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REGRESSION ANALYSIS OF THE INFLUENCE OF A CHEMICAL COMPOSITION ON THE MECHANICAL PROPERTIES OF THE STEEL NITRONIC 60

REGRESIJSKA ANALIZA VPLIVA KEMIJSKE SESTAVE NA MEHANSKE LASTNOSTI JEKLA NITRONIC 60

Almaida Gigović-Gekić, Mirsada Oruč, Hasan Avdušinović, Raza Sunulahpašić
University of Zenica, Faculty of Metallurgy and Materials Science, Zenica, Bosnia and Herzegovina
almaida.gigovic@famm.unze.ba

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Nitronic 60 (UNS S21800) is a highly alloyed austenitic stainless steel with increased amounts of manganese and silicon that has good mechanical and corrosion properties. This paper presents the results of a regression analysis of the influence of the chemical composition, i.e., the alphagenic (Si and Cr) and gamagenic (Mn and Ni) elements on the tensile properties of the steel. The results of the analysis are the equations with which we can calculate the strength for a given chemical composition when a measurement is disabled. The regression analysis showed that the strength of the steel can be increased with an increased amount of alphagenic elements and that the influence of Mn on the strength depends on the Si amount.

Keywords: austenitic stainless steel Nitronic 60, alphagenic elements, gamagenic elements, tensile properties, regression analysis

Nitronic 60 (UNS S21800) je visoko legirano avstenitno nerjavno jeklo s povečano vsebnostjo mangana in silicija ter z dobrimi mehanskimi in korozijskimi lastnostmi. Ta članek predstavlja rezultate regresijske analize vpliva kemijske sestave, to je alfagenih (Si in Cr) in gamagenih (Mn in Ni) elementov na natezno trdnost jekel. Rezultati analiz so enačbe, s katerimi lahko izračunamo trdnost jekla iz dane kemijske sestave, če meritev ni mogoča. Regresijska analiza je pokazala, da se trdnost povišuje z naraščanjem vsebnosti alfagenih elementov in tudi, da je vpliv Mn na trdnost odvisen od vsebnosti Si.

Ključne besede: avstenitno nerjavno jeklo Nitronic 60, alfageni elementi, gamageni elementi, natezna trdnost, regresijska analiza

1 INTRODUCTION

Microstructure stability is the most important requirement for obtaining proper mechanical properties of an austenitic stainless steel (ASS).[1] The microstructure of Nitronic 60 is primarily monophasic, i.e., austenitic, but a precipitation of the delta ferrite (δ-ferrite) in an austenite matrix is possible, too. A higher volume fraction of the δ-ferrite in a microstructure can be achieved by changing the chemical composition. The main alloying elements in austenitic stainless steel can be classified as alphagenic and gamagenic elements. The alphagenic elements (Cr, Si, Ti, Al, Mo, V, Nb and W) stabilize and support the formation of δ-ferrite, while the gamagenic elements (Ni, Mn, C, N, and Cu) stabilize the austenitic phase.[2,3] The presence of δ-ferrite with a BCC crystalline structure slows down the grain growth and increases the strength properties of the steel because the interphase boundaries act as strong barriers to the dislocation motion.[4] This paper presents the testing results for the mechanical properties (the tensile and yield strengths) of the austenitic stainless steel Nitronic 60, and the regression analysis of the relationships between the chemical composition and mechanical properties of the steel Nitronic 60.

