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Statistical Assessment of the Effect of Chemical Composition on Mechanical Properties of Hypereutectic AlSi17CuNiMg Silumin

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Abstract

The paper presents a statistical assessment of the effect of chemical composition on mechanical properties of hypereutectic AlSi17 silumin, which is expected to act as a counterpart of alloys used by automotive industry and aviation for casting of high-duty engine parts in West European countries and USA. The studies on the choice of chemical composition of silumins were preceded by analysis of the reference literature to state what effect some selected alloying elements and manufacturing technology may have on the mechanical properties (HB, R_m and A_5) of these alloys. As alloying additives, Cu, Ni and Mg in proper combinations were used. The alloy after modification with phosphorus (CuF) was cast into a metal mould. Basing on the results obtained, it has been reported that the developed silumin of hypereutectic composition is characterised by properties similar to its Western counterparts.

Keywords: Innovative foundry materials and technologies, Hypereutectic silumins, Mechanical properties, Statistics

1. Introduction

Good physical and technological properties are the reason why silumins have found wide application in various branches of the engineering industry, among others, in aviation, building industry, electronic and electro-engineering industry and, last but not least, in automotive industry. And yet, though offering numerous advantages, silumins are also characterised by a very important drawback. From the technical viewpoint this is their tendency to the formation of a coarse-grained structure, adversely affecting the mechanical properties of castings. For this reason, silumins after the refining treatment should be subjected to modification.

Of special significance are the hypereutectic silumins containing from 16 to 18 % silicon, assigned for casting of high-duty parts for automotive applications. A wide range of these alloys has been specified by Western standards. Using information given in these standards, it was the aim of the authors of this study to “enrich” the family of “slightly” hypereutectic silumins with alloying additions (Cu, Ni and Mg).

2. Methods of investigation

Own investigations on the choice of chemical composition were preceded by analysis of the reference literature [1-3], discussing the effect of selected alloying elements on properties of these alloys. The studies described in [2-4] report that the main alloying elements are, among others, Cu, Ni and Mg, but it is not precisely stated what effect these elements may have on the mechanical properties (HB, R_m and A_5) of silumins and how strong this effect really is. It is also worth noting that the choice of chemical composition of the examined alloys is mainly determined by their application, and hence by a complex of their utilisation properties.

Taking the above into consideration, for investigations the following alloys were selected: a hypereutectic AlSi17 silumin which was “enriched” with additions of ~3%Cu, ~1,5%Ni and ~1,5%Mg (added separately or jointly). A compilation of the examined silumins is given in Table 1.

Table 1.
Plan of melts for the examined Al-Si-Me alloys

Experiment No.	Alloy
1	AlSi17
2	AlSi17Cu3
3	AlSi17Cu3Ni1,5
4	AlSi17Cu3Mg1,5
5	AlSi17Cu3Mg1,5Ni1,5

The above mentioned alloys were fabricated from the following starting materials (Table 1): aluminium in grade AR1 (99,96% Al), silicon of 98,5% purity (rest Fe and other elements), copper (99, 98% Cu), nickel (99, 98% Ni) and cast AG10 alloy (about 10 wt.% Mg). Melts were conducted in a Leybold-Heraeus IS5/III induction furnace with crucible of 0,7kg capacity made from magnesite refractory material. A protective coating of 2NaF and KCl was used. When the furnace temperature of ~ 820^{o}C had been reached, the melt was subjected to refining treatment with Rafglin-3 in an amount of 0,3 wt.%, followed by modification with Cu-P (~9,95%P). The temperature of pouring was controlled by a NiCr-NiAl TP-202K-800-1 thermocouple immersed in the bath of molten metal.

From the manufactured castings specimens were taken for analysis of the chemical composition. The results are given in Table 2.

Table 2.
Analysis of chemical composition [in wt. %]

Exp. No.	Alloy	Content of elements					
		Si	Cu	Ni	Mg	Fe	Al
1	AlSi	16,56	-	-	-	0,10	rest
2	AlSiCu	16,77	2,79	-	-	0,09	rest
3	AlSiCuNi	16,93	2,72	1,23	-	0,09	rest
4	AlSiCuMg	16,45	2,81	-	1,32	0,07	rest
5	AlSiCuMgNi	16,65	2,79	1,39	1,30	0,08	rest

Liquid silumins were cast into steel moulds producing specimens of dimensions Φ12×100mm according to EN 10002-1. The specimens were next subjected to machining to dimensions 10×100mm.

