www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

DOI: 10.24425/122510

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

ISSN (2299-2944)
Volume 18
Issue 2/2018

105 – 111

18/2

Evaluation of the Effect of the Cr, Mo, V and W Content in an Al-Si Alloy Used for Pressure Casting on its Proof Stress

T. Szymczak*[a], J. Szymszal[b], G. Gumienny[a]
[a] Department of Materials Engineering and Production Systems, Lodz University of Technology,
Stefanowskiego 1/15 Street, 90-924 Łódź, Poland
[b] Production Engineering Department, Silesian University of Technology,
ul. Krasińskiego 8, 40-019 Katowice, Poland
* Corresponding author: Email address: tomasz.szymczak@p.lodz.pl

Received 28.07.2017; accepted in revised form 31.10.2017

Abstract

The study presents the results of the application of a statistical analysis for the evaluation of the effect of high-melting additions introduced into a pressure cast Al-Si alloy on the obtained level of its proof stress $R_{p0.2}$. The base Al-Si alloy used for the tests was a typical alloy used for pressure casting grade EN AC-46000. The base alloy was enriched with high-melting additions, such as: Cr, Mo, V and W. The additions were introduced into the base Al-Si alloy in all the possible combinations. The content of the particular high-melting addition in the Al-Si alloy was within the scope of 0.05 to 0.50%. The investigations were performed on both the base alloy and alloy with the high-melting element additions. Within the implementation of the studies, the values of $R_{p0.2}$ were determined for all the considered chemical compositions of the Al-Si alloy. A database was created for the statistical analysis, containing the independent variables (chemical composition data) and dependent variables (examined $R_{p0.2}$ values). The performed statistical analysis aimed at determining whether the examined high-melting additions had a significant effect on the level of $R_{p0.2}$ of the Al-Si alloy as well as optimizing their contents in order to obtain the highest values of the Al-Si alloy's proof stress $R_{p0.2}$. The analyses showed that each considered high-melting addition introduced into the Al-Si alloy in a proper amount can cause an increase of the proof stress $R_{p0.2}$ of the alloy, and the optimal content of each examined high-melting addition in respect of the highest obtained value of $R_{p0.2}$ equals 0.05%.

Keywords: Mechanical properties, Statistical methods, Multi-component Al-Si alloys, Pressure casting, Proof stress

1. Introduction

Aluminium alloys constitute a very popular group among casting alloys. After iron alloys, they are the second most frequently used alloy group for cast production [1-3]. In 2015 the share of aluminum alloys in the global castings production was 15.4% [3]. The most common representative of aluminium casting alloys are Al-Si alloys. The industry applies many methods of increasing the mechanical properties of Al-Si alloys, such as: thermal treatment (precipitation hardening) [4], modification [5], unique cast production conditions [6, 7] and with using alloy additions [8, 9]. Among the alloy additions, a special group is constituted by the elements of a relatively high melting point, such as: Cr, Mo, V and W. These elements create solutions of unlimited solubility among each other, e.g. Cr-V [10], Cr-Mo [11] or Mo-V [12]. However, Al-Cr [13], Al-V [14], Al-W [14] and Al-Mo [15] phase diagrams show very limited solubility of high melting additives in solid aluminum. This causes the formation of intermetallic compounds in the Al-Si alloy's microstructure, which increase the alloy's brittleness. The Al-Si alloys especially exposed to such phenomenon are the ones which crystallize with relatively slow heat removal (casting into sand and ceramic moulds). The increase of the intensity of heat removal from the crystallizing cast (die casting and pressure casting) makes it possible to oversaturate the solid Al-Si alloy solutions with high-melting elements. This may cause an increase of selected properties of the Al-Si alloy. The possibility of influencing the properties of a pressure cast hypoeutectic Al-Si alloy containing Cr, Mo, V and W in various combinations is proved by the results presented in the studies [16-19]. It can be inferred from them that introducing relatively low amounts of high-melting additions into the Al-Si alloy usually causes an increase of the tensile strength R_m and unit elongation A of the Al-Si alloy. This is probably connected with the oversaturation of the solid solution α(Al) of the Al-Si alloy with high-melting additions. Increasing the content of the examined additions to the amount causing the formation of relatively large precipitates of intermetallic phases in the microstructure leads to a secondary decrease of these properties. The data concerning the effect of the content of the Cr, Mo, V and W additions applied in different combinations on the obtained values of proof stress $R_{p0,2}$ do not demonstrate the tendency mentioned above. In the cited studies, the use of high-melting elements in pressure cast Al-Si alloys lowered the values of $R_{p0.2}$ [16, 18], slightly increased $R_{p0.2}$ [17] or affected $R_{p0.2}$ in a random manner [19]. The aim of this study is to present the results of a statistical analysis of the effect of the Cr, Mo, V and W contents on the proof stress $R_{p0.2}$ of the Al-Si alloy, which was performed on the data from the whole scope of combinations of these elements.

2. Test methodology

Figure 1 shows a flowchart of the research methodology. The base alloy was the Al-Si alloy grade EN AC-46000. The scope of the chemical composition of the base Al-Si alloy is presented in Table 1.