2 DESIGN OF THE EXPERIMENT

The plan of the experiment predicted a programming of the amounts of the basic alphagenic (Cr and Si) and gamagenic (Ni and Mn) elements in the experimental melts. The plan required that the amounts of the alloying elements in the experimental melts should have a range of values equal to ± 0.5 % for Ni, Mn, Si and ± 1.0 % for Cr in relation to the mean value of the chemical amount prescribed by standard A276. Another requirement is that the amounts of the other chemical elements (C, N, P and S) should be kept at approximately the same level, i.e., 0.05 % C, 0.15 % N, 0.06 % P and 0.03 % S. The number of melts (N) is determined with a fragmented dynamic planning model as $N = 2^{k-1}$ (the k-number of independent variables). The checking of the reproducibility of the results includes a randomization and a double repetition of each experimental melt. This means that the total number of the produced melts was 16. The chemical compositions of the produced melts are in accordance with the standard of ASTM A276-96, **Table 1**. After forging and rolling the melts into Ø 15 mm bars, the produced bars were heat treated at 1020 °C for 1 h and quenched in water to obtain austenitic microstructures. The testing of the tensile properties was carried out on the samples in the heat-treated state according to standards EN 10002-1/02 and EN 10002-5/01. The results of testing are given in **Table 1**.

3 ANALYSIS AND DISCUSSION OF THE EXPERIMENTAL RESULTS

3.1 Regression analysis

A multifactorial experiment was used for the analysis of the influence of alphagenic and gamagenic elements on the tensile properties. The MATLAB software (version 7) and its module Model-Based Calibration Toolbox was used for the regression analysis and graphical interpretation.[5] A second-order mathematical model, i.e., a square regression model was assumed. This approach enabled an analysis of not only the individual effects of the factors but also of their mutual, i.e., coupled effects.[6,7] On the basis of the testing and statistical data, the regression equations for R_m and $R_{p0.2}$ are as follows:

$$R_m/\text{MPa} = 3997.21 - 758.84x_1 - 962.44x_2 - 1759.93x_3 + 3020.52x_4 + 89.64x_1^2 - 16.02x_1x_2 + 92.26x_1x_3 - 35.87x_1x_4 + 30.45x_2^2 + 17.48x_2x_3 - 12.30x_2x_4 + 43.36x_3^2 + 49.55x_3x_4 - 181.30x_4^2 \quad (1)$$

$$R_{p0.2}/\text{MPa} = 3\,695.62 - 484.99x_1 - 280.03x_2 - 1225.70x_3 + 1011.87x_4 + 50.59x_1^2 - 17.83x_1x_2 + 113.22x_1x_3 - 48.53x_1x_4 + 14.90x_2^2 + 5.50x_2x_3 - 17.76x_2x_4 + 27.88x_3^2 + 28.19x_3x_4 - 44.07x_4^2 \quad (2)$$

Note: x_1/% = w(Si); x_2/% = w(Cr); x_3/% = w(Mn); x_4/% = w(Ni) (mass fractions: w)

The values of the tensile properties calculated with regression equations (1) and (2) have a very good match with the values obtained experimentally. **Table 1** shows the deviations of the tensile values (R_m and $R_{p0.2}$) obtained using the regression model (K_M) from the experimentally obtained values (K_E) according to the following equation:

$$Deviation = \frac{(K_M - K_E)}{K_E} \cdot 100(\%) \quad (3)$$

From **Table 1**, it can be seen that the deviations of the $R_{p0.2}$ values are slightly higher than the deviations of the R_m values. The maximum deviation of the $R_{p0.2}$ value is 2.5 %. The deviation of the R_m value does not exceed 0.6 %, which is the maximum deviation obtained for No. 5. In terms of mathematical precision, small deviation values indicate that the model is suitable. The statistical data confirming the adequacy of the model is given in **Table 2.**

3.2 Graphical interpretation of the results

The MATLAB software with module Model-Based Calibration Toolbox was also used for a graphical interpretation. Considering that a three-dimensional space can be represented with only two independent variables and their impact on the dependent variable, in this case, it is not possible to graphically present the impact of four independent variables on the dependent variable. The

Table 1: Chemical composition of steel Nitronic 60 and a review of the experimental and model-based values of the tensile properties with the corresponding deviations
Tabela 1: Kemijska sestava jekla Nitronic 60 in pregled eksperimentalnih ter modelnih vrednosti za natezno trdnost s pripadajočimi odmiki

