both now and in the future [2].

Many researchers agree that the terms sustainability and sustainable development could be described together as an improving of the life quality, in terms of a healthy environment, ie. improving the social, economic and environmental conditions, for current and future generations [2].

Vollenbroek argued that sustainable development is the balance between available technologies, innovative strategies and laws, passed by the Government of the country. Sustainable development is a challenge, on one hand there is a meeting of the growing needs of humanity to natural resources, energy, food, transport and waste management and on the other hand there are conservation and protection of the environment and basic resources, for the life of future generations and their development. This concept includes the view that in the long run human needs can not be met, without preserving the physical, chemical and biological systems on the planet [2].

Sustainable development encompasses three aspects, which are commonly referred to as pillars viability [2]:
- the economic aspect,
- aspect of the environment and
- social aspect.

Previous ilustrates the next figure 2.

For the economic aspect it is necessary to ensure economic growth, in order to improve the life quality. The economy is therefore essential for long-term survival of the community. When we talk about sustainability, it is often associated with the aspect of the environment business practices, energy efficiency and sustainable business [2].

Fig. 2: Sustainable development [7]
For the environmental aspect it is necessary to reduce to a minimum damage of the environment, pollution and exploitation of natural resources. Environmental issues make up the core of sustainable development and they are inextricably linked with the economic and sociological component. Community cohesion with its environment is complex and involves the exploitation of resources and consumption which acts to a local and also global eco-region [2].

For the social aspect it is necessary to ensure fairness in the resource distribution between the riches and poor. Social equality, in terms of sustainability, is usually considered as intergenerational, because the activities taken today affect the life of the community in the future. Sustainable development is aimed at improving the living standards of individuals, with short, medium and long-term preservation of the environment. Its goal is threefold; development which is based on economic efficiency, social justice and sustainable environmental protection. Discussion of the concept of the sustainable development in particular contribute the challenges that come with the vulnerability of the environment. Some of these challenges are: global warming, ozone layer depletion, the greenhouse effect, deforestation, the phenomenon of acid rain, the extinction of plant and animal species and the climate change, as the biggest and the most complex challenge that human society faces today [2].

3.1. Main aspects of the sustainability of the power system

The electricity system consists of generation, transmission, distribution and consumption of the electricity. The main task of this system is a reliable and quality supply of the consumers. This is the largest, most influential, the most necessary and the most widely used technical system, and it is, therefore, the most expensive.

Once the electricity is produced in power plants it is handed over to customers. The settlements, cities and finally the whole country are interwoven with power lines that transmit electricity [8].

The electricity system is the most widely used, which follows from its size. The only system which could be compared to the power system is the Internet. But, even comparing it to the Internet, we can say that the power system is more widespread than the Internet because there are places where the electricity is available, but the Internet isn’t. As well, to connect to the Internet, in most cases, it is necessary to have the electricity infrastructure. Nowadays, there is a number of 30 main energetic indicators of the sustainable development which are classified according to the three dimensions of the sustainable development [8]:

- economic dimension (16 indicators),
- dimension of the environment (10 indicators),
- social dimension (4 indicators).

Taken together, these indicators can give a picture of the whole energy system, including interconnections and exchanges between the different dimensions of sustainable development, as well as the long-term consequences of the current decisions and behavior.

Changes in the indicators, over the time, show the progress or its absence in relation to the sustainable development.

The next tables 1, 2 and 3 show mentioned indicators.

Table 1: Energy indicators for sustainable development - economic aspect [8]

<table>
<thead>
<tr>
<th>ECO 1</th>
<th>The use of energy per capita.</th>
</tr>
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<tbody>
<tr>
<td>ECO 2</td>
<td>The use of energy per unit of GDP.</td>
</tr>
<tr>
<td>ECO 3</td>
<td>The efficiency of the energy conversion and the distribution of energy.</td>
</tr>
<tr>
<td>ECO 4</td>
<td>The ratio of the energy reserves and production.</td>
</tr>
<tr>
<td>ECO 5</td>
<td>The ratio of natural resources and production.</td>
</tr>
<tr>
<td>ECO 6</td>
<td>The energy intensity in the industry.</td>
</tr>
<tr>
<td>ECO 7</td>
<td>The energy intensity in the agriculture.</td>
</tr>
<tr>
<td>ECO 8</td>
<td>Services/energy intensity in the store.</td>
</tr>
<tr>
<td>ECO 9</td>
<td>The energy intensity in the households.</td>
</tr>
<tr>
<td>ECO 10</td>
<td>The energy intensity of the traffic.</td>
</tr>
<tr>
<td>ECO 11</td>
<td>The fuels shares in the electricity and energy.</td>
</tr>
<tr>
<td>ECO 12</td>
<td>The energy shares that does not contain carbon in the power generation and energy.</td>
</tr>
<tr>
<td>ECO 13</td>
<td>The renewable energy shares in the electricity generation and energy.</td>
</tr>
<tr>
<td>ECO 14</td>
<td>The energy prices for end users by sectors and by fuels.</td>
</tr>
<tr>
<td>ECO 15</td>
<td>The dependence on energy imports.</td>
</tr>
<tr>
<td>ECO 16</td>
<td>The inventories of missing fuels at an appropriate consumption.</td>
</tr>
</tbody>
</table>

Table 2: Energy indicators for sustainable development - environmental aspect [8]

<table>
<thead>
<tr>
<th>ENV 1</th>
<th>The emissions of greenhouse gases due to the energy production and use per capita and per unit of GDP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENV 2</td>
<td>The concentration of the air pollutants in urban areas.</td>
</tr>
<tr>
<td>ENV 3</td>
<td>The emissions of air pollutants from the energy system.</td>
</tr>
<tr>
<td>ENV 4</td>
<td>The discharge of the contaminated substances in the fluids, from the energy system, including the discharge of oil.</td>
</tr>
<tr>
<td>ENV 5</td>
<td>The land where acid rains exceed the allowable limits.</td>
</tr>
<tr>
<td>ENV 6</td>
<td>The ratio of the deforestation and the use of energy.</td>
</tr>
<tr>
<td>ENV 7</td>
<td>The production of solid waste per unit of produced energy.</td>
</tr>
<tr>
<td>ENV 8</td>
<td>The ratio of the correctly deflected solid waste and the total quantity of produced waste.</td>
</tr>
<tr>
<td>ENV 9</td>
<td>The solid radioactive waste per unit of produced energy.</td>
</tr>
<tr>
<td>ENV 10</td>
<td>The ratio of the solid radioactive waste, which is waiting to be removed, and total produced solid radioactive waste.</td>
</tr>
</tbody>
</table>
Table 3: Energy indicators for sustainable development - sociological aspect [8]

<table>
<thead>
<tr>
<th>SOC 1</th>
<th>The share of the households without electricity or commercial energy, high dependence on non-commercial energy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC 2</td>
<td>The share of the households income on fuel or electricity.</td>
</tr>
<tr>
<td>SOC 3</td>
<td>The energy use in households for each income group and corresponding fuel combination.</td>
</tr>
<tr>
<td>SOC 4</td>
<td>The number of accidents and injuries of the produced energy in the chain of the energy production.</td>
</tr>
</tbody>
</table>

4. THE GREEN ENERGY - THE ENERGY OF THE FUTURE

The role of the energy is to encourage the growth and the economic development of the Republic of Srpska, taking into account environmental protection. The development of the energy sector will be achieved by technological development, strengthening of the domestic companies, increasing of the investment and competitiveness of the economy of the Republic of Srpska. In the Republic of Srpska, the most important renewable energy sources are the energy of the watercourse (in large hydro power plants) and wood (for heating in households). The potential for hydropower development is significant and largely untapped, but in the terms of renewable energy here is emphasis on the smaller streams, i.e. the construction of small hydropower plants. Also, there is a significant potential for using wind, solar, agricultural biomass and geothermal energy, but unfortunately, now they are particularly not used [9]. In the Republic of Srpska, producers of electricity from the renewable energy sources are entitled to incentives. Right at the instigation of electricity, produced from the renewable energy sources and efficient cogeneration, based on the Agreement on mandatory purchase of electricity for the production from the renewables at the guaranteed purchase price for electricity which is delivered to the network, currently achieve 52 companies [9]. The right to an incentive is realized by companies that own hydroelectric power, solar power, biomass or biogas. It is interesting that, at the moment, there are no wind turbines or power plants that utilize the energy of the Earth, during the electricity production, even though the objective conditions exist. Percentage share of various energy plants that are entitled to incentives is shown in the following figure 3.

Figure 4 provides information about the total amount of the mentioned power plants. Although the percentage share of hydro power plants is lower than the solar plants, the total planned production of the electricity by hydro power plants is about 35 times higher than the solar plants. Also, the total planned electricity production of a biogas plant is about 2 times higher than the total planned production of all 35 solar power plants, although the solar power plants overall strength is much higher than the power of the biogas plant. Above said is shown in the figure 5.

Period, which is analyzed is the time interval of 4 years, from 2012 to 2016. The following figure 6 shows how varied the number of companies that have received the right to incentives, during the said period.
Since 2012, the share of renewable energy is steadily increasing, due to their enormous benefits. Figure 7 shows the share of renewable energy in the system of incentives in the total consumption of the electricity in the Republic of Srpska and the figure 8 displays it graphically.

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Total gross of the electricity production (kWh)</td>
<td>3,670,321.440</td>
<td>3,693,716.900</td>
<td>3,682,021.225</td>
<td>3,821,051.340</td>
<td>4,002,584.204</td>
</tr>
<tr>
<td>The total electricity production from renewables (kWh)</td>
<td>5,049,206</td>
<td>24,650,412</td>
<td>42,095,078</td>
<td>45,143,269</td>
<td>112,902,081</td>
</tr>
<tr>
<td>Participation of the renewables in total consumption (%)</td>
<td>0,14</td>
<td>0,67</td>
<td>1,14</td>
<td>1,18</td>
<td>2,82</td>
</tr>
</tbody>
</table>

Fig. 7: The share of renewable energy in the system of incentives in total consumption of the electricity in the Republic of Srpska [9]

Fig. 8: The growth of the renewable energy sources in the system of incentives in the total consumption of the electricity in the Republic of Srpska

5. CONCLUSION

Humanity today faces great problems in the energy sector. There are growing energy needs of mankind, which is every day more and more increasing. Limited reserves of non-renewable energy sources with its emissions exhaust gases and particulates significantly affect climate change in the world. Currently, as an environmentally friendly solution there are renewable energy sources. Like all new technologies, at this stage of development, the exploitation of renewable energy economically is not, yet, fully viable. As a result, many countries, with theirs various measures of incentives are affecting the development and the use of renewable energy sources, including the Republic of Srpska. Republic of Srpska with these measures seeks to increase the spread of so-called application of the green energy. Interconnection of economic and socio-cultural development, with the state of the environment, the need for the necessary natural balance, processes and global living conditions, today have become the part of the economic, political, normative-institutional and cultural reality of the modern humanity.

REFERENCES


[7] https://www.google.ba/search?q=sustainable+development&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjdtL3EmabUAhU1LAKHWAiCIQQ_AUIBigB&biw=679&bih=468#imgrc=U2ocg41WBdvGZM: (05.06.2017.)


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Abstract: The strategic objective of the Republic of Srpska should be to increase the production of electricity on the basis of new hydropower plants that will use equipment developed and manufactured in their own industry.

The question that arises is: what kind of effects will be and what projects would be realized as a result of the realization of the set goal.

The effects would be historical, as the Republic of Srpska would get a stable, growing economic development system. First of all, from the classical capital-intensive model of low-power electricity generation, a modern labor-intensive model would be created that would enable the employment of an extremely large number of highly educated engineers of various profiles. Secondly, there would be a significant reduction in the cost of electricity. Reducing the cost of electricity costs means higher profit and the possibility of reducing prices and services in the Republic of Srpska, because electricity is included in the cost of cutting all other products and services. In this way, the products and services of the Republic of Srpska would be significantly more competitive on the export market.

Projects that would be realized through this concept of development are:
1. Development and production of turbines.
3. Development and production of energy electronics and automation.
4. Development and production of mechanical equipment and
5. Development and production of logistics technology for advanced and other systems.

Authors have been working for years on research on this extremely complex problem. The results of the research will be presented in the paper and indicated the necessary further directions of the research and the direction of realization of the set strategies and goal.

Key words: Development, production, system, hydro power, technologies.

1. INTRODUCTION

The transformation of renewable resources, a certain geographic space, into products that have performance of high level of value is the best known strategy of high intensity of economic development of this area. If this strategy is implemented at the same time in a very short time, we have a dynamic growth of economic development. Furthermore, if such changes are supported exclusively by domestic knowledge embedded in their own technologies and, ultimately, if such an economy is managed effectively, then this can be called the economy of excellence [6]. Today, in conditions of intense and dynamic changes in the environment of the observed entity, the appropriate force, that is, energy for a proactive change within the entity itself, is the system observed from the angle of applied system theory is required. [28]

Within the overall economic system, the energy production sub-system is today the basic subsystem of economic development. When it comes to the territory of the former Yugoslavia, then it is the production of electricity, and it is a priority production of electricity based on renewable resources and own technologies. The scientific-research project on the basis of which this applied scientific research was created deals with the problem of economic development of the Republic of Srpska, whose central sub-development is the development of the energy sector. Within this sector, viewed from the angle of value, the most important area is the area of renewable resources for the production of electricity. The key renewable source of electricity is the hydro-potential of watercourses. Within the overall problem of development and production of...
electricity based on hydro-power, the subject of this work is the production of electricity in hydroelectric power plants that would be built with their own technology, that is, equipped with equipment based on their own development and own production. Through the research published in this paper, the effects of the development and production of mechanical and electrical systems based on their own technologies that make up the hydroelectric power plant and logistic systems for energy transmission (First transfer of hydropower to hydro power plant and other, transmission and transformation from hydroelectric power plant to consumer).

The main goal of the work is to determine possible effects of development and production: turbines, generators, energy electronics and automation, machine equipment and various logistics equipment. The second goal is to create a development model for optimal management of the development and production of hydroelectric equipment. The third goal is for the practically realistic research space, Republika Srpska, to determine the benefits in case of realization of this integrated economic development project and production of the mentioned equipment. The paper sees the exceptional complexity of the research problem and subjects, as well as the huge number of questions that will have to be answered through the implementation of an extremely large number of projects.

The tasks that need to be realized in the paper are not defined. The task assignment is a huge project in itself. It is logical that the work of this volume can not be dealt with in the direction of further research, but in the end, a framework organizational model is defined which could provide effective strategic and operational management of this enormous project enterprise. A number of research hypotheses have been raised in this paper. All hypotheses have been confirmed on the basis of relevant data using the well-known and proven scientific-research methods and techniques. The paper consists of the following parts: Introduction, Problem Analysis, Model Development, Swot Analysis, Research and Conclusion.