Table 1.
Scope of the chemical composition of the investigated initial Al-Si alloy grade EN AC-46000

Chemical composition, % wt.								
Si	Cu	Zn	Fe	Mg	Mn	Ni	Ti	Al
8.69 ÷ 9.35	2.09 ÷ 2.43	0.90 ÷ 1.07	0.82 ÷ 0.97	0.21 ÷ 0.32	0.18 ÷ 0.25	0.05 ÷ 0.13	0.042 ÷ 0.049	balance

The base Al-Si alloy was melted in a gas-heated shaft furnace with the capacity of 1.5 tons. Inside the shaft furnace, the Al-Si alloy was refined with the solid refiner Ecosal Al113.S. It is a NaCl + KCl based refiner for the purification and deslagging of Al and its alloys. After the melting and refining, the Al-Si alloy was deslagged and transported into a heating furnace placed near a die casting machine. In the heating furnace, the initial Al-Si alloy was enriched with so-called high-melting elements, i.e. Cr, Mo, V and W. These elements were introduced into the Al-Si alloy in various combinations: individually, in combinations of two (CrMo, CrV, CrW, MoV, MoW and VW), three (CrMoV, CrMoW, CrVW and MoVW) and all of them together. Due to the relatively high melting points of Cr, Mo, V and W and the relatively low temperature of holding the Al-Si alloy in the heating furnace, the examined additions were introduced into the Al-Si alloy in the form of master alloys: AlCr15, AlMo8, AlV10 and AlW8. The master alloys were applied in the amounts making it possible to obtain the assumed amount of the particular additions in the given melt. The content of chromium, molybdenum, vanadium and tungsten in the Al-Si alloy was in the range of 0.0-0.5% and graded every 0.1%. In the case of introducing more than one high-melting element into the Al-Si alloy, all the elements were introduced in the same amount. For the combinations of two, the scope of the additions was 0.0-0.4% each; and their content was increased by 0.1% in the consecutive melts. In the case of the combinations of three and the one of four, the scope of the introduced additions was 0.00-0.25% each, and in the consecutive melts, their content was increased by 0.05%.

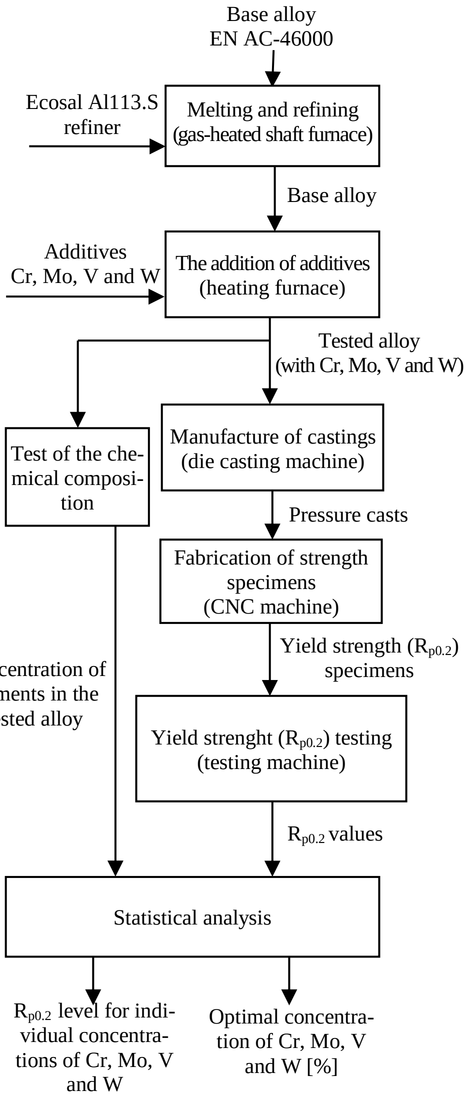

Fig. 1. Flowchart for methodology

For each variant of the chemical composition, pressure casts of the side cover of a roller blind casing were made. They were made on a die casting machine with a cold horizontal pressure chamber Idra 700S. The casts had the shape of a panel with the wall thickness of 2 mm. Pouring temperature was 710°C, the pressure of the third phase was 1100 bar. The pressure mold was made of hot-working tool steel 1.2343 (ESR). The values of proof stress $R_{p0,2}$ were determined by means of static tension tests. The tests were conducted on the strength machine Instron 3382 with the application of the rate of 1 mm/min. The test specimens were cut out of the prepared pressure casts. For each examined chemical composition of the Al-Si alloy, 3 specimens were cut out of one cast. The specimens were rectangular cross-section with a height of 2 mm and a base length of 10 mm, recommended by the standard [20].

As the statistical tool for the evaluation of the effect of the Cr, Mo, V and W content in the Al-Si alloy on the level of its proof stress $R_{p0.2}$ the analysis of variance (ANOVA - ANalysis Of VAriance) test was applied for the main effects [21-23].

The database was elaborated with the use of the Excel worksheet, whereas, for the statistical calculations, the licensed packets: Statistica v. 7.1.PL by Statsoft and MedCalc Statistical Software v.14.10.2 (MedCalc Software bvba, Ostend, Belgium) were applied.

3. Test results

Within the implementation of this study, a database was created for the purpose of a statistical analysis. Also, an analysis of the effect of the high-melting additions, i.e. Cr, Mo, V and W on the proof stress $R_{p0.2}$ level of the pressure cast Al-Si alloy was made. The analysis aimed at determining whether the examined additions had a significant effect on the level of $R_{p0.2}$ of the investigated Al-Si alloy and at optimizing their content in order to obtain the highest values of the proof stress $R_{p0.2}$.

In all the statistical analysis, the assumed level of significance (type 1 error) was **p(α) = 0.05**.