Melt	Chemical composition, w/%				R_m/MPa		Deviation /%	$R_{p0.2}$/MPa		Deviation /%
	Si	Cr	Mn	Ni	K_E	K_M		K_E	K_M	
1	4.25	16	8.4	8.8	749	747.45	–0.21	385	381.5	–0.89
2	4.41	18	7.4	8.1	821	821.13	0.02	467	467.29	0.062
3	3.81	18	7	8	791	790.17	–0.10	463	461.20	–0.39
4	3.74	18	8.6	8	750	747.22	–0.37	400	393.98	–1.50
5	3.69	17.8	8.2	8	706	710.21	0.60	365	374.13	2.50
6	3.5	16.9	7.9	8.6	681	677.55	–0.51	331	323.52	–2.26
7	3.5	16.9	7.2	8.6	716	720.02	0.56	366	374.70	2.38
8	4.5	16	8.6	8	793	792.20	–0.10	442	440.27	–0.39
9	4.54	16	7.5	9	718	718.06	0.01	365	365.13	0.03
10	3.8	17.3	7.4	8.6	724	719.94	–0.56	387	378.22	–2.27
11	3.5	16.6	7.2	8	707	706.35	–0.09	357	355.59	–0.39
12	4.39	16.8	8	8.8	746	747.34	0.18	394	396.91	0.74
13	4.39	16	7.9	8	734	734.81	0.11	378	379.75	0.46
14	3.8	17	8.9	9	708	707.76	–0.03	356	355.49	–0.14
15	3.7	17.7	7.9	8.6	734	736.16	0.29	378	382.68	1.24
16	3.9	16	9	8.7	731	732.64	0.22	340	343.55	1.04

Table 2: Statistical data for the model
Tabela 2: Statistični podatki za model

Tensile property	Coefficient correlation R	R^2	Adjusted R square	Standard error	SS regression	SS residual
R_m	0.998	0.996	0.938	9.173	20262.79	84.143
$R_{p0.2}$	0.992	0.984	0.755	19.868	23785	394.753

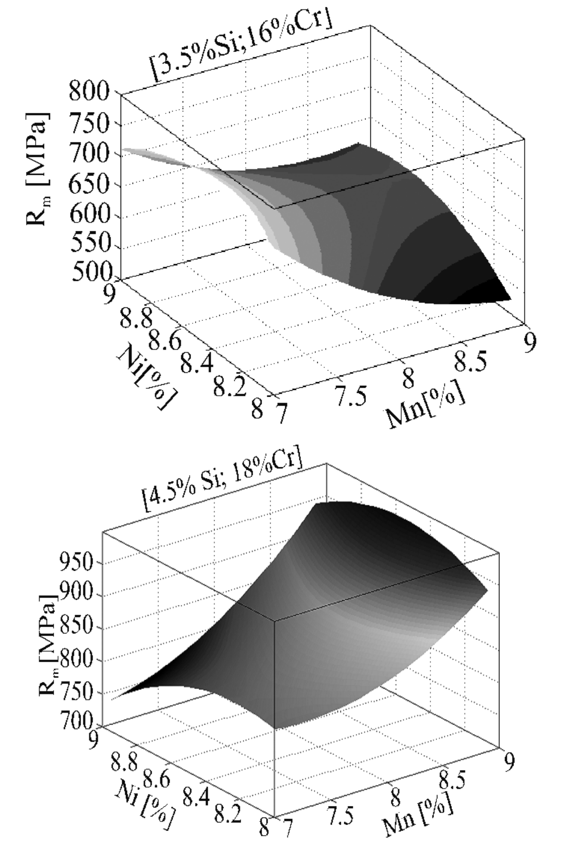

Figure 1: Functional dependence of R_m on the amounts of Mn and Ni
Slika 1: Funkcionalna odvisnost R_m od vsebnosti Mn in Ni

