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Effect of Alloy Additions on the Structure and Mechanical Properties of the AlSi7Mg0.3 Alloy

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Abstract

The study presents the results of the investigations of the effect of Cu, Ni, Cr, V, Mo and W alloy additions on the microstructure and mechanical properties of the AlSi7Mg0.3 alloy. The examinations were performed within a project the aim of which is to elaborate an experimental and industrial technology of producing elements of machines and devices complex in their construction, made of aluminium alloys by the method of precision investment casting. It was demonstrated that a proper combination of alloy additions causes the crystallization of complex intermetallic phases in the silumin, shortens the SDAS and improves the strength properties: Rm, $Rp_{0.2}$,HB hardness. Elevating these properties reduces A_t, which, in consequence, lowers the quality index Q of the alloy of the obtained casts. Experimental casts were made in ceramic moulds preliminarily heated to 160 °C, into which the AlSi7Mg0.3 alloy with the additions was cast, followed by its cooling at ambient temperature. With the purpose of increasing the value of the quality index Q, it is recommended that the process of alloy cooling in the ceramic mould be intensified and/or a thermal treatment of the casts be performed (ageing)(T6).

Keywords: Innovative materials and casting technologies, Precision investment casting, Aluminium alloys, Alloy additions, SDAS, Quality index

1. Introduction

The EN AC-AlSi7Mg0.3 alloy is designed for the precision casting of casts of medium-thick or thick walls in a wide range of technical applications. Its mechanical properties mainly depend on the casting technology and the applied thermal treatment [1]. It characterizes in a high corrosion resistance. Table 1 compiles the mechanical properties of this alloy for a cast in a sand mould (S), in the as-cast condition (F) and after solutionizing and artificial ageing (T6), for a cast in: a gravity die (G), a ceramic mould (L) and a pressure casting die (HPDC).

Table 1.
Mechanical properties of the EN AC-AlSi7Mg0.3 alloy [1]

Casting method	Condition	Rm min, MPa	$Rp_{0.2}$ min, MPa	A, %	HB
S	F	140	80	2	45
S	T6	230	190	3	75
G	F	180	90	4	50
G	T6	250	210	5	80
L	T6	260	200	3	75
HPDC	F	264	130	10	-
HPDC	T6	320	246	9,7	-

In the literature, there is no information on the properties of this alloy in the as-cast condition, cast into a ceramic mould in the investment casting technology (L/F).

Introducing, separately or simultaneously, alloy additions such as Ni, Cu, Cr, Mo, V, W into the AlSi7Mg0.3 alloy, cast in a gravity die or a pressure casting die, results in changes in its microstructure. In the microstructure of the alloy, a series of additional intermetallic phases crystallize, such as: Al_2Cu, Mg_2Si, Al_3Ni, AlNiCu, AlCuMgSi(FeNiCrMoWV) and others. In consequence of these changes, the mechanical properties of this alloy increase, both in its as-cast condition and after the thermal treatment [2–4].

From the analysis of the literature one can infer that introducing alloy additions such as: Cr, Mo, V, W also affects the microstructure and improves the mechanical properties of the 226-type aluminium alloys [5,6], bronzes [7,8], as well as spheroidal cast iron [9].

The aim of this study was – for the technology of producing precise casts by the investment (lost wax) casting method – a synthesis of new aluminium alloys in such a way so that a realistic alternative can be created for the process of pressure casting of construction components of high technical and economical effectiveness, at the small lot and medium series scale. The article presents the analysis of the microstructure refinement: solid solutions, eutectics, especially SDAS measurements in the examined alloys. The measurements of the distance between the secondary dendritic arms (SDAS) allow a measurable determination of the effect of the changes in the physico-chemical liquid alloy on the degree of their refinement [10-12]. The mechanical properties of the analyzed alloys (Rm, $Rp_{0.2}$, A_t and HB) will also be presented. Based on the latter, the quality index Q will be determined according to equation (1) [13]:

$$Q=Rm+150\cdot\log_{10}(A_t),\ \text{MPa}. \quad (1)$$

In combination with equation (1), the isolines Rp will be determined, described by relation (2):

$$Rp=Rm-60\cdot\log_{10}(A_t)-13,\ \text{MPa}. \quad (2)$$

2. Test methodology

Due to the requirements for the aluminium alloys to increase: the strength and plasticity, high-temperature creep resistance and heat resistance, as well as abrasion resistance, the AlSi7Mg0.3 alloy was selected, with the additions (according to the invention [2]) of: Cu, Ni, Cr, V, Mo, W. The chemical composition of the AlSi7Mg0.3 alloy is presented in Table 2.

