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OPTIMIZATION OF THE MECHANICAL PROPERTIES OF THE SUPERALLOY NIMONIC 80A

OPTIMIRANJE MEHANSKIH LASTNOSTI SUPERZLITINE NIMONIC 80A

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The superalloy Nimonic 80A has found its major application in the production of the parts for the vehicle and airplane industries. It is a relatively expensive material and it is very important to reduce its production costs to acceptable levels. The aim of this research was to produce the superalloys with varying supplements of alloying elements.

The investigations carried out included chemical testing and the testing of the mechanical properties of the superalloy Nimonic 80A, followed by a regression analysis of the obtained data to show the influence of certain alloying elements that can significantly affect the improvement of the mechanical properties of Nimonic 80A.

The results of the regression analysis are the equations with which, on the basis of the known chemical composition, i.e., the content of the main alloying elements – Al, Ti and Co – the mechanical properties of the materials at increased temperatures can be predicted. On the basis of the obtained squared regression equations, an optimization of the chemical composition for the selected values of the mechanical properties was carried out.

Keywords: Nimonic 80A, mechanical properties, regression analysis, optimization

Glavni področji za uporabo in izdelavo delov iz superzlitine Nimonic 80A sta avtomobilska in letalska industrija. Zlitina je relativno drag material, zato je zelo pomembno, da se zmanjšajo stroški njene proizvodnje na sprejemljiv nivo. Namen te raziskave je bila izdelava superzlitine z različnim dodatkom legirnih elementov.

Opravljene preiskave so vključevale kemijsko analizo in preskušanje mehanskih lastnosti superzlitine Nimonic 80A, sledila pa je regresijska analiza dobljenih podatkov, da bi pokazali vpliv legirnih elementov na izboljšanje mehanskih lastnosti Nimonic 80A.

Rezultati regresijske analize so enačbe, ki omogočajo napovedovanje mehanskih lastnosti zlitine pri povišanih temperaturah na podlagi kemijske analize, to je vsebnosti legirnih elementov Al, Ti in Co. Na podlagi dobljenih regresijskih enačb je bilo izvršeno optimiranje kemijske sestave za izbrane vrednosti mehanskih lastnosti.

Ključne besede: Nimonic 80A, mehanske lastnosti, regresijska analiza, optimizacija

1 INTRODUCTION

The superalloy Nimonic 80A is a wrought nickel-based alloy (min. 65 % Ni) containing chromium (20 %), with minor additions of carbon, cobalt and iron, as well as major alloying elements of aluminum (1 % to 1.8 %), titanium (1.8 % to 2.7 %) (according to DIN 17742 its alloy mark is NiCr20TiAl, W.Nr. 2.4952, 2.4631).

This alloy has good mechanical properties and good corrosion resistance at both ambient and elevated temperature. It is designed for the operation at temperatures of up to 815 °C)[1,2], for the parts exposed to high stresses in the temperature range from 600–750 °C[3].

The Ni-based superalloy Nimonic 80A is a multi component alloy that gains its appropriate microstructure and precipitation strength at higher temperatures through the precipitation hardening. The precipitation hardening is obtained by forming γ' phases Ni_3 (Al, Ti). A further strengthening and increase of resistance at elevated temperatures is gained by adding Co[4,5]. The alloying elements that largely affected the mechanical properties of the superalloy Nimonic 80A were Al, Ti and Co.

The surveys carried out included chemical testing and tensile testing of the superalloys Nimonic 80A at a temperature of 750 °C, on the basis of which a regression analysis of the impact of the chemical composition on the mechanical properties was conducted.

This paper presents the results of the tensile tests at a temperature of 750 °C of the superalloys Nimonic 80A, as well as the functional dependence of the influences of the major alloying elements on the mechanical properties.

It also presents an analysis of the influence of the mass fractions (w/%) of Al, Ti and Co on the tensile properties at elevated temperatures (750 °C). The objective function sets the parameters for finding the content of the elements Al, Ti and Co, as well as their interactions, which will give the optimum (selected) mechanical properties of the superalloys Nimonic 80A used at an operating temperature.

