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Prediction of the Mechanical Properties of Chrome-Nickel Austenitic Stainless Steels with Respect to their Chemical Composition

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Abstract

The research was concerned with the influence of chemical composition of austenitic steels on their mechanical properties. Resulting properties of castings from austenitic steels are significantly influenced by the solidification time that affects the size of the primary grain as well as the layout of elements within the dendrite and its parts with regard to the last solidification points in the interdendritic melt. During solidification an intensive segregation of all admixtures occurs in the melt, which causes a whole range of serious metallurgical defects and it has also a significant influence on subsequent precipitation of carbides and intermetallic phases. Chemical heterogeneity then affects the structure and mechanical properties of the casting. In a planned experiment, we cast melted steels containing 18 to 28 % Cr and 8 to 28 % Ni with variable carbon and nitrogen contents. Testing the tensile strength of the cast specimens we could determine the $Rp_{0.2}$, Rm, and A_5 values. The dependence of the mechanical properties on the chemical content was described by regression equations. The planned experiment results allow us to control the chemical content for the given austenitic steel quality to achieve the required values of the mechanical properties.

Keywords: Austenitic steels, Planned experiment, Mechanical properties, Regression analysis

1. Introduction

Material properties of castings are generally influenced mainly by the chemical composition of a particular alloy, the alloy structure (phase content and grain size) and the heat treatment used. Austenitic chrome-nickel steels belong to non-polymorphic materials which cannot change its basic metal substance (austenite) by heat treatment. The properties of these steels are therefore influenced mainly by the chemical composition of the steel and the grain size [1,2]. The chemical composition influences the substitution and interstitial strengthening of the austenitic structure as well as the character of steel g. In the case of the austenitic steels of the typical composition of 18/8 (18% Cr + 8% Ni), solidification takes place in the form of peritectic. Solidification begins with ferrite deposition when primarily deposited ferrite in the subsequent peritectic reaction reacts with molten metal forming austenitic and ferrite grains. The peritectic structure of such austenitic steel has finer grains and the segregations are distributed more coherently than in the case of austenite being deposited in the primary phase (fig. 1). Therefore, the steels with about 20% Cr and 8-10% Ni contain a certain amount of ferrite. If we require exclusively austenitic structure of the steel, fully austenitic steels are used with higher concentration of austenitic elements [3]. By

changing the chemical content, or rather changing the chromium and nickel equivalent, we can change the solidification conditions depending on the chemical composition of the steel with regard to the peritectic diagram. The influence of the chemical composition on the properties of the chrome-nickel steels martensitic steels is described in [4]. The influence of the phase content of the chrome-nickel steels on their properties is detailed in [5]. The chemical composition of the steel can have a significant impact on the size of the austenitic grain during solidification of the austenitic and austenitic-ferrite steels. For ferrous materials and thus also for austenitic steels, so called Hall-Petch equation holds (1), giving the dependence of yield stress (R_e) on the grain size [6] for a particular material.

$$Re = \sigma_i + k \cdot d^{-\frac{1}{2}} \tag{1}$$

σ_i – is a materials constant for the starting stress for dislocation movement [MPa]
k – a constant for a given material [MPa.m$^{1/2}$]
d – grain size [m]

To increase the yield stress and thus the tensile strength, it is necessary to create conditions for forming a finer grain structure. A significant influence on the grain size depends on how fast the cooling of the steel is carried out, that is, how fast the solidification process is. That depends on the wall thickness of the casting, but also on the material of the mould used. The mechanical properties of the austenitic steels depend on the temperature. The higher the temperature the lower the tensile strength of the material, the yield stress and the steel ductility. The changes in the mechanical properties at higher temperatures of the steels according to AISI 304L and 316L qualities are described in [7]. The heat treatment of the austenitic steels, as stated above, cannot change the basic metal substance – the steel matrix. The matrix stays the same, but using temperatures as high as 1050 – 1200°C with the subsequent quenching in water, we can change the amount and disposition of carbides and intermetallic phases in the structure. The use of such heat treatment leads to decreasing the steel tensile strength and the yield stress, but at the same time increasing the steel ductility [8,9]. The sigma phase dramatically decreases the plasticity of the austenitic steel and its stability is affected by the steel chemical composition and temperature. For austenitic and super-austenitic steels, the stability conditions of this phase are examined based both on the thermodynamic (CALPHAD) and ab initio calculations [10,11].

