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The influence of chemical composition on the properties and structure Al-Si-Cu(Mg) alloys

M. Kaczorowski [a], **A. Krzyńska** [b]
[a] Institute of Mechanics and Design
[b] Institute of Materials Processing
Faculty of Production Engineering, Warsaw University of Technology, ul. Narbutta 85, 02-524 Warszawa, POLAND

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Summary
The mechanical properties of different chemical composition AlSiCuMg type cast alloys after precipitation hardening are presented. The aim of the study was to find out how much the changes in chemistry of aluminum cast alloys permissible by EN-PN standards may influence the mechanical properties of these alloys. Eight AlSi5Cu3(Mg) type cast alloys of different content alloying elements were selected for the study. The specimens cut form test castings were subjected to precipitation hardening heat treatment. The age hardened specimens were evaluated using tensile test, hardness measurements and impact test. Moreover, the structure investigation were carried out using either conventional light Metallography and scanning (SEM) and transmission (TEM) electron microscopy. The two last methods were used for fractography observations and precipitation process observations respectively. It was concluded that the changes in chemical composition which can reach even 2,5wt.% cause essential differences of the structure and mechanical properties of the alloys. As followed from quantitative evaluation and as could be predicted theoretically, copper and silicon mostly influenced the mechanical properties of AlSi5Cu3(Mg) type cast alloys. Moreover it was showed that the total concentration of alloying elements accelerated and intensifies the process of decomposition of supersaturated solid solution. The increase of Cu and Mg concentration increased the density of precipitates. It increases of strength properties of the alloys which are accompanied with decreasing in ductility.

Key words: Aluminum Cast Alloys; Mechanical properties; Structure

1. Introduction

Aluminum alloy casting can be produced by virtually all casting processes in range of chemical compositions possessing a wide variety of useful engineering properties. Among many aluminum alloys Al-Si and Al-Si-Cu are most popular. These usually contain some amount magnesium which is very helpful for its precipitation hardening. According to the standards, the quantity off elements may differ a lot from the average value. For example, the chemical composition of an alloy designed as AlSi5Cu3Mg. According to PN-EN 1706: 2001) is: Si = 4.5 – 6 wt. %, Cu = 2.6 – 3.6 wt. % and Mg = 0.15 – 0.45 wt. %. It means that in extreme cases, the total concentration main elements Si+Cu may differs even 2.5% with respect to the minimum permissible concentration silicon and cooper. This 2.5 wt. % equals 35% of the minimum total concentration Si+Cu and probably might influence a lot the structure and mechanical properties of real casting, just because Si and Cu are the main alloying element in this AlSi5Cu3Mg alloy. Another problem is their influence on precipitation hardening, which is the typical heat treatment used for strengthening of these aluminum cast alloys. Although, other elements were omitted it is (well known that they influence the properties of aluminum alloys, even if they appear in minor quantities [1].

The aim of these investigations is to find out how much the chemical composition changes influence the structure and mechanical properties of age hardenable AlSiCu(Mg) cast alloys.

2. Experimental procedure

Aluminum AlSiCu(Mg) type cast alloy of different chemical composition were selected for the study. The composition of these alloys is given in table 1.

Table 1.

The chemical composition of alloys

No	Chemical composition [wt. %]					Si+Cu	$\Sigma_{elements}$
	Si	Cu	Mg	Zn	Ti		
1	4.51	2.28	0.05	0.10	0.12	**6.79**	7.78
8	4.68	2.20	0.15	0.45	0.11	**6.88**	8.68
10	4.72	2.34	0.13	0.08	0.10	**7.06**	8.08
9	4.80	3.10	0.12	0.22	0.09	**7.90**	9.24
7	4.56	3.89	0.06	0.53	0.11	**8.45**	10.24
4	5.87	2.64	0.13	0.44	0.08	**8.51**	9.87
5	6.68	2.55	0.05	0.08	0.06	**9.23**	10.37
2	5.95	3.77	0.14	0.09	0.06	**9.72**	10.83