3.1. Database for statistical analysis

The database elaborated in order to perform an analysis of variance is composed of the independent variables (explanatory features) and the dependent variables (response features). The independent variables are the examined high-melting additions introduced into the initial Al-Si alloy, i.e. the variable concentration of elements: ***Cr, Mo, V*** and ***W*** expressed in [%]. The dependent variables are the results of the measurements of the proof stress $R_{p0.2}$ value *[MPa]* of the investigated Al-Si alloys.

The elaborated database contains the independent and dependent variables concerning the Al-Si alloy containing 15 combinations of high-melting additions and the Al-Si alloy without such additions. It includes the values of the independent and dependent variables concerning 69 pressure casts of Al-Si alloys containing the high-melting additions and 4 casts made of the base Al-Si alloy. As three specimens were collected for the statistical tensile tests from each cast, the database considered 207 results of the $R_{p0.2}$ measurement obtained for the Al-Si alloy with the high-melting element additions an 12 results for the initial Al-Si alloy.

For the purpose of the statistical analysis, the independent variables were coded into **quality variables** (so-called factors): ***Cr_1, Mo_1, V_1*** and ***W_1***; which had **nine** levels (from **1** to **9**), depending on the content of the high-melting additions in the Al-Si alloy: 0.00% = **1**; 0.05% = **2**; 0.10% = **3**; 0.15% = **4**; 0.20% = **5**; 0.25% = **6**; 0.30% = **7;** 0.40% = **8;** 0.50% = **9**.

The dependent variables were included in the database also in the form of their ***standardized values***. The standardized values of the proof stress were denoted in the database as $Sost\_R_{p0.2}$. They can be used to optimize the effect of the content of the high-melting additions in the examined Al-Si alloy on the values of proof stress $R_{p0.2}$. The standardized value of proof stress can be calculated according to relation (1):

$$Sost\_R_{p0.2} = (R_{p0.2} - SR\_R_{p0.2}) / \sigma\_R_{p0.2} \qquad (1)$$

where:
$Sost\_R_{p0.2}$ – standardized value of proof stress [-],
$R_{p0.2}$ – empirical value of proof stress [MPa],
$SR\_R_{p0.2}$ – mean value of proof stress [MPa],
$\sigma\_R_{p0.2}$ – standard deviation of proof stress [MPa].

The standardization makes it possible to obtain the absolute variable by means of a transformation of the denominate variable. A standardized quantity also characterizes in the fact that its mean value equals zero, and the standard deviation equals one.

The mean value of proof stress calculated for specimens of the base Al-Si alloy equals $R_{p0.2}$ = 120 MPa. The standard deviation is $\sigma\_ R_{p0.2}$ = 9.3 MPa.

3.2. Evaluation of the effect of Cr, Mo, W and V content on $Sost\_R_{p0.2}$

For the evaluation of the effect of the content of Cr, Mo, V and W in the Al-Si alloy on the dependent variable $Sost\_R_{p0.2}$ the analysis of variance (ANOVA) test was applied for the main effects. The contents of the examined alloy elements: ***Cr***, ***Mo***, ***V*** and ***W*** in the Al-Si alloy, coded with numbers from **1** to **9**, were used as the factors in the analysis of variance. Each factor (***Cr_1***, ***Mo_1***, ***V_1*** and ***W_1***) had nine levels.

The optimization of the effect of the ***Cr***, ***Mo***, ***V*** and ***W*** content in the investigated Al-Si alloy on the obtained values of its proof stress $R_{p0.2}$ was performed with the aim to obtain the maximal values of $R_{p0.2}$. The standardized quantities of proof stress $Sost\_R_{p0,2}$ were used as the target variable.

3.2.1. Analysis of the effect of factors *Cr_1*, *Mo_1*, *V_1* and *W_1* in the Al-Si alloy on $Sost\_R_{p0.2}$

Table 2 shows the results of the statistical evaluation of the effect of factors ***Cr_1***, ***Mo_1***, ***V_1*** and ***W_1*** (i.e. the chromium, molybdenum, vanadium and tungsten content) in the Al-Si alloy on the dependent variable $Sost\_R_{p0.2}$.

Table 2.

Results of the statistical evaluation of the effect of factors ***Cr_1***, ***Mo_1***, ***V_1*** and ***W_1*** in the Al-Si alloy on ***Sost_ R***$_{p0.2}$

ANOVA of main effects. Dependent variable: *Sost_R*$_{p0,2}$					
Parameter	**Sum of squares**	**Degree of freedom**	**Mean square**	**F**	**p**
Constant	5,8474	1	5,8474	8,6349	**0,0037**
Cr_1	**32,9493**	**8**	**4,1187**	**6,0821**	**0,0000**
Mo_1	**11,1093**	**8**	**1,3887**	**2,0507**	**0,0428**
V_1	**30,5577**	**8**	**3,8197**	**5,6406**	**0,0000**
W_1	**14,9598**	**8**	**1,8700**	**2,7614**	**0,0066**
Error	125,9548	186	0,6772		
Bartlett's test: χ^2 = 13,88; p = 0,084					

For the verification of the basic assumption of uniformity (homogeneity) of variance within all the groups (levels of the examined factors), the Bartlett test was applied. It was established that the investigated variances are homogeneous (p = 0.084) and a further analysis can be performed. Prior to the ANOVA test, Bartlett's test for equality of variances is performed. If the Bartlett test is positive ($P<0.05$) then the variances in the groups are different (the groups are not homogeneous), and therefore the assumptions for ANOVA are not met [24].

