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ANALYSIS OF THE INFLUENCE OF CHEMICAL COMPOSITION AND TEMPERATURE ON MECHANICAL PROPERTIES OF SUPERALLOYS NIMONIC 80A

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Superalloys Nimonic 80A is a wrought nickel base alloy (min. 65 % Ni) and chromium (20 %), with minor additions of carbon, cobalt and iron, as well as major alloying elements of aluminum (1 to 1,8 %) and titanium (1,8 to 2,7 %). Chemical composition of the alloy Nimonic 80A has a dominant influence on its mechanical and technological properties. Increasing of the temperature also has a large influence on the mechanical properties of superalloy Nimonic 80A

Investigations which were carried out have included chemical testing and testing of mechanical properties of superalloy Nimonic 80A at room and higher temperatures. Regression analysis was done on the base of chemical analyses and results of mechanical properties. The results of regression analysis are equations by which on the basis of known chemical composition, ie content of main alloying elements Al, Ti and Co, the mechanical properties of materials at room and higher temperatures can be predicted.

Key words: Nimonic 80A, chemical composition, temperature, mechanical properties, regression analysis

INTRODUCTION

Modern theory of experimental research is based on plans of statistical analysis of multiple factoring. This theory makes possible mathematical modeling of processes and phenomena, the study of the nature of the internal mechanisms of the process and optimization of process control.

The starting point of research and development of reinforce superalloy Nimonic 80A are the technical requirements for the conditions of exploitation, on which is based design of chemical composition of materials [1]. Alloying elements present in the material, individually and in interaction with other present elements, dominantly influence the formation of microstructure, which is directly related to the mechanical properties and exploitation [2].

This multiple component of alloys based on nickel is essentially consisted of a solid solution of Ni-Cr, with the cubic lattice regularly face centered. In general, the alloys of this type have high mechanical properties as a result of double-acting [3], as follows:

- Increasing the effect of dispersion hardening by putting into solid solution of Ni-Cr elements that dissolve poorly in it, such as titanium and aluminum, which in the solid solution of Ni-Cr formed intermetallic compounds, such as Ni_3(Al, Ti) Ni_3Al; Ni_3Ti etc.;
- Strengthening of the interatomic bonds of solid solution of Ni-Cr by putting elements that are well dissolved in it (cobalt). Cobalt increases the stability of the γ'-phase, and contributes to improving usually poor deformability of alloys based on Ni.

For the planning of the experiment was used MATLAB software package (version 7,0), i.e. its module of Model-Based Calibration Toolbox [4, 5]. One advantage of using this technique is a simple analysis of the results. As options for planning an experiment MATLAB provides an optimal design, classic design and design for ”space filling”. Optimal design as selected, which based on the given model, determined the best point of the experiment, and that without losing the reliability of the results [6].

The factors were varied at two levels, with repeated experiment at each point of the plan. For optimal design MATLAB ordered 8 degrees of freedom system. After experimental tests of mechanical properties (yield strength $R_{p0,2}$ or R_{eH}, tensile strength R_m) they will be listed in the MATLAB model as a system response.

On the basis of known factors, x_i (wt. % Al, wt. % Ti and wt. % Co) and y_i ($R_{p0,2}$, R_m) is established the analytical dependence, ie the mathematical model of the response function of the process which is called the regression equation. The regression equation in the multidimensional space describes the studied process, which is limited by the limit values of varying factors. The

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resulting equation allows a qualitative analysis of the studied process.

Equations of second order of regression model can be successfully used as a base to explore the area optimum, and is selected for further analysis of the quadratic mathematical model. In connection with these mathematical models, i.e. obtained regression equations it should be emphasized that the analysis was conducted under the assumption that all the influential factors and their interactions are significant, what's not the case very often. Keeping factors that are considered to be insignificant provides fuller insight into the complexity of the investigated processes. On the other hand, the insignificance of rejection simplifies the analysis of influencing factors, especially the geometric presentation of the regression equation. Not even for one approach cannot, a priori, be claimed that is gives better performance of mathematical models [7].

