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ARCHIVES of FOUNDRY ENGINEERING

DOI: 10.2478/afe-2013-0088

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 13
Issue 4/2013

87 – 92

Assessment of AlSi21CuNi Alloy's Quality with Use of ATND Method

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Received 28.06.2013; accepted in revised form 02.09.2013

Abstract

Majority of combustion engines is produced (poured) from Al-Si alloys with low thermal expansion coefficient, so called piston silumins. Hypereutectic alloys normally contain coarse, primary angular Si particles together with eutectic Si phase. The structure and mechanical properties of these alloys are highly dependent upon cooling rate, composition, modification and heat-treatment operations. In the paper one depicts use of the ATND method (thermal-voltage-derivative analysis) and regression analysis to assessment of quality of the AlSi21CuNi alloy modified with Cu-P on stage of its preparation, in aspect of obtained mechanical properties ($R_{0,02}$, R_m, A_5, HB). Obtained dependencies enable prediction of mechanical properties of the investigated alloy in laboratory conditions, using values of characteristic points from curves of the ATND method.

Keywords: Hypereutectic Al-Si alloy, Modification, ATND, Mechanical properties

1. Introduction

Aluminum-silicon alloys are well known as typical low density and wear resistant cast materials for use at high temperatures. Hypereutectic alloys are characterized by eutectic matrix containing primary silicon crystals of various sizes and shapes. Low thermal expansion coefficient, high strength to weight ratio and excellent wear resistance are among the properties of these alloys, which account for their popularity as the chosen materials for automotive pistons and engine block [1-6].

Hypereutectic Al-Si alloys are used in conventional casting processes such as die casting, permanent mould casting and squeeze casting, and by more recent emerging technologies such as semi-solid processing and duplex casting techniques [3,7-12].

In case of such alloys, the main problem is connected with big precipitations of primary silicon, which make machining treatment difficult or even impossible. Large and segregated primary Si particles may shorten the tool life on machining and also drastically degrade the mechanical properties of the castings [7,12-14]. Refine the primary silicon phase results in change of morphology, size, and distribution of silicon particles, affect directly the mechanical properties, machinability, and wear resistance of the alloy.

The industrial procedure is to treat the alloy with phosphorus. In hypereutectic Al-Si alloys, CuP master alloy is recognized as the best Si refiner [4,15-22]. Action of the phosphorus in modification of hypereutectic silumins is connected with creation of its compound with aluminum in form of the AlP phosphide, which creates micro-particle catalysts for heterogeneous nucleation of primary silicon crystals, reducing its size and increasing its quantity, what have direct effect on improvement of mechanical and technological properties of the alloy [16,17].

Qualitative requirements for castings of heavy duty machinery parts have resulted in introduction of more stringent quality standards, aimed at elimination of defective components. Unfortunately, such quality verifications are performed ex-post, i.e. after production of the components. In this aspect, usage of the opportunities offered by implementation of prediction of a given parameters enables avoidance of production of defective components, and offers savings resulted from breaks in technological process needed for introduction of necessary modifications. Due to this, information on mechanical properties of the material poured into mould is important, because they have direct effect on quality of final products. However, determining the mechanical properties of a material requires testing specified in relevant standards, with use of special devices and qualified staff during specified time.

In the present study one used the author's method of thermal-derivative-voltage method (ATND), and regression method to elaboration of mathematical dependencies enabling prediction of mechanical properties of the AlSi21CuNi silumin modified with the CuP10 master alloy.

2. Metodology of the research

The AlSi21CuNi alloy belongs to hypereutectic, multicomponent alloys and due to high abrasion resistance, high mechanical properties at increased temperatures and very low thermal expansion are commonly used in production of heavy duty pistons to combustion engines.

Chemical composition of the alloy is presented in the Table 1.

Table 1
Chemical composition of the AlSi21CuNi alloy

Chemical composition / mass %				
Si	Cu	Zn	Fe	Mg
21,9	1,27	0,02	0,4	0,47
Ni	Mn	Pb	Cr	Al
0,92	0,14	0,004	0,006	rest

The analysis of the chemical composition was performed with the use of the emission spectroscopy (spectrometer type ARL 3440).

Investigated alloy was melted in electric resistance furnace and next the alloy underwent treatment of refinement (Rafal 1 - 0,4%) and modification with phosphor copper, CuP10, in quantity of 0,1% mass of metallic charge (0,01% P).