The results of the ANOVA test for the main effects show that the mean values of ***Sost_R***$_{p0.2}$ in all the groups (for all the levels) of the examined factors Cr_1, Mo_1, V_1 and W_1 differ in a statistically significant way (p: <0,0001; 0,0428, <0,0001; 0,0066, respectively). And so, all the examined input variables (***Cr***, ***Mo***, ***V*** and ***W***) coded into factors affect the target variable ***Sost_R***$_{p0.2}$.

Another condition for the use of the results of the ANOVA test presented in Table 2 is the verification of the agreement of the examined target feature's distribution (***Sost_R***$_{p0.2}$) with the normal distribution (Figure 2) as well as the agreement of the distribution of residues with the normal distribution (Figure 3). The obtained results prove a sufficient matching of the examined target feature and the residues with the normal distribution.

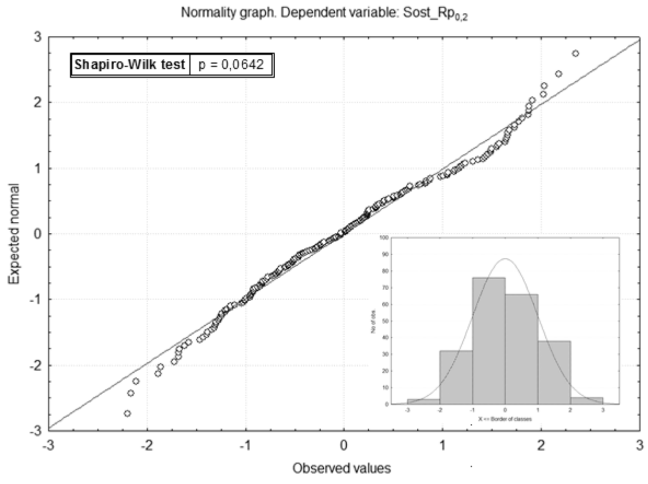

Fig. 2. Verification of the agreement of the distribution of the examined variable target feature ***Sost_R***$_{p0.2}$ with the normal distribution

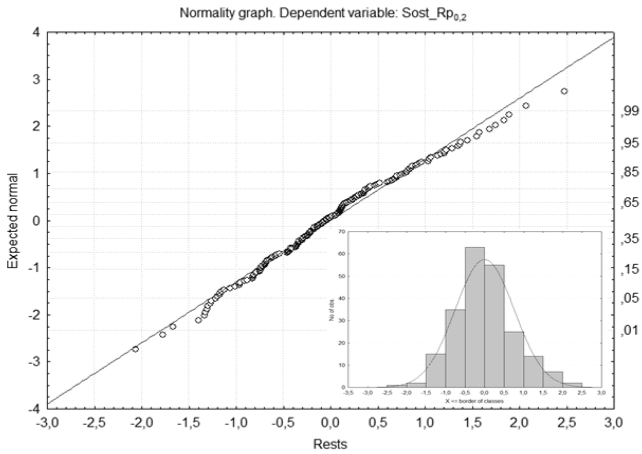

Fig. 3. Verification of the agreement of the distribution of the ***Sost_R***$_{p0.2}$ variable residue with the normal distribution

With the purpose to determine the optimal level (content) of the investigated factor, an estimation of the mean values of the dependent variable (***Sost_R***$_{p0.2}$) was made for each examined level of one of the four factors (***Cr_1, Mo_1, V_1*** and ***W_1***) and NIR post-hoc tests were conducted.

3.2.2. Analysis of the effect of factor *Cr_1* in the Al-Si alloy on *Sost_R*$_{p0,2}$

Figure 4 shows the results of the statistical evaluation of the effect of factor ***Cr_1*** (chromium content) in the Al-Si alloy on the dependent variable ***Sost_R***$_{p0.2}$.

Dependent variable: *Sost_R*$_{p0,2}$							
Factor	**Level of the factor**	**N**	**Sost_R$_{p0,2}$ Mean**	**Sost_R$_{p0,2}$ SD**	**Sost_R$_{p0,2}$ Std. error**	**Sost_R$_{p0,2}$ -95,0% CI**	**Sost_R$_{p0,2}$ +95,0% CI**
Cr_1	1 (0,00%)	108	-0,375	0,813	0,078	-0,530	-0,220
Cr_1	**2 (0,05%)**	**12**	**0,710**	**0,972**	**0,281**	**0,092**	**1,328**
Cr_1	**3 (0,10%)**	**24**	**0,523**	**1,202**	**0,245**	**0,016**	**1,031**
Cr_1	4 (0,15%)	12	0,265	0,996	0,287	-0,367	0,898
Cr_1	**5 (0,20%)**	**24**	**0,550**	**0,962**	**0,196**	**0,144**	**0,957**
Cr_1	6 (0,25%)	12	0,187	1,222	0,353	-0,589	0,964
Cr_1	7 (0,30%)	12	0,306	0,851	0,246	-0,235	0,846
Cr_1	8 (0,40%)	12	0,027	0,749	0,216	-0,449	0,502
Cr_1	9 (0,50%)	3	-1,058	0,206	0,119	-1,570	-0,545