2. PROBLEM ANALYSIS

2.1. General about the problem

In times of global economic crisis and the increasing development gap between rich and poor, energy is getting more and more important. State communities that have their own energy are less vulnerable to the strong effects of the economic crisis, while those who are dependent on energy are increasingly lagging behind in development. Rich western countries that do not have enough of their own energy, through the mechanism of faster technological development and the knowledge-based knowledge in technology, provide energy not only for themselves, but also in trade in energy. In this way, they achieve a double effect. The problem of electricity generation must be viewed from the angle of change. Changes are the only possible solution. The solution is the result of a change activity [1].

Economy grown on the basis of its own natural potential is able to withstand not only the greatest crisis, but also disasters. Nations that are bravely preserving their natural resources, which are more fully processed in their own country, are visibly advanced in economic development. Resilience in the use of one’s own natural resources is shown by the first and the starting conditions for successful development Economy [28].

2.2 Analysis of the current situation

The production of electric power in hydropower plants in all countries formed on the territory of the former Yugoslavia for more than 30 years is realized on the basis of the same capacities, if the construction of an extremely small number of mini hydroelectric power plants is neglected. Considering the age of the equipment and the increased losses in the production, transmission and consumption of the consumer itself, probably the volume of electricity consumption is reduced in comparison with the 1990s of the last century.

The issue is arisen promptly, what will it be using the additional electricity generation? In order to make a correct conclusion we must know that electricity is technically marketed as a product that is embedded in other products and as a commodity for consumption. A state community that wants to develop and grow in the performance of its economic system must develop new production systems in which new added value will be created and in which new people will be motivated to participate in the development and growth of their company and the community as a whole.

3. MODEL DEVELOPMENT

3.1. The new development state of the problem

In this paper, we will only look at the new development state of the problem from the perspective of design, and the implementation of the projected state will be the subject of special work. The first question that arises now is the question that technology uses to transform the old system. From the front of the analysis it is evident that this is a new situation with the new structures, that is, the new production and business system with other structures and processes. It is a technology for change management, reengineering, or the tenology of comprehensive systemically integrated development changes based on one’s own knowledge. For such a complex set of managerial and technological activities it is inevitable to

\footnote{The activity of change is movement}

\footnote{The author of this quotation made a wrong conclusion
Except possible drought, ie lack of water, and thus reduced hydropower regarding the need to save water hydromechanical energy (the exception is dry periods).}
use intelligent business mechanisms and systems of excellence [34].

The new developmentally integrated situation will be the result of developmental changes not only in the management of the electricity generation system, but also in this case, and development changes in the field of their own technological development.

Considered the whole systemic level from a certain entity, the new state of the electricity production system in hydroelectric power plants means new generation of capacities for electrical, mechanical and logistic equipment. At the same time, it means a lot of employment in development and technology, above all the highly skilled technical staff, as well as staff for marketing and sales. The new state of the system is characterized by increased economies of scale, which will result in a reduction in the production cost of the unit of electricity. In this way, economically, they would get a new product that is significantly more competitive on the market.

New corporations that should emerge as a result of a public-private partnership would be socially very responsible and would have developed a corporate governance system.

3.2. Synthesis of effects and limitations

The effects, or the values of the newly developed electricity generation system, would be in the following:

1. New value would be multiplied: through a product that is more competitive, through its own technologies for electricity generation, through the development and conquest of a new product, through new employees who possess a large amount of technological and managerial knowledge of contemporary and traditional character and motivated for long term results. In terms of efficiency and effectiveness.

2. A long-term, realistic growth in electricity generation would be ensured, which would be safe from the aspect of efficiency and effectiveness. This would have a stable and significant growth in the overall economy of the entity or state community concerned. Poverty and developmental differences in wealthy countries and fast-growing economies would soon be reduced.

3. The production of electricity based on equipping hydroelectric power plants with equipment developed and produced by their own technologies based on their own knowledge is the only option for the poor to get out of poverty. To get out of poverty, they will not be helped by administrative membership in the EU or other world and European global institutions. [18]

4. The subject development and production will enable extremely high employment of young highly educated engineers of various profiles and technicians in the processes of operational production of electrical energy and mechanical equipment for the needs of the construction of new hydropower plants. It will be significant that the departure of young highly educated and skilled people to work abroad will be reduced. Some traditional development and production knowledge that is archived in dirty warehouses and heads of a small number of other top researchers and experts who have worked on development projects in former powerful research and development centers and institutes for a long time [6].

5. It is known that the complexity of the management of a single-hierarchical system SU = N! And multi-hierarchical system SU = Nm (N is the number of elements in one level, and m is the number of levels).

6. The present state of changes in the economy is primarily the result of financial flows and the impact of global character. The estimate is that today we have ten times higher GDP expressed through financial flows than is real, the result of a real economy. [30] This means that money is the largest commodity and largest demand in the global financial market. Of course, the most beneficial of this greatest benefit are wealthy entities (from a wealthy individual to a rich country). The result of this is the fact that the number of rich people is decreasing, but their wealth grows rapidly, and on the other hand, the number of the poor grows and their wealth.

Those who manage and decide on global financial flows are profit-oriented and secure and strengthen their positions by causing permanent financial and economic crises. However, in essence, the poor have a technological development crisis, better to say catastrophic, or no technological advancement. The current growth rates of the poor at the existing or somewhat higher level of wealth growth are in favor of the rich and are created through the IMF by wealthy countries and wealthy individuals.

7. The right solution for the emerging countries in the former Yugoslavia is to turn to their own technological development based on the growth of their own technologies in the field of natural resources. The authors of this paper, not only are not against EU accession, but are also about to do the same as soon as possible, because in this case they would have far fewer bureaucratic barriers in achieving their own technological progress. In addition, it would be easier to get the favorable investment funds needed for the development of their own technologies.

8. With the disappearance of this generation with the experience of applied development, we are in danger of
5. There is no doubt that the most complex constraint, that is, resistance to the implementation of this historically possible project is expected from the administration and people in the administrative decision-making positions. The most common resistance to implementation will be the result of ignorance and unwillingness, as well as the lack of ability to make such a major change on all levels. The personnel, primarily technical and economic profiles, are to study the model and expand the necessary messages that the project can bring. It is necessary that many people change in order to be able to deal with developmental changes, because the solution is still the most complex social activity. Development is concerned with the design and implementation of the future, the future is always uncertain and full of risk.

6. The realization of this project would mean parallel development of education and continuous learning and education of people. Then the growth of citizens' standards through, increase in consumption, and hence the growth of public revenues. There would be a huge increase in the social responsibility for responsible allocation for projects of social development. An appropriate outcome is also expected in the area of democracy, human freedom and the development of legal security and the reduction of all forms of deviant behavior by individuals and institutions, as well as the growth of all forms of civilized behavior and accountability towards human values.

7. Significant resistance can be expected among university teachers and scientists at the institutes, who do not possess knowledge in the field of applied research and applied development.

3.3. Optimization of technology management

The first author of this paper has developed an enormous number of mathematical models of optimization solving in his long-standing career, dealing with development, various development problems and situations. His scientific point of view is that any sort of complex situation can be mathematically modeled in order to search for the optimum solution. [7].

If E is the measure of the efficiency of electricity generation, and Xi is a set of input factors that affect efficiency. In mathematical form, the dependence of efficiency (E) on input variables can be given in the following form:

\[ E(X) = F(X_1, X_2, \ldots, X_n, t) \]  

Since the input quantities are subject to change, that is, the function of time, the efficiency (E) will be simultaneously in function of time (t). The key input parameter X is the technology. In addition to the technology, the structure of the parameters Xi will be different depending on the hydroelectric power plant to the hydroelectric plant, from situation to situation.

Since the construction and production of the hydroelectric power plant is a very long-term project, with small fluctuations in the production volume on an annual basis. Time as an independent variable in formula (1) can be excluded.

Technology as a key influencing factor on the effect of electricity generation consists of external and internal (own) technology.

If K is external technology and L is an internal (own) result of our own knowledge and operational work, then the efficiency of electricity production will be a function of these two technologies. We will explain efficiency (E) in the form of costs, and as such, as a sum of the cost of external technology K and internal L, so we will have it:

\[ T = K + L = f(L) + L \]  

Where the K = f (L) project determined the correlation between external and internal technology. If there is no correlation between external and internal technology then the cost will be a function of two unrelated variables K and L.

Optimization is now reduced to a differential account of the correlation of one or two variables. In the case of one variable L - native (own) technology, the optimal solution will be where \( (dT/dL) = 0 \) and where \( (d^2T/dL^2) > 0 \).

How is the correlation between external and internal technology

\[ K = f(L) \text{ and } T = f(L) + L \]  

We will have optimal production of electricity in the hydroelectric power plant where:

\[ (DT/dL) = 0 \text{ and } (dK/dL) = -1 \]  

In this way we can determine the optimal combination of external K and internal L technology.

The problem of electricity generation can be modeled in mathematical form by setting that the costs of electricity generation are the sum of the costs of investing (I) and operating costs of production.

\[ T = I + L \]  

\[ (DI/dL) + I = 0 \text{ and } (d^2L/dL^2) > 0 \]  

The subject of optimization can be various indicators related to the technology of electricity production in hydroelectric power plants:

- The relation between modern and traditional technology,
- The relation between internal (own) and external technology,

12 Except possible drought, ie lack of water, and thus reduced hydropower.
• Optimization of automated management,
• Optimization of capacities, more precisely, installed power of turbines and generators.
• Optimization of water flow,
• Optimization of the repair period,
• Optimizing the relationship between investment and operational costs,
• Optimizing the investment risk,
• Optimization of the degree of justification of investment,
• Optimizing investment in knowledge, ie human resources,
• Optimization of the management of the construction phase of the hydroelectric power plant,
• Optimizing the sales price of electricity
• Optimization of quality control and other.

Figure 2 presents a graphic illustration of risk optimization related to the degree of change in the existing initial state technology. Curve 1 represents the flow of costs due to the rate of change (SP). Curve 2 represents the risk, that is, of the costs of possible non-performance, and they decrease with the growth of the degree of change. Curve 3 is the overall risk and total cost. The optimum level of technology change will be in the lowest cost zone, that is, at the lowest risk zone.

![Figure 2: Costs and risks depending on the degree of change](image)

Optimization in this case consists in determining the optimal degree of change. The optimal degree of change is the one with the least total cost (Curve 3).

In conditions of intense and dynamic changes in the environment, we need to be trained for proactive management, that is, behaviors that will constantly lead us to finding optimal solutions. Looking for the optimum flow of the process of replacing external technologies with an internal (own) project is of exceptional complexity, but undoubtedly of enormous benefits, both from the aspect of the economic and from the aspect of social justification.

3.4. Organizational mechanism

The project for the development and production of mechanical and electrical systems and other logistic systems for the start must be organized as a complex project for which governments of individual countries will make decisions on how to operate. The project should have initial management and operational management. In Serbia, the project could be organized locally in the Ministry of Education and Technological Development, and in the Republic of Srpska within the Ministry of Science and Technological Development.

At a later stage, when the project becomes a reality with sufficient support for functioning, the Ministry of Development or a department should be set up parallel to one of the existing ministries. In parallel with this latest activity, it is necessary to establish at the beginning a public institution for the development of machinery and electrical equipment for new hydropower plants. In the next step, a public institution would be transformed into a modern corporation that would involve various partners in accordance with corporate governance rules.

4. SWOT ANALYSIS

The objective of the SWOT analysis, as well as the overall work of this paper, is to create a critical mass of research and development and research and professional individuals based on argued scientific research and proofs that will follow the goals and possibilities of this paper. This would also be a strategy created through this work. It is known that swot analysis involves an analysis of: power, weaknesses, opportunities and threats related to a particular project or activity.

**The strengths of the project are:**

The greatest strength of the project is that the former Yugoslavia has a huge amount of unused energy hydro potentials.

We still have a significant amount of knowledge related to the production of electricity in hydropower plants.

We have a critical mass of young engineers of various professions, as well as students at technical faculties, who will be a competent logistical support to the project.

The project provides the possibility of partnerships of interested partners.

Possible phase realization of the project and phase financing.

The Republic of Srpska has exceptional hydro potential for the construction of hydro power plants of various sizes of power.

**The disadvantages of the project are:**

The biggest weakness of the project is that we do not have a critical mass of people from knowledge and science who are able to understand how important this project is. Hydroelectric power plants are projects that are cost-effective in the long run, efficient and effective in the long run.

The disadvantages are that young people in reality do not have enough competence for development projects. Electricity companies do not allocate depreciation funds to a separate account in order to invest in new projects. Lack of development initiative in ministries and public enterprises in the field of electric power industry. Great financial indebtedness of public utility companies. Abuse in public procurement.

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In Republic of Srpska, and partly in Serbia tycoons have been installed in a very important position, from which they have a huge influence on decision-making. Adapting laws to their own needs and abusing public positions for personal interests. On the other hand, the bravest are leaving us. Those who went away significantly reduced the average level of intelligence and abilities to those who remained. It is valid for all areas, and of course for sports.

The possibilities of the project are:
The project can integrate traditional and modern technological and management values of electricity generation by choosing the optimal combination of one and the other values.

Electricity produced in hydropower plants on the basis of own technologies will be much more flexible, and thus significantly more adaptive to the requirements of the market, that is, different buyers.

By incorporating low-cost electricity into other products, it will lead to more competitiveness of exports from the observed space.

The need for a highly educated staff profile will lead to the development of higher education.

Using our traditional values and capabilities, we create conditions for more efficient business in the field of electricity generation and some other products.

The threats of the project are:
At the level of global economy and at the level of smaller economies and economic systems and at the current level, the prevailing speculative financial economy is the realm of the real economy, which is offered by the project. The real biggest threat to the project is the administration, traditional entrepreneurs, holders of political functions and tycoons. They are all short-term oriented both for efficiency and effectiveness, and most often for profit. Problem centralization of decision making. Lack of development organizations.

Problemrn structure of ministries:
Lack of planning system. Lack of integrated management and decision-making. Lack of the concept of technology development based on its own technologies. The existing higher education system does not educate personnel for development activities. Lack of study programs for economic development, but only a study program for improving operational activities.

5. RESEARCH

5.1. Synthesis of research

Due to the limited scope of work, as well as the complexity of the problems and the projects on which these research is based, the paper gives a shorter shorter synthesis of the research.