The alloys were prepared from commercial AlSi5Cu3 alloy.. The molten metal was refined, modified and finally purred into green sand mould where the step wedge test blocks of different thickness section were cast. All casting were subjected to 7h solution heat treatment at temperature 515 ± 5°C followed by quenching in water of temperature 70 ± 5°C. Then the castings were aged 7h at the temperature 170°C. From the central part of the each casting the specimen for mechanical measurements were cut. From each casting three specimens for tensile and five specimens for impact were taken. Metallography sample were prepared traditionally by grinding and polishing. The SEM observations were carried out on the fracture surface of the specimen used in impact test. TEM studies were performed only for selected casting. First 3mm diameter rods were cut from the casting. From these rods 0.1mm discs were sliced using load less wire saw. Finally these discs were carefully grinded and electro-polished using one-jet method. Moreover DTA analysis were carried out to determine temperature of typical reactions accompanying the heating of solution treated alloys.

2. Results

2.1. Mechanical testing

The results of mechanical testing are given in table 2. As follows from table 2, the mechanical properties of AlSi5Cu3Mg type alloys differ a lot either in strength and ductility. Compare the values collected in table 2 with the chemical composition in table 1, where it is given in a sequence Si+Cu concentration increase (7^{-th} column) it can be seen, that the lowest strength properties correspond the minimum and maximum Si+Cu content.

However, it would be very difficult at this moment to say more precisely what is the reason so big differences.

Table 2.

The results of mechanical testing

Alloy No	Mechanical properties				
	$R_{e,0.2}$ [MPa]	R_m [MPa]	A_5 [%]	HB	KCU
1	138	201	1.75	97	1.15
8	214	289	3.10	112	1.45
10	225	300	2.20	120	-
9	251	322	0.77	118	-
7	259	316	1.70	128	0.91
4	228	287	2.20	117	1.14
2	299	328	1.30	138	0.93
5	127	224	4.70	97	1.22

2.2. Structure investigations

Metallography

The examples of microstructure AlSi5Cu3(Mg) studied here are showed in show in fig.1. As can be seen from fig.1, both specimens are hypoeutectic type, with α solid solutions dendrites embedded in α + Si matrix.

a.

b.

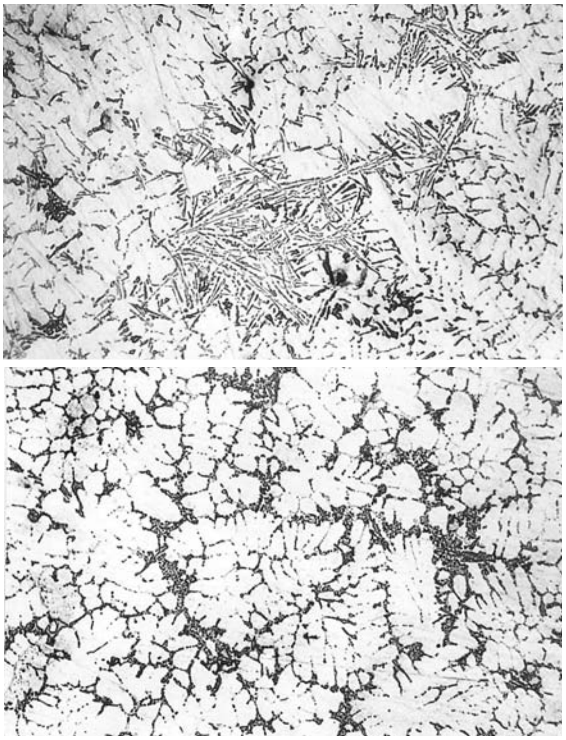


Fig.1. The microstructure AlSi5Cu3(Mg) alloy: a – alloy No 5 (Si + Cu = 9.23%) and b – No 8 (Si + Cu = 6.88%) (magn. x50)