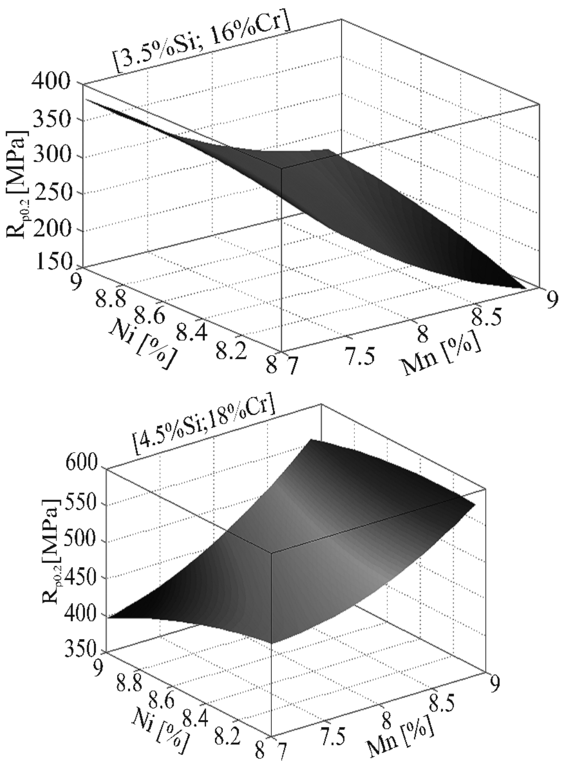

Figure 2: Functional dependence of $R_{p0.2}$ on the amounts of Mn and Ni
Slika 2: Funkcionalna odvisnost $R_{p0.2}$ od vsebnosti Mn in Ni

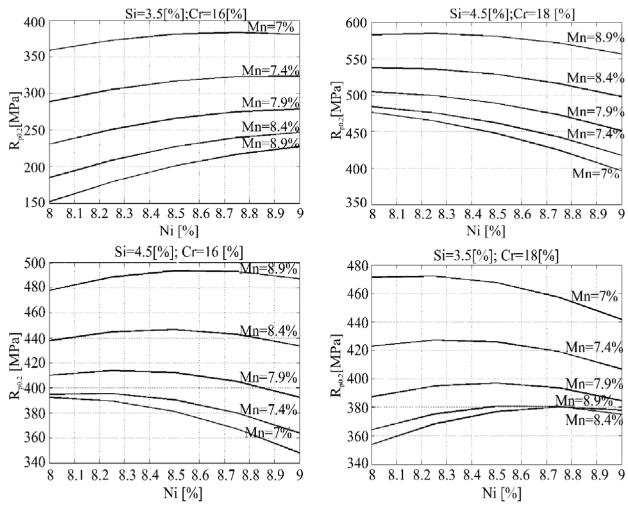

Figure 3: Interaction between alphagenic and gamagenic elements
Slika 3: Interakcije med alfagenimi in gamagenimi elementi

analysis of the results was based on the observation of the impact of alphagenic elements on the strength because of their tendency to form δ-ferrite that increases the strength. The studies have shown that the amount of δ-ferrite can be up to 10 % if the amount of alphagenic elements is maximum and the amount of gamagenic elements is minimum.[8] However, the δ-ferrite amount in

