PERFORMANCE ANALYSIS OF SUBSTITUTION OF APPLIED MATERIALS USING FRACTURE MECHANICS PARAMETERS

Nedeljko Vukojević, Mirsada Oruč, Dušan Vukojević, Fuad Hadžikadunić, Omer Beganović

By replacing the S355 conventional structural steel with V/Nb base micro-alloy steel it is possible to achieve a considerable reduction in the structure mass itself without safety risk, which is also proved by testing fracture mechanics properties of the materials. The numerical results have been also confirmed by analyzing the reliability of the selected materials, with special reference to safety from fracture hazard in the steel welded joints under consideration. Presented in the paper are the results of the numerical evaluation of the bridge crane steel structure under static and dynamic conditions for two steel grades and dimensions. This testing methodology can be applied to any kind of mechanical structure. It can also stress the importance of fracture mechanics application to the evaluation of the condition and behaviour of significant mechanical structures. The immediate effect of this investigation is the saving in the mass of the material used, together with a considerable fracture risk reduction, as well as an improvement in the working properties of the bridge crane steel structure.

Keywords: dynamic response, finite element analysis, fracture mechanics, bridge crane, safety from fracture hazard, welded joint

1 Introduction

Conventional steel plates used for the manufacture of significant mechanical structures have long been in need of replacement in view of increasingly demanding industrial working conditions and needs [1]. The application of low-alloy and micro-alloy steels, as well as special structural shapes, besides a saving in the mass of the material, results in a cheaper transport, lower operating costs, a larger useful load, easier accelerating and braking, potential higher operating speeds, etc.

The introduction of micro-alloy steels brings about a considerable increase in mechanical structure load carrying capacity but also poses a problem concerning the weldability of such steels [2]. Besides high yield stress and strength, micro-alloy steels have good impact toughness even at lower temperatures. A more intensive drop in toughness can be expected in the heat-affected zone (HAZ) due to the grain growth and rapid cooling. Using V/Nb base alloying elements, steels with exceptional tensile and fatigue resistance properties have been obtained, which, using adequate welding technology, can completely replace conventional S355 J2G3 structural steel. This leads to a considerable reduction in the structure mass with an increase in the working performance and safety.

The weld joining the materials under consideration has been experimentally tested. The testing methodology described is aimed at justifying the materials substitution on grounds of an additional increase in safety [3].

The numerical analysis makes it possible to test the main beams of the two-beam bridge crane model for two types of applied materials and two plate widths. This analysis has been carried out in order to test the static load carrying capacity of the structure, and evaluate its dynamic behaviour, the final purpose being to test its structural and geometric parameters [4].

2 Experimental part

2.1 Material properties

For the purpose of carrying out the experimental testing, two types of materials have been used, i.e. S355 J2G3 carbon structural steel, defined in EN 10027-1, having a thickness δ=12 mm and labelled S, and Nb/V-1 micro-alloy steel having a thickness δ=7 mm, labelled ML. The chemical composition of the materials delivered is shown in Tab. 1. The selected specimens labelled S have been welded using MAG (CO₂) technique, and those labelled ML, using REL technique.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>V</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0.21</td>
<td>0.53</td>
<td>1.47</td>
<td>0.038</td>
<td>0.029</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ML</td>
<td>0.04</td>
<td>0.58</td>
<td>0.89</td>
<td>0.032</td>
<td>0.004</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.033</td>
</tr>
</tbody>
</table>

The tensile tests have been carried out on the standard rectangular test specimens, defined as ASTM E8-86 [5], with the filler metal in the central section of the work and transversely to the direction of the load application. The Nb/V-1 steel flat specimens tested are labelled Z-ML and the structural steel ones are labelled Z-S. During each testing, three test specimens have been used, the results...
being shown in Tab. 2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield stress $R_{0.2}$/MPa</th>
<th>Tensile strength $R_m$/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-ML</td>
<td>501.5</td>
<td>583.6</td>
</tr>
<tr>
<td>Z-S</td>
<td>335.5</td>
<td>444.0</td>
</tr>
</tbody>
</table>

The analysis of the fractured surfaces shows that ductile fracture has been involved in all these cases. The fracture of the ML test specimens has occurred in the base metals and in close proximity with the heat-affected zone, meaning that the strength of the filler metal is higher than that of the base metals.

