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Modelling of the mechanical properties of steel 316L after EB treatment

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Abstract. Investigation of the variation of the mechanical properties of 316L steel after electron beam surface modification is performed. The samples were processed at an installation in IE BAS - ELIT – 60. The irradiated plates were with thickness of 0.5 mm. The experiments were carried out with a change in the beam power in the range of 0.6 to 0.9 kW and different irradiation times between 1 to 120 seconds. Regression analysis was performed on the obtained results.

1. Introduction
The austenitic stainless steel 316/316L has excellent mechanical properties and very good weldability. It is a chromium-nickel-molybdenum alloy developed to provide improved corrosion resistance in moderately corrosive environments. It also provides higher (for example compared to steel 304/304L) creep, stress-to-rupture and tensile strength at elevated temperatures. The alloy has an excellent resistance to intergranular corrosion in welded condition. The alloy 316/316L is non-magnetic in the annealed condition, but it can become slightly magnetic as a result of cold working or welding. Due to its low carbon content the Alloy 316L should be used in environments that are sufficiently corrosive to cause intergranular corrosion of welds and heat-affected zones. The properties of this type of stainless steel define it as a preferred alloy for various architectural, industrial and transport applications. The chemical composition of 316L austenitic stainless steel is presented in table 1.

| Elements          | Weight content in 316L steel, % (maximum) |
|-------------------|------------------------------------------|
| Chromium          | 16.0 min – 18.0 max                      |
| Nickel            | 10.0 min – 14.0 max                      |
| Molybdenum        | 2.00 min – 3.00 max                      |
| Carbon            | 0.030                                    |
| Manganese         | 2.00                                     |
| Phosphorous       | 0.045                                    |
| Sulphur           | 0.03                                     |
| Silicon           | 0.75                                     |
| Nitrogen          | 0.1                                      |
| Iron              | Balance                                  |
In this paper an investigation of the variation of the mechanical properties 0.2% proof strength $R_{P0.2}$, tensile strength $R_m$ and percentage elongation after fracture $A_{30}$ of 316L steel after electron beam surface modification is performed. The samples were processed at an installation in IE BAS - ELIT – 60 (figure 1). Regression models for the dependencies of the physical-mechanical properties of the irradiated samples on the electron beam modification process parameters – electron beam power and irradiation time are estimated.

2. Experimental conditions and test results

Samples of austenitic stainless steel 316L were irradiated in 60 kW electron beam installation in order to investigate the change in their physical-mechanical properties. The thickness of the irradiated samples was 0.5 mm and in figure 2 are given their dimensions. The experiments were performed by varying the power of the electron beam in three levels: 0.6 kW, 0.75 kW and 0.9 kW and different irradiation times (from 1 s to 120 s). Samples were irradiated with different powers over a time of 1 to 120 s. The focal length was 340 mm and the spot size with a diameter of 20 mm was changed to 30 mm on account of the deflection angle. The irradiation was stopped before the sample was melted. The highest power 0.9 kW lead to the melting of the sample after 12 seconds.

![Figure 1. 60 kW electron beam installation.](image1)

![Figure 2. Sample dimensions.](image2)

| Test temperature - $T$ $^\circ\text{C}$ | 0.2% proof strength $R_{P0.2}$ MPa | Tensile strength $R_m$ MPa | Percentage elongation after fracture $A_{30}$ % |
|--------------------------------------|-----------------------------------|--------------------------|----------------------------------|
| 20                                  | 264                               | 610                      | 30.3                             |

The mechanical properties 0.2% proof strength $R_{P0.2}$, tensile strength $R_m$ and percentage elongation after fracture $A_{30}$ of 316L steel are laboratory tested at temperature 20 $^\circ$C for non-irradiated sample (table 2) and the irradiated samples according the standard EN ISO 6892-1:2016. The standard specifies the method for tensile testing of metallic materials and defines the mechanical properties which can be determined at room temperature. Tests were performed using tensile testing machine ZD10/90.

The test results for the EB irradiated samples are presented in table 3 for different EB powers and different irradiation times. It can be seen that generally the 0.2% proof strength $R_{P0.2}$ and the tensile strength $R_m$ were reduced due to the electron beam irradiation. The maximal reduction of the proof strength $R_{P0.2}$ was 29.17%, while that of the tensile strength $R_m$ was 14.59%.
On the other hand, the percentage elongation after fracture $A_{30}$ was increased for all the experiments, compared to that of the not irradiated sample. The maximal increase was 59.3, which is a double magnification.

\[
\begin{array}{cccccccccc}
0.2\% \text{ proof strength } R_{P0.2} \text{, MPa} & \text{Tensile strength } R_m \text{, MPa} & \text{Percentage elongation after fracture } A_{30} \text{, } \% \\
\hline
0.6 & 0.75 & 0.9 & 0.6 & 0.75 & 0.9 & 0.6 & 0.75 & 0.9 \\
\hline
\text{t(s)} & P & \text{kW} & \text{kW} & \text{kW} & \text{kW} & \text{kW} & \text{kW} & \text{kW} \\
1 & 264 & 254 & 256 & 604 & 609 & 610 & 59.3 & 54.0 & 53.3 \\
6 & 264 & 262 & 230 & 603 & 605 & 586 & 57.7 & 56.3 & 39.3 \\
12 & - & 246 & - & - & 597 & - & - & 54.0 & 46.7 \\
15 & 266 & 243 & 204 & 606 & 597 & 550 & 59.3 & 44.3 & 37.3 \\
90 & 260 & 187 & - & 605 & 534 & - & 54.0 & 46.7 & - \\
120 & 224 & 187 & - & 571 & 521 & - & 48.0 & 51.3 & - \\
\end{array}
\]