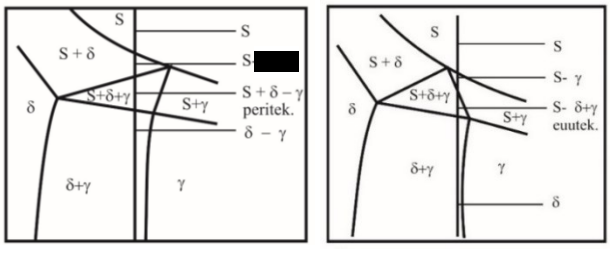

Fig. 1. Solidification of the austenitic steels depending on peritectic reaction

2. Design of experiment

The actual research is focused on the development of production of castings from austenitic stainless steels up to approx. 20t for a significant casting manufacturer in the Czech Republic. A part of this research focuses on determining the effect of chemical composition on the mechanical properties of the CrNi austenitic steels. In some papers, for example [1], it is stated that casted austenitic Cr-Ni steels have low proof stress $Rp_{0,2}$ and tensile strength Rm. By altering the chemical composition, we can significantly improve the strength properties of steel.

The influence of chemical composition on the mechanical properties of austenitic CrNi steels was verified by a designed experiment (DOE). The designed experiment was performed by the MINITAB 15 statistical program. Concentrations of carbon, chromium, nickel and nitrogen were considered independent parameters with the tensile strength, proof stress, and ductility being dependent variables. Orthogonal design was chosen for the experiment. For the given number of variables (4), it was necessary to carry out at least $2^n = 2^4 = 16$ melts for each extreme value of the set. The whole procedure was repeated twice, that is with 32 melts, to increase the statistical significance. The extreme concentration value for each element is given in tab. 1. It contains the lower and higher concentration values for each element as it was designed (DOE). There are also the actual concentration values measured for each melt. Subsequently, we also carried out 10 melts corresponding to the central point of the orthogonal design, which is given by the mean concentration values for 4 selected elements (tab. 1). The concentration of other elements was held at approx. 0.80% for Mn, approx. 0.50% for Si, approx. 0.3% for Mo and maximum 0.02 for concentrations of S and P.

The melts were made in a vacuum induction furnace. The steel was decarbonized in a vacuum after melting so the manufacturing process was similar to the VOD procedure which is used by a collaborating foundry for manufacturing castings. After melting and alloying the steel to the desired chemical composition, the steel was vacuumed for 20 minutes at a pressure of 50 to 70 hPa. The desired pressure in the furnace above the metal level was achieved within 3 to 5 minutes. Carbon boil was occurring in the steel during the vacuuming process, in which the content of both carbon and nitrogen was decreasing. The required decrease of nitrogen content was regulated by the vacuuming time and the increase nitrogen, if desired, was achieved by nitrogenous ferrochrome alloying. Also, when the desired content of carbon was exceeded, the vacuum process was prolonged until obtaining the required carbon content. During melts with higher carbon content, the carbon was added to the steel by alloying just before tapping.

3. Designed experiment results

From the melts listed above we casted test blocks with a wall thickness of 60 millimetres. The blocks were subjected to dissolving annealing at a temperature of 1080°C for 8 hours and then cooled down in water. The material for manufacturing test bars for the tensile test was taken from the bottom part of the block. The tensile tests were carried out for bars each with a diameter of 10 millimetres and with an M16 thread head. The temperature during

the test was 20 °C. The mechanical values were measured for two test bars from each melt. Comparing the tensile test results for the same wall thickness of the block in individual melts, we do not need to account for the influence of the amount of ferrite and the grain size on the mechanical properties. We can presume that these values are controlled by the speed of the solidification process, i.e. mostly by the wall thickness of the block, which is identical for all measured test objects. In tab. 2 you can find basic statistical characteristics of the chemical composition and mechanical properties of the melts according to the designed experiment mentioned above. In the research, we also evaluated the mechanical properties of blocks with wall thicknesses of 20 and 100 millimetres and the tensile test at a temperature of 200 °C. However, these results are not part of this paper.

Table 1.
Element concentrations according to the designed experiment and those actually measured in melts

	Design of Experiment				Reality			
Element	%C	%Cr	%Ni	%N	%C	%Cr	%Ni	%N
Min.	0.030	18.00	9.00	0.010	0.010	17.03	8.42	0.030
Max.	0.140	28.00	28.00	0.140	0.142	29.70	30.98	0.170
Central Point	0.08	23.00	18.50	0.060				

Table 2.
Basic statistical characteristics of the chemical composition and the mechanical values

Characteristic	%C	%Cr	%Ni	%N	Rp0.2 [MPa]	Rm [MPa]	A [MPa]
Average	0.063	22.38	13.56	0.092	289.4	544.9	39.3
Standard deviation	0.048	4.48	7.71	0.040	89.7	88.0	11.4
Min	0.010	17.03	8.42	0.030	154.0	395.0	14.8
Max	0.142	29.70	30.98	0.170	516.0	708.0	60.8