The variable load testing technique is defined by the ASTM E466 [6] and E468 [7] standards. The test specimens used for dynamic testing are rectangular in shape. They have been taken from the welded plates, with only the middle of the weld being taken into account.

The dynamic testing is carried out within the force control, the relationship being $\sigma_{\text{min}}/\sigma_{\text{max}}=0.1$, which corresponds with the character of the variable load application with this type of cranes [8]. The fatigue resistance values achieved for these two test specimens, i.e.

- $S_f=339.4$ MPa - for the ML welded joint and
- $S_f=279.3$ MPa - for the S welded joint,

show that the fatigue resistance of the selected ML welded joint is 21.5% higher than that of the S selected welded joint (Figs. 1 and 2).

The impact tests of the ML and S specimens of the welded plates have been carried out with a purpose of determining the overall impact energy ($E$) at $+20$, $-20$, $-60$ °C, as well as that of its components, i.e. the energy absorbed in initiating the fracture ($E_{\text{inc}}$), and in its propagation ($E_{\text{prop}}$). The procedure of determining the overall impact energy is defined by the ASTM E23 [9] standard.

Figs. 3 and 4 show typical force vs. time curves for the heat-affected zone in the ML and S test specimens.

The test specimens for the impact tests have been taken along the thickness of the welded joint notched at characteristic parts of the welded joint, i.e. with the notch in the base metal (BM), in the weld metal (WM) and in the heat-affected zone (HAZ). The dimensions of the ML test specimen are $6\times8\times55$ mm, the notch depth being 2 mm, whereas the dimensions of the S test specimen are $8\times10\times55$, its notch depth being also 2 mm. Liquid nitrogen in petrol-ether has been used as a cooling agent. The results of the overall impact energy average values are given in Tab. 3.

A visual inspection of the fractured test specimens shows that the fracture at higher temperatures has been markedly ductile, whereas that at extremely low temperatures has become markedly brittle.
where:
- stress intensity factor, \( M_a \)
- J-integral plastic component, \( kJ/m \)
- modulus of elasticity, \( MPa \)
- Poisson's coefficient.

The characteristic unloading stages on the curve serve the purpose of determining the reduction in the test specimen load-carrying capacity. Consequently, it is possible to measure the current crack length by means of the reduction in its load-carrying capacity represented by the relationship between elongation and force extensions on the regression line.

For very slight elongations during a plane state of deformation, the values and defined at the same point on the curve are joined by the expression:

\[
J_{(i)} = \frac{K_c^2}{E} (1-\nu^2) + J_{pl(i)},
\]

where:
- \( K_c \) – stress intensity factor, \( MPa\sqrt{m} \)
- \( J_{pl(i)} \) – J-integral plastic component, \( kJ/m^2 \)
- \( E \) – modulus of elasticity, \( MPa \)
- \( \nu \) – Poisson’s coefficient.

The characteristic unloading stages on the \( J-R \) curve serve the purpose of determining the reduction in the test specimen load-carrying capacity. Consequently, it is possible to measure the current crack length by means of the reduction in its load-carrying capacity represented by the relationship between elongation and force extensions on the regression line.

For very slight elongations during a plane state of deformation, the values \( K_c \) and \( J_{(i)} \) defined at the same point on the \( F-\delta \) curve are joined by the expression:

\[
K_c = \frac{J_{Ic} \cdot E}{1-\nu^2}.
\]

The critical value of the J-integral \( J_c \) can be \( J_{Ic} \) defined either in the vicinity of the initial ductile crack propagation or, at the instant when the unstable crack propagation results in separation.