The main goal of the work is to determine possible effects of development and production: turbines, generators, energy electronics and automation, machine equipment and various logistics equipment. The second goal is to create a development model for optimal management of the development and production of hydroelectric equipment. The third goal is to determine the effects for the realization of this integrated economic development project and the production of the mentioned equipment for the practically realistic research space, Republic of Srpska.

The following research hypotheses are set out in this paper:

**Basic hypothesis:**
Production of electricity in hydropower plants built on the basis of mechanical, electrical and logistic equipment which is developed and produced on the basis of its own technologies is a project of economic excellence and a revolutionary-radical character for the premises, that is, entities that have hydropower potential.

**Additional hypotheses:**
First: For the realization of this revolutionary-radical development project, people who possess the applied research and development skills are needed. They must, in partnership with state institutions, be effective and efficient in the long-term oriented since this is a long-term project. Second: In addition to the exceptional economic and wider social benefits of the project, huge resistance to the realization is expected Project by a large number of powerful and influential individuals and institutions.

**Specific hypotheses:**
First: Republika Srpska has huge unused hydro power potential, and from that aspect it represents an ideal area for the realization of the project of electricity production in hydroelectric power plants that would be built on the basis of equipment that would be developed and produced by its own technologies. Second: Republika Srpska does not have enough competent human resources to implement the entire project in the Republic of Srpska. Third: The Republic of Serbia has competent human resources, institutions and institutions, and can organically, along with the installation of the necessary organizational mechanism as a partner, stand behind the successful realization of the project of electricity generation based on equipment that would be developed and produced by its own technologies results of the Based on the analysis given in the points: 2. Analysis of the state of the problem, 3. The development of the model, the swot analysis and the research given and published in other projects and scientific research papers [6, 9, 12, 13] can be accepted that all hypotheses Confirmed with high probability using the scientific method of analysis and synthesis and logical conclusion.

5.2. Directions of new research

Research carried out in this paper is of a strategic nature and should serve as a scientific and research logistics to create a scientific and professional climate that it is possible to develop and produce equipment for hydroelectric power plants in the former Yugoslavia that would generate electricity with significantly lower cost price than the situation now. It will be necessary to define a very large number of research projects such as:

1. Development and production of turbines.
3. Development and production of energy electronics and automatics.
5. Development and production of logistics technologies for forward and other systems
In particular, new research has to be research related to investment and investment financing, as well as the organizational mechanism necessary for the successful implementation of the project. A special subject of research must be possible resistance to the launch of a power generation project based on equipment that would be developed and produced by its own technologies. One of the key research projects would be the education of personnel for the needs of the new economic system, which is the result of the production of "New Electricity".

6. CONCLUSION
With this work, in the spirit of scientific knowledge, it is clearly revealed and defined what would be the subject of management and decision-making. It would be a new excellent product "new electricity" as a result of systemic creative thinking. With great reliability, it can be argued that the new electricity will have better performance than the electricity transformation that would be produced in hydropower plants built on the basis of equipping equipment from abroad.

The second and most complex question about change and decision making is to translate the system from the current state of the value into a newly created project. The mechanism of transformation using own technologies for the production of hydroelectric equipment is possible with a huge economic and environmental benefit. However, it is indisputable that many of the resistance and problems will be found along the way of project realization. The research carried out in this paper is sufficient for the competent authorities on the basis of the same to determine in the first step the strategy for the production of electricity in hydropower plants based on equipment developed and produced by internal (own) technologies. By entering this model of electricity generation, in the Republic of Srpska and in other countries in the region, in the second phase, the production capacities of the new technological form should be built. This involves the processing of existing raw materials with the use of new electricity.

It will be possible to build a large number of industrial capacities for primary and secondary wood processing. In addition to this area, new electricity will also be used in agriculture and the food industry. New electricity will be used for heating in households, in this way we will be less dependent on gas imports. The electricity produced in this way can be used for electrically powered vehicles.

REFERENCES


[28] MILOJEVIĆ, A. (2007), Male hidroelektrane,


[34] ZELENIVIČ, D. (2011), Inteligenitalno privređivanje, Promet, Novi Sad, Serbia


[38] Biynis asocijacije ya 21 vijek, Centar za medunarodno privatno preduzetništvo, Sarajevo.


[40] Postkrizni model privrednog rasta i razvoja Srbije 2011 – 2020, USEID i Fond razvoja ekonomskih nauke.

[41] Vodič kroz korpus znanja za upravljanje projektima (PMBOK vodič), Prevod FTN Novi Sad.

[42] Program podrške malim i srednjim preduzećima u Republici Srbiji, Ministarstvo ekonomije i regionalnog razvoja.

[43] Program upravljanja riječnim slivom za BiH. Program Evropske unije.

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HYDRAULIC ANALYSIS OF THE WATER SUPPLY SYSTEM IN TOWN NEVESINJE

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Abstract: The water supply network is an essential part of water supply system. It has a task to provide distribution of necessary quantities of water under appropriate pressure from the source to each consumer while keeping the process cost sensitive. In this paper, a hydraulic design of water supply network of the town of Nevesinje, Bosnia and Herzegovina, have been conducted applying an original and newly developed numerical model for simulation and calculation of pipe networks in steady operating conditions. This model is created in Visual Fortran and is used for simultaneous solving of systems of equations which describe a steady flow in pipe networks, regardless of the number of pipes and nodes. The system of equations is solved by the Newton-Raphson Method. The results obtained by the numerical model have been compared with those obtained by means of the commercial software AFT Fathom 6.0. Based on good matching of the compared results it can be concluded that the developed numerical model is applicable in engineering practice.

Keywords: hydraulic analysis, numerical modelling, optimization, water supply system.

1. INTRODUCTION

In accordance with quantities of water required for water supply and characteristics of a water supply network (material performance, position and operating conditions of network facilities, topographic conditions) it is necessary to carry out a hydraulic network design to provide a sufficient amount of water and pressures to fulfill customer demand. The water supply system has to be modeled and analyzed under the various physical and hydraulic parameters or conditions. The hydraulic analysis serves as an efficient decision-support tool for the management, development and reconstruction of the water supply system. Hydraulic modelling is a technique to represent mathematically the water distribution system using software programs and applications. Regardless of technical or other differences among water supply networks that meet needs of various users, there are also similarities that provide a unique approach to their hydraulic analysis based on creation of a mathematical model [1, 2]. The novel contribution of this paper is in its presentation of results obtained from a newly and originally developed numerical code written in Visual Fortran. This model is developed for a hydraulic analysis of water supply networks in steady conditions, regardless of the number of pipes and nodes. In the first part of the paper, the mathematical model of the flow in water supply networks is presented along with the main methods for their numerical solution. In the second part of the paper, were stated the main characteristics of that part of town’s water supply network for which the analysis had been done and the results obtained by a developed numerical code (in-house software) are compared with those obtained by commercial software AFT Fathom 6.0. for the present state of the part town of Nevesinje water supply system. Based on a very good match between them it is concluded that in-house developed software is applicable in engineering practice.

The mathematical model of water flow in pipe networks is created by applying the basic laws of Fluid Mechanics to network elements, customizing these laws to specific conditions of movement in certain areas of flow and expressing them in the form of algebraic, differential and integral equations. Resulting equations describe idealized flow field at each point at any time. The changes of the flow field described in this way depend on the initial state, boundary conditions and the value of flow parameters. A solution exists but it cannot be found directly. In these cases, some methods providing approximate solutions are used (empirical methods, theoretical and analytical methods and simulation methods [1, 2]). The most commonly used approach is a numerical simulation that provides approximate solutions of equations of mathematical models obtained by the application of numerical methods. The choice of a numerical method depends on the manner of formulation of a mathematical model.

In order to speed up the calculation, reduce the number of unknowns and increase transparency of results, certain rules and assumptions are used to design a mathematical model of pipeline network which ultimately influences the quality of a numerical simulation. Key assumptions introduced in the hydraulic calculation, under which these laws apply, are as follows [2]:

- the flow is steady
- the fluid is incompressible,
all variables (flow, velocity,...) were integrated per cross-section of pipes and replaced by corresponding mean values,
- it is admitted that dominant forces are gravity and friction forces,
- number of drain and water supply spots in the network is large and they are fictively reduced into nodes for reasons of simplification,
- pipes and nodes are the main elements of distribution network,
- the assumption is that cross-sections are constant along the pipe,
- other elements of pipe network (fasteners, pumps, etc...) are usually included in calculation through the pressure loss at the points of their installation i.e. local losses that occur at those locations,
- there are two main variables defining the situation in the network: the pressure at certain points and flow rates through the pipes. Piezometric heads presented mostly in network nodes are used instead of pressures.

The computational model of a network, obtained in this way, should provide a reliable engineering analysis and hydraulic calculation in spite of being significantly simpler than the real distribution network.

1. **MATHEMATICAL MODEL**

Pipe networks are system of complex pipelines containing one or more lines in the form of closed circuits whereas consumers are supplied from the nodes through manifolds and branches. While forming a mathematical and numerical model of pipe network it is usually considered that water consumption along the pipe is concentrated in nodes. Then, considering the assumption that the flow is steady, continuity equation for the pipe provides a trivial result \( Q = \text{const} \). It is commonly assumed that a piezometric head is the same at the ends of all pipes meeting in a node, which eliminates the need to consider the equations for conservation of momentum or energy for nodes. Therefore, only equations of continuity for nodes and energy equation for pipes or conservation equations for momentum are used in the steady flow model of pipe networks [1, 3]. The equation of continuity states that the sum of the flow in each of the nodes is equal to zero.

\[
\sum_{j} \pm Q_{ij} + Q_{ji} = 0
\]  

(1)

where: \( Q_{ij} \) - the flow through the pipe that connects node \( i \) and node \( j \), \( Q_{ji} \) - nodal consumption assigned to the node \( i \), \( n_{i} \) - number of pipes meeting at node \( i \). Equations of continuity can be written for all network nodes. Out of these there are \( i-j \) mutually independent equations where, \( i_{j} \) is a number of nodes with known piezometric heads. Number of equations provided in this way is sufficient for solving problems only in the simplest cases of dendritic pipe networks whereas for looped pipe networks additional equations must be set. In order to form additional equations a second condition is used, i.e. pressure drop (or algebraic sum of all energy losses) per closed contour is equal to zero. This condition arises from the energy (Bernoulli) equation written for the beginning and the end of each pipe. Based on this condition a following equation can be written for each circle [4, 8]:

\[
\sum_{i} \Delta p_{q(i)} = 0
\]  

(2)

The pressure drop through the pipes can be calculated using the expression:

\[
\Delta p = \rho \lambda \frac{t_{y}}{d_{y}^{2}} \frac{v_{y}^{2}}{2}
\]  

(3)

Where, \( v_{y} \) -is the velocity \((\text{m/s})\), \( \rho \)-density\((\text{kg/m}^{3})\), \( \lambda \)-coefficient of friction, \( t_{y} \)-pipe length\((\text{m})\), \( d_{y} \)-diameter of pipe\((\text{mm})\). If velocity is expressed in terms of the flow rate, \( Q = vA \), and piezometric head or head \((H=\rho g z)\) are introduced instead of pressure, the equation for the circular cross-section pipe can be written in the form:

\[
\sum_{i} r_{ij} Q_{q(i)}^{o} - Q_{q(i)}^{o} = 0
\]  

(4)

where, \( r_{ij} \) is the characteristic of the pipe which is equal to,

\[
r_{ij} = \frac{8 \lambda l_{y}}{\pi d_{y}^{2} g}
\]  

(5)

where, \( \pi \)-Ludolph’s number \((\pi=3.14159)\), \( g \)-the constant of gravity.

The equation (4) is used to calculate the energy loss along the section of length \( l_{y} \) because differences in piezometric heads and energy differences are the same within the pipes of a constant cross-section.

\[
\Delta E_{y} = \Delta H_{y}
\]  

(6)

Number of equations formed in this manner is equal to the number of natural loops that not overlap each other. In the cases when there are at least two reservoirs (nodes with known heads), a concept of a pseudo loop is introduced whereas a pseudo loop ends with a single fictive pipe which connects two reservoirs. A pseudo loop might be understood as a usage of the condition that per any path connecting two reservoirs the sum of energy losses is equal to a difference between the levels of these two reservoirs. Number of equations for pseudo loops is equal to \( i_{j} - 1 \), and the total number of equations that can be obtained in this manner is \((i + k_{j} - 1)\) and it is equal to the number of unknown flows in pipes. Number of linear equations is \( i - i_{j} \), and the rest of them are non-linear and can be linearized during the process of solving. For the calculation of a circular network some of iterative methods of calculation are mostly used, which can be obtained by the application of numerical analysis and some numerical techniques for linearization of equations. The most commonly used methods are: the numerical method of minimization, the Hardy-Cross method, the Newton-Raphson method and the linear theory method . The Newton-Raphson method is based on simultaneous solving of \( M \) non-linear equations in the form of
\[ \sum_{j=1}^{n} r_{ij} Q_{ij}^2 = 0 \] where, \( r_{ij} = \frac{8 \lambda l_{ij}}{d_{ij} \pi^2 g} \) and \( N \) linear equations in the form \( \sum_{j=1}^{k} Q_{ij} + Q_{ip} = 0 \) [1, 3].

The newly developed numerical model is created for the hydraulic analysis of the circular pipe network with simultaneous solving of systems of equations describing steady flow in pressurized pipe networks. Software is created in a Visual Fortran numerical code based on a mathematical and numerical model for solving problems of a steady flow in pipe networks and it is applicable to any water supply network regardless of the number of pipes and nodes [14]. The mathematical model of a steady flow has been reached by the application of equations for conservation of mass for nodes and equations for conservation of momentum for pipes and the formation of systems of equations for the observed pipe network. In this manner, a system of non-linear algebraic equations was obtained whose number is equal to the number of unknown piezometric heads in nodes:

\[ \sum_{j} SGN(H_{i} - H_{j}) \left( \frac{H_{i} - H_{j}}{r_{ij}} \right)^{1/2} + Q_{ip} = 0 \] \text{(7)}

For the purpose of linearization (that is solving the system) Newton-Raphson method was applied.

\[ \frac{1}{2} \sum_{i=1}^{n} \frac{H_{i}^{(k+1)} - H_{i}^{(k)}}{r_{ij} Q_{ij}^{(k)}} + Q_{ip} + \frac{1}{2} \sum_{j} Q_{ij}^{(k)} = 0 \] \text{(8)}

A resulting system of equations is solved by the iterative approach applying the method of a successive over-relaxation [2,4].

3. DESCRIPTION OF THE WATER SUPPLY SYSTEM

The distribution network operation analysis was performed on the basis of established hydraulic scheme (fig 1). This scheme was created using the geometry system, connections of nodes, lengths and diameters of sections, objects in the system and their capacity, and distribution to consumers. All data has been taken from the existing scheme of the water supply system of the town of Nevesinje and consumption data available from a local water supply company.