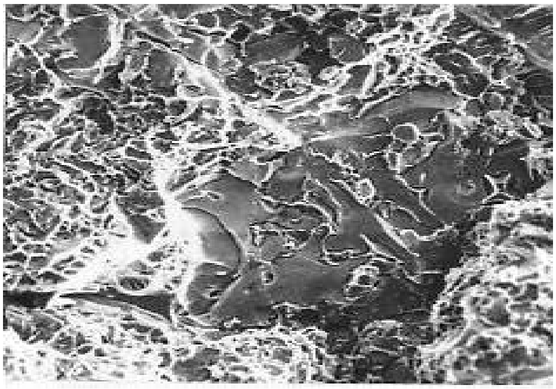
As can be seen from these micrographs, it is some difference in refining of eutectic silicon, which probably resulted from different efficiency of inoculation process. As follows from table

1, this unmodified eutectic silicon really did not influence on ductility of the alloy No5.The observations taken at higher magnification did not discover the influence of cooper on the microstructure of alloys being studied in these investigations.

SEM observations

The aim of scanning electron microscope observations was to study the fracture surfaces of the specimens after they were broken at impact test experiment. The example fracture surfaces in specimens No 8 is shown in fig.2.

a.



b.

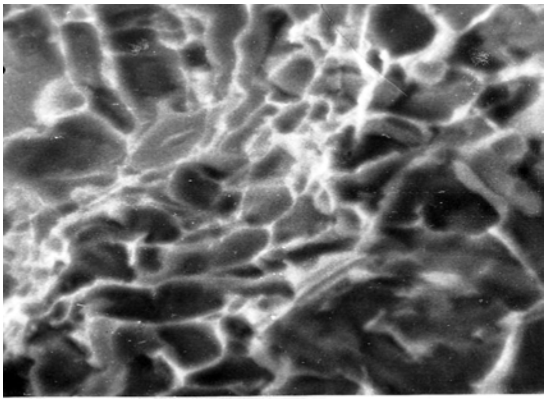


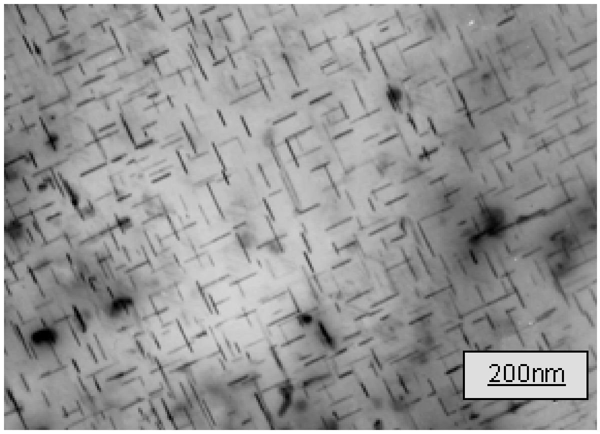
Fig.2. The fracture surface of impact tested specimens No 8 taken at different magnification: a – x1000 and b – x5000

In the first picture (fig.2a) the facets of brittle fractured {100} type planes of Si crystal are visible. Fig.2b illustrates magnified region of α matrix. In this case dimples, characteristic for are ductile mode of fracture are visible [2]. These depths of dimples are rather moderate and their edges not elongated as for very ductile material, e.g. pure aluminum [3]