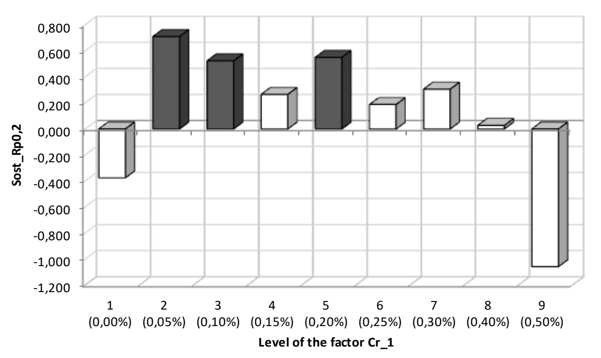

Fig. 4. Estimations of selected characteristics of the descriptive statistics of the ***Sost_R***$_{p0.2}$ dependent variable value for factor ***Cr_1***

As it can be inferred from the presented data, the optimal level of chromium in the examined Al-Si alloy in respect of the total standardized value of ***Sost_R$_{p0.2}$*** should be at the level of 0.05% Cr. The result of the NIR post-hoc test (Table 3) made it possible to demonstrate many statistically significant differences between the particular groups differing in the level of factor ***Cr_1.***

Table 3.
Result of the NIR post-hoc test of the particular groups differing in the level of factor ***Cr_1***

Dependent variable: *Sost_R$_{p0,2}$*									
Level of the factor Cr_1	1 (0,00%)	2 (0,05%)	3 (0,10%)	4 (0,15%)	5 (0,20%)	6 (0,25%)	7 (0,30%)	8 (0,40%)	9 (0,50%)
1 (0,00%)	p =	**0,0000**	**0,0000**	**0,0113**	**0,0000**	**0,0258**	**0,0072**	0,1100	0,1583
2 (0,05%)	**0,0000**	p =	0,5225	0,1873	0,5842	0,1216	0,2305	**0,0434**	**0,0011**
3 (0,10%)	**0,0000**	0,5225	p =	0,3760	0,9099	0,2495	0,4551	0,0894	**0,0020**
4 (0,15%)	**0,0113**	0,1873	0,3760	p =	0,3284	0,8170	0,9043	0,4786	**0,0136**
5 (0,20%)	**0,0000**	0,5842	0,9099	0,3284	p =	0,2138	0,4015	0,0735	**0,0017**
6 (0,25%)	**0,0258**	0,1216	0,2495	0,8170	0,2138	p =	0,7251	0,6331	**0,0201**
7 (0,30%)	**0,0072**	0,2305	0,4551	0,9043	0,4015	0,7251	p =	0,4074	**0,0111**
8 (0,40%)	0,1100	**0,0434**	0,0894	0,4786	0,0735	0,6331	0,4074	p =	**0,0426**
9 (0,50%)	0,1583	**0,0011**	**0,0020**	**0,0136**	**0,0017**	**0,0201**	**0,0111**	**0,0426**	p =

3.2.3. Analysis of the effect of factor *Mo_1* in the Al-Si alloy on *Sost_R$_{p0.2}$*

Figure 5 shows the results of the statistical evaluation of the effect of factor ***Mo_1*** (molybdenum content) in the Al-Si alloy on the dependent variable ***Sost_R$_{p0.2}$***.

Dependent variable: *Sost_R$_{p0,2}$*							
Factor	**Level of the factor**	**N**	**Sost_R$_{p0,2}$ Mean**	**Sost_R$_{p0,2}$ SD**	**Sost_R$_{p0,2}$ Std. error**	**Sost_R$_{p0,2}$ -95,0% CI**	**Sost_R$_{p0,2}$ +95,0% CI**
Mo_1	1 (0,00%)	108	-0,123	0,975	0,094	-0,309	0,063
Mo_1	**2 (0,05%)**	**12**	**0,794**	**0,875**	**0,253**	**0,238**	**1,350**
Mo_1	3 (0,10%)	24	0,130	1,079	0,220	-0,326	0,585
Mo_1	**4 (0,15%)**	**12**	**0,481**	**0,814**	**0,235**	**-0,035**	**0,998**
Mo_1	5 (0,20%)	24	0,056	1,148	0,234	-0,429	0,541
Mo_1	6 (0,25%)	12	0,123	1,391	0,402	-0,761	1,006
Mo_1	7 (0,30%)	12	-0,197	0,635	0,183	-0,601	0,207
Mo_1	8 (0,40%)	12	-0,337	0,468	0,135	-0,634	-0,040
Mo_1	9 (0,50%)	3	-0,505	0,316	0,183	-1,290	0,281

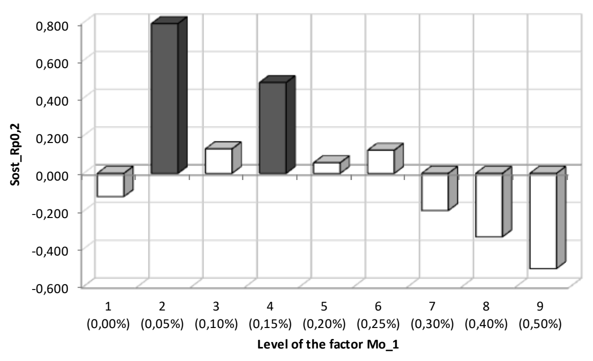

Fig. 5. Estimations of selected characteristics of the descriptive statistics of the ***Sost_R$_{p0.2}$*** dependent variable value for factor ***Mo_1***

It can be inferred from the presented data that the optimal level of molybdenum in the investigated Al-Si alloy in respect of the total standardized value of ***Sost_R$_{p0.2}$*** should be at the level of 0.05% Mo. The result of the NIR post-hoc test shown in Table 4 made it possible to demonstrate many statistically significant differences between the particular groups differing in the level of factor ***Mo_1***.