- During the formation of the mathematical model for the pipeline networks, apart from the previously mentioned basic assumptions in application of fundamental equations of Fluid Mechanics, following simplifications are introduced for the real network, [2,4]: Small individual ports along the pipe are not considered individually but the total flow at all junctions along the pipe is divided and assigned to neighboring nodes as "nodal consumption"; local losses at regulating valves, pressure reducers and similar elements that actively influence water distribution must be taken into consideration; available pipes of a smaller diameter with the known consumption are excluded and their flows are added to the nodal consumption of the node;

This schematic overview presents all real elements of the water supply system (reservoirs, pump stations, pipelines), and the resulting model comprises the following:

- 32 nodes defined by name, label, terrain elevation and consumption.
- 45 sections defined by name, diameter, length and type of material.
- 1 reservoir determined by the bottom elevation, spillway elevation, elevation of the feeder pipeline, shape etc.

In determination of the total consumption, the water losses in the system that could not be accurately determined, because of lack of data, have been taken into consideration as well. Total specific consumption by the population is adopted to be 210 l/s/day. Average daily consumption is determined based on the billing information obtained from the local water supply company and according to the number of consumers. The overall average household and industry consumption is \( Q_{av} = 38.83 \text{ l/s}. \) Seasonal fluctuations in consumption and daily variations were determined based on available data and a daily coefficient of non-regularity was adopted [4]: for household \( k_{dn} = 1.35, \) for industry \( k_{dn} = 0.75. \) Maximum daily consumption is determined based on average daily consumption and adopted daily coefficients of non-regularity i.e. \( Q_{max,d} = 27.75*1.35 + 11.08*0.75 = 45.77 \text{ l/s}. \) Daily oscillations of consumption are presented by hourly coefficient of non-regularity. For households it is \( k_{max,h} R_{min} = 1.80/0.24, \) and for industry \( k_{max,h} R_{min} = 1.35/0.70. \) Maximum hourly consumption is \( Q_{max,h} = 37.46*1.8 + 8.31*1.35 = 78.646 \text{ l/s}. \) They are relevant for design of distribution network [4]. Spatial distribution of consumption per node was conducted in order to carry out the analysis of the system operation.

4. RESULTS AND DISCUSSION

In this section a comparison of results obtained from the developed numerical model (in-house software) and commercial software for the current condition of the water supply system is given. Firstly, a hydraulic analysis of the present situation has been carried out. On the basis of these results the reconstruction of the system has been suggested. The schematic view of the water supply network of the town of Nevesinje with the applied numerical model is given in Fig. 1 and it presents geometrical characteristics of the pipes and elevations of all nodes. The scheme has been made in commercial software AFT Fathom 6.0 [6].
Absolute roughness of asbestos-cement pipes that compose the whole distribution network is 0.06 mm and a flow rate of some nodes is shown in Table 1. Reference node is a node 1 and computational parameters used in all calculation are: coefficient of over-relaxation $\omega = 1.85$ and allowed difference between two consecutive iterations is 0.001. Table 1. and Table 2. present results of calculation of the urban water supply network of the part town of Nevesinje in its current state by applying in-house software and corresponding results obtained using the commercial software AFT Fathom.

The flow rate of the reference node is, $Q = 78.417$ l/s for in-house software and $Q = 78.110$ l/s for AFT Fathom.

Results of the hydraulic analysis of the current system condition showed that the water supply system of the town of Nevesinje has numerous shortcomings. The calculation of the network in the reconstructed state has been made based on the proposal for the reconstruction of the water supply network and it proved that the water supply network would be able to meet the requirements of the town with respect to the pressure and quantities of water needed.

The obtained results show that the planned reconstruction would provide the elimination of the identified deficiencies in the network. Results of the calculation of the network obtained using a developed numerical model are in a good agreement with those obtained using commercial software AFT Fathom 6.0. The differences between the obtained values are within tolerable limits and range from 0.0 to 0.1 m/s. The main advantages of using the developed numerical model (in-house software) are the possibility of access to the source code. This enables a user to carry out changes in a program, to adapt, expand and upgrade the program according to his own needs. Unlike the applied commercial software, that has a good graphic platform and allows the user to communicate with the program in an interactive way through appropriate dialogue boxes, the developed numerical model is fairly simple. The data have been entered as well as the results obtained by processing the data are in a written form and currently there is no possibility of graphic display. Precisely, the access to the source code would allow for deficiencies to be eliminated in the future by upgrading the existing program, as well as the precision of the results to be improved if it is necessary. On the basis of the obtained results and a good agreement with those obtained by using the commercial software, it can be concluded that the developed numerical model can be successfully applied in the engineering practice.
Table 1: Results of calculation of the water supply
network using the developed numerical code and
commercial software AFT Fathom 6.0. for the pipes
Results given Results given
by in-house by
AFT
software
Fathom 6.0.

Input data
Pipe
fromto
1-2
2-3
3-4
5-4
6-5
7-6
8-7
8-5
1-8
8-3
4-11
11-10
10-25
9-10
5-9
11-12
12-13
13-14
14-15
15-16
17-16
2-17
2-13
25-24
12-24
14-22
22-21
15-21
21-20
20-19
16-19
16-18
19-18
22-26
27-26
20-27
28-27
19-28
27-29
24-23
23-22
23-29
6-32
25-31
29-30

L(m)

Dh
(mm)

Q
(l/s)

v
(m/s)

Q(l/s)

v
(m/s)

3800.0
390.0
115.0
105.0
75.0
150.0
100.0
160.0
4650.0
100.0
70.0
75.0
45.0
50.0
55.0
85.0
120.0
50.0
50.0
65.0
85.0
135.0
100.0
50.0
55.0
50.0
80.0
50.0
40.0
170.0
155.0
225.0
190.0
100.0
40.0
100.0
155.0
50.0
145.0
50.0
125.0
190.0
30.0
30.0
30.0

200.0
150.0
150.0
150.0
150.0
150.0
80.0
150.0
250.0
80.0
150.0
100.0
150.0
150.0
150.0
125.0
125.0
150.0
150.0
150.0
80.0
100.0
150.0
80.0
80.0
80.0
80.0
150.0
150.0
150.0
150.0
80.0
80.0
80.0
80.0
80.0
80.0
80.0
80.0
150.0
150.0
80.0
150.0
150.0
80.0

31.65
2.36
6.15
9.24
0.61
5.08
7.08
29.77
46.77
7.35
13.78
1.35
11.21
13.80
16.16
9.67
2.64
21.79
16.56
5.44
3.93
6.45
21.52
6.06
4.83
3.22
1.14
9.11
7.78
1.80
5.60
1.31
1.03
3.42
0.53
3.02
1.34
3.38
1.45
8.74
3.44
2.84
2.33
2.24
2.14

1.01
0.13
0.35
0.52
0.04
0.29
1.41
1.69
0.95
1.46
0.76
0.17
0.64
0.78
0.92
0.79
0.22
1.23
0.94
0.31
0.78
0.82
1.22
1.21
0.96
0.64
0.23
0.52
0.44
0.10
0.32
0.26
0.21
0.68
0.11
0.60
0.27
0.67
0.29
0.50
0.20
0.57
0.13
0.13
0.43

31.53
2.35
6.12
9.20
0.61
5.07
7.06
29.68
46.58
7.33
13.32
1.35
11.19
13.76
16.11
9.62
2.62
21.74
16.53
5.43
3.92
6.43
21.46
6.05
4.82
3.21
1.13
9.09
7.77
1.81
5.59
1.31
1.04
3.42
0.53
3.02
1.34
3.38
1.45
8.72
3.44
2.84
2.32
2.23
2.14

1.01
0.14
0.35
0.52
0.04
0.29
1.40
1.68
0.95
1.46
0.76
0.17
0.64
0.78
0.91
0.79
0.22
1.23
0.94
0.31
0.78
0.82
1.21
1.21
0.96
0.64
0.22
0.51
0.44
0.10
0.32
0.26
0.21
0.68
0.11
0.60
0.27
0.67
0.29
0.49
0.19
0.56
0.13
0.13
0.43

Table 2: Results of calculation of the water supply etwork
using the developed numerical code and commercial
software AFT Fathom 6.0. for nodes

Input data

Results given by Results given by
in-house
AFT
Fathom
software
6.0.

Vol.Flo
Elevatio
w Rate
Head
n Inlet
Node
Jct Net
(m)
(m)
(l/s)
reserv
-78.11 940.0 940.0
oir
1
1.29
894.4 922.2
2
3.50
893.0 922.2
3
2.00
896.5 922.1
4
4.90
890.5 922.3
5
2.14
887.0 922.3
6
1.99
902.3 922.4
7
2.52
899.0 925.1
8
2.35
890.0 921.9
9
3.92
890.5 921.8
10
2.35
890.0 921.8
11
2.19
894.0 921.3
12
2.35
895.0 921.3
13
2.00
895.5 920.8
14
2.00
893.0 920.5
15
2.45
900.0 921.4
16
2.51
901.0 920.2
17
2.34
899.4 920.2
18
2.99
900.0 920.3
19
2.95
897.5 920.4
20
2.45
899.4 920.4
21
2.10
898.0 920.5
22
2.45
895.5 920.5
23
2.14
894.4 920.6
24
2.91
890.5 921.6
25
3.95
897.8 919.8
26
2.37
898.9 919.8
27
2.04
899.5 919.9
28
2.15
900.0 919.6
29
2.14
899.0 919.5
30
2.23
887.0 921.6
31
2.32
900.0 922.3
32
0.00
900.0 922.3
33
0.00
887.0 921.7
34
0.00
899.0 919.5

Head
Pressur
Inlet
e (bar)
(m)

P Static
Out
(bar)

0.00

940.0

1.01

2.73
2.86
2.51
3.12
3.46
1.97
2.56
3.14
3.07
3.12
2.68
2.58
2.48
2.70
2.01
1.98
2.04
1.99
2.24
2.06
2.21
2.50
2.57
3.05
2.16
2.05
2.01
1.92
2.01
3.40
2.18
2.18
3.40
2.013

922.4
922.3
922.2
922.4
922.5
922.5
925.1
922.1
921.9
922.0
921.5
921.4
921.0
920.7
920.7
921.4
920.4
920.5
920.6
920.6
920.7
920.7
920.8
921.8
920.0
920.0
920.2
919.8
919.7
921.8
922.5
922.5
921.8
919.7

3.76
3.89
3.54
4.14
4.49
2.99
3.58
4.16
4.09
4.15
3.71
3.60
3.51
3.73
3.04
3.01
3.07
3.03
3.27
3.09
3.24
3.49
3.59
4.08
3.19
3.08
3.04
2.95
3.04
4.43
3.21
3.21
4.43
3.04

441


5. CONCLUSION

This paper presents the results of the hydraulic analysis of the water supply network of the town of Nevesinje, Bosnia and Herzegovina, achieved by applying the newly developed numerical model for simulation and calculation of circular water pipeline networks in steady operating conditions. Calculations have been first made for the present system state. The obtained results revealed that the water supply network has many shortcomings and that some parts that do not meet consumers’ needs require reconstruction and optimization. The proposal for the reconstruction has been made and new calculations for the modified network state have been carried out demonstrating that the suggested state of the system significantly improves network characteristics and quality of water supply. Verification of the results obtained by the developed numerical model has been carried out by comparison with results obtained by application of commercial software "AFT Fathom 6.0. Based on good matching between two models it is concluded that the developed numerical del can be successfully applied in engineering practice.

REFERENCES


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SIMPLIFIED EQUILIBRIUM MODEL FOR BIOMASS AND WASTE GASIFICATION

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Filip KOKALJ
Aleksandar JOVOVIĆ
Niko SAMEC

Abstract: Gasification of waste with synthetic gas production is an alternative to conventional waste to energy process based on incineration. Depending on predicted composition and quality of synthetic gas (calorific value, supporting process heat/fuel needed) preparation of waste derived fuel or study of process parameters is possible. Because of waste composition diversity there is not enough experimental results for gasification available and synthetic gas composition prediction models are often used to estimate which waste fractions are suitable for gasification.

A simplified thermodynamic equilibrium based prediction model for different waste composition gasification has been developed. A stand-alone computer application of the mathematical models has been developed. Standard numerical methods have been implemented for solving the mathematical problem formulation. Limits set by legislation for implementation of waste gasification technology have been also considered. Model predicted results have been compared with published results for the biomass and some waste types - municipal solid wastes and refuse derived fuels. Accuracy of model predictions and experimental results has been evaluated. Results obtained by stoichiometric model have been presented for most cases of practical use offering main information about produced synthetic gas quality from different kind of waste.

Key words: Biomass, Waste, Gasification, Equilibrium model, Waste – to - Energy

1. INTRODUCTION

The aim of this work is to show that simple equilibrium model is a good enough for prediction of waste gasification process and gasification products for most full scale applications. In the lack of large number of experiment results for waste gasification many authors use equilibrium models also for biomass gasification, as shown by [1], [2], [3]. In literature there are two basic approaches for equilibrium gasification model: stoichiometric and nonstoichiometric or Gibbs energy minimization approach. The last one gives the possibility to include more synthetic gas species into consideration, is more suitable to consider higher process pressures (real gas properties instead of ideal gas) but one is faced with more complex system of nonlinear equations that has to be solved together with much bigger solver convergence stability problems.

Many of waste gasification reactors are operating at or about at the atmospheric pressure as well with air as oxidation agent– fluidized bed reactor, updraft and downdraft reactor except of the entrained flow reactor which does not operate at atmospheric pressure and is generally suitable only for fine particle wastes (wood sawdust or sewage sludge) [4].

Mathematical prediction of gasification end products is very useful because it helps to find conditions for the elimination of tar and soot from synthetic gas. Authors [5] showed that exergetic efficiency is nearby the carbon deposition optimum point.

Industrial Emissions Directive EC 2010/75 [6] covers also gasification of waste. It is requested by that Directive that gasified waste should be handled at least 850°C for 2 s and in case of hazardous waste at 1100°C. At such conditions it could be considered that thermodynamic equilibrium will occur.

Some authors showed that in case of stoichiometric equilibrium model predictions methane is underestimated and carbon monoxide is estimated too optimistic, so the mathematical model should include some form of calibration possibility to overcome this weakness. Because of all above mentioned it was decided to develop simple stoichiometric equilibrium model for gasification of waste.