Table 2.
Chemical composition of the AlSi7Mg0.3 alloy

Chemical composition, % wt.							
Si	Cu	Mg	Mn	Fe	Ti	Ni	Al
7.07	0.013	0.35	0.54	0.17	0.13	0.15	remainder

The alloy was melted in an induction furnace, in an AC20-type crucible made of silicon carbide. The alloy additions were introduced in the form of master alloys: AlCu50/50, AlNi20, AlCr15 and AlV10, as well as technically pure metals: Si, Mg, W and Mo. The alloy was modified with Sr (AlSr10), and next refined for 5 min N_2.

The experimental cast models for the strength tests had the form of cylinders, 14 mm in diameter and L=200 mm long. The experimental casts were made in ceramic moulds according to the investment casting technology, from refractory materials REFRACORSE (flour and sands). They consisted of 7 coatings made in mixers and a fluidizer, at the „Armatura" foundry in Łódź, Poland. Each coating was created as a result of applying a binder onto the wax model and next covering it with quartz sand of a specific granularity. The configuration and type of the applied coatings have been presented in the study [14]. After drying from the ceramic mould, the mould material was melted in an autoclave at 50 °C. Next, the mould was reinforced at 800 °C in a tunnel furnace. After the burning process, the ceramic moulds were cooled down to 160 °C, and next filled with liquid metal of the temperature of 750 °C±5 °C.

Figure 1 (a,b) shows: the ceramic mould for the casting of 6 strength samples (a) and the ATD10C-PŁ sampler (b), in which the thermal and derivative analysis of the examined alloys was performed.

a) b)

Fig. 1. Ceramic mould for strength sample casting (a) and ATD10C-PŁ sampler (b)

Records were made of the ATD characteristics of: cooling ($t=f(\tau)$), kinetics ($t=dt/d\tau=f'(\tau)$) and dynamics of the thermal processes ($d^2t/d\tau^2=f''(\tau)$). This made is possible to read the characteristic transformation points in the alloys: AlSi7Mg0.3 without additions and with Cu, Ni, Mo, Cr, V, W additions, marked as Y, Z, A–N.

The AlSi7Mg(CuNiCrVMoW) alloy constitutes the, so-called, object in the planned experiments, as it is shown in Figure 2. The considered object is described by the characteristics y=f(X1, X2, X3, Z), where **Y** is constituted by the selected mechanical properties of the alloys, i.e. Rm, $Rp_{0.2}$, A_t, HB, and: **X1**=Cu%, **X2**=Ni%, **X3**=(Cr,V,Mo,W)% (the same percentage of each element: Cr, V, Mo, W) denote the object inputs, **Z** is the non-measurable disturbance, and **C** is the set of continuous factors of constant values which describe the process realized on the object.

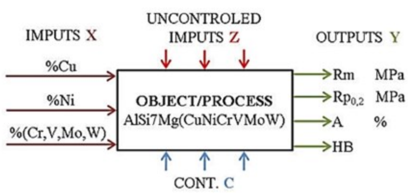


Fig. 2. Considered non-linear object in the planned experiment for the AlSi7Mg(CuNiCrVMoW) alloy

The experiment plan allowing the description of the effect of the changes in the amount of the introduced additions Cu, Ni, Cr, V, Mo and W on the mechanical properties of the examined type of aluminium alloys was implemented with the use of the Box-Wilson method in the vicinity of the central point Ec at two levels „+" and „-" ΔX_S. The factors controlling the properties were assumed as the change in the concentration of Cu, Ni and the simultaneously introduced additions Cr, V, Mo and W. A diagram of the settings is presented in Table 3.

