

## STATISTICAL ASSESSMENT OF THE IMPACT OF ELEVATED CONTENTS OF Cu AND Ni ON THE PROPERTIES OF AUSTEMPERED DUCTILE IRON

The article presents a statistical analysis of data collected from the observation of the production of austempered ductile iron. The impact assessment of the chemical composition, i.e. high contents of Cu and Ni on the properties of ductile iron isothermal tempered is critical to find the right chemical composition of austempered ductile iron. Based on the analyses range of the percentage of Cu and Ni which were selected in the cast iron to obtain material with high strength properties.

*Keywords:* Austempered Ductile Iron, statistical analysis, analysis of variance ANOVA, Grubbs Test, Statistica.

### 1. Introduction

History of austempered ductile iron dates back to the 70s of the twentieth century, when the American company General Motors replaced the carburized forged steel, from which was produced a part of the rear axle of Pontiac cars [1].

Quickly persuaded that the ADI cast iron is a material with unusual properties combining high tensile strength and resistance to abrasive wear with very good plasticity. Moreover, it is susceptible to cold-work hardening, and the mechanical processing of it is possible i.e. machining. Therefore, there was no problem with the replacement of the alloy steel, carburized steel or hardened and tempered steel[2,3].

The unique properties of ADI are prepared by austempering of ductile iron. During the heat treating amount of ferrite and austenite in matrix is shaped. This mixture is crucial for most of the mechanical properties of ADI [1].

In economic terms, the production of ADI castings is very cost-effective, which affect, among other factors, such as the low cost of manufacture, good workability and flexibility of design and thus we obtain sufficiently high strength properties which is tensile strength and elongation.

It is well known that the knowledge of the chemical composition allows to predict the mechanical properties of cast iron. Especially important are two elements: nickel and copper. Their increased content in ductile iron improves the tensile strength and elongation. Therefore, it is reasonable to determine the percentage of these elements.

For this purpose the statistical analysis turns out to be useful, allowing for rapid exploration data collected from various heats, thanks to which it is possible to extract the values of Cu and Ni affecting the increase properties of ductile iron.

Copper in ductile iron influences the formation of pearlite phase, while nickel favors the formation of graphite with solidification. Increased copper content affects the increase

of hardness of cast iron, thus decreases the plasticity. Among other alloying elements worth mentioning are Mn and Mo which contents reduce the tensile strength and elongation [4].

### 2. Work methodology

The data from the existing database of 1328 records was subject to the statistical analysis. The output database contained among others the following parameters: the percentage of particular elements of ductile iron, the proportion of pearlite, ferrite [%], the proportion of graphite [%],  $R_m$  [MPa] A5 [%]. Among all of the records 106 results were selected, which were subject to further analysis. The selection criteria was the existence of any values of parameters  $R_m$  and A5. On this basis, a new database (Fig. 1) was created containing the parameters: the percentage of Cu, Ni percentage, the tensile strength  $R_m$  [MPa], and elongation A5 [%] as cast. In addition, a value of Cu + Ni [%] as the correlation between these two elements was input.

For the collected data was performed:

- Histograms of percentage of Cu, Ni, Ni + Cu.
- ANOVA analysis of parameter  $R_m$  [MPa] and A5 [%] dependence of the classification of the percentage of elements.
- The “box and whisker” plots of the parameter  $R_m$  [MPa] dependence of the classification percentage of elements.
- A scatter plot Cu in relation to Ni.
- Grubbs statistical test.

For the statistical evaluation of the impact of increased content of Cu and Ni was used STATISTICA.

In order to classify the percentage of elements Ni, Cu and Ni + Cu histograms were created. It was noted that a natural division in the database existed, so an initial histogram was created, on the basis of which the range of the percentage of each element in the cast iron was determined. Values are

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divided into compartments, for example for copper content were determined ranges of 0 to 1,6 with increments of 0,2. The individual compartments were chosen in order to obtain the highest accuracy while maintaining readability of the charts. To facilitate statistical analysis, element content less than 0,1% was assumed as 0%. An exemplary histogram is shown in Fig. 3.