The investigated alloy was poured into metal mould adapted to registration of crystallization processes with use of the ATND method [23].

Static tensile strength test was performed on the Schenck testing machine according to the EN ISO 6892-1:2010 standard. Measurement of the elongation was performed with use of the Schenck-DSA 25/10M type extensometer. Measurement of the Brinell hardness was performed according to the PN-EN ISO 6506-1:2008 standard with use of the Brinell hardness tester of PRL 82 type, with steel ball having 10 mm diameter, under load of 9800 N applied for 30 seconds.

Crystallization course of the investigated alloy recorded with use of the ATND method, with marked characteristic points of the thermal (t_1 - t_4) and voltage (U_1 - U_4) curves, is shown in the Fig. 2.

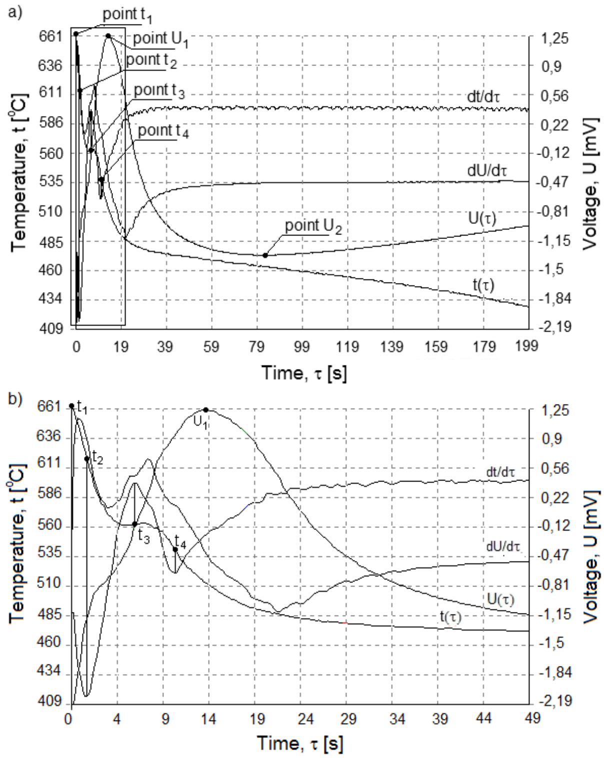

Fig. 2. Curves of the ATND method with marked characteristic points for the investigated alloy: a) full range of the crystallization process, b) magnification of a selected area

On the base of obtained values of characteristic points from the ATND method (independent variables) and mechanical properties (dependent variables) one created a computer files containing data, used to regression analysis, performed with use of the Statistica version 10 packet developed by StatSoft.

The first order polynomial was assumed as a function of the tested object (1).

$$z = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + ... + b_nx_n \pm \varepsilon \quad (1)$$

where:

z - dependent variable ($R_{0,02}$, R_m, A_5, HB),
$x_1, x_2, ..., x_n$ - independent variables ($t_1 \div t_4$, $U_1 \div U_4$),
$b_0, b_1, ..., b_n$ - estimator of regression,
ε - standard error of estimation.

3. Description of obtained results

In the Table 2 are listed obtained mechanical properties of the investigated alloy after performed modification treatment.

Table 2.
Mechanical properties of investigated alloys

$R_{0,02}$ [MPa]	R_m [MPa]	A_5 [%]	HB
97 - 120	154 - 192	0,4 - 1,1	98 - 104

In result of performed regression analysis one obtained the dependencies (2-9), presenting effect of characteristic points' values on change of mechanical properties of the investigated alloy

3.1. Limit of elasticity $R_{0,02}$

Linear regression – complete model for value of the $R_{0,02}$ is presented by the equation (2).

$$R_{0,02} = 1216{,}5 - 0{,}03t_1 - 0{,}04t_2 - 0{,}76t_3 - 1{,}13t_4 + 1{,}03U_1 + 15{,}26U_2 \pm 2{,}1 \text{ [MPa]} \quad (2)$$

It has been obtained determination coefficient $R^2 = 0{,}91$, what means that as much as 91% of general variability of the $R_{0,02}$ can be explained by this model. In the presented model are two variables with significant effect only, which fulfill condition of $p<\alpha=0{,}05$.