2 DESIGN OF EXPERIMENT

For the specific analysis of the influence of the alloying elements on the tensile properties, the multifactorial experiment was proposed. The MATLAB software (version 7.0) and its module Model-Based Calibration Toolbox was used for designing the experiments[6]. The essence of this method is in the planning, the implementation and the analysis of the appropriate number of experimental measurements of the tensile properties of the alloy Nimonic 80A through simultaneous variation of the main factors ($x_1 = w$(Al); $x_2 = w$(Ti); $x_3 = w$(Co). The influential factors were the contents of Al (x_1), Ti (x_2) and Co (x_3). The second-order mathematical model, i.e., the square regression model was assumed. The equation of the second-order regression model can be successfully used as a base for exploring the field of optimum. This approach enables an analysis of not only the individual effects of the factors, but also of their mutual, i.e., coupled effects, as well as determining the optimum values of the factors[5].

According to the 2nd plan of the experiments, the number of melts was determined. The factors were varied at two levels, with repeated experiments for each point of the plan. Tests were conducted using 16 different melts[7].

The making of the melts and the tensile testing were performed at the University of Zenica, "Kemal Kapetanović" Institute. The results of the chemical analysis are shown in **Table 1**. The results of the chemical analysis of the used melts are in accordance with the standard chemical composition for the Nimonic 80A superalloy (DIN 17742, alloy designation NiCr20TiAl). After being forged and rolled into φ = 15 mm bars, the tested materials were heat treated using the standard parameters for this type of superalloys. The standard heat treatment consists of a solution annealing at 1080 °C/8 h and cooling in the air to the room temperature, followed by the precipitation annealing at 720 °C/16 h and cooling in the air[4]. The testing of the tensile properties was carried out in the Laboratories for Mechanical Testing of the "Kemal Kapetanović" Institute, Zenica (**Table 1**). The specimens for testing and tensile testing were prepared in line with Standard BAS EN 10002-5 (for the testing at an elevated temperature)[8].

3 ANALYSIS OF EXPERIMENTAL RESULTS

On the basis of the testing and the statistical-data analysis, the optimum regression equation, as a system response, was chosen for $R_{p0,2}$ (equation 1) and R_m (equation 2) at a temperature of 750 °C:

$$R_{p0,2} = -112.58x_1 + 662.85x_2 - 509.02x_3 + 70.86x_1x_2 - 15.72x_1x_3 - 49.76x_2x_3 + 20.58x_1^2 - 124.83x_2^2 + 245.11x_3^2 \quad (1)$$

$$R_m = -127.11x_1 + 1039.83x_2 - 798.58x_3 + 122.98x_1x_2 + 15.77x_1x_3 - 14.94x_2x_3 - 44.48x_1^2 - 244.91x_2^2 + 300.78x_3^2 \quad (2)$$

In general, an appropriate regression equation provides important information about the influence of the factors on the regression coefficients. The values of the tensile properties calculated with regression equations, (1) and (2), have a very good match with the points obtained with the experiments and are given in **Table 1**.

Table 1 also lists deviations of values $R_{p0,2}$ and R_m obtained by using the model (regression equation K_M), related to the experimentally obtained values for $R_{p0,2}$ and R_m (K_E) and calculated with the following general expression:

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

Table 1: Chemical composition of Nimonic 80A and a review of the experimental and the model values of the tensile properties of the specimens at a temperature of 750 °C
Tabela 1: Kemijska sestava Nimonic 80A in pregled eksperimentalnih in modelnih vrednosti nateznih trdnosti vzorcev pri temperaturi 750 °C