2. GASIFICATION MODEL

A stoichiometric equilibrium gasification model has been developed for modeling process conditions with remaining solid phase – solid carbon – at and below carbon boundary point (CBP) and without solid carbon deposition – above CBP. Air, oxygen or oxygen enriched air can be considered as oxidation agent in the model. Model is based on presumption that all process conditions of the system are steady state. Temperature and pressure are uniform across the observed system. Temperature is high enough and process time is long enough that
thermodynamic equilibrium of the system is achieved. The presumption of an adiabatic system is also fulfilled. Nitrogen and ashes do not participate in chemical reactions. Presence of sulfur is regarded as not high enough to influence the reaction and is accounted as ash. Model is supposed to be valid for gasification temperatures between 800°C and 1200°C and gasification pressure at the level of atmospheric pressure. All gases are regarded as ideal gases. Higher hydrocarbon gases are neglected, only H₂, CO, CO₂, H₂O, CH₄, N₂ and solid carbon as gasification products are taken into account. Primary oxidation reactions are regarded as fast and completely finished.

2.1. Modeling thermodynamic properties of predict species

Specific heats of formation hᵢ₀ and specific Gibbs energies gᵢ₀ of species at standard pressure are obtained by [7]. Polynomial correlations for species temperature dependency of specific heat capacity have been implemented, because it has been more suitable for numerical formulation of the model. The temperature dependency of gases heat capacity is calculated according Equation (1), where c_pᵢ is the specific heat capacity of a gas species, T is absolute temperature in Kelvin, c_pᵦ are correlation coefficients as obtained by [7].

\[
c_{pᵢ} = \sum_{j=1}^{d} c_{pᵦj} T^{(i-1)}
\] (1)

Equation (2) shows the correlation for specific heat capacity of solid carbon – graphite, where, c_pᵛ are correlation coefficients obtained by [8].

\[
c_{pᵛ} = c_{pᵛ₁} + c_{pᵛ₂} T - c_{pᵛ₃} T^{-3}
\] (2)

2.2. Mathematical formulation of the model

Mathematical formulation of the model relays on three sets of equations: mass balance, energy balance and thermodynamic equilibrium of representative chemical reactions. Equation (3) represents summarized reaction of gasification, where νᵢ are the stoichiometric coefficients of reactants and νᵢ’’ the stoichiometric coefficients of gasification process products, νᵢ₄ is the coefficient for moisture, νᵢ₂ for water steam, νᵢ₁ for air and νᵢ₈₂ for pure oxygen.

\[
CH₄ + H₂O → CO + 3H₂
\] (3)

Equation (4) represents the relation between supplied air νₖ in the summarized reaction of gasification in connection to equivalence ratio (ER) and hydrocarbon composition of dry ash free waste.

\[
νₖ = ER(1 + 0.25α - 0.25β)
\] (4)

Mass balance

Equation (5) is presenting mass balance for carbon, hydrogen, oxygen and nitrogen, where [bₓₓ], [bᵧᵧ], [bᵦᵦ], [bₙₙ] are composition matrixes of oxidizing agent air, pure oxygen and water steam, presented respectively.

\[
[aₓₓ] = [bₓₓ] + [bᵧᵧ] + [bᵦᵦ] + [bₙₙ]
\] (5)

\[
[bₓₓ] = \begin{bmatrix}
  0 & 1 & 1 & 0 & 1 & 0 & 1 \\
  2 & 0 & 0 & 2 & 4 & 0 & 0 \\
  0 & 1 & 2 & 1 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\] (6)

\[
[bᵧᵧ] = \begin{bmatrix}
  1. & (α + 2ν₈₁) & (β + ν₈₂) & 0.5ν₇₂
\end{bmatrix}
\] (7)

\[
[bᵦᵦ] = \begin{bmatrix}
  0 & 0 & 2ν₈₁ & 3.76ν₈₂
\end{bmatrix}
\] (8)

\[
[bₙₙ] = \begin{bmatrix}
  0 & 0 & 2ν₈₁ & 2ν₈₂ & 0 & 0 & 0
\end{bmatrix}
\] (9)

\[
[bᵦᵦ] = \begin{bmatrix}
  0 & 0 & 2ν₈₁ & ν₈₂ & 0 & 0 & 0
\end{bmatrix}
\] (10)

\[
[bₙₙ] = \begin{bmatrix}
  ν₇₂ & ν₇₁ & ν₇₁ & ν₇₁ & ν₇₁ & ν₇₁ & ν₇₁
\end{bmatrix}
\] (11)

Thermodynamic equilibrium of representative chemical reactions

Because of different representative chemical reactions for gasification conditions at, above or below CBP the sets of thermodynamic equilibrium equations are different. Below and at CBP gasification process is described by methane decomposition reaction (12) and equation (15), water gas shift reaction (13) and equation (16) and heterogeneous water gas shift reaction (14), equation (17).

\[
CH₄ + H₂O ↔ CO + 3H₂
\] (12)

\[
CO + H₂O → CO₂ + H₂
\] (13)

\[
C(s) + H₂O ↔ CO + H₂
\] (14)

\[
f₁ = ψ₁ψ₂ - tₕψ₁ψ₄ψ₅ = 0
\] (15)

\[
f₂ = ψ₂ψ₃ - tₕψ₂ψ₄ψ₆ = 0
\] (16)

\[
f₃ = ψ₃ψ₄ - tₕψ₃ψ₅ψ₆ = 0
\] (17)

\[
ψᵢ = \frac{vᵢ}{∑_{j=1}^{d} vᵢ’’}
\] (18)

where ψᵢ is mole fraction of component in gas phase, tₕ is temperature and pressure dependent equilibrium constant of partial chemical reaction, tₕ is the reflecting overestimation of methane predicting, while t₁₂ is the reflecting overestimation of carbon oxide.
The above CBP gasification process is described by water gas shift reaction (13) and equation (16) and methane reaction (19) and equation (20).

\[
C(s) + 2H_2 \leftrightarrow CH_4
\]  
(19)

\[ f_e = \psi_e - t_e K_e v_e^2 = 0 \]  
(20)

Equation (21) is presenting the temperature dependency of equilibrium constant at standard pressure,

\[
\ln K_T (T) = \frac{-\Delta G_f^0}{R_m T}
\]  
(21)

where \( R_m \) is universal gas constant, \( \Delta G_f^0 \) is total Gibbs energy of the system for the observed partial gasification reaction given by Equation (22).

\[
\Delta G_f^0 = \sum_{j} \psi_j \Delta H_{f,j}^0 + \sum_{j} \psi_j \Delta H_{f,j}^0 \ln \left( \frac{v_j - v_{j-1}}{v_{j+1} - v_j} \right)
\]  
(22)

\[
H_R = H_{f,p}^0 + v_{f1} h_{f1}^0 + v_{f2} \left( h_{f2}^0 + \int c_{p2} dT \right) + v_{f3} \left( 3.76 c_{p6} + c_{p8} \right) dT + v_{f4} \int c_{p4} dT
\]  
(23)

Equation (26) represents the equation for calculation of the enthalpy of the produced syngas, where \( h_{f,j}^0 \) are standard heats of formation for gaseous species.

\[
H_p = v_{f1} h_{f1}^0 + v_{f2} h_{f2}^0 + v_{f3} h_{f3}^0 + \sum_{j=2}^{7} v_{fj} h_{fj}^0 + \sum_{j=2}^{7} v_{fj} c_{p,j} dT
\]  
(26)

### 2.3. Numerical formulation of the model

For solving the system of equations numerical methods have been implemented including Newton Raphson for system of nonlinear equations according equations (27) and (28).

\[
\begin{bmatrix}
\psi_2(k+1) \\
\psi_5(k+1) \\
\psi_7(k+1)
\end{bmatrix} =
\begin{bmatrix}
f_2(k) \\
f_5(k) \\
f_7(k)
\end{bmatrix}
\]  
(27)

\[
\begin{align}
\psi_2(k+1) &= \psi_2(k) + \Delta \psi_2 \\
\psi_5(k+1) &= \psi_5(k) + \Delta \psi_5 \\
v_7(k+1) &= v_7(k) + \Delta v_7
\end{align}
\]  
(28)

For better convergence initial guess has been set according equations (29), (30) and (31).
determine higher cold gas efficiency for the predicted value than that of the experiments.

Zainal [3] developed stoichiometric equilibrium gasification model for biomass gasification. Heat losses of gasifier were not considered and included in his model. Air gasification model and experimental results of wood with 20% water content at 800°C were compared. Results show that $H_2$ (21.06 vol. % vs. 15.23 vol. %) and $H_2$-CO (40.67 vol. % vs. 38.27 vol. %) calculation of the model is higher than the experiment results. CO (19.61 vol. % vs. 23.04 vol. %) and CO$_2$ (12.01 vol. % vs. 16.42 vol. %) calculation values are lower than experimental results. CH$_4$ (0.64 vol. % vs. 1.58 vol. %) is quite negligible and CV (4.72 MJ/Nm$^3$ vs. 4.85 MJ/Nm$^3$) calculated and experimental values are quite close to each other.

Jayah [10] made experimental test and stated that heat losses for updraft fixed bed reactor is between 5% and 15% of feedstock HHV.

### 3.1. Model validation and simulation with wood

There are published results of other models developed for gasification of biomass – wood (cashew nut) which have also been used for the validation of this model. The CHO syngas system analysis has yield that gasification is taking part abowe the CDP, so solid carbon is not considered in prediction.

Table 1 presents validation data for 4 runs: run R1 is experimental for downdraft lab-scale gasifier as presented in reference [10], runs R2 and R3 are reference non-calibrated and calibrated models predictions by [2], while run R4 is calibrated prediction by this model. As the gasification temperature has been maintained at level of experimental run R1, the ER value for runs of this model calibrated prediction comply better with experiment then reference model. RMS is within 2% what is compared to [11] negligible when taking into account real circumstances (untight gasifier, introduction of air with feedstock stream). As in the reference model gasifier heat losses were not presented, this model has considered it by 5% of fuel LHV. Preserved energy suited good to experiment, specially LHV for this model and RMS for syngas composition. For reference non-calibrated model methane prediction is under estimated and originated from model non considered chemical kinetics. In runs of calibrated models (reference and this model) also carbon-monoxide estimation is calibrated to get results closer to reference experiment.

<table>
<thead>
<tr>
<th>Ultimate analysis [wt. %, daf]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>50.6</td>
</tr>
</tbody>
</table>

Table 2 Dry basis synthetic gas composition (vol.%), equivalence ratio (-), gasification temperature (°C), low heating value (MJ/Nm$^3$), dry base synthetic gas yield (Nm$^3$/kg) for wood gasification

<table>
<thead>
<tr>
<th>run</th>
<th>$H_2$ [vol. %]</th>
<th>$CO$ [vol. %]</th>
<th>$CO_2$ [vol. %]</th>
<th>CH$_4$ [vol. %]</th>
<th>ER [-]</th>
<th>$T$ [°C]</th>
<th>LHV [MJ/Nm$^3$]</th>
<th>V [Nm$^3$/kg$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 [10]</td>
<td>17.0</td>
<td>18.4</td>
<td>10.6</td>
<td>1.3</td>
<td>0.36</td>
<td>827</td>
<td>4.23</td>
<td>2.56</td>
</tr>
<tr>
<td>R2 [2]</td>
<td>18.0</td>
<td>17.9</td>
<td>11.8</td>
<td>0.1</td>
<td>0.49</td>
<td>827</td>
<td>3.57</td>
<td>2.66</td>
</tr>
<tr>
<td>R3 [2]</td>
<td>18.0</td>
<td>17.9</td>
<td>12.1</td>
<td>1.1</td>
<td>0.47</td>
<td>827</td>
<td>3.72</td>
<td>2.56</td>
</tr>
<tr>
<td>R4</td>
<td>16.7</td>
<td>19.3</td>
<td>11.4</td>
<td>1.3</td>
<td>0.40</td>
<td>827</td>
<td>3.99</td>
<td>2.95</td>
</tr>
</tbody>
</table>

### 3.2. Model simulation with municipal solid waste

Reference modeled results for downdraft fixed bed gasifier by [2] have been compared with this model prediction. As presented in Table 5 this model – run R6 (calibrated) has been compared to reference model run R5. Both predictions suit very well except by predicting gasification temperature.

Table 3 Ultimate analysis of referent fuels – MSW [2]

<table>
<thead>
<tr>
<th>Ultimate analysis [wt. %, daf]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>51.0</td>
</tr>
</tbody>
</table>

Table 4 Fraction composition of MSW (wt%) [2]

<table>
<thead>
<tr>
<th>paper</th>
<th>vinyl, plastics</th>
<th>wood</th>
<th>bio-waste</th>
<th>non-combustable</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.8</td>
<td>17.3</td>
<td>4.0</td>
<td>54.2</td>
<td>11.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 5 Dry basis synthetic gas composition (vol.%), equivalence ratio (-), gasification temperature (°C), low heating value (MJ/Nm$^3$) for municipal solid waste gasification

<table>
<thead>
<tr>
<th>run</th>
<th>$H_2$ [vol. %]</th>
<th>$CO$ [vol. %]</th>
<th>$CO_2$ [vol. %]</th>
<th>CH$_4$ [vol. %]</th>
<th>ER [-]</th>
<th>$T$ [°C]</th>
<th>LHV [MJ/Nm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5 [2]</td>
<td>16.0</td>
<td>25.0</td>
<td>6.0</td>
<td>0.1</td>
<td>0.40</td>
<td>1100</td>
<td>3.08</td>
</tr>
<tr>
<td>R6</td>
<td>16.1</td>
<td>25.2</td>
<td>6.0</td>
<td>0.0</td>
<td>0.40</td>
<td>1062</td>
<td>3.05</td>
</tr>
</tbody>
</table>
3.3. Model simulation with RDF

RDF model calculation results have been compared with our model calculations.

Table 6 Ultimate analysis of referent fuels (wt%)

<table>
<thead>
<tr>
<th>run</th>
<th>name</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8[12]</td>
<td>PE-12</td>
<td>85.0</td>
<td>13.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>R10</td>
<td>GS3-5</td>
<td>84.4</td>
<td>14.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>R12</td>
<td>N4</td>
<td>68.1</td>
<td>10.2</td>
<td>14.3</td>
<td>0.0</td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 7 presents data for experimental runs for derived fuel gasification to be compared with this model. Gasification results by [12] of runs R8, R10 and R12 are compared respectively with this model prediction runs R9, R11 and R13. Original runs have been performed with air as oxidizing agent at pilot scale bubbling fluidized bed gasifier. RDF originated from MSW and household packaging waste with low moisture content. While syngas yield data was not presented it could not be compared with model. Due absence of higher hydrocarbons in model this share of carbon converted was considered in methane and LHV has been lower than estimated in experiment by RMS 10% to 25%. In two out of three runs, the composition RMS is quite well calculated with accuracy 3 to 7%.