### Table 3 Impact energy of the base metal, weld metal and heat affected zone

<table>
<thead>
<tr>
<th>Temp. °C</th>
<th>Specimen</th>
<th>Base metal</th>
<th>Weld metal</th>
<th>Heat affected zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy/J</td>
<td>Total impact energy, ( A_{u}/J )</td>
<td>crack initiation energy, ( A_{I}/J )</td>
<td>crack propagation energy, ( A_{p}/J )</td>
</tr>
<tr>
<td>+20</td>
<td>ML-1</td>
<td>130</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>S-1</td>
<td>60</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>-20</td>
<td>ML-2</td>
<td>109</td>
<td>35</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>S-2</td>
<td>32</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>-60</td>
<td>ML-3</td>
<td>86</td>
<td>22</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>S-3</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

\( J_{(i)} = \frac{K_c^2}{E} (1-\nu^2) + J_{pl(i)}, \)

Fracture mechanics investigations have made it possible to plot the R-curve and the \( J - a \) curve, which consists of the \( J \)-integral values for uniform crack extensions \( a \).

The experiments have been carried out using a single-specimen procedure, during which the test bar has been subjected to successive partial loading/unloadings, as specified in the ASTM E813 [10] and ASTM E1152 [11] standards. The test has been carried out on three standard CT fracture mechanics test specimens each, with the initial fatigue notches cut at characteristic welded joint sections.

The basic diagrams for the ML and S test specimens notched in the heat-affected zone have been plotted in the \( F - \delta \) - system of coordinates (force vs. displacement of its point of application) and are shown in Figs. 5 and 6. The \( J \)-integral for the expanding crack is calculated by:

\[
J_{(i)} = \frac{K_c^2}{E} (1-\nu^2) + J_{pl(i)},
\]

\( J_{(i)} \) being the total J-integral for the expanding crack.

The critical value of the J-integral \( J_c \) can be \( J_{Ic} \) defined either in the vicinity of the initial ductile crack propagation or, at the instant when the unstable crack propagation results in separation.

Figs. 7 and 8 show a characteristic diagram of the \( J-\Delta a \) curve for the heat-affected zone of the ML and S test specimens plotted by means of the data calculated and the

Technical Gazette 17, 4(2010), 411-418
construction lines in order to determine a deviation from a real stable rupture on the regression line. The critical values of the J-integral $J_{ic}$ obtained at the intersection of the regression and construction lines are shown in Tab. 4.

$K_{ic}$ – critical value of the stress intensity factor during a plane state of deformation, MPa√m.

**Table 4 Stress intensity factor and critical crack length**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial crack length $a_i$/mm</th>
<th>Critical J-integral $J_{ic}$/kJ/m²</th>
<th>Critical stress intensity factor $K_{ic}$/MPa√m</th>
<th>Yield stress $R_{p0,2}$/MPa</th>
<th>Critical crack length $a_c$/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML-OM</td>
<td>25,9</td>
<td>177</td>
<td>202</td>
<td>502</td>
<td>51,6</td>
</tr>
<tr>
<td>ML-ZUT</td>
<td>27,4</td>
<td>153</td>
<td>188</td>
<td>541</td>
<td>38,4</td>
</tr>
<tr>
<td>ML-MZ</td>
<td>26,1</td>
<td>157</td>
<td>190</td>
<td>541</td>
<td>39,5</td>
</tr>
<tr>
<td>S-OM</td>
<td>18,6</td>
<td>153</td>
<td>188</td>
<td>336</td>
<td>99,9</td>
</tr>
<tr>
<td>S-ZUT</td>
<td>21,0</td>
<td>126</td>
<td>171</td>
<td>373</td>
<td>66,6</td>
</tr>
<tr>
<td>S-MZ</td>
<td>21,0</td>
<td>143</td>
<td>182</td>
<td>373</td>
<td>75,5</td>
</tr>
</tbody>
</table>

The analysis of the fatigue crack propagation calls for introducing fracture mechanics into fatigue investigation. It has been observed that the higher stress causes faster fatigue crack propagation and that the fracture occurs after a smaller number of load alternations. The purpose of determining the fatigue crack propagation rate is to determine the stress intensity scope threshold $\Delta K_{th}$ below which there are no conditions for crack propagation.

To determine the dependence of the fatigue crack propagation rate per cycle $\frac{da}{dN}$ on the stress intensity factor scope $\Delta K$ means to determine the $C$ and $n$ coefficients in Paris equation [13]:

$$\frac{da}{dN} = C \cdot (\Delta K)^n,$$

where:

- $\Delta K$ – scope of the stress intensity factor during a plane state of deformation, MPa√m
- $C$- constant,
- $n$ - exponent in Paris equation.