Table 3.
Experiment plan for the AlSi7Mg0.3+(CuNiCrVMoW) aluminium alloys

	Mass concentration, %		
Factor X_S (S={1,2,3})	X1 Cu	X2 Ni	X3 (Cr,V,Mo,W) x% each
Central point Ec(Cu_0,Ni_0,$(Cr,V,Mo,W)_0$)	4	2.5	0.3
Test step ΔX_S	2	1.5	0.2
Upper level $X_{0S}+\Delta X_S$	6	4	0.5
Lower level $X_{0S}-\Delta X_S$	2	1	0.1
E1	6	4	0.5
E2	6	4	0.1
E3	6	1	0.1
E4	6	1	0.5
E5	2	4	0.5
E6	2	4	0.1
E7	2	1	0.1
E8	2	1	0.5

With the purpose to demonstrate the particular phases in the microstructure, the microsections were etched with the HF reagent. The microstructures of the examined alloys were observed by means of the optical microscope MA200. A digital image analysis was performed with the use of the NIS-Elements Br program.

The tensile strength tests, for the determination of the basic mechanical properties, i.e. Rm, A%, were conducted according to the standard PN-EN ISO 6892-1:2010 [15], with the use of the Zwick/Roell Instron 4485 tester. For the determination of the hardness of the tested alloys, HB hardness measurements were made by the Brinell method, with the application of the load force F = 613N, the penetrator (globule) diameter d = 2,5 mm and the load coefficient k = 10.

3. Test results

Table 4 and Figure 3 show the measurement results for the mechanical properties of the AlSi7Mg0.3 alloy without additions and with the alloy additions Cu, Ni, Cr, V, Mo, W (according to Tab. 3). For most of the samples, it was impossible to clearly determine the value of $Rp_{0,2}$. The determined values of $Rp_{0,2}$ changed in the range of about 100–170 MPa.

Table 5, for the examined types of the AlSi7Mg(CuNiCrVMoW) aluminium alloys with different amounts of the Cu, Ni and Cr, V, Mo, W additions (of an equal percentage of each element: Cr, V, Mo, W at the given level) according to the assumed experiment plan (Tab. 3.), presents the following:

- the form of the mathematical model of the surface which contains the vector of the gradient showing the direction of the recommended changes of the chemical composition in order to maximize the analyzed mechanical properties,
- the statistics describing the degree of model approximation:
  R^2 – square of the multi-dimensional correlation coefficient,
  SEE – standard error of estimation,
  MAE – mean absolute error;
- the optimal alloy compositions (from the experimental composition database) determining the obtaining of the maximal response values of: Rm, A, HB.

Table 4.
Mechanical properties of the AlSi7Mg0.3 and AlSi7Mg0.3+(CuNiCrVMoW) aluminium alloys

Experiment No., n En(Cu,Ni,(Cr,V,Mo,W))	Rm, MPa	A, %	HB
AlSi7Mg0.3	135	1.30	60.0
Ec	157	0.40	95.0
E1	145	0.30	109.0
E2	160	0.40	101.0
E3	160	0.40	82.5
E4	140	0.20	108.0
E5	143	0.45	101.0
E6	140	0.60	93.0
E7	144	0.60	97.6
E8	158	0.50	91.9

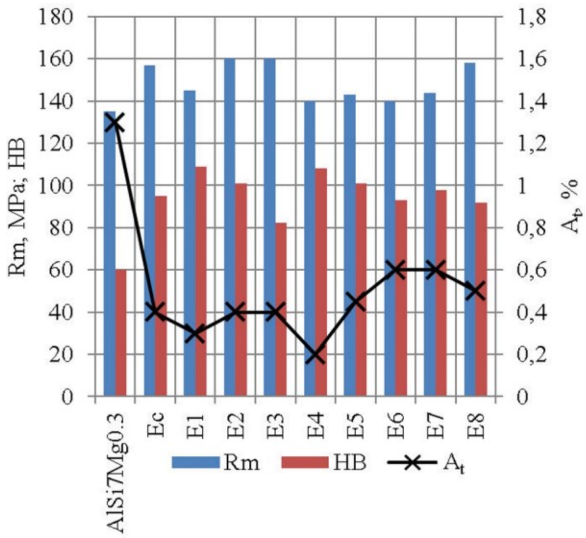
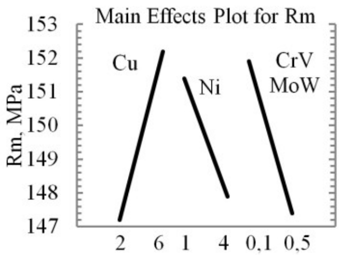
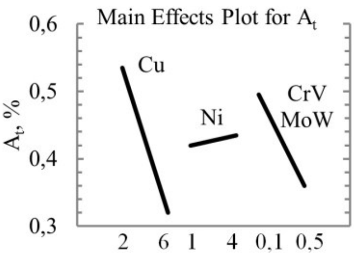
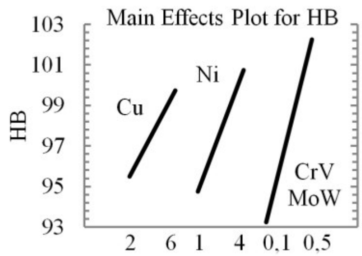