EXPERIMENTAL RESEARCH AND RESULTS

To define the scope of the required tests and analysis of the results was used 2^k factorial model experiment. Factors that determine the experiment are the content of aluminum (x_1), titanium (x_2) and cobalt (x_3) in wt. %. All factors are variable in accordance with specified values (limits) for the alloy NiCr20TiAl according to DIN 17742, and, for alloy Nimonic 80A by Special Metals.

The mechanical properties of superalloys, which are monitored as the output parameters for the alloy Nimonic 80A, depend on various factors such as chemical composition, manufacturing technology and plastic processing, heat treatment, etc.

Because of very demanding conditions for the realization of the experiment is possible to follow only the content of the main elements that affect the mechanical properties, and other factors were tried to be kept constant, thus reducing the number of input parameters.

In the framework of the research were produced 16 experimental melts, but in this paper, due to the introduction of yet another influential factor (temperature), are selected four of the melts with the minimum and maximum values of the content of aluminum, titanium and cobalt. Chemical composition of selected melts is given in Table 1.

The contents of certain elements in the melt were differed from each other, because according to the plan of the experiment it was tended to get the alloy with the lower and upper limits wt. % Al, wt. % Ti. and wt. % Co, in order to determine the effects of these elements on the mechanical properties of superalloys. Chemical tests and tests of basic mechanical properties were carried out at the Institute "Kemal Kapetanović", Zenica. Results of tensile tests at room and elevated temperatures (450 °C, 650 °C, 750 °C and 850 °C) are shown in Table 2. for selected melt. Tensile properties (R_m and $R_{p0,2}$) are not changed significantly until the temperature of 650 °C when they slowly decreasing.

The above is a consequence of the fact that the γ' phase by increasing temperature strengthens the matrix which to some extent eliminate the effect of softening of austenite matrix.

Regression analysis of the influence of chemical composition and temperature on mechanical properties of superalloys

Considering the fact that the parameters of wt. % Al and wt. % Ti work together on the mechanical properties by creating γ '-phase, i.e. hardening alloy precipitation by intermetallic compounds, and the parameter Co. strengthens the alloy by forming a solid solution. For analyze of the influence of temperature on mechanical properties is taken the sum of the parameters wt. % Al and wt. % Ti (i.e. x_1+x_2) as first parameter, wt. % Co as the second parameter and temperature as the third parameter.

The functional dependence of the results of tensile values $R_{p0,2}$ and R_m on the basic parameters of the wt. % Al, wt. % Ti and wt. % Co for different test temperatures is given by the following equations:

$R_{p0,2}$ =215,4(wt. % Al+ wt. % Ti)+148,7(wt. % Co)+0,373(t °C)-70,33(wt. % Al+ wt. % Ti)(wt. % Co)-0,049 (wt. % Al+ wt. % Ti)(t °C) +0,165(wt. % Co)(t °C)+ 31,5(wt. % Co)^2-0,00087(t °C)^2 **(1)**

R_m=179,61(wt. % Al+ wt. % Ti)+840,84(wt. % Co)+0,322(t °C)-57,44(wt. % Al+ wt. % Ti)(wt. % Co)-0,074(wt. % Al+ wt. % Ti)(t °C)+0,1605(wt. % Co)(t °C)-215,64(wt. % Co)^2-0,00117(t °C)^2 **(2)**

Overview of calculated and experimental values for $R_{p0,2}$ and R_m are given in Table 2.

Output data from MATLAB model show that these models provide high accuracy of the counts of experimental research, because there is a significant difference between regression and residual sum of squares. Also, all the values of the correlation coefficient are above

Table 1 **The chemical composition of experimental melts of Nimonic 80A / wt. %**

	Chemical composition /%										
Melt \ Prescribed	C	Si	Mn	S	Al	Co	Cr	Fe	Ti	P	Ni
	max. 0,10	max. 1,00	max. 1,00	max. 0,015	0,50-1,80	-	18-21	max. 3,00	1,80-2,70	-	remainder
V1669	0,03	0,06	<0,01	0,008	1,68	1,88	19,7	0,33	2,92	0,007	remainder
V1672	0,02	0,01	<0,01	0,008	1,81	1,09	19,7	0,52	2,8	0,008	remainder
V1664	0,05	0,02	<0,01	0,007	0,93	1,9	19,3	0,1	1,69	0,008	remainder
V1665	0,05	<0,01	<0,01	0,007	0,98	1,04	19,7	0,14	1,71	0,008	remainder