The investigation is conducted according to the ASTM E647 standard [12]. This standard recommends measuring the propagation rate of the fatigue crack $\frac{da}{dN}$, developing from the existing crack, and calculating the scope of the stress intensity factor $\Delta K$.

A critical crack length $a_c$ can be determined using the fracture mechanics equation:

$$K_{ic} = \sigma \sqrt{\pi \cdot a_c},$$

where:

- $\sigma = R_{p0,2}$ – yield stress, MPa
- $a_c$ – critical crack length, mm

**Figure 6 Force-displacement diagram for the S spec. notched in HAZ**

**Figure 7 J-Δa diagram for the ML specimen notched in HAZ**

**Figure 8 J-Δa diagram for the S specimen notched in HAZ**

**Figure 9 da/dN - ΔK diagram for the ML specimen notched in HAZ**
Tab. 5 shows the values of the coefficients $C$ (constant) and $n$ (exponent) for the ML and S welded joint test specimens taken from the heat-affected zone. Figs 9 and 10 are typical diagrams showing the dependence of the crack propagation rate on the scope of the stress intensity factor ($da/dN - \Delta K$) for ML and S specimens notched in the heat-affected zone.

Welded joint toughness should be linked with the change in the inclination of part of the curve in the zone of application of Paris law (middle part of the $S$-curve shown in Figs. 9 and 10). As a rule, materials having a slower crack propagation rate also have a less severe slope on the $da/dN$ diagrams.

### Table 5

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\Delta K$/MPa $\sqrt{m}$</th>
<th>Parameter $C$</th>
<th>Parameter $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZUT-ML</td>
<td>11.2</td>
<td>$1.49 \times 10^{-14}$</td>
<td>3.831</td>
</tr>
<tr>
<td>ZUT- S</td>
<td>7.5</td>
<td>$2.53 \times 10^{-14}$</td>
<td>3.438</td>
</tr>
</tbody>
</table>

### 3 Finite element analysis

#### Numerical model

Using contemporary numerical methods, an ordinary preliminary design of the two-beam bridge crane has been analyzed, and the possibility of replacing the main beam materials has been investigated with the purpose of reducing the overall mass, respecting the prescribed boundary conditions.

In addition to the analysis of the stress-deformation conditions, also applied has been the dynamic analysis of both of the crane model structures, this being an efficient instrument in evaluating the structure behaviour under operating conditions.

A bridge crane having a load-carrying capacity $Q = 70$ kN, and a beam span $L = 19700$ mm (Fig. 11) has been taken as a basic model for a numerical analysis of the behaviour of a real structure.

The main longitudinal beams are made of box-like sections: the preliminary S model is made of the S335 structural steel plate, with a thickness of 12 mm, and the substitution ML model is made of the Nb/V-1 micro-alloy steel plate with a thickness of 7 mm. Tab. 6 shows the basic and the modified structure dimensions of these two models.

Fig. 12 shows a finite-element model (FEM) of the preliminary two-beam bridge crane. The FEM analysis has been performed on 12512 2-D finite elements and 12284 nodes. The boundary conditions have been defined in such a way that the main beams have been statically determined and the movement of the wheels prevented. The analysis has been carried out for the effective load position $Q = 70$ kN at the mid-point of the main beam length.

### Table 6

<table>
<thead>
<tr>
<th>Index</th>
<th>Rate/mm</th>
<th>Principal dimensions of both models</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_k$</td>
<td>3000</td>
<td>wheel span</td>
</tr>
<tr>
<td>$l_s$</td>
<td>1000</td>
<td>hoist wheel span</td>
</tr>
<tr>
<td>$l_v$</td>
<td>1200</td>
<td>hoist shaft span</td>
</tr>
<tr>
<td>$b_S=b_{ML}$</td>
<td>348</td>
<td>main beam width</td>
</tr>
<tr>
<td>Index</td>
<td>Rate/mm</td>
<td>modified dimensions</td>
</tr>
<tr>
<td>$H_S$</td>
<td>762</td>
<td>model S main beam height</td>
</tr>
<tr>
<td>$H_{ML}$</td>
<td>900</td>
<td>model ML main beam height</td>
</tr>
<tr>
<td>$\delta_S$</td>
<td>12</td>
<td>model S vertical plate thickness</td>
</tr>
<tr>
<td>$\delta_{ML}$</td>
<td>7</td>
<td>model ML vertical plate thickness</td>
</tr>
</tbody>
</table>