3. The results of investigations and their analysis

At the first stage of own investigations the quality (stability) of the specimen casting process was evaluated using for numerical evaluation the $\overline{X}$ –*R* and $\overline{X}$ -*S* control charts [5]. Because of the adopted technique of specimen casting, including each time four specimens poured from one gating system, the evaluation of the casting process was based on the specimen size n=4.

Figure 1 shows complex analysis of the process quality done with the use of $\overline{X}$ -*R* control charts. The analysis referred to the tensile strength R_m of an AlSiCuMgNi alloy cast after modification into metal moulds.

As follows from Figure 1, the casting process was stable, and in a few minute time after the modification treatment a considerable increase in the value of R_m was obtained.

Table 3 and Figure 2 show the results of an assessment of the effect of chemical composition on the tensile strength R_m of the examined alloys.

As proved by the statistical analysis using monofactorial ANOVA test [6], there is a statistically significant ($p<0,0001$) effect of chemical composition on the value of R_m.

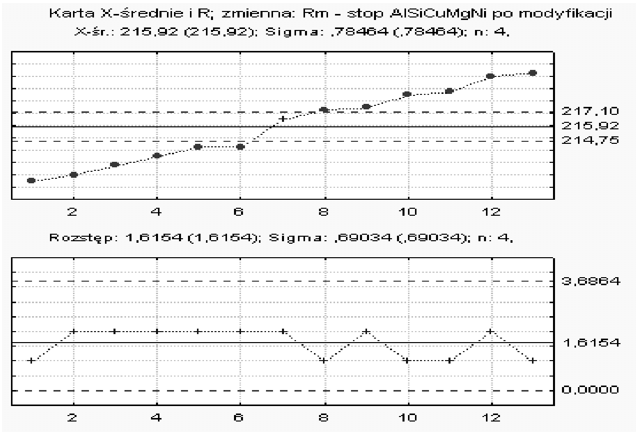

Fig. 1. Analysis of melt stability and its effect on R_m of the modified AlSiCuMgNi alloy cast into metal moulds

Table 3.
Effect of chemical composition on the tensile strength R_m of the examined alloys

Rm [MPa]	The investigated alloy - metal mould + modification				
	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
Mean	**147,79**	**165,98**	**166,69**	**175,21**	**215,92**
Median	148,0	166,0	167,0	175,0	216,0
Std. dev.	4,07	2,80	2,86	3,13	3,07
SEM	0,564	0,389	0,397	0,435	0,426
Minimum	140	159	160	169	211
Maksimum	156	171	172	181	222
Quartile 25%	146	164	165	173	213
Quartile 75%	150	168	169	178	219
N	52	52	52	52	52
	ANOVA test: F = 3212,34, p<0,0001				
Conclusion: alloys show statistically significant difference in respect of Rm					

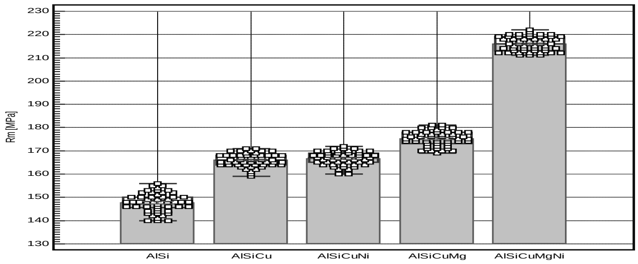

Fig. 2. Effect of chemical composition on the tensile strength R_m of the examined alloys

The highest value of R_m had the hypereutectic silumin (AlSi17) with additions of Cu (3%), Ni (1,5%) and Mg (1,5%). A mono-factorial ANOVA test was applied after checking with Levene's test the hypothesis of equality of R_m variances of the examined alloys [6] (Table 3).

To trace differences in the values of the tensile strength R_m of the examined alloys, a post-hoc test [6] of the least significant difference (LSD) was made, as shown in Table 4.

Table 4.
Statistical assessment of differences in the values of R_m of the examined alloys (across-group comparison)

Levene's test of variances equality p=0,0766					
Post-hoc test of LSD	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
AlSi		p < 0,0001	p < 0,001	p < 0,0001	p < 0,0001
AlSiCu	p < 0,0001		p = 0,2661	p < 0,0001	p < 0,0001
AlSiCuNi	p < 0,0001	p = 0,2661		p < 0,0001	p < 0,0001
AlSiCuMgNi	p < 0,0001	p < 0,0001	p < 0,0001		p < 0,0001

At the next stage of the statistical analysis, a multifactorial ANOVA test (MANOVA) was carried out to determine the significance of an effect of some alloying elements on the tensile strength R_m (Table 5).