Table 7 Dry basis synthetic gas composition (vol.%), equivalence ratio (-), gasification temperature (°C), synthetic gas low heating value (MJ/Nm³), dry base synthetic gas yield (Nm³/kg, for RDF gasification)

<table>
<thead>
<tr>
<th>run</th>
<th>H₂ [vol. %]</th>
<th>CO [vol. %]</th>
<th>CO₂ [vol. %]</th>
<th>CH₄ [vol. %]</th>
<th>C₅H₈ [vol. %]</th>
<th>ER [-]</th>
<th>w [wt.%]</th>
<th>T [°C]</th>
<th>LHV [MJ/Nm³]</th>
<th>V [Nm³/kg⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8[12]</td>
<td>27.1</td>
<td>20.1</td>
<td>2.1</td>
<td>0.5</td>
<td>0.28</td>
<td>1.3</td>
<td>816</td>
<td>6.50</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>R9</td>
<td>24.3</td>
<td>25.8</td>
<td>0.4</td>
<td>0.2</td>
<td>-</td>
<td>0.34</td>
<td>817</td>
<td>5.86</td>
<td>6.12</td>
<td></td>
</tr>
<tr>
<td>R10[12]</td>
<td>29.5</td>
<td>19.9</td>
<td>1.7</td>
<td>0.7</td>
<td>0.24</td>
<td>1.0</td>
<td>829</td>
<td>7.00</td>
<td>5.14</td>
<td></td>
</tr>
<tr>
<td>R11</td>
<td>24.4</td>
<td>24.8</td>
<td>0.6</td>
<td>0.2</td>
<td>-</td>
<td>0.35</td>
<td>827</td>
<td>5.79</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>R12[12]</td>
<td>6.8</td>
<td>3.7</td>
<td>11.1</td>
<td>7.3</td>
<td>4.8</td>
<td>0.22</td>
<td>6.7</td>
<td>869</td>
<td>6.80</td>
<td></td>
</tr>
<tr>
<td>R13</td>
<td>22.6</td>
<td>24.4</td>
<td>2.6</td>
<td>0.1</td>
<td>-</td>
<td>0.36</td>
<td>6.7</td>
<td>868</td>
<td>5.32</td>
<td>2.35</td>
</tr>
</tbody>
</table>

3.4. Model simulation with plastics

Table 9 presents data for experimental run R14 for waste plastics material gasification by [13] to be compared with this model prediction run R15. Original run have been performed with air as oxidizing agent preheated at 448°C at pilot scale bubbling fluidized bed gasifier with special bed material named olivine, which is acting also as bed catalyst for tar cracking reactions. Experimental data show presence of solid carbon in syngas at 0.1 gC/kgₐₙₑₙ, while model prediction is 0.6 gC/kgₐₙₑₙ – it could be accounted to bed material tar cracking reaction for experimental run. Due absence of higher hydrocarbons in model this share of carbon converted was considered in higher carbon monoxide and carbon dioxide presence, while LHV and syngas yield is similar estimated in model prediction as in experiment by RMS 10% to 25%.

Table 8 Ultimate analysis of referent fuels (wt%)

<table>
<thead>
<tr>
<th>run</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>R14[13]</td>
<td>79.5</td>
<td>13.1</td>
<td>4.5</td>
<td>0.2</td>
<td>0.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 9 Dry basis synthetic gas composition (vol.%), equivalence ratio (-), gasification temperature (°C), synthetic gas low heating value (MJ/Nm³), dry base synthetic gas yield (Nm³/kg) for waste plastics gasification

<table>
<thead>
<tr>
<th>run</th>
<th>H₂ [vol. %]</th>
<th>CO [vol. %]</th>
<th>CO₂ [vol. %]</th>
<th>CH₄ [vol. %]</th>
<th>C₅H₈ [vol. %]</th>
<th>ER [-]</th>
<th>w [wt.%]</th>
<th>T [°C]</th>
<th>LHV [MJ/Nm³]</th>
<th>V [Nm³/kg⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R14</td>
<td>8.4</td>
<td>5.2</td>
<td>9.6</td>
<td>7.1</td>
<td>5.9</td>
<td>0.21</td>
<td>0.7</td>
<td>810</td>
<td>9.40</td>
<td>3.4</td>
</tr>
<tr>
<td>R15</td>
<td>24.8</td>
<td>14.4</td>
<td>4.6</td>
<td>0.4</td>
<td>-</td>
<td>0.21</td>
<td>0.7</td>
<td>800</td>
<td>9.39</td>
<td>3.2</td>
</tr>
</tbody>
</table>
4. CONCLUSION

Simple gasification model is accurate enough for computing process parameter trends and the study of gasification process settings since:

- majority of waste is capable of the gasification at atmospheric pressure - it means that an atmospheric gasification reactor is used (various kind) because of its physical structure and generally bigger particle size.
- only part of waste is capable of gasification and technology runs at elevated process pressure. Entrained flow gasifier is used because parts have to be of the very fine structure – sewage sludge, fine shredded waste, waste biomass pellets.

For the majority of the gasifiers this simple model can be used because of good accuracy that is verified by experimental results and compared with nonstoichiometric model. It is useful tool for process parameter study and selecting the mixture of wastes gasified.

Some waste composition elements and synthetic gas end-product components that are not included in the model are of low concentration. This study also shows that they have no significant impact on the heating value of waste neither on the heating value of produced synthetic gas.

REFERENCES


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ANALYSIS COMBUSTION LIGNITE OF GACKO IN THE STEAM BOILER P - 64

Borivoje VUJIĆ
Ženja VUJOVIĆ

Abstract: Process of production of electric energy in thermal power plant Gacko has begun in 1983 year. Basic fuel is from surface pit Gacko. Power on threshold of thermal power plant is exclusively in function of disposable fuel. Characteristics of Gacko lignite are variable, so that process and conditions for its combustion are different. Coal deposit is in multiple layers (two surface, main layer, and two floor layers). Exploitation of coal from the above mentioned layers and its burning by technology – burning in flight, causes significant changes in firebox itself and combustion products are cubically different.

Because of great stadalstill and untimely detection of the main layer, thermal power plant is constrained to use only lignite from immediate roof zone (shallowest layer). Lignite from immediate roof zone is rich in great amount of silicon, light metals and clay, which significantly slow down speed of combustion and latently consume released heat for evaporation of trapped moisture, as well as for transformation of incombustible material and compound of new oxides. As a consequence is oscillation of disposable power on treshold of thermal power plant, and which most frequently departs from expected.

Key words: combustion, combustion products lignite, steam boiler, firebox

ANALIZA SAGORJEVANJE GATAČKOG LIGNITA U PARNOM KOTLU P-64


Key words: sagorjevanje, produkti sagorjevanja, parni kotao, ložište

1. INTRODUCTION


TE Gacko radi u jedinstvenom elektroenergetskom sistemu RS u mješovitom holdingu Elektroprivreda RS ( MH ERS).

Glavna oprema Rudnika i TE Gacko isporučena je uglavnom iz bivšeg Sovjetskog Saveza i montirana u periodu 1977-1983. godine. Mašinsko-tehnološki dio Termoelektrane "Gacko" čini kondenzaciono-oduzimni blok sa povratnim zatvorenim sistemom hlađenja, projektno instalirane snage 300 MW i raspoložive snage na pragu TE od 276 MW, kompletno sa

2. TOPLOTNA ŠEMA BLOKA 300 MW

Tehnološki proces termoelektrane sastoji se u postepenom pretvaranju hemijske energije sagorijevanja goriva u toplostnu i električnu energiju. Radno tijelo (nosilac toplote) u procesu proizvodnje energije u termoelektrani je voda i vodena para. Gorivo sagorijeva u kotlu i predaje toplotu vodi, voda se pretvara u vodenu paru koja se dodatno pregrijava na račun čega se povećava njena potencijalna energija. Prolazeći kroz protočni dio turbine, para se širi, potencijalna energija...
pare pretvara se u kinetičku a kinetička u mehaničku energiju obrtanja rotora. U generatoru se mehanička energija parne turbine pretvara u električnu.

3. SISTEM UGLJENE PRAŠINE

Kotao P-64 je opremljen sa 8 individualnih zatvorenih sistema ugljene prašine sa direktnim uduvavanjem. Sistem ugljene prašine se sastoji od:
1. bunkera sirovog uglja,
2. kombinovanog dozatora-transportera sirovog uglja,
3. usisnog kanala (sa GZO)
4. ventilacionog mlina tipa S 40.50
5. inercionog separatora
6. kanala ugljene prašine, vrložnika i gorionika
7. šibera, klapi i druge stop i regulacione armature.

Princip rada sistema ugljene prašine je sledeći:
Ugalj u potrebnoj količini i sa granulacijom manjom od 40 mm dodaje se u usisni kanal pomoću dozatora i transportera. Pomoću ventilacionog mlina dimni gasovi se sa temperaturom koja odgovara opterećenju kotla (500 - 1000°C) usisavaju u šahtu za uzimanje gasova (GZO). Pri padanju ugalja predaje vlagu dimnim gasovima, hlađi ih do temperature 300-450°C, a sam se suši. Komadi ugalja padaju na radno kolo mlina. U mlincu se čestice ugalja udarajući u oklop i radne ploče pretvaraju u ugljenu prašinu. Pri mljevenju ugalja vrši se njegovo završno sušenje. Smjesa ugljene prašine i dimnih gasova potiskuje se na krovnik i dolazi do mljenja. Smjesa koji dolazi u separator dolazi do recirkulacije. Smjesa u separator dolazi u mlin, gdje se vrši još jedan ciklus mljevenja. U separatoru dolazi do završnog sušenja. Smjesa iz separatora dolazi u stojičicu, gdje se recirkulira. Smjesa iz stojičice dolazi u kondenzator, gdje se završno suši i dolazi u mlin za mljevenje.

4. PRODUKTIVNA UGLJENA ZONA

Uokviru neogene ugljenosne serije ležišta "Gacko" razvijene su tri ugljena sloja veće dubine zalijeganja i povratna zona (sa tri krovinska ugljena sloja). Svi slojevi su složene strukturne grade. Pri tome su slojevi povratne zone specifični izraženi po morfološkim, strukturnim, litofacijalnim i drugim geološkim karakteristikama, jer ugljeni slojevi nemaju kontinuitet u dubini ili padu. Slojevi ugalja u ležištu "Gacko" se odlikuju s izrazitom promjenljivostima po vertikalnom međusobnom razmeru. Ova promjenljivost u vertikalnom međusobnom razmeru se izražava kroz različite vlastite vrloške i slojeve u pojedinim dijelovima ležišta. Na slici Fig. 4. prikazan je geološki stub gatačke ugljenske formacije (centralni dio ležišta).

Fig. 4. Geološki stub gatačke ugljenske formacije
5. RESURSI UGLJA KAO ENERGETSKO GORIVO ZA SADAŠNJE I BUDUĆA TE - POSTROJENJA

Geološke rezerve ležišta uglja Gacko iznose cca 330 Mt. Prema aktuelnoj geološkoj dokumentaciji bilanske rezerve iznose ≈185 milijuna tona sa prosječnom toplotnom vrijednošću od 9,9 M J/kg i energetskim potencijalom od 545 TWh. Prema obrađenim pokazateljima uspješnosti, bilanske rezerve uglja omogućavaju dugoročno obezbeđenje gorivom sadašnjeg i budućih termoenergetskih postrojenja po povoljnim ekonomskim uslovima. Ležište uglja Gacko zahvaljujući ukupnoj količini rudnih rezervi i kvalitetu, predstavlja najznačajniji izvor te sirovine za potrebe termoelektrana u Republici Srpskoj.

Prosječna uglononosnost, u ležištu uglja Gacko, po pojedinim ugljenim slojevima, samo za glavni sloj, iznosi 9,36 t/m². Za svatri ugljeni nivoa prvog podinskog ugljenog sloja, prosječna uglononosnost iznosi 13,73 t/m².

6. REZERVE I KVALITET UGLJA

U tabelama koje slijede prikazane su rezerve i kvalitet uglja u ležištu "Gacko". U tabeli 1. prikazane su rezerve uglja (bilanske, vanbilanske, potencijalne, ukupne geološke i eksploatacione) u ležištu "Gacko" sa stanjem na dan 31.12.2016. godine.

Table 1: Rezerve uglja (bilanske, vanbilanske, potencijalne, ukupne geološke i eksploatacione) u ležištu "Gacko"

<table>
<thead>
<tr>
<th>Ležište</th>
<th>REZERVE UGLJA (tone)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BILANSNE (A+B+C₁)</td>
</tr>
<tr>
<td>„Gacko“</td>
<td>186.909.806</td>
</tr>
</tbody>
</table>

Table 2:

<table>
<thead>
<tr>
<th>Komponenta</th>
<th>%</th>
<th>Komponenta</th>
<th>%</th>
<th>Standardna norma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>10.3</td>
<td>S</td>
<td>0.22</td>
<td>ASTM D6349:2009</td>
</tr>
<tr>
<td>Ba</td>
<td>0.034</td>
<td>Sr</td>
<td>10.020</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>18.71</td>
<td>SiO₂</td>
<td>40.83</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>5.24</td>
<td>Ti</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>1.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.041</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ležište uglja "Gacko" podijeljeno je na 4 eksploataciona polja:
- Centralno polje,
- Istočno polje,
- Povlatna zona i
- Zapadno polje – PK „Gračanica“ (Sjeverna kosina i Gojkovića potok).

1250°C. Za transformaciju i nastajanje novih oksida i legura treći se značajna količina oslobođene toplote, što veoma mnogo umanjuje radijaciju i preddavanje toplote radnom fluidu i produkciu pare na kotlu, a samim tim i snagu na pragu termoelektrane.

 drugi efekat taj proces stvaranja novih jedinjenja prati i okrupnjavanje čestica koje po svojoj karakterici i težini završavaju na dnu ložišta. U hladnom lijevu se sustižu i formiraju veće komade koji po gabaritu i težini završavaju na dnu ložišta. Velike količine toplote prilikom sagorjevanja lignita sa velikim procentom šljaka, koji se proteže na dolje, koriste se za zagrijavanje radnog fluida i proizvodnju pare na kotlu, a samim tim i snagu na pragu termoelektrane.

 taj, proces stvaranja novih jedinjenja prati i okrupnjavanje čestica koje po svojoj gabaritu i težini završavaju na dnu ložišta. U hladnom lijevu se sustižu i formiraju veće komade koji po gabaritu i težini završavaju na dnu ložišta. Velike količine toplote prilikom sagorjevanja lignita sa velikim procentom šljaka, koji se proteže na dolje, koriste se za zagrijavanje radnog fluida i proizvodnju pare na kotlu, a samim tim i snagu na pragu termoelektrane.