Ni [%]	Cu [%]	Ni+Cu	Klasyfikacja Cu	Rm [MPa]	A5 [%]
0,0000	0,0000	0,0000	0 < 0.2	572	6,7
0,0000	0,0000	0,0000	0 < 0.2	507	12,1
0,0000	0,0000	0,0000	0 < 0.2	495,3	0,000
0,0000	0,0000	0,0000	0 < 0.2	495,3	0,000
0,0000	0,0000	0,0000	0 < 0.2	495,3	0,000
0,0000	0,000	0,0000	0 < 0.2	404	22,7
0,0000	0,000	0,0000	0 < 0.2	463	21,4
0,0000	0,000	0,0000	0 < 0.2	404	22,7
0,0190	0,0000	0,0190	0 < 0.2	696,4	4
0,0200	0,000	0,0200	0 < 0.2	548	12
0,3100	0,000	0,3100	0 < 0.2	409	24,1
0,3100	0,000	0,3100	0 < 0.2	409	24,1
0,4900	0,000	0,4900	0 < 0.2	411	26,7
0,4900	0,000	0,4900	0 < 0.2	411	26,7
0,7100	0,000	0,7100	0 < 0.2	412	27,4
0,7100	0,000	0,7100	0 < 0.2	412	27,4
0,8800	0,000	0,8800	0 < 0.2	413	24
0,8800	0,000	0,8800	0 < 0.2	413	24
1,0000	0,0000	1,0000	0 < 0.2	552,4	0,000
1,2200	0,000	1,2200	0 < 0.2	421	20,4
1,2200	0,000	1,2200	0 < 0.2	421	20,4
1,4000	0,000	1,4000	0 < 0.2	548	6,42
1,4100	0,000	1,4100	0 < 0.2	548	10,4
1,4200	0,000	1,4200	0 < 0.2	548	3,7

Fig. 1. One part of created database by using the correlation of Ni and Cu elements

### 3. Results

On the Fig. 2 was shown a scatter plot of the percentage of Ni relative to Cu. Plot analysis allows notice the lack of correlation between the elements.

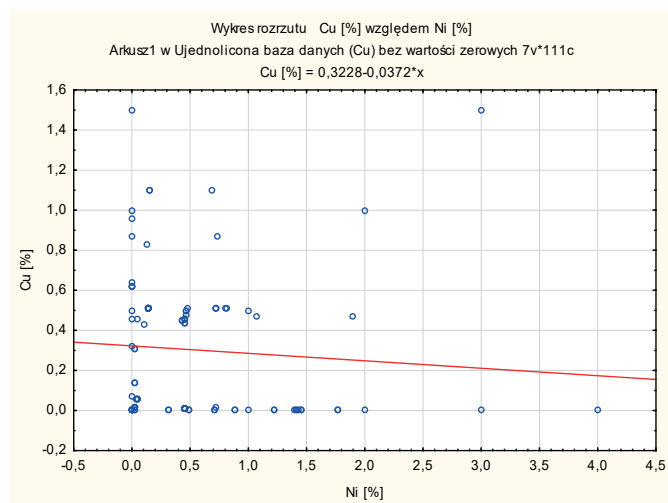


Fig. 2. A scatter plot of the percentage of Cu relative to the percentage of Ni in ductile iron

The most research carried out in all of the database related to the content of elements Ni + Cu for the range of 0,45 to 0,90%. Value of more than 0% content of Cu and Ni is noted

for a range of 0,5% for Cu and 0,5 ÷ 1% Ni. This represents less than half of all obtained results. On this basis, it can be said that the analyzed chemical composition of iron contained a minimum of Cu and Ni.

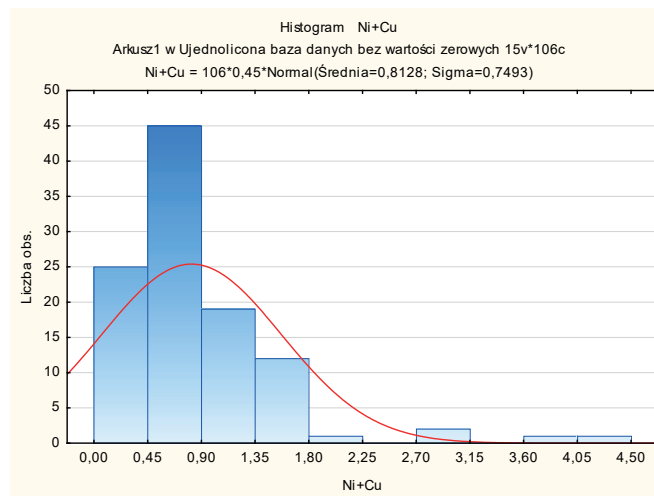


Fig. 3. The number of occurrences of a given percentage of Ni + Cu in ductile iron

A further step was to carry out a statistical analysis “ANOVA”. The ANOVA analysis of variance examining parameters dependent on one or more factors occurring at the same time. The main objective of the analysis of variance to test the significance of differences between means [2].