Fig. 3. Mechanical properties of the AlSi7Mg0.3 alloy without the additions and with the alloy additions AlSi7Mg0.3+(CuNiCrVMoW)

Table 5.
Optimal chemical compositions of the AlSi7Mg0.3 aluminium alloys with Cu, Ni, Cr, V, Mo and W additions in the function of mechanical properties maximization

	Rm	A_t	HB
Model	*Rm=150.958+1.25·Cu-1.16667·Ni+ -11.25·CrVMoW*, MPa	*A_t=0.732986-0.053125·Cu+0.00416667·Ni+ -0.34375·CrVMoW*, %	*HB=81.7042+1.0625·Cu+2.0·Ni+ +22.375·CrVMoW*
Statistics	R^2 = 18.49% SEE = 10.07 MPa MAE = 6.63 MPa	R^2 = 94.75% SEE = 0.04% MAE = 0.02%	R^2 = 48.82% SEE = 7.50 MAE = 4.60
Major effect plot			
Alloy compo sition	For Rm→max AlSi7Mg0.3 +6%Cu+1%Ni+ + 0.1% (Cr,V,Mo,W) each /E3/	For A_t →max AlSi7Mg0.3 +2%Cu+4%Ni+ + 0.1% (Cr,V,Mo,W) each /E6/	For HB→max AlSi7Mg0.3 +6%Cu+4%Ni+ + 0.5% (Cr,V,Mo,W) each /E1/

The higher the value of the square of the multi-dimensional correlation coefficient (R^2), the more accurate the approximation of the mathematical model of the surface on which the gradient vector is situated. The low values of R^2 are probably caused by the disturbance of the methodology present during the experiment, e.g. variables in a narrow range:

- Casting time (manual casting),
- Casting temperature,
- Deviations from the alloy addition concentration in relation to the values assumed in the experiment plan.

Due to the discrepancy of the direction of the Rm, A_t, HB vector gradient, the optimal composition for the Eopt silumin was selected (4% Cu, 2% Ni and 0,1% of CrVMoW each), as it is shown in Figure 4. This is a compromise between the increase of both Rm and At and the reduced increase of HB.

Figure 5 shows a set of ATD characteristics of the AlSi7Mg0.3 (AK7) and AlSi7Mg(CuNiCrVMoW) (AK7+) alloys, whereas Figure 6 presents their microstructure.

The introduction of the Cu, Ni, Cr, V, Mo and W additions into the AlSi7Mg0.3 silumin lowered the temperature t of the charactersitic phase transformations, prolonged the time $\Delta\tau$ of their occurrence and changed the kinetics of the thermal processes $dt/d\tau$ taking place during the alloy solidification.