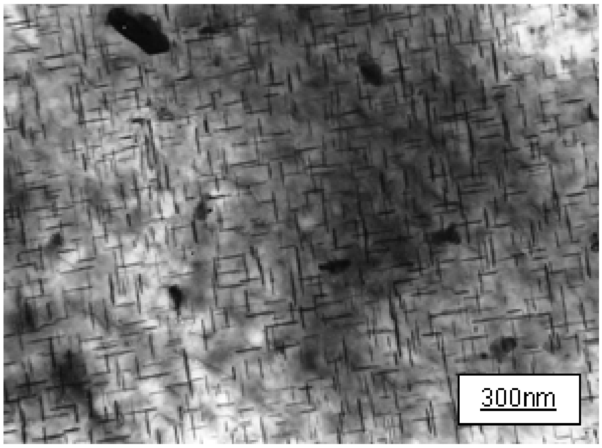
TEM observations

The aim of TEM observations was to observe the precipitates formed during age hardening, for which this method is the most effective an was used by author before [4-8] Thin foils were observed in Philips EM 300 electron microscope working at 100kV accelerate voltage. Examples of bright field electron micrograph [9, 10], together with one of characteristic selected area diffraction pattern (SAD) are shown in fig.3. In micrographs (fig3.a, b) very tiny rod-like precipitates are visible. The set of pictures (fig.4) illustrates electron micrographs taken either in bright- and dark-field condition, together wit SAD where the diffraction reflex used for dark-field imaging was marked The micrographs presented in fig.4 looks to be very similar but there are big difference between them and those showed in fig.3.

a.



b.



c.

Fig.3.An electron micrographs of age hardened AlSi5Cu3(Mg) type cast alloys: a – No 1 (x45.000),b – No 2 (x40.000) and c – SAD from the area showed in fig 3b.

a.

b.

c.

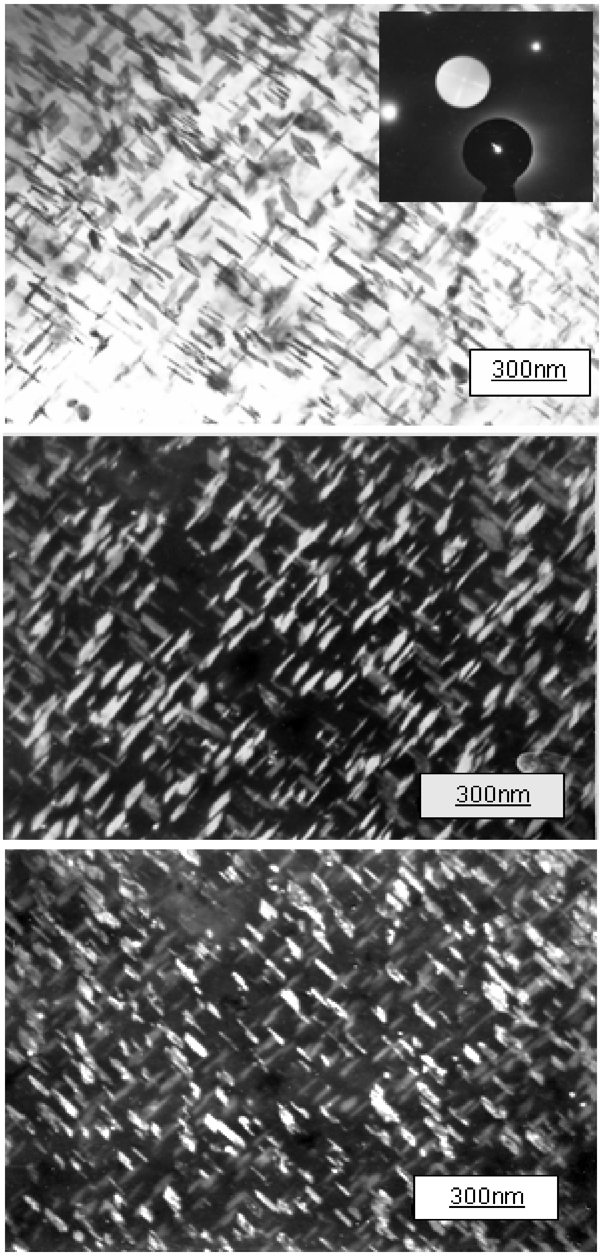


Fig.4. The structure AlSi5Cu3(Mg) type alloy - No4: a – bright-field, b and c – dark-field micrographs taken from two opposite reflexes, one of which is marked in selected area diffraction pattern (SAD) showed in right corner fig.4a

The first of these differences is the shape of the precipitates. These visible in fig 4a are rather plates and not rods as could be stated on basis fig.3a and b. Moreover, the dark-field micrographs formed with two cross reflex [11,12], one o which is marked in SAD, discover that the precipitates are distributed in three perpendicular directions with are <100> type in FCC matrix lattice. Two of this <100> direction are clear visible and the third is perpendicular to the plane of the micrograph. In this case the precipitates are seen as white dots either in fig.4 b and 4c.