Melt	Content elements, w/%			$R_{p0,2}$/MPa		Deviation /%	R_m/MPa		Deviation /%
	Al	Ti	Co	Experim.	Model		Experim.	Model	
V1647	1.14	2.13	1.67	558	542.7	–2.7	679	681.8	0.4
V1653	1.66	1.82	0.90	533	512.3	–3.9	658	643.3	-2.2
V1651	1.08	2.9	0.83	604	609.4	0.9	673	674.5	0.2
V1669	1.68	2.92	1.88	686	674.4	–1.7	764	741.9	-2.8
V1648	1.20	1.90	0.89	503	505.1	0.4	662	674.5	1.9
V1656	2.14	1.87	1.89	617	614.0	–0.5	680	680.6	0.1
V1652	1.07	2.79	1.83	560	596.9	6.6	677	675.5	-0.2
V1672	1.81	2.8	1.09	634	653.7	3.1	708	711.4	0.5
V1664	0.93	1.69	1.90	532	518.4	–2.6	648	642.9	-0.8
V1654	1.53	1.86	0.87	518	519.9	0.4	660	667.9	1.2
V1671	1.15	2.78	1.10	592	567.0	–4.2	664	646.0	-2.7
V1670	1.40	2.73	1.69	609	605.9	–0.5	685	696.3	1.6
V1665	0.98	1.71	1.04	400	427.9	7.0	606	585.1	-3.5
V1657	1.59	1.80	1.82	521	541.6	3.9	647	655.2	1.3
V1666	1.13	2.66	1.57	583	561.4	–3.7	633	655.6	3.5
V1668	1.64	2.67	1.16	615	616.4	0.2	693	703.0	1.4

Table 2: Statistical characteristics of the used model
Tabela 2: Statistične značilnosti uporabljenega modela

Tensile properties	R^2	Coefficient correlation R	Standard error	SS regression	SS residual	Ficher test		Significant
						Tabular	Model	
$R_{p0,2}$	0.9990	0.9995	26.95303	5197281.74	5085.261	3.69	794.91	YES
R_m	0.9998	0.9996	19.04061	7220737	2537.815	3.69	2212.98	YES

Statistical characteristics of the used model are given in **Table 2**.

Taking into account that regression surfaces cannot be presented in a three-dimensional space, the independent variables are successfully replaced by their average values. Presentation of the 3D model for different values of changeable variables in a specific interval is given in **Figure 1**.

An equation (1 and 2) can be used to calculate the default characteristics at 750 °C by entering the specific values of certain factors. This provides the values for $R_{p0,2}$ and R_m that are close to the experimentally obtained amounts.