Table 4.
Result of the NIR post-hoc test for the particular groups differing in the level of factor ***Mo_1***

Dependent variable: *Sost_R$_{p0,2}$*									
Level of the factor Mo_1	1 (0,00%)	2 (0,05%)	3 (0,10%)	4 (0,15%)	5 (0,20%)	6 (0,25%)	7 (0,30%)	8 (0,40%)	9 (0,50%)
1 (0,00%)	p =	**0,0003**	0,1749	**0,0167**	0,3354	0,3276	0,7686	0,3952	0,4294
2 (0,05%)	**0,0003**	p =	**0,0236**	0,3538	**0,0121**	**0,0472**	**0,0036**	**0,0009**	**0,0154**
3 (0,10%)	0,1749	**0,0236**	p =	0,2281	0,7573	0,9806	0,2630	0,1107	0,2097
4 (0,15%)	**0,0167**	0,3538	0,2281	p =	0,1454	0,2867	**0,0449**	**0,0158**	0,0650
5 (0,20%)	0,3354	**0,0121**	0,7573	0,1454	p =	0,8196	0,3854	0,1787	0,2672
6 (0,25%)	0,3276	**0,0472**	0,9806	0,2867	0,8196	p =	0,3427	0,1733	0,2392
7 (0,30%)	0,7686	**0,0036**	0,2630	**0,0449**	0,3854	0,3427	p =	0,6782	0,5632
8 (0,40%)	0,3952	**0,0009**	0,1107	**0,0158**	0,1787	0,1733	0,6782	p =	0,7521
9 (0,50%)	0,4294	**0,0154**	0,2097	0,0650	0,2672	0,2392	0,5632	0,7521	p =

3.2.4. Analysis of the effect of factor *V_1* in the Al-Si alloy on *Sost_R$_{p0.2}$*

Figure 6 presents the results of the statistical evaluation of the effect of factor ***V_1*** (vanadium content) in the Al-Si alloy on the dependent variable ***Sost_R$_{p0.2}$***.

Dependent variable: *Sost_R$_{p0,2}$*							
Factor	**Level of the factor**	**N**	**Sost_R$_{p0,2}$ Mean**	**Sost_R$_{p0,2}$ SD**	**Sost_R$_{p0,2}$ Std. error**	**Sost_R$_{p0,2}$ -95,0% CI**	**Sost_R$_{p0,2}$ +95,0% CI**
V_1	1 (0,00%)	108	-0,368	0,931	0,090	-0,546	-0,190
V_1	**2 (0,05%)**	**12**	**0,611**	**1,039**	**0,300**	**-0,049**	**1,271**
V_1	3 (0,10%)	24	0,458	1,041	0,213	0,019	0,898
V_1	4 (0,15%)	12	0,452	0,869	0,251	-0,100	1,004
V_1	5 (0,20%)	24	0,384	0,826	0,169	0,036	0,733
V_1	6 (0,25%)	12	0,427	1,091	0,315	-0,266	1,120
V_1	7 (0,30%)	12	0,235	0,905	0,261	-0,340	0,810
V_1	8 (0,40%)	12	0,124	0,719	0,207	-0,333	0,581
V_1	9 (0,50%)	3	-0,893	0,740	0,427	-2,731	0,946

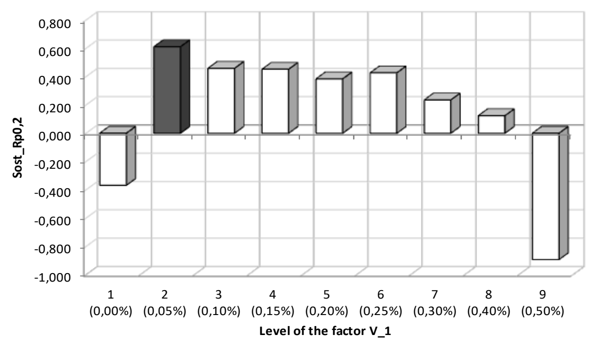

Fig. 6. Estimations of selected characteristics of the descriptive statistics of the ***Sost_R$_{p0.2}$*** dependent variable value for factor ***V_1***

As it can be inferred from the data presented in Fig.5, the optimal level of vanadium in the examined Al-Si alloy in respect of the total standardized value of ***Sost_R$_{p0.2}$*** should equal 0.05% V, as it was the case of chromium and molybdenum. The result of the NIR post-hoc test is presented in Table 5.

Table 5.
Result of the NIR post-hoc test for the particular groups differing in the level of factor ***V_1***

Dependent variable: *Sost_R$_{p0,2}$*									
Level of the factor V_1	1 (0,00%)	2 (0,05%)	3 (0,10%)	4 (0,15%)	5 (0,20%)	6 (0,25%)	7 (0,30%)	8 (0,40%)	9 (0,50%)
1 (0,00%)	p =	**0,0001**	**0,0000**	**0,0013**	**0,0001**	**0,0018**	**0,0170**	0,0510	0,2775
2 (0,05%)	**0,0001**	p =	0,6007	0,6366	0,4370	0,5837	0,2648	0,1488	**0,0052**
3 (0,10%)	**0,0000**	0,6007	p =	0,9824	0,7555	0,9129	0,4439	0,2518	**0,0080**
4 (0,15%)	**0,0013**	0,6366	0,9824	p =	0,8163	0,9397	0,5195	0,3301	**0,0122**
5 (0,20%)	**0,0001**	0,4370	0,7555	0,8163	p =	0,8847	0,6088	0,3719	**0,0121**
6 (0,25%)	**0,0018**	0,5837	0,9129	0,9397	0,8847	p =	0,5696	0,3688	**0,0139**
7 (0,30%)	**0,0170**	0,2648	0,4439	0,5195	0,6088	0,5696	p =	0,7409	**0,0351**
8 (0,40%)	0,0510	0,1488	0,2518	0,3301	0,3719	0,3688	0,7409	p =	0,0572
9 (0,50%)	0,2775	**0,0052**	**0,0080**	**0,0122**	**0,0121**	**0,0139**	**0,0351**	0,0572	p =

The results shown in Table 5 made it possible to demonstrate many statistically significant differences between the particular groups differing in the level of factor V_1.