To eliminate variables with insignificant effect one performed analysis of reverse stepwise regression terminated on the step no. 3. Regression equation for the value $R_{0,02}$, after elimination of the variables takes form of (3):

$$R_{0,02} = 809 - 1{,}25t_4 + 16{,}89U_2 \pm 2{,}1 \text{ [MPa]} \quad (3)$$

It has been obtained equation comprising only three variables (together with the free term) complying with condition of significance. Determination coefficient R^2 amounts to 0,90 (90% of variability of the $R_{0,02}$ is explained by the regression). Corrected coefficient R^2 is bigger than the coefficient for complete model with 0,02 and amounts to 0,89. It means, that obtained model is well „matched", and to the equation are introduced variables having significant effect.

The Fig. 3 illustrates how are shaped predicted values (from the model) and observed values (from the test) for the limit of elasticity $R_{0,02}$.

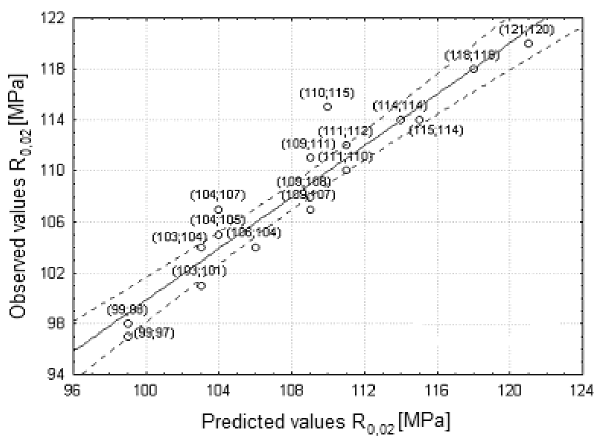

Fig. 3. Diagram of predicted and observed values for the variable $R_{0,02}$

Analysis of variance confirms that total effect of influence of the independent variables (t_4 and U_2) on the dependent variable $R_{0,02}$ is statistically significant, because condition - $F_{obl} > F_{(\alpha;df1;df2)}$ ($F_{obl} = 71{,}33 > F_{(0,05;2;15)} = 3{,}68$) is fulfilled. Value of the test is high, what results in critical significance level of p = 0,000001.

From general sum of squares of the variable $R_{0,02}$ only 10% of the variability can not be explained by the regression. The confirmation of complete elimination of the variables in the third step is obtained value of the statistics $C_p = 2{,}56$ – featuring minimal value, and the fact that in the model are remained only variables having significant effect on value of the $R_{0,02}$.

The Fig. 4 presents graphical picture of the effect of the variables t_4 and U_2 on value of the limit of elasticity $R_{0,02}$.

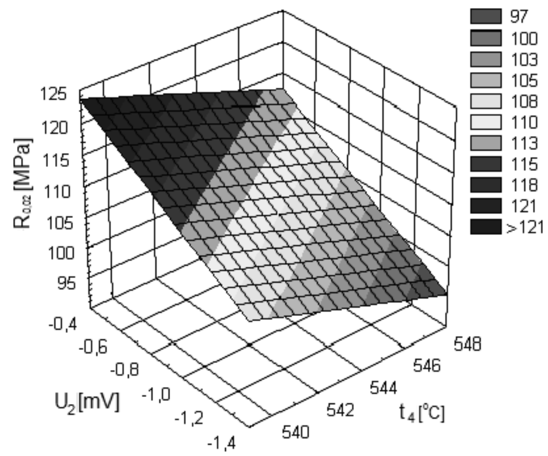

Fig. 4. Effect of change of values of the points U_2 and t_4 on the limit of elasticity $R_{0,02}$

Taking into consideration presence in the equation of two variables only, it can be assumed that drop of voltage in the point U_2 has the main effect on growth of value of the $R_{0,02}$.

3.2. Tensile strength R_m

Lineal regression – complete model for value of the R_m is presented by the equation (4).

$$R_m = 434{,}9 - 0{,}89T_1 + 0{,}53T_2 - 1{,}3T_3 + 1{,}26T_4 + 2{,}93U_1 - 33{,}26U_2 \pm 4{,}9 \text{ [MPa]} \quad (4)$$

It has been obtained determination coefficient R^2 equal to 0,90, meaning that 90% of general variability of the R_m was explained by obtained complete model. Corrected determination coefficient (corr. R^2) amounts to 0,85. In the presented complete model are present two variables with significant effect only, which fulfill condition of significance $p<\alpha=0{,}05$.