DTA analysis

Differential thermal analysis (DTA) were carried out with Derivatograph MOM 1500^{o}C at sensitivity 1/3 and heating speed V_g = 5^{o}C/min. The aim of these investigations was to collect the information on the processes accompanying the alloys being studied while heating after solid solution heat treatment. The two examples of DTA curves obtained for AlSi5Cu3(Mg) type alloys numbered as 1 and 2 were shown in fig.5. Analyzing DTA curves for all alloys studied in this work we identified 3 exothermic peaks of different size and temperature position. Fig.5 is an example for alloy with minimum and maximum alloying elements. Two large exothermic peaks corresponds pre-eutectic and the eutectic reaction respectively. Except them small peak can be observed in DTA curve. In case of alloy No 1 the peak is very small and its maximum lies in the temperature 526^{o}C. In case of alloy No2 which is richer in alloying elements this first peak is more intensive with maximum at 508.3^{o}C.

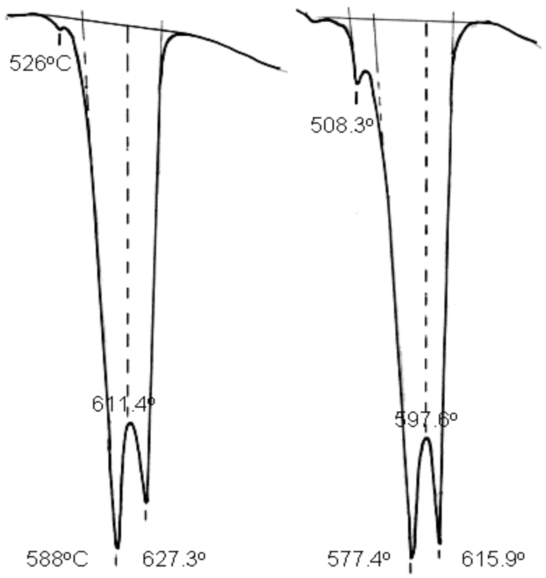


Fig.5. The example of DTA curve obtained for on of AlSi5Cu3(Mg) – type cast alloy studied in this elaboration

Both these small exothermic peaks were interpreted as a caused by precipitation from supersaturated solid solution. Neglecting detail analysis of these reaction it can be concluded that higher content of alloying element accelerate the decomposition of supersaturated solid solution.

3. Discussion

First of all the results of mechanical testing collected in table1 should be considered. The discussion of these results will be more convenient if they would be transformed into graphs. First of the dependence (fig. 6) shows the influence of silicon and cooper on tensile and yield strength of AlSi5Cu3(Mg) type alloys. It looks that there is some maximum for Si + Cu content at the range between 7 – 9wt.%.