3.2.5. Analysis of the effect of factor *W_1* in the Al-Si alloy on *Sost_R$_{p0.2}$*

Figure 7 shows the results of the statistical evaluation of the effect of factor ***W_1*** (tungsten content) in the Al-Si alloy on the dependent variable ***Sost_R$_{p0.2}$***.

Dependent variable: *Sost_R$_{p0,2}$*							
Factor	**Level of the factor**	**N**	**Sost_R$_{p0,2}$ Mean**	**Sost_R$_{p0,2}$ SD**	**Sost_R$_{p0,2}$ Std. error**	**Sost_R$_{p0,2}$ -95,0% CI**	**Sost_R$_{p0,2}$ +95,0% CI**
W_1	1 (0,00%)	108	-0,064	0,997	0,096	-0,255	0,126
W_1	**2 (0,05%)**	**12**	**0,338**	**0,940**	**0,271**	**-0,259**	**0,935**
W_1	**3 (0,10%)**	**24**	**0,265**	**1,022**	**0,209**	**-0,167**	**0,696**
W_1	4 (0,15%)	12	-0,044	0,729	0,210	-0,507	0,419
W_1	5 (0,20%)	24	0,134	1,080	0,221	-0,322	0,590
W_1	6 (0,25%)	12	-0,108	1,341	0,387	-0,960	0,744
W_1	7 (0,30%)	12	-0,106	0,523	0,151	-0,438	0,226
W_1	8 (0,40%)	12	0,049	1,049	0,303	-0,617	0,715
W_1	9 (0,50%)	3	-1,385	0,422	0,244	-2,433	-0,336

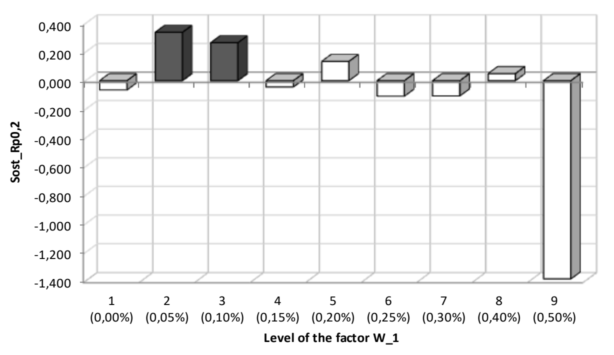

Fig. 7. Estimations of selected characteristics of the descriptive statistics of the ***Sost_R$_{p0.2}$*** dependent variable value for factor ***W_1***

It can be inferred from the data presented in Fig. 6 that the optimal level of tungsten in the examined Al-Si alloy in respect of the total standardized value of ***Sost_R$_{p0.2}$*** should be at the level of 0.05 – 0.10 % W.

Table 6.
Result of the NIR post-hoc test for the particular groups differing in the level of factor ***W_1***

Dependent variable: *Sost_R$_{p0,2}$*									
Level of the factor W_1	1 (0,00%)	2 (0,05%)	3 (0,10%)	4 (0,15%)	5 (0,20%)	6 (0,25%)	7 (0,30%)	8 (0,40%)	9 (0,50%)
1 (0,00%)	p =	0,1099	0,0777	0,9344	0,2861	0,8614	0,8672	0,6507	**0,0067**
2 (0,05%)	0,1099	p =	0,8026	0,2575	0,4850	0,1859	0,1878	0,3913	**0,0014**
3 (0,10%)	0,0777	0,8026	p =	0,2900	0,5827	0,2012	0,2035	0,4591	**0,0013**
4 (0,15%)	0,9344	0,2575	0,2900	p =	0,5414	0,8481	0,8525	0,7824	**0,0124**
5 (0,20%)	0,2861	0,4850	0,5827	0,5414	p =	0,4058	0,4094	0,7703	**0,0029**
6 (0,25%)	0,8614	0,1859	0,2012	0,8481	0,4058	p =	0,9956	0,6401	**0,0172**
7 (0,30%)	0,8672	0,1878	0,2035	0,8525	0,4094	0,9956	p =	0,6441	**0,0171**
8 (0,40%)	0,6507	0,3913	0,4591	0,7824	0,7703	0,6401	0,6441	p =	**0,0076**
9 (0,50%)	**0,0067**	**0,0014**	**0,0013**	**0,0124**	**0,0029**	**0,0172**	**0,0171**	**0,0076**	p =

The result of the NIR post-hoc test (Table 6) made it possible to demonstrate many statistically significant differences between the particular groups differing in the level of factor ***W_1***.