Performed analysis of variance for complete model confirms, that from general sum of squares of the variable R_m only 10% of variability can not be confirmed by the regression, while statistic significance of the effect of influence of the independent variables on the dependent variable R_m is fulfilled on level of p = 0,00005 ($F_{obl} > F_{(\alpha;df1;df2)}$ ($F_{obl} = 17{,}64 > F_{(0,05;6;11)} = 3{,}09$). Elimination of variables with insignificant effect was terminated after removal of four variables, what is presented in the dependency (5).

$$R_m = 600{,}8 - 0{,}69t_1 - 34{,}7U_2 \pm 5{,}39 \text{ [MPa]} \quad (5)$$

It has been obtained equation comprising three variables only (together with the free term), complying with condition of significance. Determination coefficient R^2 was changed to 0,85. Corrected coefficient R^2 amounts to 0,83. Obtained model is well "matched" and in the equation are present only variables with significant effect.

Performed analysis of variance confirms statistic significance of total effect of influence of the independent variables t_1 and U_2 on the dependent variable R_m on the level of $p = 0{,}000001 < \propto = 0{,}05$ - $F_{obl} > F_{(\alpha;df1;df2)}$ ($F_{obl} = 41{,}63 > F_{(0{,}05;2;15)} = 3{,}68$).

In the Fig. 5 is presented graphical interpretation of the effect of variables from the equation (5) on value of the tensile strength R_m.

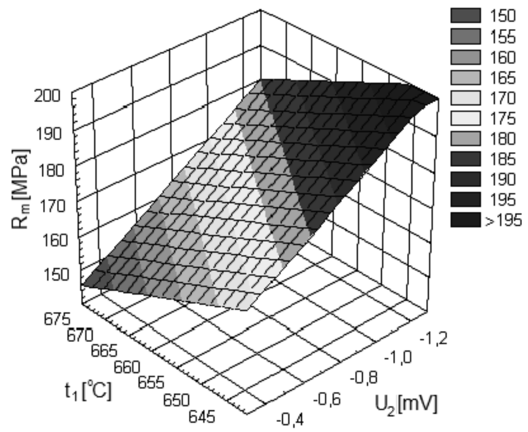

Fig. 5. Effect of change of values of the points t_1 and U_2 on the R_m

Change of voltage in the point U_2 has the biggest effect on change of the tensile strength R_m.

Fig. 6 presents system of predicted values (from the model) and observed values (from the test) for the dependent variable R_m.

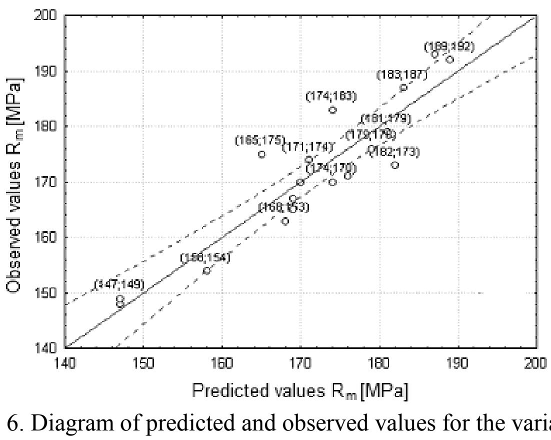

Fig. 6. Diagram of predicted and observed values for the variable R_m

3.3. Elongation A_5

Linear regression – complete model of value of the A_5 is presented by the equation (6).

$$A_5 = 28{,}4 - 0{,}001t_1 - 0{,}03t_2 - 0{,}07t_3 + 0{,}06t_4 - 0{,}16U_1 + 0{,}54U_2 \pm 0{,}08 \; [\%] \tag{6}$$

It has been obtained determination coefficient $R^2 = 0{,}86$ denoting that 86% of general variability of the elongation A_5 was explained by the model. In the presented complete model are present three variables fulfilling condition of significance (t_2, t_4, U_2), other variables have insignificant effect, not complying with condition of significance ($p<\alpha=0{,}05$).