 7. ZAKLJUČAK

 Neophodno je obezbijediti kontinuirani rad bloka i proizvodnju električne energije, iz raspoloživog goriva gatačkog basena. Organizaciju sagorjevanja lignita sa povratne zone vršiti isključivo sa miješanjem lignita iz glavnog sloja. Proces zašljakivanja donjeg dijela ložišta kontrolisati sa količinom goriva i ložištu i doziranjem dodatnog goriva (mazuta). Izbjegavati korišćenje lignita sa velikim procentom nesagorivih materija.

 REFERENCES

 [1] TE GACKO, Izvještaj o ispitivanju uzoraka - Institut za rudarstvo i metalurgiju Bor
 [2] TE GACKO, Upustvo za eksploataciju bloka

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MINI HYDRO POWER PLANT BASED ON PELTON TURBINE

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Marko RAŠOVIĆ
Vasilije SAMARDŽIĆ
Nikola ĆIRKOVIĆ
Radoslav TOMOVIĆ

Key words: power plant, pelton, electric, bucket

Hydroelectric power plant is an electric for the production of electricity obtained by the power of water. Any water turbine is a means of extracting energy from falling water. Different types of turbines prefer different operating conditions. Propeller turbines work best at low head and high flow. Crossflow turbines require medium heads and flows. Pelton turbines work best under conditions of high head and low flow.

For our design of mini hydro power plant, we decided to construct and make the model of Pelton turbine.

Pelton turbine have many advantages. Firstly, because they can utilize high heads, they can produce a lot of power from a small unit. Secondly, they are reasonably to make. Thirdly, a given turbine can be used for a range of heads and flows. Fourthly, Peltons are particularly useful for driving small electrical generators. Even at modest heads, small Pelton wheels can be made to run at high speeds, which allows them to be matched to generators without the need for a belt drive or gearbox to change the speed.

Table 1: Setting the task and changing properties

<table>
<thead>
<tr>
<th>First step: Setting the task and changing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties of input products</td>
</tr>
<tr>
<td>Operation from the nozzle, flow 50 l/min, and pressure 4 bar</td>
</tr>
<tr>
<td>Voltage 12V</td>
</tr>
<tr>
<td>Additional Requirements</td>
</tr>
<tr>
<td>Fixed requirements:</td>
</tr>
<tr>
<td>- max dim.</td>
</tr>
<tr>
<td>a x b x c = 1000 mm x 1000 mm x 1000 mm</td>
</tr>
<tr>
<td>Tolerated requirements:</td>
</tr>
<tr>
<td>- flow 50 l/min</td>
</tr>
<tr>
<td>- pressure 4 bar</td>
</tr>
<tr>
<td>- position of nozzle</td>
</tr>
<tr>
<td>Wishes:</td>
</tr>
<tr>
<td>- Bigger current</td>
</tr>
</tbody>
</table>

When choosing a number of buckets for a Pelton turbine the best solution seems to be using as few as possible and to fit them as close to the shaft. The problem is that if there are too few of the buckets some of the water in the
jet will not be caught, and therefore efficiency of the turbine will be smaller. The exact number depends on the bucket design, but is generally between 18 and 22 buckets. The number of buckets can be found by drawing or by using following equations.

\[ z_k = \frac{D}{d_0} \sqrt{17}, \text{ when is } \frac{D}{d_0} > 12 \]  

(1)

\[ z_k = 0.4 \cdot \frac{D}{d_0} + 16, \text{ when is } \frac{D}{d_0} = 12 \]  

(2)

\[ z_k = 0.5 \cdot \frac{D}{d_0} + 15, \text{ when is } 6 < \frac{D}{d_0} < 35 \]  

(3)

Calculating the forces on the shaft in a Pelton turbine is relatively straightforward. The main forces come from the water jets, the runner and the shaft weight, the bearings, and the drive system. Formula for the calculation of the jet force:

\[ F_{\text{jet}} = \frac{T}{n_{\text{jet}} \cdot \frac{D}{2}} = \frac{60 \cdot P_{\text{mech}}}{\eta_{\text{force}} \cdot \pi \cdot n_{\text{jet}} \cdot D} \]  

(4)

\( D \) – pitch circle diameter, a diameter where the jet hits the bucket
\( d_0 \) – diameter of the nozzle

In this project we have chosen 18 buckets as an optimal number for this application.

If they are numbered make sure that they are numbered consequently. Put the numbers in parentheses flush with the right-hand margin level with the last line of the equation.

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Hydropower or water power is power derived from the energy of falling water or fast running water, which may be harnessed for useful purpose. The water is collected through the blades and piped where it is pressurized through the nozzle aimed to hit the hydraulic wheel. The power that spins the wheel will be connected to the electric generator. Electricity is transformed and transmitted through the power transmission network and directed to further use.

The project that we are launching with the construction of a small hydro power plant will give us a new experience, and thus we will also gain new working habits in the field of science.

The task is determined that the project has to be compiled into the dimension space axbxcx (1m x 1m x 1m). For the start we’ll have to determine which generator and also turbine to choose based on power of water. The water power from the initial conditions (50 l/min = 0.000833 m³/s at 4 bar pressure) is calculated from the formula:

\[ P(W) = Q \left[ \frac{m^3}{h} \right] \cdot \rho [Pa = \frac{m^3}{m^2 s^2}] \] (1)

With the power of water and certain losses on turbine blades, bearing and certain power transformer we would determine the power and the type of electric motor that would turn to the operation mode as a generator. We were planing on using Pelton’s type turbine or Turgo's type turbine that would provide us with great efficiency, taking in account that we will be working with small low water flow, and efficiency is playing a big role in this project. We were planing on using pvc materials for the turbine and simple house spoons for the blades of the turbine that would be connected to the turbine wheel.

For calculating diameter of turbine our priority would be to achieve enough momentum for starting entire system, and at the same time to get as much speed as possible for rotation of the turbine so we could harness more power at generator output.

Additionally, we would choose an adequate pair of bearings to bring the power of water, brought to the turbine blades to the generator with as little loss as possible. The turbine would be enclosed with glass or plexiglass so that there would not be water dissipation around the same. On the next picture we have presented hand drawn idea of our project.

Fig.1: Hand drawn idea of our project
For the start of the project we tried to construct a single blade for peltons turbine and prototype and it went pretty well taking in account that we used simple only simple spoons. We’ve taken two spoons removed handles and welded bowls of the spoon togeather to create as similar as possible shape to peltons blade.

The next picture only shows the prototype and if we would be using this type of blades we would do our best to improve them in every possible way.

Fig.2 : Our prototype of blade for peltons turbine

Under the turbine we would construct an opening that would be used as water output from turbine. On the end of the system, that is behind the generator there would be a bulb to signal generation of electricity and battery charger as it is was requested by the task.

On the end of this presentation there will be presented a table with names and price of the used materials. Everything needed for construction of the project would be either purchased on internet or homemade.

Table 1 : Necessary materials for the project

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Generator</td>
<td>The generator is the main thing for this project.</td>
</tr>
<tr>
<td>2.</td>
<td>Bearings</td>
<td>They are responsible for the transfer of power from the turbine to pulley.</td>
</tr>
<tr>
<td>3.</td>
<td>Belt drive</td>
<td>Transmits power with pulleys to the generator.</td>
</tr>
<tr>
<td>4.</td>
<td>Tablespoons</td>
<td>It will be used for making turbine.</td>
</tr>
<tr>
<td>5.</td>
<td>Water hose</td>
<td>It serve to bring water to the turbine.</td>
</tr>
<tr>
<td>6.</td>
<td>Plexiglas</td>
<td>Preventing the water spray.</td>
</tr>
</tbody>
</table>

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ACHIEVING LOW COST, HIGH EFFICIENCY PELTON TURBINE

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Emir NEZIRIĆ

Key words: Pelton turbine, hydroelectricity, electricity, sustainability, hydropower

Hydroelectric power is a relatively inexpensive, efficient and sustainable form of energy. Given the increasing focus on developing energy without the use of fossil fuels, hydroelectricity stands as a viable option. Therefore, it is important for today’s engineers and scientists to optimize existing hydroelectric technology so that it may better serve as a standard mechanism for generating power. Specifically, Lester Allen Pelton’s “Pelton Wheel” has been in existence since the 1870s, yet remains the preferred design choice for some of the world’s largest and most advanced hydroelectric power plants. We believe the Pelton Turbine is the best candidate for the continued development and reliance on hydroelectric power. Our miniature turbine will demonstrate how this design can be applied at a small scale and built to exact specifications to produce the desired outcome of 12 volts to power a light bulb. Additionally, our Pelton Turbine will prove that reaching the target energy output can be affordable, elegant and compact.

The Pelton Turbine utilizes buckets instead of paddles, which allows for as much as 95 percent hydraulic efficiency. We hope ours will achieve 65 percent efficiency. With the given data:

\[ Q = 50 \text{ l/min} = 0.000833 \text{ m}^3/\text{s}, \quad p = 4 \text{ bar} \]

We calculated the maximum power of water:

\[ P = \gamma \times Q \times H = 9.802 \text{ m/s}^2 \times 0.000833 \text{ m}^3/\text{s} \times 40.77371 \text{ m} = 326.60 \text{ W} \]

Given the limitations in this specific project, and factoring in some net loss from the max power of water, we hope to obtain 60 W of electricity from our turbine.

To determine the dimensions for our turbine, we had to calculate the diameter of the nozzle, where \( ds \) is the diameter of the nozzle, \( Q \) is flow, \( z \) is the number of nozzles, and \( V_a \) is the real velocity of the jet:

\[ ds = \sqrt{\frac{4Q}{\pi\times V_a} \approx \sqrt{\frac{4\times 0.000833}{\pi \times 27.44}} = 0.0061 \text{ m} = 6.1 \text{ mm} } \]

From there, we determined the diameter of the turbine, where \( V_1 \) is the theoretical velocity of the jet, \( V_a \) is the real velocity of the jet and \( C_v \) is the coefficient of the velocity of the jet (0.98-0.99):

\[ V_1 = \sqrt{2 \times g \times H} = \sqrt{2 \times 9.81 \times 40.77471} = 28 \text{ m/s} \]

\[ V_a = V_1 \times C_v = 28 \times 0.98 = 27.44 \text{ m/s} \]

\[ D = 30 \times ds = 30 \times 6.1 = 183 \text{ mm} \]

We also calculated the dimensions of the bucket, according to the following diagram:

![Fig. 2: Dimensions of the bucket](image)
L = 20 to 30 * 6.1 = 122 mm
B = 25 to 50 * 6.1 = 152.5 mm
M = 11 to 15 * 6.1 = 67.1 mm
D = 8 to 12 * 6.1 = 48.8 mm

Given these calculations, we determined velocity of the wheel and revolutions per minute:

\[
\begin{align*}
\frac{V}{V_1} &= 0.45 \\
U &= V_1 \times 0.45 = 28 \times 0.45 = 12.6 \text{ m/s} \\
n &= \frac{V_0 \times \theta}{\pi \times D} = \frac{12.6 \times 60}{\pi \times 0.139} = 1314 \text{ rpm}
\end{align*}
\]

To build our turbine, we were faced with three options: Create a mold, use a 3-D printer, or construct it using aluminum piping. Creating and sourcing materials for a mold proved too costly, so we are left to choose between 3-D printing and manual construction. There are pros and cons to both methods:

A 3-D printer is cleaner and simpler. However, the cost and access for 3-D printers is not ideal – it can be expensive and not everyone has ready access to such technology.

Manual construction with aluminum piping involves more labor, but such materials are inexpensive and easy to find.

Even with a focus on reducing cost and complexity, we are confident the Pelton Turbine is the best design for this task.

Hydroelectricity has great use for both large- and small-scale applications. We hope our Pelton Turbine will demonstrate effectively that, even with limited budgeting and resources, it is very possible to generate the necessary amount of electricity to power a light bulb, store energy or perform other minor tasks. Today, with our over-

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HYDROTURBINE MADE FROM RECYCLED SCRAP MATERIALS

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Sead IMAMOVIĆ
Alem KARAOSMANOVIĆ
Emir NEZIRIĆ

Key words: hydroturbine, recycling, electric power

The idea for project is to use recycled material in this case it is an Aluminium, which will be taken to made a turbine.

Blades of turbine will be made of pipe irregular (D) shape, and the pipe will be cuted longitudinally and transversally. Blades will be attached for carrier by screws. The carrier of the blades presents two disks which will be taken from the washing machine. Shaft will be made of steel and have full cross section. For the bearings it will be used standard definition 6004.

Fig. 1. Recycled materials for turbine parts

To made carrier of a construction it will be used steel pipe with dimensions 40x40x2. Protection construction of external influences will be provide by plexiglas panels. On the top of construction it will be made a hole for supply turbine with water, and after it pass turbo blades water will go out on bottom drain pipe.

Dynamo will be situated into the housnig of a construction and it will be protected out of water effect. Then it will be mounted on construction by steel carrier. The transfer of the force from turbine to alternitor will be realized by two pulleys. Mechanical work on pulley 1 will be transfer with belt to pulley 2 respectively on dynamo.

Fig. 2. 3D model of turbine

Fig. 2. 3D model of turbine
Table 1. Parts used for power plant

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Irregular (D) shape pipe</td>
<td>Used for turbine blade.</td>
</tr>
<tr>
<td>2.</td>
<td>Wash machine pulley</td>
<td>Turbine blade carrier.</td>
</tr>
<tr>
<td>3.</td>
<td>Steel pipe with dimension (40x40x2)</td>
<td>Used for main frame.</td>
</tr>
<tr>
<td>4.</td>
<td>Automotive dynamo</td>
<td>Producing electric energy.</td>
</tr>
<tr>
<td>5.</td>
<td>Plexiglass</td>
<td>Used for covers.</td>
</tr>
</tbody>
</table>

REFERENCES


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MINI HYDRO POWER PLANT

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Dragi TIRO

Key words: brief insight into our project.

In the following text, we will briefly refer you to our system and our solution to the problem of "mini hydroelectric power plants". Our way of implementing this project stands for the simplest way to get electricity and maximize the capacity of machine elements used in our project. The project itself gives the possibility of various contralateral performances. Our team is committed to the simplest contractual performance, the better the aesthetics of the project itself, and the great economic convenience of performing it.

First of all, we have decided that all parts used for the project are already used parts (due to economics). In our electricity production system the greatest attention is given to the greater utilization of natural resources (water). By design we decided to accumulate water and increase the water pressure acting on our turbine. Due to the high pressure on the turbine blades, the turbine speed is increased.