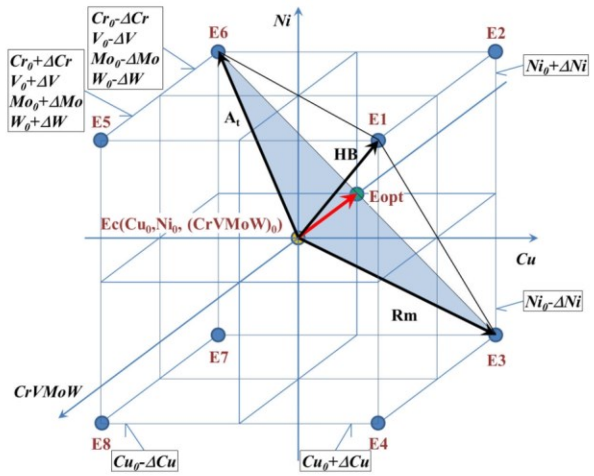
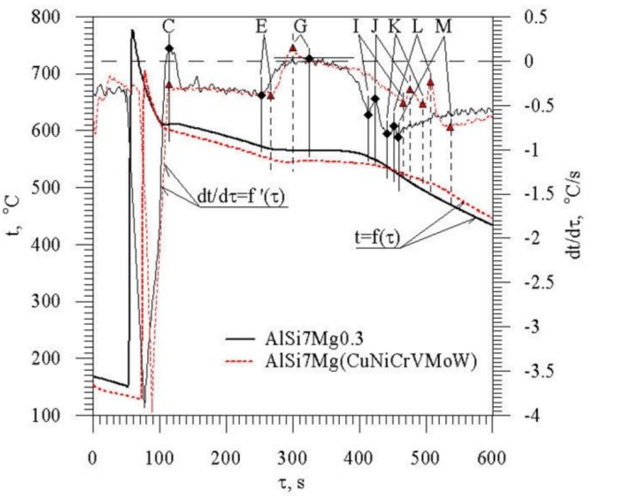


Fig. 4. Directions of the vectors of the Rm, A_t, HB change gradient – selection of the optimal composition of the Eopt silumin (AK7+) AlSi7Mg0.3+4% Cu+2% Ni+0,1% (CrVMoW) each



Point	τ, s		t, °C		dt/dτ, °C/s	
	AK7	*AK7+*	AK7	*AK7+*	AK7	*AK7+*
C	114.6	*114.6*	610.3	*600.3*	0.143	*-0.270*
E	253.0	*266.9*	571.6	*549.3*	-0.389	*-0.369*
G	325.0	*300.2*	564.8	*544.8*	0.030	*0.143*
I	413.8	*466.6*	553.3	*523.6*	-0.606	*-0.485*
J	423.4	*476.2*	548.1	*519.6*	-0.430	*-0.330*
K	441.0	*495.4*	536.8	*511.8*	-0.818	*-0.496*
L	451.4	*507.5*	528.5	*506.9*	-0.737	*-0.239*
M	458.6	*537.0*	522.8	*488.9*	-0.856	*-0.755*

Fig. 5. ATD charactersitics set of the AlSi7Mg0.3 (AK7) and AlSi7Mg(CuNiCrVMoW) (AK7+) alloys and the values of τ, t and dt/dτ for the charactersitic points

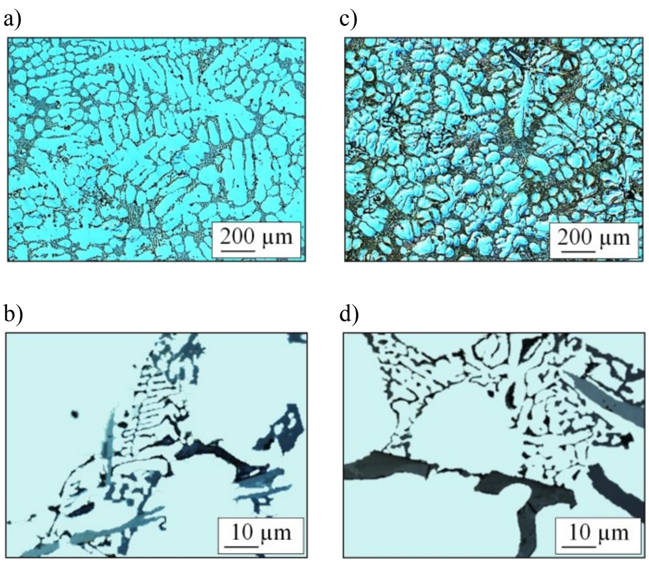


Fig. 6. Microstructure of the alloys:
a-b) AK7, c-d) AK7+

The thermal effect of the crystallization of the primary dendritic phase α (C–E) was reduced, and a clear shortening of the main dendritic branch can be seen in the microstructure images (Fig. 6 a,b). In turn, the thermal effects of the crystallization of both the binary eutectic α+β (E–I) and the complex multi-phase eutectics rich in Mg (I–K), especially (K–M) rich in Cu and Ni, increased. This proves that the introduced alloy additions significantly shift the chemical composition of the AK7+ alloy towards the eutectic compspositions. The microstrcuture of the analyzed types of alloys consists of:

AK7: α+eut. (α+β)+eut. (α+β+Mg_2Si)+eut. (α+β+Al_3Ni)+AlSiFeMn,
AK7+: α+eut. (α+β)+eut. (α+β+MM_{Mg2Si})+eut. (α+β+MM_{Al2Cu})+$MM_{AlSiCuNiFeMnCrVMoW}$.

The additions of Cu, Ni, Cr, V, Mo and W introduced into the AK7 alloy form complex non-equilibrium intermetallic phases (MM), such as: Mg_2Si (MM_{Mg2Si}), Al_2Cu (MM_{Al2Cu}) of different concentrations and combinations of the elements present in the alloy ($MM_{AlSiCuNiFeMnCrVMoW}$). A precise analysis of the microstructure of the examined alloys will be the subject of future publications. For the AK7 i AK7+ alloys, Table 6 presents the measurement results for the distance between the SDAS dendritic arms of the α phase. From the presented data it can be inferred that the introduced alloy additions lowered the SDAS value by about 13%.

Table 6.
SDAS for AK7 and AK7+ alloys

	AK7	*AK7+*
Number of measurements	65	*66*
	SDAS, μm	
Mean value	54.675	*47.610*
Standard error of estimation	9.913	*7.938*
Median	53.778	*46.673*

Table 7 shows the mechanical properties of the AK7 and AK7+ alloys, as well as the quality index Q determined from equation (1). The orientation of the quality index Q for the analyzed alloys on the background of the Drouzy nomogram is shown in Figure 7. The Cu, Ni, Cr, V, Mo and W additions introduced into the AK7 alloy significantly increased Rm and $Rp_{0,2}$ at the cost of a decreased elongation A_t. In comparison to the AK7 alloy, the quality index Q decreased by about 28%. Its increase is probably possible by way of intensifying the the AK7+ alloy's cooling process in the ceramic mould and/or performing an ageing process on the alloy (T6).

Table 7.
Strenght and quality properties of the AK7 and AK7+ alloys

Alloy	Rm, MPa	$Rp_{0.2}$, MPa	A_t, %	HB	Q, MPa
AK7	136	104	1.3	60	153.1
AK7+	170	166	0.4	94	110.3

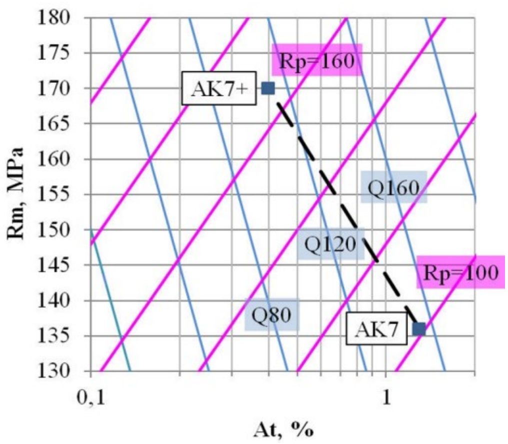


Fig. 7. Nomogram of Drouzy et al. [14] for the quality evaluation of the AlSi7Mg0.3 -type alloys with the use of the quality index Q, on the background of the plasticity isolines Rp

4. Conclusions

From the conducted research one can draw the following conclusions:

- based on the two-level planning, it was established that the AlSi7Mg0.3 +4% Cu+2% Ni+ 0,1% (CrVMoW) alloy will characterize in the optimal mechanical properties (in the examined range of variations of the alloy additions' chemical compositions),
- the introduced additions:
  - prolong the alloy's solidification time and increase the participation of the intermetallic eutectic phases in the microstructure,
  - reduce the SDAS value for the α phase,
  - increase Rm, $Rp_{0.2}$, HB and reduce A_t,
  - reduce the quality index Q,
- an increase of the quality index Q is possible by way of intensifying the cooling process of the AK7+ alloy in the ceramic mould and /or performing the (T6) process on the alloy.

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