4. Conclusions

The following conclusions can be drawn from the data included in this study:

- Each analyzed high-melting addition introduced into the Al-Si alloy in the proper amount can cause an increase of the alloy's proof stress $R_{p0.2}$;
- The optimal content of each examined high-melting addition in respect of obtaining the highest value of $R_{p0,2}$ equals 0.05%;
- The above-mentioned content of Cr, Mo, V and W results in a value of ***Sost_R$_{p0.2}$*** of 0.710; 0.794; 0.611 and 0.338, respectively;
- After decoding the standardized values ***Sost_R$_{p0.2}$***, the following optimal $R_{p0.2}$ values were obtained: 128 MPa for Cr; 129 MPa for Mo; 127 MPa for V and 123 MPa for W, it resulted in an increase of $R_{p0.2}$ by 6.8%; 7.8%; 5.7% and 2.5%, respectively in comparison to the base alloy;
- For the optimal content of each high-melting addition equaling 0.05%, the strongest positive effect on the level of $R_{p0,2}$ is exhibited by molybdenum;
- The increase in the $R_{p0.2}$ for 0.05% Cr, Mo, V and W is probably due to the supersaturation α(Al) solid solution by high melting additives.

Acknowledgements

Project financed from the means of the National Centre for Research and Development in the years 2013 ÷ 2015 as project UDA-POIG.01.04.00-10-079/12.

References

[1] 48th Census of World Casting Production. Modern Castasting, December 2014, 17-21.
[2] 49th Census of World Casting Production. Modern Castasting, December 2015, 26-31.
[3] 50th Census of World Casting Production. Modern Castasting, December 2016, 25-29.

[4] Pezda, J. (2015). Effect of the T6 heat treatment on change of mechanical properties of the AlSi12CuNiMg alloy modified with strontium. *Archives of Metallurgy and Materials*. 60(2), 627-632.

[5] Pezda, J. (2014). Modification of the EN AC-42000 aluminium alloy with use of multicomponent electrolysis of sodium salt. *Metalurgija*. 53(1), 55-58.

[6] Wróbel, T. & Szajnar, J. (2013). Modification of pure Al and AlSi2 alloy primary structure with use of electromagnetic stirring method. *Archives of Metallurgy and Materials*. 58(3), 941-944.

[7] Piątkowski, J., Gajdzik, B. & Matuła, T. (2012). Crystallization and structure of cast A390.0 alloy with melt overheating temperature. *Metalurgija*. 51(3), 321-324.

[8] Pietrowski, S. (2001). *Silumins*. Łódź. Publishing house of Lodz University of Technology.

[9] Jiang, W., Fan, Z., Dai, Y. & Li, C. (2014). Effects of rare earth elements addition on microstructures, tensile properties and fractography of A357 alloy. *Materials Science and Engineering A*. 597(3), 237-244.

[10] Smith, J.F., Bailey, D.M. & Carlson, O.N. (1982). The Cr-V (Chromium-Vanadium) System. *Bulletin of Alloy Phase Diagrams*. 2(4), 469-473.

[11] Venkataraman, M. & Neumann, J.P. (1987). The Cr-Mo (Chromium-Molybdenum) System. *Bulletin of Alloy Phase Diagrams*. 8(3), 216-220.

[12] Zheng, F., Argent, B.B. & Smith, J.F. (1999). Thermodynamic Computation of the Mo-V Binary Phase Diagram. *Journal of Phase Equilibria*. 20(4), 370-372.

[13] Okamoto, H. (2008). Al-Cr (Aluminum-Chromium). *Journal of Phase Equilibria and Diffusion*. *29*(1), 111-112. DOI: 10.1007/s11669-007-9225-4.

[14] Alloy Phase Diagrams. ASM Handbook Vol. 3. 1992.

[15] Okamoto, H. (2010). Al-Mo (Aluminum-Molybdenum). *Journal of Phase Equilibria and Diffusion*. 31(5), 492–493.

[16] Szymczak, T., Gumienny, G., Stasiak, I. & Pacyniak, T. (2017). Hypoeutectic Al-Si Alloy with Cr, V and Mo to Pressure Die Casting. *Archives of Foundry Engineering*. 17(1), 153-156.

[17] Szymczak, T., Gumienny, G. & Pacyniak, T. (2015). Effect of tungsten on the solidification process, microstructure and properties of silumin 226. *Transactions of the Foundry Research Institute*. *55*(3), 3-14.

[18] Szymczak, T., Gumienny, G. & Pacyniak, T. (2016). Effect of molybdenum on the crystallization, microstructure and properties of silumin 226. *Transactions of the Foundry Research Institute*. 56(3), 193-204.

[19] Szymczak, T., Gumienny, G. & Pacyniak, T. (2016). Hypoeutectic silumin to pressure die casting with vanadium and tungsten. *Archives of Metallurgy and Materials*. 61(4), 2103-2110.

[20] PN-EN 1706:2011. Aluminum and aluminum alloys. Castings. The chemical composition and mechanical properties. (in Polish).

[21] Kleinbaum, D.G., Kupper, L.L., Nizan, A. (1998). *Applied Regression Analysys and Other Multivariable Methods.* (3rd. ed.). Duxbury Press, Pacific Grove.

[22] Altman, D.G. (1991). *Practical statistics for medical research*. London: Chapman and Hall.

[23] Armitage, P., Berry, G., Matthews, J.N.S. (2002). *Statistical methods in medical research*. (4th ed.). Blackwell Science.

[24] Dobosz, M. (2004). *Computer-aided statistical analysis of research results.* Warsaw: Academic Publishing House EXIT.