The turbine made of lightweight material will be connected to the alternator over the shaft. For the shaft we will use the best material to reduce the power losses we achieve on the turbine. Given that the bearings are paying great attention to the budget and having a great impact on the loss of strength in our case we will strive to choose the best. Through the shaft to the pulley and from the twist to the alternator found on the car waste and our reconstruction, we are coming to the most important part of our system. The alternator will be our "generator" in our mini power generator.

The more efficient transmission of power, torque and torque from the turbine to the pulley and the better the performance of the pulley, the greater the amount of electricity we will have, as well as the budget. With the first practical turbine testing we found that we did not make a mistake when selecting the turbine construction itself. The great advantage of our system is quiet and quiet work. The machine system itself will be protected by a tin-plated construction so that there is no injury to the system. In order to have a better look in use, it will be the best color and varnish.

Table 1: Parts

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bearings</td>
<td>According to our needs and according to the market price, we will cost us &lt; 20 BAM</td>
</tr>
<tr>
<td>2</td>
<td>Bracing pulleys</td>
<td>According to our needs and according to the market price, we will cost us about 50 BAM</td>
</tr>
<tr>
<td>3</td>
<td>Alternator</td>
<td>60 BAM</td>
</tr>
<tr>
<td>4</td>
<td>Box</td>
<td>We did not find out</td>
</tr>
<tr>
<td>5</td>
<td>Shafts</td>
<td>We did not find out</td>
</tr>
</tbody>
</table>
Below 1.(Parts) are some of the parts that will be used in our project and their prices, and the financial part of the funds is provided by our faculty. By consulting with our mentor, we have found that it is economical and fairly easy to implement, which gives us a certain amount of confidence that this kind of mini-hydro power plant will work. In the forthcoming period, we will work to provide you with a more detailed 3D rendering system that we will model in one of the most up-to-date software, namely SOLID WORKS.

**Fig.1: Turbine**

In Figure 1(Turbine) is the model of our turbine, drawn in solidworks. In this software we also performed a simulation, which helped us to perform the equation for the output power.

**Fig.2: Scheme**

In Figure 2(Scheme) we see the schematic representation of electricity generation. The diagram shows the turbine (1), spindle bracket (2), alternator (3). Although not shown in the alternator scheme, part of the energy obtained will be used to work bulbs and the remaining energy to another consumer. Also not shown are constructions and bearings.

**REFERENCES**


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Nowadays the machine industry is unimaginable without modern CNC (Computer Numerical Control) machines. CNC machines have more or less the same parts as old, hand-controlled machines. The important difference is the addition of a control (CNC) unit and servo motor to all shafts. CNC calculates the coordinates where the shaft should be and controls the servo motors that move the tool, the turning machine, or the treated part, (milling machine) through the ball screw.

The programming of these machines is done in several ways:

- ISO programming (G-code, M-code, cycles, etc.),
- Dialogue programming (symbols, drawings and many other features),
- CAM programming 3D (complex drawings are transformed into a mechanical program).

For the programming of this CNC machine we used the G-code, the working environment of the Processing program.

To assemble the mechanical part of the CNC plotter, the following materials were used:

- wooden stand,
- two wooden battens (holders),
- two aluminum tetrix holders,
- four steel shafts (shock absorbers of the rear doors on the car) for movement in the direction X and Y axis,
- one aluminum tetrix holder (for marker, movement in the direction of Y axis),
- plywood as a paper base (movement in the direction X axis),
- marker holder, printed on 3D printer
- marker (as writer)
- silk (fishing thread) and two wheels (as a pulley)

As well as parts of electronics:

- Arduino UNO microcontroller
- 2x ULN2003 stepper driver + 2x 5V step motors (for drive in X and Y direction)
- 1x micro servo (to lower marker)
- breadboard
- wires

Key words: CNC, machine, G-code
REFERENCES

[1] https://www.youtube.com/watch?v=szXNpI4GydA.

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For the connection between the G-code and the microcontroller we used a program written in the Arduino working environment, and for the operation of the CNC plotter we used the Processing program.

How to Operate and Launch the Program Code:
1. Connect Arduino to the computer, then compile and upload the program (Arduino code) on the development board.
2. Run the program (G-code) in the Development environment Processing.
DEVELOPMENT OF A THERMAL POWER PLANT TUBULAR BOILER CLEANING MACHINE

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Key words: development, boiler, cleaning, thermal power plant, cleaning

1. INTRODUCTION

This study is made in order to show the potential of innovative mechanised and semi-automatised solutions for a cleaning process, that happens in the boiler section of a thermal power plant, with the supporting analysis for developed solution.

As the cleaning process of these sections of thermal power plants represents very hard labour, it needs a great number of participants, varying from 60 to even a 100, which also means that this process needs a significant amount of financial resources, taking in the fact that the cleaning needs to happen at least 5 times annually. Clothes, tools and the environment that characterizes the cleaning process is shown in Fig. 1.

For this study, the team has made a questionnaire, that was sent to 20 recipients working in this area, some of them being regular participants. Also, the team investigated the market, seeking existing solutions with the abovementioned function. As a final task, the team will evaluate three possible variants, that will be assessed using methods of variant evaluation, and develop a model of the one that is satisfying the requirements the most.

The team will use several methods in order to determine the functionality and profitability of the machine in question, using the CHECK list, regarding the financial, functional, ergonomic, aesthetic and maintenance requirements, as a starting point. Also, the cleaning process in thermal power plants located in Gacko and Ugljevik will be set as an example and a basis for the analysis.

2. PRODUCT DESCRIPTION AND PURPOSE

The cleaning machine is developed for semi-automatized removal of the sediment rock shown in Fig 2., that’s made of sublimated particles of combustion products, which is located on the tubes in the boiler section. These tubes have a “chess” layout, with the vertical and diagonal gaps between them and, while tubes mustn’t be damaged, the rock needs to be totally removed from those gaps.

To achieve that, the developed machine has a saw-like cutting tool, that is breaking off the chunks of rock while moving through the space between the tubes (approx. 80 mm). Also, the machine possesses the ability to rotate at
the maximum angle of 45 degrees in one or either side, in relation to the ground, allowing the cutting tool to breach through the diagonal gaps filled with sediment. Although this process leaves some chunks of sediment untouched, that is a small amount, and can be cleaned with the manual tools (ex. "spears"). Through the analysis of variant solutions, few options emerged concerning the mechanism for driving of the cutting blade, two of which were plausible solutions – an electromotor and a pneumatic motor. The team decided to implement the pneumatic motor as it is cleaner, quieter, with smaller amount of parts and maintenance needed, as well as the fact that the pneumatic lines, with the appropriate pressure, are accessible and free to use in the boiler section.

As for the machine movement, the team settled for the manual labour, because of its simplicity, from the automatization and maintenance aspect, and versatility, as well. Taking into the account the information from the questionnaire, and information that derived from the simulation, we conclude that the machine:

- Weights approximately 50 [kg],
- Has a light for additional illumination,
- Works in low noise level as possible,
- Has soothing colour,
- Has a modular design with a removable cleaning body,
- Can clean vertical and diagonal gaps,
- Has additional cleaning bodies in the reserve.

3. ADVANTAGES

The team has made an analysis of the market, seeking for the existing solutions and estimating the possible market demand for this type of product, taking into consideration the number of the thermal power plants existing in the vicinity, from which the following can be stated:

- The team failed to find similar existing solutions on the market;
- The market demand for this type of product is significant;

Substantial advantages of this solution are, as follows:

- Modular design,
- Lightweight construction,
- Versatility in different environments,
- Cleanliness,
- Simple design for maintenance, assembly and disassembly,
- Inexpensive parts.

4. CONCLUSION

After the consideration of the acquired information, it can be concluded that:

- There is a number of thermal power plants in the vicinity, that could invest in this innovative solution;
- The machine should perform the work more effectively and efficiently compared to the existing method;
- The machine has dimensions compatible with the boiler section, and it must not damage the tubes or the boiler,
- There is a significant demand for the innovative solution on the market,
- The team failed to find another competitive product.

REFERENCES


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MOBILE NXT ROBOT THAT IS MANAGED VIA A BLUETOOTH CONNECTION

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Key words: NXT, microcontroller, sensors

This robot is managed using the NXT microcontroller. Lego Mindstorms NXT is the second set of Lego Mindstorm collections, which is designed by Lego. The set consists of NXT microcontrollers, various sensors (color sensor, sound, ultrasonic sensor ..) servo motors, as well as cubes of various shapes and sizes, wheels, etc. NXT is a microcontroller consisting of 4 input ports for sensors, 3 output motor ports, and a USB port port, and is shown in Figure 1.

The robot is made of parts from the TETRIX set and the NXT microcontroller. The following parts were used to assemble a robot: TETRIX rails, fixed wheels (drive front wheels), wheels with 2 degrees of freedom (rear wheels), 12V DC TETRIX motor, casing for DC motor, power supply of 12 V, 3000 mAh motors (batteries), DC motor controller for TETRIX, power switch, NXT microcontroller.

DC TETRIX motors are powered by a 12V battery and connected to a DC motor controller for TETRIX, which is connected to the NXT Microcontroller for detecting the motor. The battery is connected to the motor controller via which it drives the motors.
The mode of communication between the robot and the computer was realized through Bluetooth, and the robot was operated via the keyboard.

The program code is written in the RobotC work environment, intended for NXT microcontrollers. Since the RobotC work environment contains pre-existing Joystick libraries, we have used PPJoy program to create a virtual joystick on the keyboard.

First, it was necessary to perform the adjustment and configuration of the PPJoy program, to select the control key.

**Fig.5: Configuration of PPJoy parameters**

After the start of the RobotC operating environment, it was first necessary to configure the DC TETRIX motor, then download the firmware to the NXT microcontroller via a USB cable. The next step was to compile and upload code on the NXT microcontroller, and then pair with Bluetooth.

**Fig.6: Bluetooth configuration**

**Fig.7: Program start**

REFERENCES


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Robotic manipulators have a very wide application today in industry, due to their flexibility and good mobility, and they are very useful in carrying out different tasks from various fields of science and industry.

This project represents the manipulator with 5 degrees of freedom of movement, or 5 independent motors. Control is done by using two buttons located on the breadboard. One button serves to enter the “learning state”, while the other serves to start executing the given movements. By pressing the button on the 6th pin, the LED lights up and the robot enters the “learning state”, then you need to move the robot arm manually, then press the same button to remember the movement. After pressing button, the robot will then return to the starting position. By pressing on the button, which is on the 7th pin, the robot will repeat the last path which was assigned to it.

This principle is used in a large number of factories all over the world, because if it is necessary for the robot to repeat its movement, or function, all that needs to be done is to manually move it, instead of typing a special code for every robot movement.

For the development of this project, the following material was used:
- Arduino UNO microcontroller
- 5 analogue feedback servo motors
- 2 buttons
- 2 resistors of 1Kohm
- Wires
- Breadboard.

Parts of the robot, respectively the motor housing, are printed on a 3D printer.
Connecting a robot to the Arduino is simple. Arduino 5V and GND should be brought on the breadboard. Connect two buttons directly to 5V and through resistor to GND. Analogue feedback servo motors have 4 wires (brown, red, yellow and white). The brown wire is connected on GND, red one on 5V, yellow wire represents motor signal and it connects to desire pin on Arduino, and the white wire represents motor feedback and it connects to the analog pin.

The program code is written in the Arduino work environment.

REFERENCES


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This project uses the Hall effect sensor that works on the principle of magnetic field detection. Whenever the magnet passes by the sensor, it detects it. It can be used for a lot of different purposes. For example, if we want to detect the closing of the door, we should just connect the magnet to the door, and put the Hall sensor on the doorpost. Whenever the door closes, the sensor would detect the magnetic field.

For the development of this project, the following material was used: Arduino UNO, piece of magnet, Hall effect sensor 44E or US5881 or US1181, 10 Kohm resistor, wires, a casing made on a 3D printer, and LCD display module.
There are several types of Hall sensor, and some types are better than others for individual applications. For applications where detection speed is not crucial, a common Hall sensor such as 44E can be used. But for an application that involves high-speed detection, such as in the case of speedometer Hall high-frequency sensors such as US5881 or US1881, should be used.

3-pin Hall effect sensor: VCC (5V), GND and Vout (Signal). Pins are shown in the picture below:

Connecting the Hall sensor with Arduino is very simple. The VCC of the sensor is connected to a 5V Arduino pin. The GND of the sensor is connected to the GND pin at Arduino. Vout (Signal pins) of the Hall sensor is connected to the interrupt pin of Arduino (digital pin 2). The Hall sensor signal pin is connected to the VCC via a resistor of 10Kohm. Wiring is shown in the picture below.

The program code for Hall sensor is written in an Arduino program environment.

REFERENCES

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PRESENTATIONS OF SPONSOR
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New programs are purchased when necessary.

Codes used for evaluation
TREBINJE

In an oasis of greenery with its typical Mediterranean spirit, at the foot of Leotar mountain, lies Trebinje, one of the most beautiful towns in the Republic of Srpska. Its magnificent scenery makes it very attractive for many visitors...

Trebinje is situated in the very south of the Republic of Srpska (Bosnia and Herzegovina), on the crossroads between the towns under the protection of UNESCO (Kotor, Mostar and Dubrovnik), and only 25 kilometers away from the Adriatic coast. Very favorable traffic-geographical position and Mediterranean climate with a lot of sunny days (260 a year) makes it an ideal place for living or spending a perfect vacation. It also favors cultivation of various agricultural crops. It has 32,000 inhabitants and occupies an area of 904 square kilometers, at an altitude of 273 meters. Trebinje is an economic, cultural and tourist center of the East Herzegovina region. It is rather harmoniously built and well planned town.

Throughout its long and turbulent history Trebinje has always been a crossroads and a link between the Mediterranean and the interior of the Balkan Peninsula. The Illyrians, Romans, Slavs, Byzantines, medieval rulers of Serbian Nemanjic state, and then the Ottoman Empire and the Austro-Hungarians all passed this crossroads, and eventually Trebinje became a town on the border of Bosnia and Herzegovina, Montenegro and Croatia. All these eras and rulers left their traces and marked local culture, both spiritual and material.

The old town “Kastel” was established in the early 18th century on the bank of the river Trebisnjica. Formerly it was a trade and crafts center and this old atmosphere can be felt during the walk through narrow paved streets, tunnels, squares... The present appearance of the town is an attractive mosaic of closely intertwined Mediterranean and Oriental styles of the past and the modern age. In the very centre of the town, in Ducic's Street, there is a well known sidewalk cafe ‘Platani’. A unique picturesque green market is located near the sidewalk cafe, on the main town square, offering the indigenous agricultural and other products of this region.