It is well known that welding parameters can greatly influence the mechanical properties of the welded materials [3]. Analogue regimes of material treatment are applied, besides during the made electron beam surface modification, during electron beam welding of thin plates or electron beam micro-welding. In [4] it is shown that during electron beam welding the tensile properties in different regions of the weld, obtained using micro tensile test specimens, are in good agreement with those determined by full field strain mapping on a standard tensile specimen whose gauge contained all the regions of the weld. Strain mapping proves to be an effective way of determining the mechanical properties within materials with heterogeneous properties (as the material across the welded region).

During the performed experiments the homogeneity of the irradiation is limited by the assumption for Gaussian distribution of the beam, which makes small heterogeneity at the ends of the tested pieces. The measured mechanical properties also can have small deviations there.

From the obtained test results in table 3 it can be seen that when the electron beam irradiation is performed with small beam power 0.6 kW for 15 seconds there is only a small reduction in the values of the 0.2% proof strength $R_{P0.2}$ and the tensile strength $R_m$, while the percentage elongation after fracture $A_{30}$ increases almost twice. In order to obtain precise optimization of the desired mechanical properties according the choice of the surface modification process parameters and the specific material application, modelling of these relationships is done.

3. Modelling of the 316L steel properties

RSM is an effective statistical technique for the investigation of complex processes where many factors and interactions affect the desired responses, and the main advantage is the reduced number of experimental runs required to provide sufficient information for statistically acceptable results [5, 6].

Regression analysis was implemented in order to estimate regression models for the dependencies of the investigated mechanical characteristics: 0.2% proof strength $R_{P0.2}$, tensile strength $R_m$ and percentage elongation after fracture $A_{30}$ on the electron beam modification process parameters: the electron beam power and the irradiation time. The considered EB process parameter variation regions are presented in table 4.

\[
\begin{array}{cccc}
\text{Factor} & \text{Dimension} & \text{Coded} & \text{Lower level (}z_{\text{min,i}}\text{)} & \text{Upper level (}z_{\text{max,i}}\text{)} \\
\hline
\text{Electron beam power – } z_1 & \text{kW} & x_4 & 0.6 & 0.9 \\
\text{Irradiation time – } z_2 & \text{s} & x_5 & 1 & 120 \\
\end{array}
\]
The estimated regression models give the relation between the mechanical properties of the irradiated samples and electron beam power $z_1$ and the irradiation time $z_2$. They are given for coded in the region [-1+1] values in table 5 and the relation between the coded ($x_i$) and the natural values ($z_i$) is given by:

$$x_i = (2z_i - z_{i,max} - z_{i,min})/(z_{i,max} - z_{i,min})$$

(1)

### Table 5. Regression Models.

| Regression Models | $R^2$, % |
|-------------------|----------|
| $R_{p0.2}$        | 216.58035 – 61.594895$x_1$ – 38.694393$x_2$ – 20.461354$x_1$x_2 + 36.068014$x_1$x_2^2 | 89.316 |
| $R_m$             | 559.63491 – 64.076692$x_1$ – 43.654002$x_2$ + 38.106777$x_1$x_2^2 – 28.184964$x_1$x_2 | 90.519 |
| $A_{30}$          | 41.89538 – 15.922916$x_1$ + 12.052033$x_2$ + 5.1331354$x_1$x_2 + 16.800547$x_1$x_2^2 | 80.355 |

These models can be used for investigation of the studied relationships, as well as for the optimization based on specific technological requirements. In figures 3-5 contour plots for the corresponding mechanical properties as a function of the process parameters are presented. The colored regions coincide with the approximate estimation of the process parameter regimes, at which melting of the sample is expected.

![Figure 3. $R_{p0.2}$ – 0.2% proof strength.](image3)

![Figure 4. $R_m$ – tensile strength.](image4)

![Figure 5. $A_{30}$ – Percentage elongation after fracture.](image5)
4. Conclusions
The present work presents experimental results of electron beam irradiation of 0.5 mm thick samples of austenitic stainless steel 316L with different beam powers and different irradiation duration. It was shown that the electron beam parameters (electron beam power and irradiation time) strongly influence the mechanical properties of the investigated steel 316L samples. Analogue regimes of material treatment are applied, besides during the made electron beam surface modification, during electron beam welding of thin plates or electron beam micro-welding. It was shown that the 0.2% proof strength \( R_{P0.2} \) and the tensile strength \( R_m \) were reduced due to the electron beam irradiation and that the maximal reduction of the proof strength \( R_{P0.2} \) was 29.17%, while that of the tensile strength \( R_m \) was 14.59%. The percentage elongation after fracture \( A_{30} \) was increased for all experiments, reaching almost a double magnification. The estimated regression models present the functional relationship between the physical mechanical properties of the irradiated samples and the electron beam process parameters – the electron beam power and the irradiation time. These models can be implemented as additional criteria at choosing the optimal working regimes for electron beam processes.

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