Performed analysis of variance confirms, that from general sum of squares of the variable A_5, 14% of variability can not be explained by the regression. Statistic significance of the effect of influence of independent variables on the dependent variable A_5 – is fulfilled on the level of $p = 0{,}0003$ ($F_{obl} > F_{(\alpha;df1;df2)}$ ($F_{obl} = 11{,}42 > F_{(0{,}05;6;11)} = 3{,}09$).

Elimination of variables with insignificant effect was terminated after the first step (elimination of variable t_1) – all other variables have significant effect on change of the elongation A_5. Linear regression – the model reduced for value of the elongation A_5 is presented by the equation (7).

$$A_5 = 31{,}7 - 0{,}03t_2 - 0{,}07t_3 + 0{,}06t_4 - 0{,}18U_1 + 0{,}54U_2 \pm 0{,}08 \; [\%] \tag{7}$$

One obtained equation consisting of six variables fulfilling condition of significance with a slight worsening of the determination coefficient R^2: 0,85. Corrected coefficient R^2 is bigger than the coefficient for complete model with 0,02 only and amounts to 0,80. Performed analysis of variance confirms statistic significance of total effect of influence of the independent variables on the dependent variable A_5 on the level $p = 0{,}000089 < \propto = 0{,}05$ - $F_{obl} > F_{(\alpha;df1;df2)}$ ($F_{obl} = 12{,}81 > F_{(0{,}05;5;12)} = 3{,}10$).

In the Figs. 7-8 is presented graphical interpretation of the effect of independent variables on value of the elongation A_5.

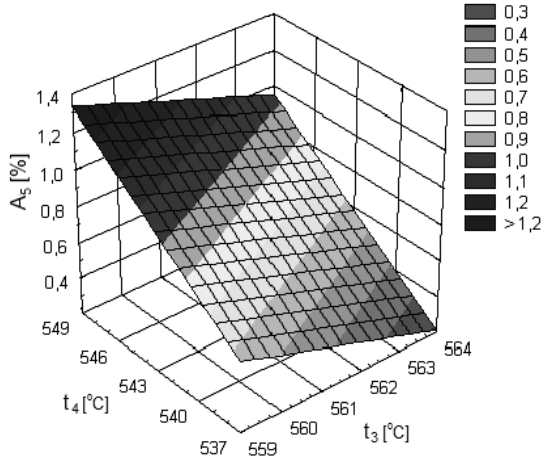

Fig. 7. Effect of change of values points t_4 and t_3 on elongation A_5

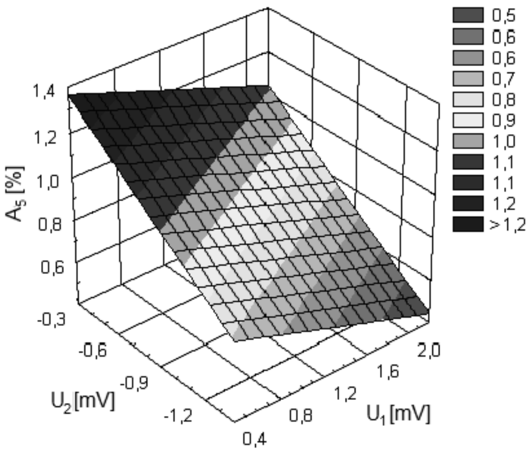

Fig. 8. Effect of change of values points U_2 and U_1 on elongation

In case of the elongation A_5 , temperature variables t_2 and t_4, as well as voltage variable U_2 have the biggest effect on change of its value (Figs. 7-8). Drop of the temperature t_2 , as well as growth of the temperature t_4 and voltage in point U_2 have advantageous effect on growth of the elongation.

In the Fig. 9 is presented a system of predicted and observed values for the dependent variable A_5.