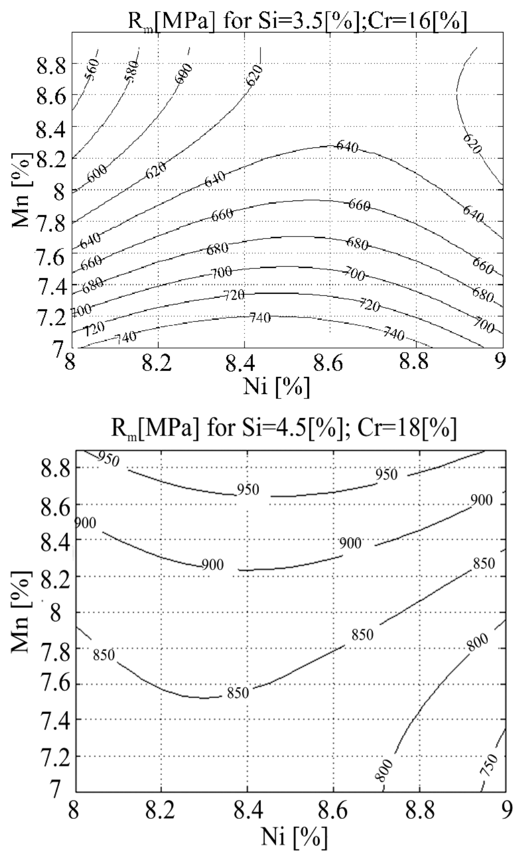

Figure 4: Graphical presentation of the tensile-strength curves according to equation (1)
Slika 4: Grafična predstavitev krivulj natezne trdnosti po enačbi (1)

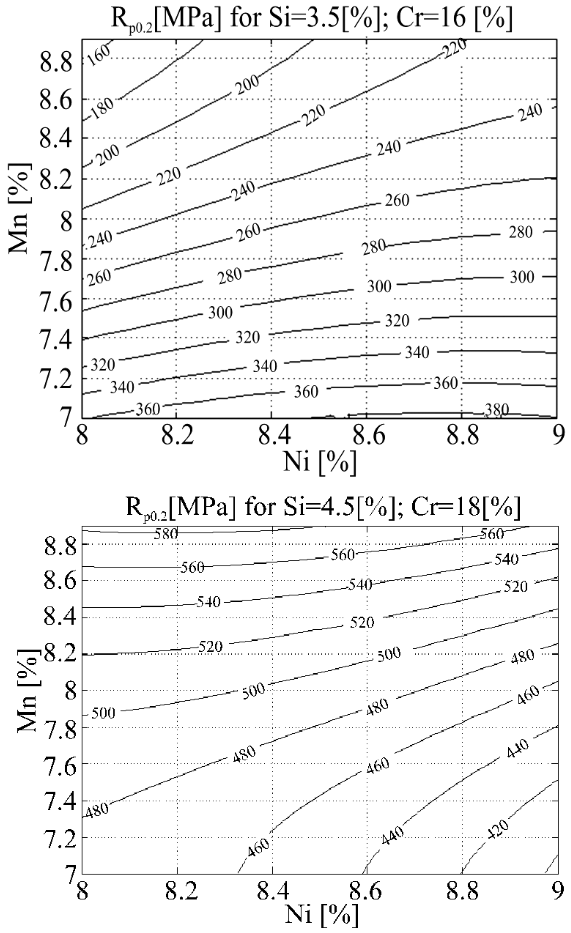

Figure 5: Graphical presentation of the tensile-strength curves according to equation (2)
Slika 5: Grafična predstavitev krivulj natezne trdnosti po enačbi (2)

this steel is limited to 2 %, which has to be taken into consideration. In the opposite case, δ-ferrite would have a negative influence on the ductile properties.[9] **Figures 1** and **2** show the influences of the minimum and maximum amounts of alphagenic elements on the strength of the steel Nitronic 60.

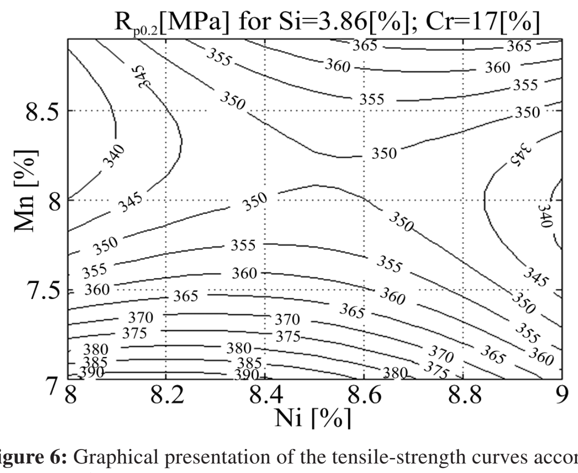

Figure 6: Graphical presentation of the tensile-strength curves according to equation (2)
Slika 6: Grafična predstavitev krivulj natezne trdnosti po enačbi (2)