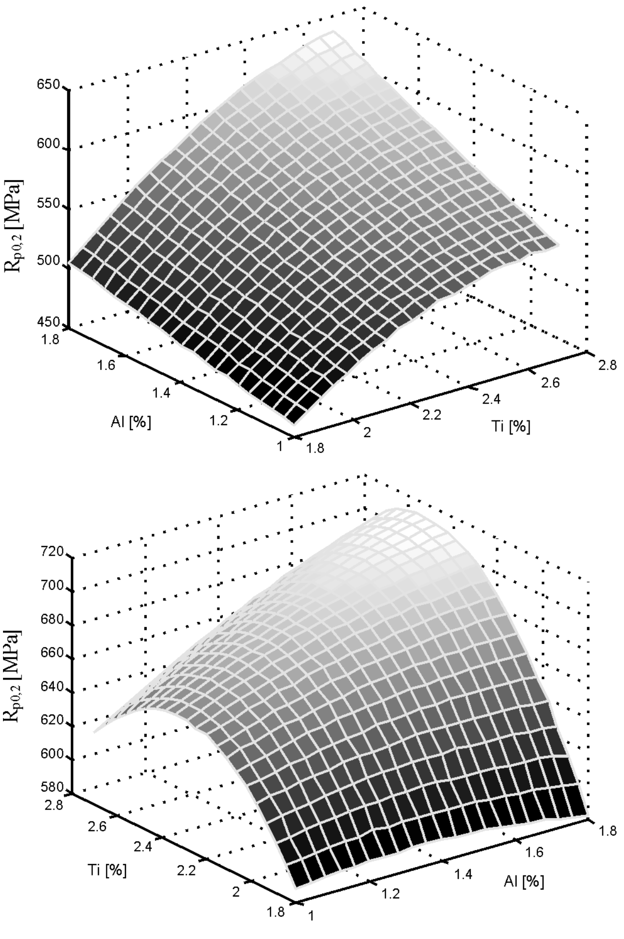

Figure 1: Functional dependence of $R_{p0,2}$, R_m and the influencing factors w(Al), w(Ti) and w(Co)
Slika 1: Funkcijska odvisnost $R_{p0,2}$, R_m in vplivnih faktorjev (masni deleži w(Al), w(Ti) in w(Co))

Those surfaces that represent a three-dimensional space can be easily reproduced and interpreted by designers as well as by technology engineers.

4 DISCUSSION

4.1 Determining the optimum values of the influential parameters x_i for the yield strength y_i ($R_{p0,2}$)

In this example a three-factor model was applied. The varied values of the influential factors of x_i, w(Al), w(Ti) and w(Co), relating to the corresponding plan matrix, are known, and so is the parameter of the investigated processes y_i after conducting the experimental tests, i.e., the value of $Y^{(E)}_{(\max)i} = R^{(E)}_{p0,2(\max)i}$ (equation 1).

The coordinates of possible optimum point in the investigated area, i.e., the global optimum is determined by solving the system of algebra equations derived from the conditions $\partial y / \partial x_i = 0$.

This requirement of the regression equation (1) in the considered case is reduced to a system of three linear algebra equations:

$$\begin{aligned} \partial y / \partial x_1 &= 41.16x_1 + 70.86x_2 - 15.72x_3 = 112.58 \\ \partial y / \partial x_2 &= 70.86x_1 - 249.65x_2 - 49.76x_3 = -662.85 \\ \partial y / \partial x_3 &= -15.72x_1 - 49.76x_2 + 490.22x_3 = 509.02 \end{aligned} \tag{3}$$

whose solutions are: x_1 = 1.8; x_2 = 2.7 and x_3 = 2, where x_1 = w(Al), x_2 = w(Ti) and x_3 = w(Co).

Since these values belong to the investigated area, the regression equation (1) has a global optimum, i.e., the next maximum value for $(R_{p0,2})_{max}$ = 725.28 MPa.

The question is whether the maximum value is also the optimum value for a given alloy. Taking into account that the alloy with the maximum value of yield strength is difficult to use in plastic processing and has lower ductile characteristics, the optimum value for the mean yield strength ($R_{p0,2}$) is used in line with the reference source[8]. At the operating temperature of 750 °C the superalloy Nimonic 80A has a yield strength of $R_{p0,2}$ = (420–620) MPa, and this value was also used as *the optimum value*.

In this case the solutions of the linear algebraic equations (3) are: x_1 = 1.4 % Al, x_2 = 2.09 % Ti and x_3 = 1.365 % Co.

Curves were presented in the form of a graph (**Figure 2**) resulting from the intersection of the surface correlation with the parallel planes (the planes at the same level). In each plane there is a part of the plane of the intersection (the value of the yield strength). With their help it is easy to determine the variation domain of the

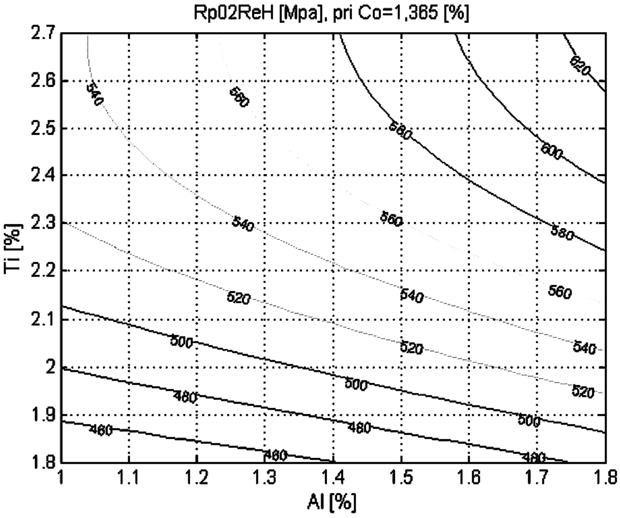

Figure 2: Graphical presentation of the yield-strength curves for Nimonic 80A according to the equation (1)