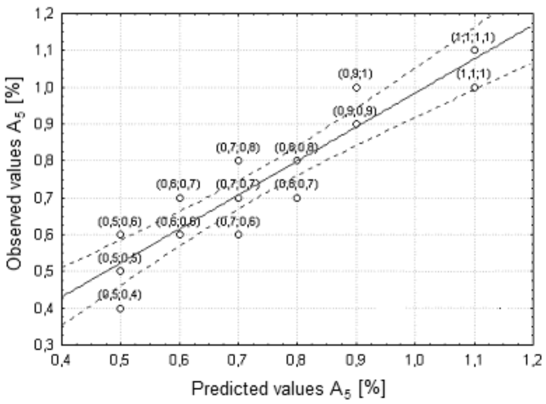

Fig. 9. Diagram of predicted and observed values for the variable A_5

3.4. Hardness HB 10/1000/30

Linear regression – complete model for values of the HB 10/1000/30 is presented by the equation (8).

$$HB = 1097,2 + 0,0001t_1 + 0,08t_2 - 2,1t_3 + 0,23t_4 - 1,02U_1 - 4,7U_2 \pm 0,68 \quad (8)$$

It has been obtained coefficient of determination R^2 = 0,86 denoting that 86% of general variability of the HB was explained by the model. In presented complete model, the free term and variables t_3, t_4 and U_2 fulfill condition of significance, other members are variables with insignificant effect, which do not comply with condition of significance ($p<\alpha=0,05$). Analysis of variance confirms statistic significance of the effect of influence of the independent variables on the dependent variable HB on the level p = 0,00027 < α = 0,05 ($F_{obl} < F_{(\alpha;df1;df2)}$ (F_{obl} = 12,08 < $F_{(0,05;6;11)}$ = 3,09), and confirms fact that from general sum of squares of the variable HB, 14% of variability can not be explained by the regression.

Reduced model for the hardness HB 10/1000/30 is presented by the equation (9).

$$HB = 1009,2 + 0,15t_2 - 1,79t_3 - 5,8U_2 \pm 0,81 \quad (9)$$

It has been obtained equation comprising four variables (inclusive of the free form) fulfilling condition of significance. Determination coefficient R^2 was changed to 0,76. Corrected coefficient R^2 amounts to 0,71. Obtained model is well „matched”, while in the equation are present only variables with significant effect. Performed analysis of variance confirms statistic significance of total effect of influence of independent variables on the dependent variable on the level of p = 0,00011 < $\propto$ = 0,05 - $F_{obl} > F_{(\alpha;df1;df2)}$ (F_{obl} = 15,07 > $F_{(0,05;3;14)}$ = 3,34). In the Fig. 10 is shown graphical interpretation of the effect of individual variables on change of value of the hardness HB 10/1000/30.

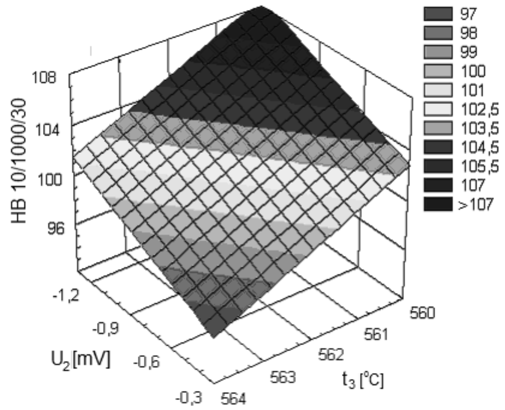

Fig. 10. Effect of change of values points U_2 and t_3 on hardness HB

In the Fig. 11 is presented system of predicted and observed values for the dependent variable HB 10/1000/30.

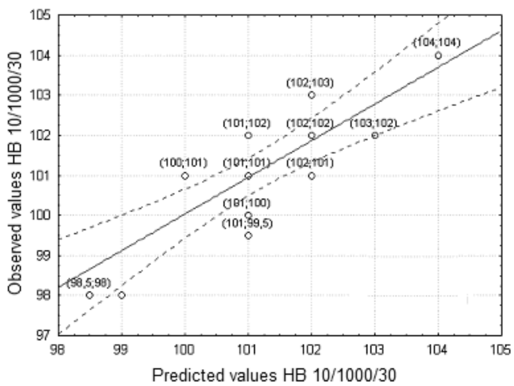

Fig. 11. Diagram of predicted and observed values for the variable HB

4. Conclusions

Implemented ATND method, allowing registration of crystallization processes, and obtained dependencies (3), (5), (7) and (9) enable quick assessment of mechanical properties of the AlSi21CuNi alloy at stage of its preparation, what is especially important in case when the alloy is used for castings of heavy duty machinery parts. Forecast of mechanical properties on the base of obtained dependencies was performed on the base of test results performed in laboratory conditions, due to this, they require verification within industrial conditions.

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