Table 2 **Overview of calculated and experimental values for $R_{p0,2}$ and R_m**

No. melt	The content of elements /%		Temperature /°C	$R_{p0,2}$ /MPa		R_m /MPa	
	Al+Ti	Co	t	Experim.	Model	Experim.	Model
4	4,6	1,88	20	777	782,31	1 153	1 153,2
			450	807	816,19	992	1 038,2
			650	734	731,15	871	837,3
			750	686	664,63	764	701,7
			850	453	582,11	508	542,8
8	4,61	1,09	20	815	845,27	1 207	1 202,3
			450	800	822,89	1 008	1 032,6
			650	770	711,69	859	806,2
			750	634	632,08	708	658,0
			850	409	536,48	417	486,3
9	2,62	1,9	20	664	621,29	1 051	1 011,9
			450	599	698,31	893	961,3
			650	572	633,34	819	790,3
			750	532	576,85	648	669,7
			850	550	504,36	561	525,7
13	2,69	1,04	20	589	579,28	955	969,0
			450	578	593,81	831	857,0
			650	477	499,76	697	657,4
			750	400	428,74	606	522,6
			850	281	341,72	293	364,3

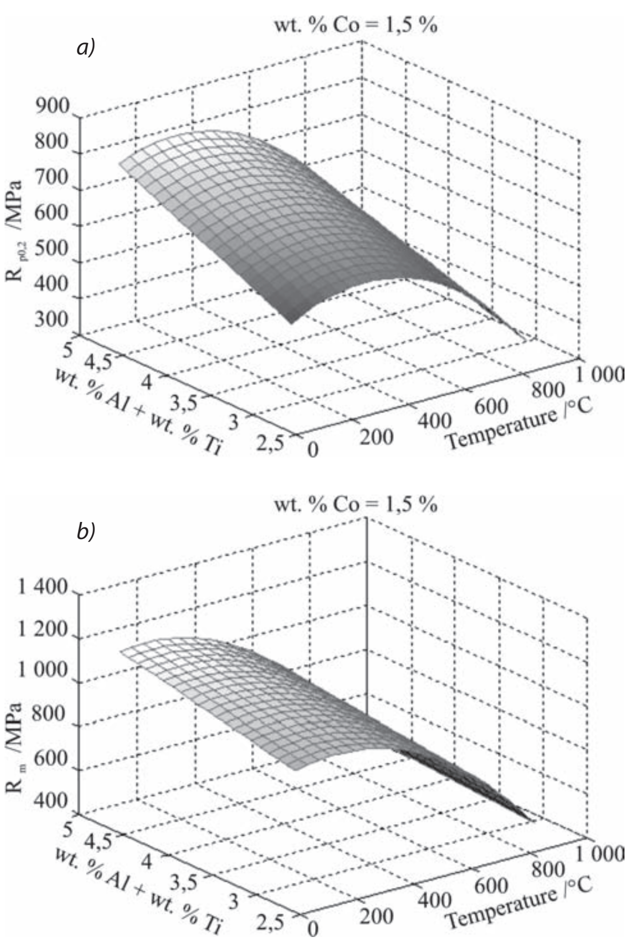

Figure 1 The functional dependence of yield strength *(a)* and tensile strength *(b)* of the content (wt. % Al + wt. % Ti), wt. % Co and temperature