To carry out ANOVA variance (i.e., the sum of the squares of the deviations from the overall average divided by n-1, where n is the sample size) are separated into pieces.

There are three groups of ANOVA, wherein for the purpose of the analyzes only one such group was used, wherein a predetermined variable (called a dependent variable) affects only one factor.

Dependent variables under consideration were tensile strength  $R_m$  [MPa] and elongation A5 [%], which was made dependent on the classification of the percentage of the elements Ni, Cu and Ni + Cu. On the Fig. 4 and 5 are presented the results for the percentage of Ni + Cu.

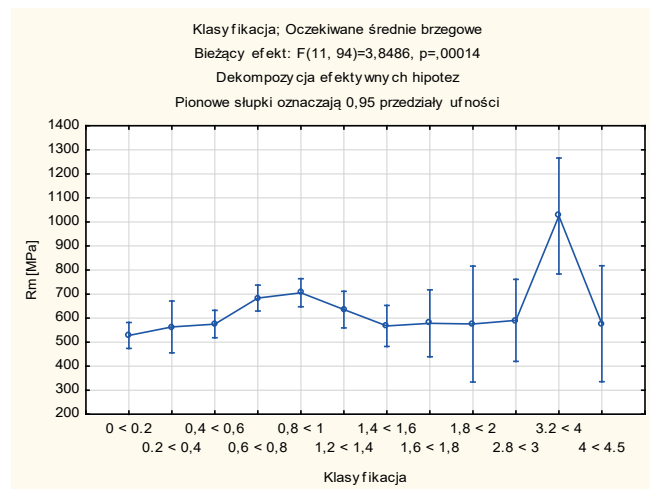


Fig.4. The dependence of tensile strength ductile iron on the classification percentage of Ni + Cu

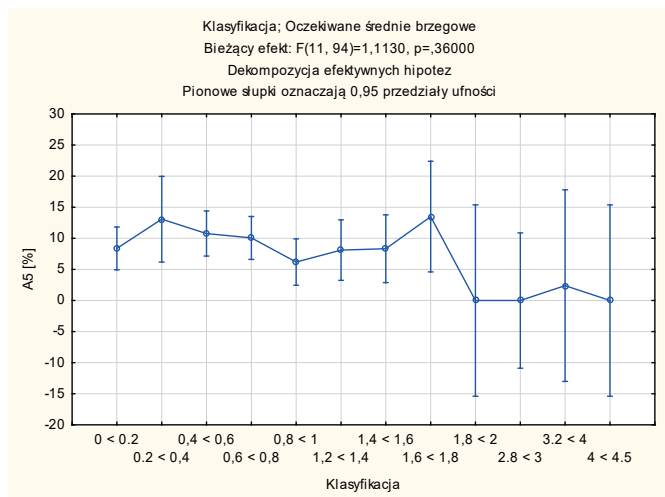


Fig. 5. The dependence of elongation ductile iron on the classification percentage of Ni + Cu

The results of ANOVA were also visualized by using “box-and-whiskers” plots, which enabled the comparison of the value  $R_m$  for each percentage classification of alloying elements. The average is shown as a point, standard errors as the frame, standard deviations as “whiskers”. The center point is defined as the average. For example, the box and whisker plot for  $R_m$  according to the classification of the percentage of Ni + Cu (Fig. 6) can be concluded that there were outliers  $R_m$ , contained in the range of 0-1,6% Ni content in ductile iron.