Table 5.
The results of MANOVA test illustrating an effect of alloying additions on the tensile strength R_m

Factor	SS	MS	F	p
Free term	3717609	3717609,3	40593,1	<0 ,0001
Cu	1994	1994,2	21,8	<0 ,0001
Ni	22306	22306,3	243,6	<0 ,0001
Mg	44431	44430,8	485,1	<0 ,0001
Error	23445	91,6		

Basing on the results of MANOVA test it has been observed that the strongest significant effect on an increase of the tensile strength R_m exerted the addition of Mg, followed by a nearly two times weaker effect of the addition of Ni. The least significant effect (nearly twenty times weaker) on an increase of the tensile strength R_m had the addition of copper.

Table 6 and Figure 3 show the results of an analysis of the effect of chemical composition on elongation A_5 of the examined silumins.

As follows from Table 6, there is a statistically significant (p<0,0001) effect of the chemical composition on elongation A_5. The highest value of elongation A_5 had the hypereutectic silumin with additions of Cu, Ni and Mg. A monofactorial ANOVA test was applied after checking with Levene's test the hypothesis of equality of A_5 variances of the examined alloys.

Table 6.
Effect of chemical composition on the elongation A_5 of the examined alloys

A_5 [%]	The investigated alloy - metal mould + modification				
	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
Mean	0,88	0,97	1,02	1,08	1,94
Median	0,9	1,0	1,0	1,1	1,9
Std. dev.	0,23	0,19	0,18	0,20	0,18
SEM	0,032	0,027	0,026	0,027	0,026
Minimum	0,5	0,5	0,6	0,6	1,5
Maksimum	1,4	1,4	1,4	1,4	2,3
Quartile 25%	0,7	0,9	0,9	1,0	1,8
Quartile 75%	1,0	1,1	1,2	1,2	2,1
N	52	52	52	52	52
	ANOVA test: F = 252,1, p<0,0001				
Conclusion: alloys show statistically significant difference in respect of A_5					

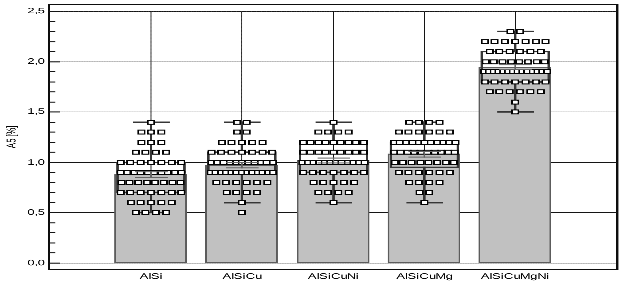

Fig. 5. Effect of chemical composition on the elongation A_5 of the examined silumins

To trace differences in the values of elongation A_5 of the examined alloys (similar as in the case of the tensile strength R_m), a post-hoc test was applied. The results are illustrated in Table 7, while Table 8 shows the results of a multifactorial ANOVA test (MANOVA) performed on the values of elongation A_5 of the examined silumins

Table 7.
Statistical assessment of differences in the values of elongation A_5 of the examined alloys (across-group comparison)

Levene's test of variances equality p=0,5166					
Post-hoc test of LSD	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
AlSi		p = 0,0156	p = 0,0003	p < 0,0001	p < 0,0001
AlSiCu	p = 0,0156		p=0,2152	p = 0,0050	p < 0,0001
AlSiCuNi	p = 0,0003	p=0,2152		p = 0,1130	p < 0,0001
AlSiCuMg	p < 0,0001	p = 0,0050	p = 0,1130		p < 0,0001

Table 8.
The results of MANOVA test illustrating an effect of alloying additions on the elongation A_5

Factor	SS	MS	F	p
Free term	203,55	203,55	2805,81	p < 0 ,0001
Cu	0,36	0,36	4,92	p = 0,0274
Ni	10,80	10,80	148,89	p < 0 ,0001
Mg	13,92	13,92	191,82	p < 0 ,0001
Błąd	18,57	0,1		

Basing on the results of MANOVA test it has been observed that the strongest significant effect on an increase of the elongation A_5 exerted the additions of Mg and Ni (both yielding almost the same values). The least significant effect (almost forty times weaker) on an increase of the value of A_5 had the addition of copper (p.=0,0274). . Table 9 and Figure 6 show the results of an analysis of the effect of chemical composition on hardness HB of the examined silumins.