Slika 2: Grafični prikaz krivulj meje tečenja za Nimonic 80A, skladno z enačbo (1)

analyzed parameters that are suitable for optimizing the yield strength (1).

From the given graph it can be observed that *the selected* optimum field of the yield strength (500–540 MPa) can be obtained with a series of combinations of the content of w(Ti) = (2.1–2.7) % and the content of w(Al) = (1–1.8) % with the stated content of Co.

4.2 Determining the optimum values of the influential parameters x_i of the tensile strength y_i (R_m)

The equation of the regression models of the second order (equation 2) is used as the basis for the research in the area of the optimum tensile strength R_m at 750 °C. Determination of the (optimum) values of the influential parameters x_i for y_i – the tensile strength (R_m) – can be done:

1. by establishing optimum values of the parameters for $R_{p0,2}$,
2. by establishing the adopted optimum value of R_m.

4.2.1 Determination of R_m with the set optimum values of the parameters for $R_{p0,2}$

Determined optimum values of the influential parameters $R_{p0,2}$ were used as the base for exploring the field of strength (R_m). These values belong to the studied area and Figure 1 shows the regression equation (2) (hypersurface) in the multidimensional space (hyperspace).

The Superalloy Nimonic 80A used at the operating temperature of 750 °C, with the set optimum values of the influential parameters being x_1 = 1.4, x_2 = 2.09 and x_3 = 1.365, has the following value of the tensile strength: R_m = 656.05 MPa. This value is at the lower limit of the tensile strength R_m = (620–820) MPa that is given in the literature[9,10].

When the criteria of the optimum values of the tensile strength are set it is necessary to determine the values of the influential parameters.

4.2.2 Determining the optimum values of the influential parameters adopted for the optimum R_m

The regression equation (2) was used to explore the optimum area. The coordinates of the possible optimum points in the studied area were determined by solving a system of algebraic equations obtained from the condition $\partial y / \partial x_i = 0$. Using this condition the regression equation (2) was reduced to a system of three linear algebraic equations:

$$\begin{aligned} \partial y / \partial x_1 &= -88.96 x_1 + 122.98 x_2 + 15.77 x_3 = 127.11 \\ \partial y / \partial x_2 &= 122.98 x_1 - 489.82 x_2 - 14.98 x_3 = -1039.83 \\ \partial y / \partial x_3 &= 15.77 x_1 - 14.946 x_2 + 601.56 x_3 = 798.58 \end{aligned} \tag{4}$$

whose solutions regarding the maximum values are: x_1 = 1.8, x_2 = 2.52 and x_3 = 2.

Since these values belong to the studied area the regression equation (2) has a global optimum with the maximum value of $R_{m\ max}$ = 837,49 MPa.

In a case of choosing the optimum value for the tensile strength with the maximum values for the contents of w(Al), w(Ti) and w(Co), the criteria for choosing the optimum value is the same as for choosing the optimum value of the yield strength.

Based on[9], the superalloy Nimonic 80A, used for the operating temperature of 750 °C, has a R_m = (620–820) MPa and the medium tensile strength R_m = 720 MPa can be adopted as the optimum value. The solutions of the linear algebra equations (4) in this case are: x_1 = 1.4 % Al, x_2 = 2.52 % Ti and x_3 = 1.705 % Co.

For the purpose of optimizing (2) shown in a graphic form (**Figure 3**) the regression equation is suitable for the tensile strength.