The overall mass of the preliminary model is 8950 kg, and that of the optimal model 6198 kg.
3.2 Results of FEM analysis
Rezultati analize konačnim elementima

Based on the static and dynamic analyses of the preliminary and modified models of the bridge crane under consideration it is possible to make an overall analysis of the stress-deformation condition values obtained, and of the dynamic behaviour frequency values for the preliminary and modified models.

Fig. 7 shows the stress-deformation condition determined by the numerical analysis. Primarily given are the model deflection values under the nominal load, and the crane weight, after which follow the stress condition values and in particular the values of the equivalent stresses (von Misses), normal stresses and tangential stresses.

The deflection parameters show a reduction, which is satisfactory in terms of the allowable deflection limit of \( L/500 \). Thus, the bridge crane, after the modification, is within the limits of allowable deflections, safety degree \( S=1.5 \), and allowable stresses [14].

The dynamic analysis has been carried out using the method of concentrated masses. It is limited to its own forms since such analysis itself indicates the structure behaviour under compulsory oscillations caused, for instance, by a sudden rise or drop of the weight, etc. The dynamic analysis results are given in Tab. 8, whereas a graphic presentation for the first oscillation mode, appearing on the x-z plane is given in Fig. 13.

### Table 7 Results of the stress-strain analysis

<table>
<thead>
<tr>
<th>PRELIMINARY MODEL 348×762 mm, Thickness ( \delta = 12 ) mm, specimen S</th>
<th>STRESS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent</td>
<td>Normal, ( \sigma )</td>
</tr>
<tr>
<td>77,6</td>
<td>77,6</td>
</tr>
<tr>
<td>Allowed stress: ( \sigma_{\text{allow}}=R_{\text{eff}}/S=444/1.5=296 ) MPa</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MODIFIED MODEL 348×900 mm, Thickness ( \delta = 7 ) mm, specimen ML</th>
<th>STRESS/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent</td>
<td>Normal, ( \sigma )</td>
</tr>
<tr>
<td>105</td>
<td>83</td>
</tr>
<tr>
<td>Allowed stress: ( \sigma_{\text{allow}}=R_{\text{eff}}/S=583/1.5=388 ) MPa</td>
<td></td>
</tr>
</tbody>
</table>

The dynamic responses of the structures under consideration within the frequency domain for the impulse on the \( y \) plane and the response on the \( x-y \) plane are shown in Figs. 14 and 15, whereas those for the impulse on the \( y \) plane and the response on the \( x-z \) plane are shown in Figs. 16 and 17.

---

**Table 7 Results of the stress-strain analysis**

**Tabela 7. Rezultati analize naprezanje-deformacije**

**S model with thickness \( \delta = 12 \) mm, the x-z plane, \( f_0 = 5.2 \) Hz**

**ML model with thickness \( \delta = 7 \) mm, the x-z plane, \( f_0 = 6.0 \) Hz**

**Figure 13 Dynamic analysis for the first mode of oscillation**

**Slika 13. Dinamička analiza za prvi mod osciliranja**

According to the results of the dynamic analysis shown in Tab. 8, the models have low values of their...
3.3 Analysis of results

The tensile tests have been used as the starting data for the determination of the J-integral. It can be concluded that the ML steel welded joint has considerably higher strength values ($R_m = 501.5$ MPa) than the selected S steel welded joint ($R_m = 335.5$ MPa). Fatigue resistance values achieved for these two test specimens, show that the fatigue resistance of the selected ML welded joint is $21.5\%$ higher than that of the S selected welded joint (Figs. 1 and 2).