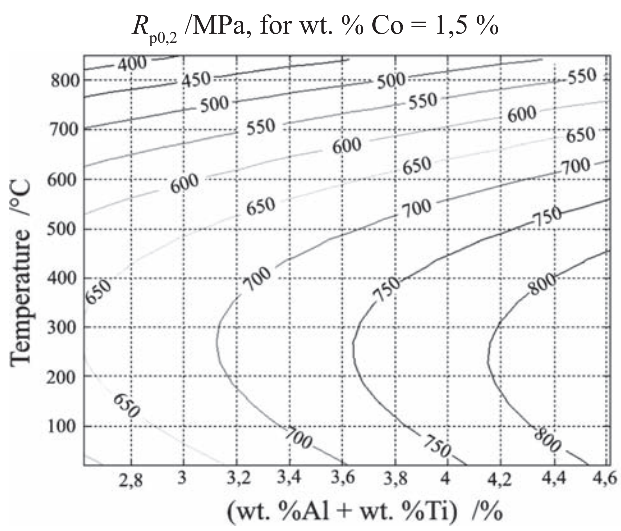

Figure 2 Graphical representation $R_{p0,2}$ depending on temperature, according to equation (1)

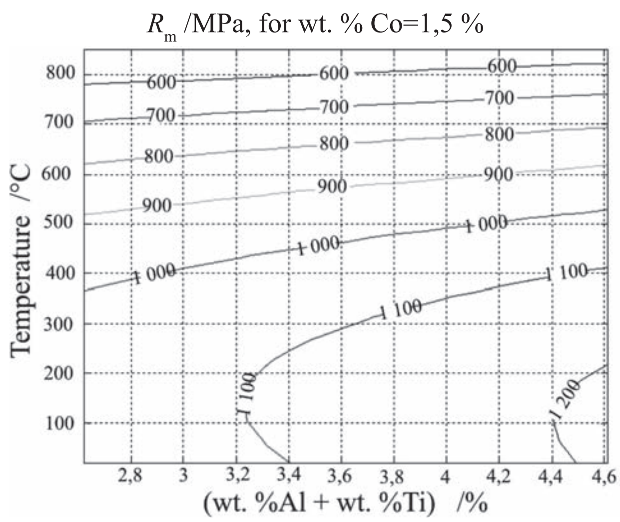

Figure 3 Graphical representation R_m depending on temperature, according to equation (2)

0,99. Checking the adequacy of quadratic regression model was performed using the F-test, where the degrees of freedom df_{reg} = 8 and df_{rez} = 12 and the threshold of significance α = 0,05 datasheet [8], i.e. critical value of $F_{(8, 12, 0.05)}$ = 2, 85, which is much less than calculated (derived) value of F=248,47 and 484,95. Thus, the quadratic regression model is adequate.

The functional dependence of the results of yield strength and tensile strength of the basic parameters of the content (wt. % Al + wt. % Ti), wt. % Co and temperature is shown in Figure 1.

For the purposes of engineering budget it is better to display blame $R_{p0,2}$, and curve R_m, in graphic form (Figures 2 and 3).

Based on equation (1) and (2) it can be graphically shown the changes of yield strength and tensile strength depending on the content of (wt. % Al + wt. % Ti) and contents of wt. % Co for a chosen temperature.

CONCLUSIONS

- Mathematical modeling of mechanical properties of superalloy Nimonic 80A proved to be reliable, accurate and cost-effective
- The applied method proved to be reliable, precise and cost-effective;
- The proposed mathematical models that establish connections between the main alloying elements (Al, Ti and Co) and mechanical properties by tensile testing satisfied both in the terms of the adequacy of the model, and in terms of its precision;
- All selected parameters related to the chemical composition influence the mechanical properties, ie they are all significant;
- Selected influential parameters in real conditions of making superalloys have a different significance and different effect on mechanical properties. The biggest impact is from titanium (Ti) and aluminum (Al), both at room as well as at elevated temperatures;
- The obtained results allow selection of the best (optimal) relationship between aluminum and titanium content in relation to the content of cobalt;
- Forms (1) and (2), can be used in the calculation of tensile properties at a selected temperature by giving specific values to individual factors. In this way we get the values for $R_{p0,2}$ or R_{eH} and R_m close to the experimentally obtained sizes.

From these data it is concluded on the controlled unfolding process of precipitation in nickel superalloy, which is of great importance, since this process is an important part of strengthening of these alloys. Of course all this is expedient to give proper attention to the structural stability of γ'-phase, as follows its growth opportunities and the phase transformation.

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