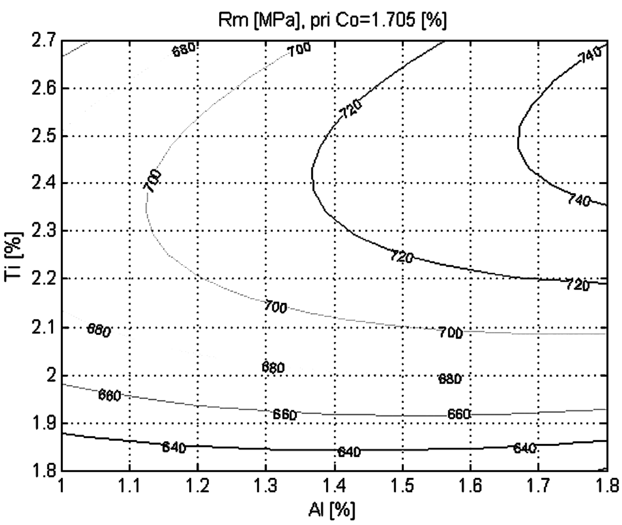

Figure 3: Graphical presentation of the tensile-strength curves for Nimonic 80A according to equation (2)

Slika 3: Grafični prikaz krivulj natezne trdnosti Nimonic 80A, skladno z enačbo (2)

Aa analysis of the gained results indicates that the samples made of superalloys Nimonic 80A have relatively good values of the influential parameters w(Al, Ti, and Co). The obtained results allow the selection of the best ratio of w(Al) and w(Ti) relative to w(Co) in order to obtain the desired values of the mechanical properties. In this case the reduction in the tensile strength Rm, i.e., its maximum value was achieved by adjusting w(Al) and w(Ti). An increase in the value of w(Co) in the range of 1–1.7% does not significantly affect ± 2.64 % a decrease or an increase in R_m.

The result of the research and an insight into the qualitative and quantitative strength contributions of the superalloy Nimonic 80A to all the acting strengthening mechanisms was a design of an acceptable theoretical model for the formation of optimum strength. On the basis of the known chemical composition, i.e., the content of the main alloying elements – Al, Ti and Co – the regression equations are gained and the mechanical properties of the materials shown at elevated temperatures can be predicted. On the basis of the square regression equations an optimization of the chemical composition of materials for the selected values of mechanical properties was carried out.[4,11]

5 CONCLUSIONS

After analyzing an experimental investigation of the influence of the contents of aluminium, titan and cobalt on the tensile properties of the superalloy Nimonic 80A at 750 °C the following can be concluded:

- A mathematical model that establishes a corellation between the main alloying elements (Al, Ti and Co) and the mechanical properties shown at 750 °C is both adequate and accurate;
- All the selected parameters relating to the chemical composition, being varied with regard to two levels, affect the mechanical properties, i.e., all of them are significant;
- In the real working conditions each influential parameter has a different influence and a different effect on the tensile properties. Ti and Al have a high impact on them. Increasing the contents of these elements leads to an improvement in the tensile properties. The influence of Co on the tensile properties is lower than the influence of the other two elements;
- Equations (1) and (2) can be used for the calculation of the tensile properties at 750 °C for the specific values of individual factors. The values for $R_{p0,2}$, and R_m were in accordance with the experimental results.
- The conducted research and analysis provide a methodology for determining the parameters of the process and decision making in terms of a proper design of the structure of the superalloy Nimonic 80A.
- The numerical analysis, carried out under the proposed methodology, can provide reliable parameters influencing the behavior of the materials at the temperature of 750 °C under a static load. Further analysis may be excluded which reduces costly and time-consuming experimental tests.
- The obtained results allow the selection of the best (optimum) ratio of the aluminum and titanium contents relative to the content of cobalt;
- The performed research and analysis provide a contribution towards a methodology for determining influential parameters of the process and decision making in terms of a proper design of the structure of the superalloys Nimonic 80A;

It is obvious that the proposed methodology can successfully solve various complex tasks of modeling, numerical simulation and optimization of an alloy composition.

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