Decreasing temperature has negative effects on the welded joint impact properties. The values of the overall impact energy of these two materials differ considerably. With almost all samples, except in the heat-affected zone of the S sample at $-60^\circ$C, the energy required to initiate a crack is basically lower than that required to expand it. Technically speaking, the higher absorption of energy in crack propagation is more preferable because this prevents the structure from brittle fracture. In other words, the energy absorbed in crack propagation, the more probability of observing a failure and reacting timely for the purpose of preventing the fracture.

Critical crack length of ML specimens is almost twice the size of critical crack length of the S specimens at all characteristic parts of the welded joint, see Tab. 4.

A slower propagation rate has been noticed on the ML welded joint specimens, because this type of specimen requires a wider scope of the stress intensity factor for the same crack propagation rate. However, on the HAZ-S specimen the crack propagation rate is faster for the same scope of the stress intensity factor.

At higher $K_I$ values, a faster crack propagation rate is necessary for transition to the brittle fracture zone, as seen in Fig. 9.

Based on the results shown in Tab. 7, it is obvious that an increase in the box-like section height of the main longitudinal beam and a decrease in the wall thickness of the vertical plates have resulted in a stress increase along the complex structure of the bridge crane, but for all that the structure strength requirements have not been neglected.

Comparing the preliminary ($\delta = 12$ mm) and modified ($\delta = 7$ mm) models in terms of the frequency analysis, it is noticeable that the modified model has a bit more favorable dynamic factor for the vertical impulse plane (Figs. 14 and 15), whereas for the horizontal impulse plane it has worse properties, (Figs. 16 and 17).

4 Discussion and conclusions

Based on extensive mechanical investigations, fracture mechanics tests, static and dynamic analyses using the finite element methods for two types of models (preliminary and modified) it can be concluded that an increase in the height of the longitudinal beams cross-section from 792 to 900 mm accompanied by a decrease in the vertical plate thickness from 12 to 7 mm has resulted in a significant reduction in the overall mass of the bridge crane by $30.75\%$. The modification has had a beneficial effect on the model deformation properties. The modification has caused a small increase in the structure stress properties but this has been within the limits of allowable stresses. The substitution of the materials and the modification of the longitudinal beams cross section resulted in improved dynamic properties of the structure in terms of its own frequency values. The substitution of the ordinary structural steel with the micro-alloy steel using adequate welding technology has brought about a significant increase in the mechanical properties even at lowered temperatures.

Thus, besides a considerable reduction in the structure mass and the materials cost savings there has been an improvement in the static-dynamic behaviour parameters of the two-beam bridge crane complex structure, in the course of which the introduction of the micro-alloy steel, welded using prescribed technology, has increased the resistance of the structure to brittle fracture and fatigue crack propagation.

Acknowledgement

This project was supported by Federal Ministry of Education and Science of Bosnia and Herzegovina under project No. 03-39-5980-50-2/08.

5 References


Authors' addresses
Adresse autora

As. Professor dr. sc. Nedeljko Vukojević, mechanical engineer
University of Zenica
Faculty of Mechanical Engineering
Fakultetska br. 1
72000 Zenica, Bosnia and Herzegovina
Contact: Phone: +387 32 449 133
Fax: +387 32 246 612
e-mail: vukojevicn@mf.unze.ba

Professor dr. sc. Mirsada Oruč, metallurgical engineer
The Metallurgical Institute "Kemal Kapetanović" Zenica
of The University in Zenica
Travnička cesta br. 7
72000 Zenica, Bosnia and Herzegovina

Professor dr. sc. Dušan Vukojević, mechanical engineer
University of Zenica
Faculty of Mechanical Engineering
Fakultetska br. 1
72000 Zenica, Bosnia and Herzegovina

Mr. sc. Fuad Hadžikadunić, mechanical engineer
University of Zenica
Faculty of Mechanical Engineering
Fakultetska br. 1
72000 Zenica, Bosnia and Herzegovina

Mr. sc. Omer Beganović, metallurgical engineer
The Metallurgical Institute "Kemal Kapetanović" Zenica
of The University in Zenica
Travnička cesta br. 7
72000 Zenica, Bosnia and Herzegovina