The tensile properties of the steel Nitronic 60 increase with the increasing amount of alphagenic elements. However, the effect of Mn on the tensile properties changes with the increasing amount of alphagenic elements. At a lower amount of alphagenic elements, Mn decreases the tensile strength, but when their amount is increased, Mn increases the strength. Ni decreases the strength of the steel independently of the influence of alphagenic elements, especially when the amount is higher than 8.5 %. Observing the interaction between alphagenic and gamagenic elements, we can see that Si has a significant influence on the effect of Mn (**Figure 3**). The role of Mn changes with the increasing amount of Si. The effect of Cr is not so significant; only at the maximum values of Cr its interaction with Mn can be seen. **Figure 3** shows an interaction in the case of determining $R_{p0.2}$; however, the same interaction was observed in the case of determining R_m.

These surfaces (**Figures 1** and **2**), belonging to a three-dimensional space, can be easily represented and interpreted by designers and technologists in the steel industry. Especially, it is possible to use the curves presented in **Figures 4** and **5**. The curves are presented in the form of a graph resulting from the intersection of the surface (**Figures 1** and **2**) correlation with the parallel planes. In each plane there is a part of the plane of the intersection. Thanks to this graph, a designer or a technologist can easily determine an expected value of the strength for a given chemical composition without executing the calculation.

From **Figures 4** and **5**, it can be seen that for the minimum amounts of Cr and Si, the amount of Ni can range from its maximum to the minimum value, but the amount of Mn should be minimal in order to obtain the strength values prescribed by standard A276. The standard minimum value for R_m is 655 MPa and the minimum value for $R_{p0.2}$ is 345 MPa. In the case of the middle values for the amounts of Si and Cr, the amount of Ni should be in the range of 8.2 to 8.8 % in order to obtain the values of $R_{p0.2}$ prescribed by the standard (**Figure 6**). It was already mentioned that with the maximum amounts of Si and Cr, the strength values will be maximum.

4 CONCLUSIONS

The regression analysis allows us to find a connection between one or more independent variables and one dependent variable, if the latter exists. The equations linking the dependent variable with the independent variables were obtained with a regression analysis. These equations represent a mathematical model, called the regression function that can be obtained only by respecting certain limitations and assumptions.[10] Since the main problem of this paper is a quantification of the effect of alphagenic and gamagenic elements on the mechanical properties of the steel Nitronic 60, the regression analysis was used as a method for predicting these influences. The practical benefit of the regression analysis is the ability to evaluate the dependent variable in the case when its measurement is difficult. In this paper we examine the effect of a chemical composition on the mechanical properties using the regression analysis. On the basis of the analysis we can conclude the following:

- On the basis of the statistical data (correlation coefficients, standard errors and deviations), it can be concluded that the obtained mathematical model satisfies the set requirements.
- The deviations of the mathematical model compared to the experimental values for R_m are below 1 %, and for $R_{p0.2}$ the maximum deviation is 2.5 %.
- On the basis of the graphic presentation of the results it can concluded that with an increase in alphagenic elements (Si and Cr) the strength increases. Increasing the amounts of these elements increases the amount of δ-ferrite, which leads to an increase in the strength but reduces the ductility.[8,9]
- Gamagenic elements decrease the strength, especially at the minimum amount of alphagenic elements.
- With an increased amount of alphagenic elements (especially Si) the influence of Mn on the strength is changed, i.e., Mn increases the strength.
- The graphical model showed that in order to reduce the cost of production (especially for Ni, whose price changes on the market), it is possible to produce a melt with minimum amounts of all the elements and, at the same time, obtain the strength values prescribed in the standard. The minimum amount of alphagenic elements decreases the amount of δ-ferrite below 2 %.
- The maximum amount of alphagenic elements gives the maximum strength values.

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