4. Deriving regression equations

As in setting up the experiment design, the MINITAB 15 program was used in statistical data processing. The aim was to determine the correlations between the chemical composition of austenitic steel represented by the concentrations of 4 elements and the values of yield stress, ultimate strength, and ultimate ductility. The regression of 4 major values was used (%C, %Cr, %Ni and %N) taking into account first and second order interactions between the elements. To reduce the variance between the actual results and the values predicted by the regression equations, logarithms were also considered of the basic variables and the first order interactions. For these conditions, the regression equations were derived with the p value checked for each term at a significance level of $\alpha = 0.05$. The statistically insignificant coefficients ($p > 0.05$) were then gradually discarded, each time leaving out the one with the p value greater than 0.05. The terms were excluded one by one. In this way, three regression equations were obtained for the austenitic steels produced by the method of vacuum metallurgy using the block wall thickness of 60 mm, testing temperature of 20 °C.

4.1. Effect of the chemical composition on the tensile strength Rm

For the chemical-composition-dependent tensile strength Rm, regression equation (2) has been derived. According to the number and type of the regression equation terms, the significance level was $\alpha = 0.05$ both for the primary terms and the interactions between the first and second order terms. Standard deviation of the regression equation from the actual results is 7.64 MPa. Equation (2) can only be used within the concentration ranges of the 4 elements: C = 0.00-0.05 %, Cr = 18-24 %, Ni = 8-14 %, N = 0.02-0.15 %.

$$\begin{aligned} Rm = -35136 - 24751 \cdot C + 1275 \cdot Cr + 4969 \cdot Ni \\ + 55.67 \cdot Cr \cdot Cr + 103.7 \cdot Ni \cdot Ni \\ + 5432 \cdot N \cdot N + 1305 \cdot C \cdot Cr \\ - 361.7 \cdot Cr \cdot Ni \end{aligned} \quad (2)$$

Lower strength values were observed in melts with a chrome content lower than 19 % or in melts with a very low content of nitrogen and carbon. Higher strength values, on the other hand, were observed in melts with a higher content of chrome and nitrogen. Fig. 2 shows the dependence of the ultimate strength values calculated on those actually measured.

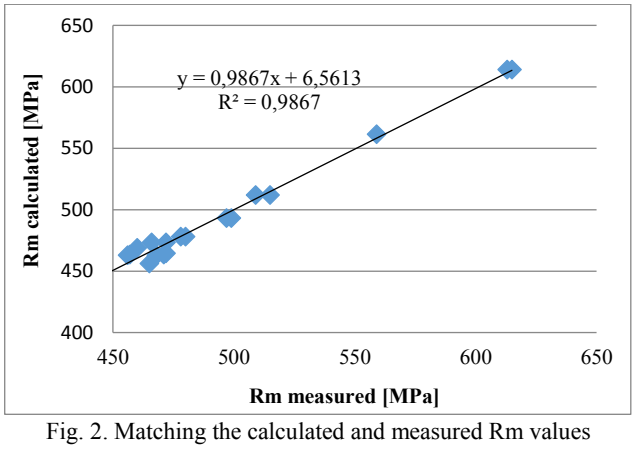

Fig. 2. Matching the calculated and measured Rm values

Fig. 2 suggests an acceptable match of the calculated and values measured of the ultimate strength for each melt of the designed experiment. Within the considered concentration ranges of the 4 elements, equation (2) can be used to predict the tensile strength Rm. With a confidence of 95% (Rm+2σ), the required steel tensile strength can be guaranteed if the value calculated for a particular chemical composition is by 15.28 MPa higher than the lower limit of Rm for the standard steel quality. Should we wish to determine the required tensile strength with a confidence of 99.7% (Rm+3σ), the chemical composition would have to be chosen for the calculated value to by at least by 22.92 MPa higher that the lower limit of Rm for the standard quality.

4.2. Effect of the chemical composition on the proof stress $Rp_{0.2}$

For the chemical-composition-dependent proof stress $Rp_{0.2}$, regression equation (3) was derived. According to the number and type of the regression equation terms, the significance level was again α = 0.05 both for the primary terms and the interactions between the first and second order terms. Standard deviation of the regression equation from the actual results is 4.95 MPa. Equation (3) can only be used within the concentration ranges of the 4 elements: C = 0.00-0.05 %, Cr = 18-24 %, Ni = 8-14 %, N = 0.02-0.15 %.

$$R_{p0.2} = -20574 + 121635 \cdot C - 80.6 \cdot Cr + 4108 \cdot Ni + 1259.8 \cdot N + 388395 \cdot C \cdot C - 182.6 \cdot Ni \cdot Ni + 5037 \cdot C \cdot Cr - 25316 \cdot C \cdot Ni \quad (3)$$

Using equation (3) the proof stress values $Rp_{0.2}$ were calculated and matched with the measured values. The deviations of the measured values of the proof stress may cause errors smaller than those in the tensile strength measurement. Fig. 3 shows the dependence of the proof stress values calculated on those actually measured.