Table 9.
Effect of chemical composition on the hardness HB of the examined alloys

HB	The investigated alloy - metal mould + modification				
	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
Mean	**67,23**	**76,85**	**77,04**	**106,98**	**140,42**
Median	67,5	77,0	77,0	107,0	140,0
Std. dev.	2,53	3,52	2,81	4,40	2,75
SEM	0,351	0,488	0,389	0,611	0,381
Minimum	60	69	70	97	134
Maksimum	72	86	83	115	146
Quartile 25%	66	75	76	104	139
Quartile 75%	69	79	79	110	142
N	52	52	52	52	52
	Kruskal-Wallis test: H = 235,26, p<0,0001				
Conclusion: alloys show statistically significant difference in respect of HB					

As proved by the statistical analysis using Kruskal-Wallis test [6], there is a statistically significant (p<0,0001) effect of chemical composition on the value of hardness HB. The highest value of the hardness HB had the hypereutectic silumin modified with additions of Cu (3%), Ni (1,5%) and Mg (1,5%).

The Kruskal-Wallis test was applied after checking with Levene's test the hypothesis of equality of HB variances of the examined alloys.

The variances have proved to be statistically different (p=0,0008). To trace the differences in the values of hardness HB of the examined alloys, a post-hoc test for medium ranks was applied, as shown in Table 10.

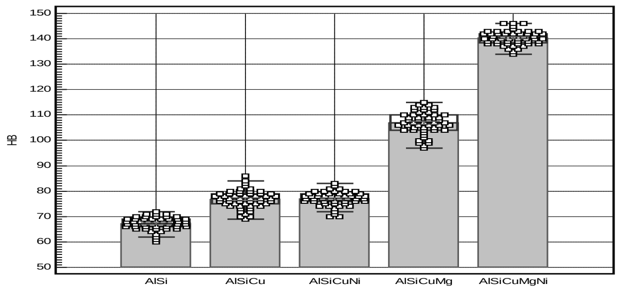

Fig. 6. Effect of chemical composition on the hardness HB of the examined silumins

Table 10.
Statistical assessment of differences in the values of hardness HB of the examined alloys (across-group comparison)

Levene's test of variances equality p=0,5166					
Post-hoc test (ranks)	AlSi	AlSiCu	AlSiCuNi	AlSiCuMg	AlSiCuMgNi
AlSi		p < 0,0001	p < 0,0001	p < 0,0001	p < 0,0001
AlSiCu	p < 0,0001		p = 0,9276	p < 0,0001	p < 0,0001
AlSiCuNi	p < 0,0001	p = 0,9276		p < 0,0001	p < 0,0001
AlSiCuNiMg	p < 0,0001	p < 0,0001	p < 0,001		p = 0,0042

At the final stage of the statistical analysis, a multifactorial ANOVA test (MANOVA) was carried out to determine the significance of effect of various alloying elements on hardness HB.

Table 11.
The results of MANOVA test illustrating an effect of alloying additions on hardness HB

Factor	SS	MS	F	p
Free term	1180756	1180755,7	17670,7	p < 0,0001
Cu	50	50,4	0,8	p = 0,3857
Ni	14707	14706,7	220,1	p < 0,0001
Mg	113696	113696,0	1701,5	p < 0,0001
Błąd	17106	66,8		

Basing on the results of MANOVA test it has been observed that the strongest significant effect on an increase of the hardness HB exerted the addition of Mg, followed by an almost eight times weaker effect of the addition of Ni. The addition of copper has proved to be statistically insignificant (p=0,3857).

4. Summary and conclusions

The obtained results enabled drawing a conclusion that the highest tensile strength R_m combined with the highest elongation A_5 and hardness HB had the specimens of alloy containing, besides aluminium and about 17% silicon, also additions of copper (in an amount of about 3%), magnesium (in an amount of about 1,5%) and nickel (in an amount of about 1,5%).

It has been observed that the strongest significant effect on an increase of the tensile strength R_m exerted the addition of Mg, followed by the addition of Ni (almost two times weaker effect). The weakest effect (almost twenty time weaker) on an increase of the tensile strength R_m had the addition of copper. It has also been proved that the strongest significant effect on an increase of the elongation A_5 had the addition of Mg, followed by the addition of Ni (almost at the same level). The weakest effect (nearly forty times weaker) on an increase of the elongation A_5 had the addition of copper. As regards hardness HB, the strongest effect had the addition of Mg, followed by Ni (nearly eight times weaker effect), while the addition of copper was statistically insignificant (p=0,3857).

The statistical relationships presented here, disclosing an effect of different alloying additions (Cu, Ni and Mg) on the examined resultant characteristics (HB, R_m and A_5), are expected to contribute to a better state of knowledge about the complex evaluation of mechanical properties of hypereutectic silumins with medium silicon content [1].

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