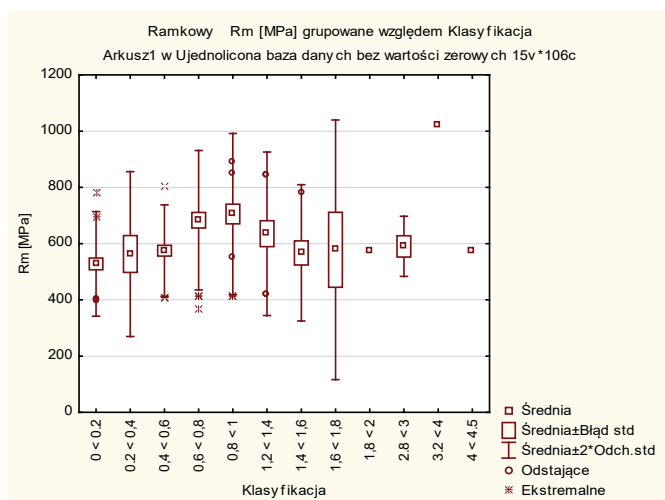


Fig. 6. The dependence of strength  $R_m$  [MPa] of the classification of the percentage of Ni + Cu

Due to the emergence of deviations in the studied cases from the data Grubbs statistical test was carried out. Grubbs statistical significance test gives information on whether the minimum value or maximum from the test set can be considered outlier from the rest of the data. It is assumed that the data comes from a normal distribution. Algorithm for the verification of the hypothesis is as follows [3]:

1. Calculation

$$\bar{X}_i = \frac{1}{n-i+1} \sum_{j \in L_i} X_{jb} \quad (1)$$

where  $L_i$  is the sample index set of elements without values

$i-1$ , which is penultimate, and “ $i$ ” is the number of iterations ( $i = 1, 2, \dots$ ).

2. Calculation of the standard deviation  $S_i$  based on the reduced sample.

3. Determination of statistic test according to the formula

$$G_i = \max_j \left( \frac{|X_j - \bar{X}_i|}{S_i} \right) \quad (2)$$

4. Determination of critical value:

$$G_{\alpha i} = \frac{n-1}{\sqrt{n-i+1}} \frac{t_{(p, n-i-1)}}{\sqrt{n-i-1+t_{(p, n-i-1)}^2}} \quad (3)$$

where  $(t_{p, n-i-1})$  is the value taken from the tables of critical values of the t-distribution with  $n-i-1$  degrees of freedom for the value

$$p = \frac{\alpha}{n-1+1} \quad (4)$$

5. If there is a dependence  $G_i > G_{\alpha i}$ , there is a value stands out from the others, which are omitted in the next step of the calculation.

6. Repeating the steps from 1 to 5 until  $G_i < G_{\alpha i}$  and accept the hypothesis that there was no outlier from the other.

In table 1 were shown the test results obtained for the maximum and minimum values  $R_m$  and  $A_5$  and the corresponding values of the critical  $G_{\alpha i}$ .

TABLE 1

Summary of critical and calculated values of Grubbs test

	For $R_m$	For $A_5$
$G_i$ for a minimum value	2,265	1,153
$G_i$ for a maximum value	1,792	2,34
Critical $G_{\alpha i}$	3,404	3,332

On the basis of calculated parameters of significance test the hypothesis of non-existence of outliers from the collected data can be accepted. The determined values  $G_i$  statistics does not exceed the critical  $G_{\alpha i}$ , therefore, it is not necessary to remove unusual values from the database.

#### 4. Conclusions

Statistics is a universal tool for data mining and translating them into the knowledge of the examined phenomenon or object. The use of analysis of variance and significance tests allowed to conclude that among the collected data there are outliers from the rest. To validate the use of the Grubbs test validation of solutions was performed. The determined test statistics for the incorrect assumption exceeded the critical values, which confirms the correctness of the results.

The ANOVA analysis of variance made it possible to determine the percentage of the elements Cu and Ni to obtain ductile cast iron of the required strength properties. The defined graphs show that the highest tensile strength belongs to a ductile cast iron with a content of Ni + Cu at 3,2 ÷ 4%. It does not correspond to the largest elongation which reaches a maximum value for the interval 1,6 ÷ 1,8%. However,

when analyzing the values in a given confidence interval it is possible to obtain ductile cast iron with the highest  $R_m$  and  $A_5$  content of Ni + Cu ranging from 3,2 ÷ 4%.

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