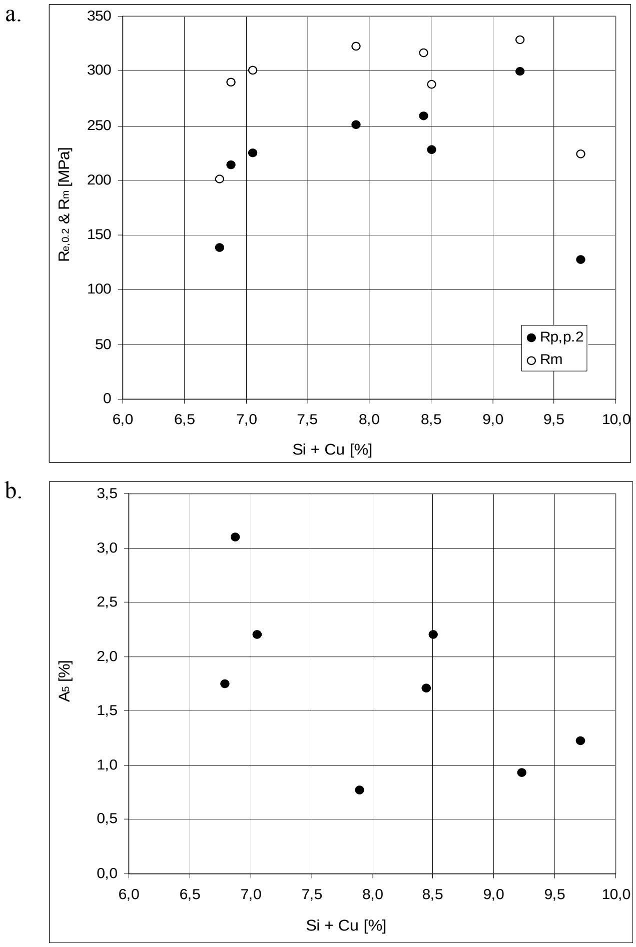


Fig.6. The influence of main alloying elements on: a - $R_{e,\ 0.2}$ and R_m values and b – A_5

In case of elongation, there is no doubt that the Si + Cu content increase decreases the ductility of alloys. It is very interesting to compare the influence of Si and Cu alone (fig.7). It follows from the graphs that cooper is more "efficient" in ductility decrease than silicon. It means that the influence of shape of brittle eutectic Si precipitates, even if these are no perfect inoculated, is less important than matrix age hardening.

The next point we would like to discus is the precipitation hardening of the matrix. First of all it should be stated, that from precipitation processes point of view, the alloy Al-S-Cu–Mg is much more complicated than Al-Si(Mg) or Al-Cu alloys. In case of simple Al-Si-Mg alloys the precipitation phases are metastable β" or β' needle-like phases. In turn Al-Cu alloy, the precipitation hardening is caused by series of metastable θ" or θ' plate-like phase which are coherent or semicoherent with the matrix.. As follow from TEM micrographs (fig.3 and 4) the precipitates are different morphology than mentioned above. According to Hatch [1] the precipitates are S' or S type which forms at given stage of supersaturated solid solution (SS) decomposition, as follows:

$$SS \rightarrow GP \rightarrow S' (Al_2CuMg) \rightarrow S (Al_2CuMg)$$

The first one (S') is coherent with {021} matrix planes while the last is noncoherent stable phase.