For the values of the proof stress $Rp_{0.2}$ ranging between about 200 MPa and about 350 MPa, there is a good match between the measured and values calculated. The highest difference between calculated and measured values of $Rp_{0.2}$ was 7.66 MPa in one case. The higher $Rp_{0.2}$ values again occur in melts with a higher chrome content. The effect of nitrogen on the proof stress $Rp_{0.2}$ is less significant. Within the considered concentration ranges of the 4 elements, equation (3) can be used to predict the proof stress $R_{p0.2}$. With a confidence of 95% (Rm+2σ), the required steel proof stress can be guaranteed if the calculated value for a particular chemical composition is by 9.9 MPa higher than the lower limit of $R_{p0.2}$ for the given standard steel quality. If we wish to determine the required proof stress with a confidence of 99,7% (Rm+3σ), the chemical composition must be chosen for the calculated value to be at least by 14.55 MPa higher that the lower limit of $R_{p0.2}$ for the given standard quality.

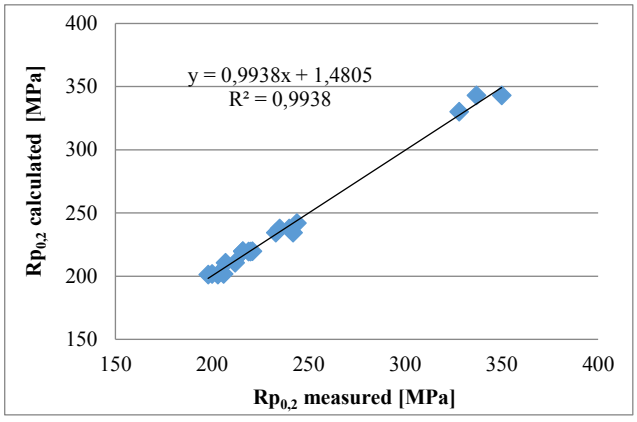

Fig. 3. Matching the calculated and measured $Rp_{0.2}$ values

4.3. Effect of the chemical composition on the ductility A

For the chemical-composition-dependent ductility, regression equation (4) has been derived. According to the number and type of the regression equation terms, the significance level was again α = 0.05 both for the primary terms and the interactions between the first and second order terms. The standard deviation of the ductility regression equation is 5.1 % Equation (4) can only be used within the concentration ranges of the 4 elements: C = 0.00-0.05 %, Cr = 18-24 %, Ni = 8-14 %, N = 0.02-0.15 %.
Fig. 4 shows the dependence of the elongation values calculated on those actually measured.

$$A = 790 - 152.8 \cdot Ni - 1772 \cdot C \cdot Cr + 3556 \cdot C \cdot Ni + 3.93 \cdot Cr \cdot Ni \quad (4)$$

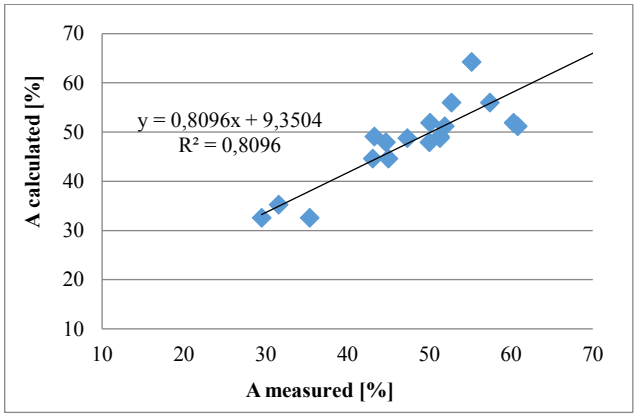

Fig. 4. Matching the calculated and measured values A

5. Conclusions

The present paper is concerned with determining the mechanical properties of CrNi austenitic steels using a designed experiment. By the regression equations derived the yield stress,

ultimate strength and ductility of austenitic steel can be predicted. The equations can be used for the 4 element concentration ranges listed in tab. 2 and the concentrations of Mn about 0,80%, about 0.50% Si, 0.3% Mo and max. 0.02 % S and P. The values calculated by the regression equations are valid for a test block wall thickness of 60 mm. The ductility predictions have variance higher than that of the ultimate strength. This is due to the fact that the property values are more susceptible to other influences such as the occurrence of micro-contractions, amount and morphology of inclusions, and grain size. To reduce the result variances and the residues between the calculated and measured values of the yield stress and the ultimate ductility, the regression equations include additional parameters such as the ferrite ratio in the structure. For the foundry work, the mechanical property values calculated by the regression equations are sufficiently precise to estimate the Rm, $Rp_{0.2}$, and A values.

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