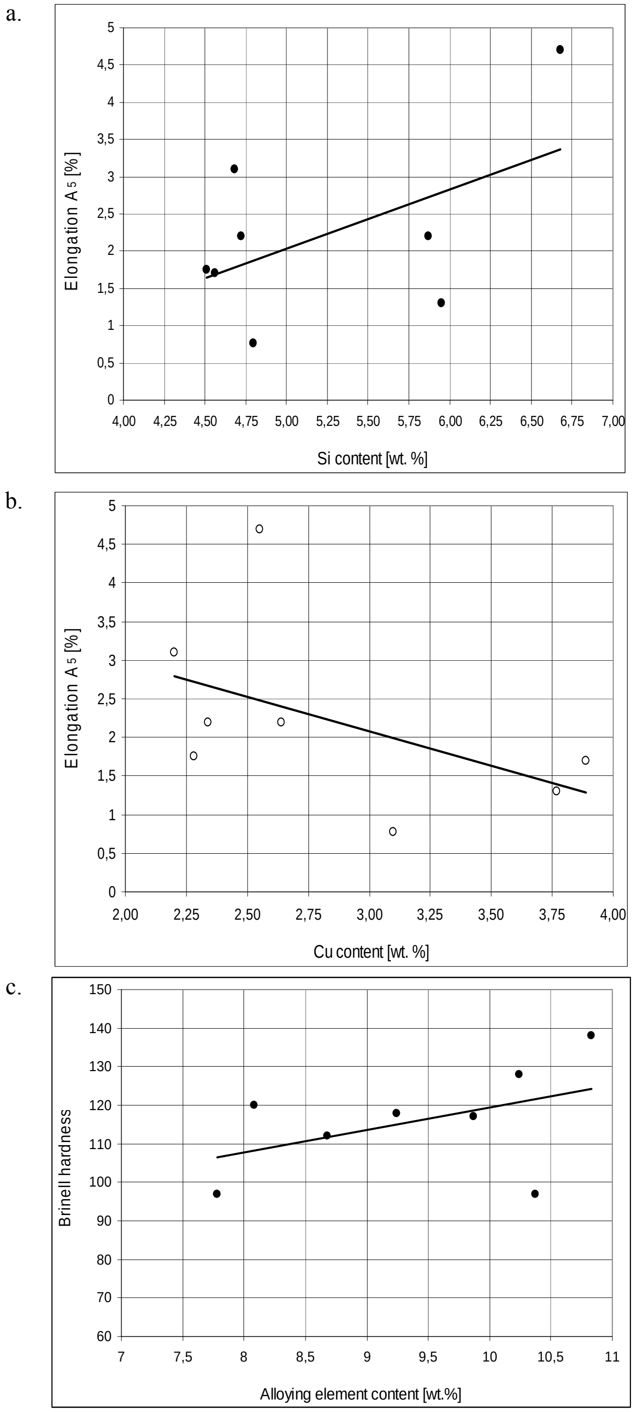


Fig.7. The dependence of ductility on: a – Si and b – Cu; c – the influence of total alloying elements content on Brinell hardness

Fig.7 shows the graph illustrating the density of precipitates as a function of total alloying elements concentration. The details of method used for evaluation the density of precipitates was described in [13]. It is clear visible from fig.7 that the density of precipitates strongly depends on the "saturation" of aluminum with alloying elements. It can be seen that increase of element 3.5% almost double the precipitation density. These precipitates highly strengthen the aluminum matrix decreasing its ductility [14]

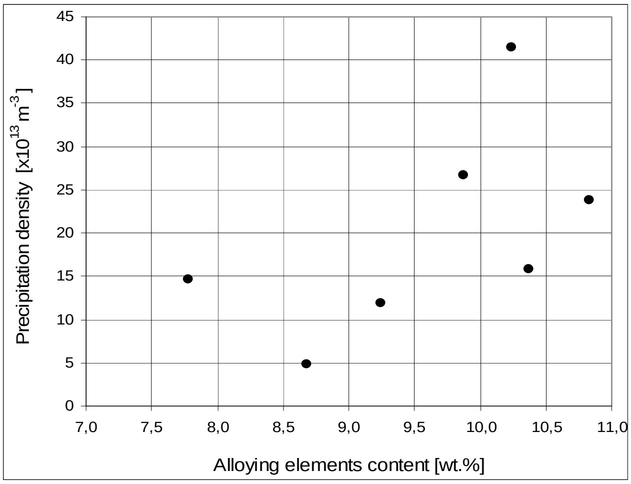


Fig.8. The density of precipitates as a function of alloying elements content

The alloying element most influencing the strength properties of AlSi5Cu3(Mg) type cast alloys is Cu. On the other hand it is very well known that strength and ductility are opposite properties so it is not surprising, that higher strength the lower ductility (fig.7b).

4. Conclusions

The results of experimental data and their analysis given above lead us to the following conclusions:

1. The difference in chemical composition of AlSi5Cu3(Mg) type age hardenable cast alloys, permissible by EN-PN standards, cause the substantial differences in tensile properties of these alloys.
2. The higher content of alloying elements the higher strength properties of AlSi5Cu3(Mg) hardenable cast alloys.
3. The maximum difference in yield and tensile strength of these alloys reaches 50 and 35% respectively.
4. Among main alloying element, cooper most efficiently increase the strength properties of AlSi5Cu3(Mg) type cast alloys and decrease its ductility.
5. The higher content of alloying elements the faster offset of precipitation hardening AlSi5Cu3(Mg) type cast alloy.
6. The higher concentration of Cu and Mg the higher precipitation density after 7h aging at temperature 170^{o}C

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