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Selection of the Manufacturing of Aluminum Casting Alloys with Hypoeutectic Aluminum Silicon Group

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Abstract
Aluminum alloys are one of the most popular casting materials. Their enormous popularity due to a wide set of desired material properties such as high strength properties, low thermal expansion coefficient, high thermal and electrical conductivity, very good casting properties, including castability. The most common group of cast aluminum alloys are silumins, where the main alloy addition is silicon. Al-Si alloys are mainly used in the transport industry and construction applications. Another area of applications using this group of materials is the electrical and power engineering industry, where the crucial meaning has the correlation of two types of properties: electrical and mechanical. This paper presents the influence of alloying elements on the electrical properties and mechanical properties of materials undergoing heat treatment. Heat treatment include solution heat treatment and next aging or overaging. Electrical properties represents the electrical conductivity tested by eddy current method. Mechanical properties are in turn represented by the results of measurements of Brinell hardness. Tests include three alloys belong to hypoeutectic silumins group with silicon content in the range of 4,5 to 7 wt%. Si.

Keywords: Casting aluminium alloys, Hypoeutectic silumins, Heat treatment

1. Introduction

Metal casting is one of the oldest methods employed in metal objects production, nowadays, however, it has been frequently replaced by the highly efficient solutions from the field of plastic working or powder metallurgy. This is primarily due to the factors affecting the economic effect of the particular metal processing method, namely, the production cost of the particular item, including material and equipment costs, as well as the functional properties of the very item. Hence, serious consideration can be given to casting production method provided that it's possible to prove both economic benefits and the sufficient level of the product functional properties. Aluminum alloys are among the basic materials used in the modern light metal and light metal alloys casting, the focus of which is mainly satisfying the needs of the car and aviation industries. However, this group of materials can be used also in a different fashion, i.a. for the purposes of the power engineering. The basic parameters of the cast products are their metallurgical quality and casting properties, however, as far as the functional properties are concerned, the set of resistance and electrical properties needs to be emphasised.

There are numerous known factors determining the properties of items manufactured with the use of the casting methods. The basic factors include: alloy's chemical composition, materials used for modification and refinement of the alloy, casting operations parameters, the casting technology employed, form structure or alloy crystallization and cooling conditions as well as the parameters of the heat treatment employed [1,2]. However, the critical factor, which most significantly determines the level of material properties of the aluminum alloy, is its chemical composition. For instance, if the only significant properties of a cast aluminum alloy casting were its resistance properties, the presence of the silicon or magnesium addition would directly result in the considerable increase of these properties. If, apart from the resistance properties, the (thermal and electrical) conductivity of the alloy is of key importance, then the effect of the kind and amount of the particular alloy addition on this property needs to be considered.

Thermal and electrical conductivity are correlated according to the Wiedermann-Franz law [3]:

$$K = \sigma \cdot L \cdot T \qquad (1)$$

where:

K – thermal conductivity, σ- electrical conductivity, T – temperature, L – Lorentz number, which approximately amounts to: $2{,}445\ 10^{-8}\ W\Omega K^{-2}$

Considering the influence of alloy additions on the level of aluminum electrical conductivity, the Matthiesen's Rule may be applied, according to which the total resistance of the alloy is the sum of the ρ_0 thermal resistance resulting from the acoustic mode and the ρ_T athermal resistance caused by lattice defects resulting from the presence of additions [4]. An example of silicon and other basic aluminum alloy additions influence on the electrical conductivity has been demonstrated in fig. 1. It has to be pointed out, however, that the available literature usually focuses on the influence of particular elements on the electrical properties of binary systems, and not, as in the case of majority of casting aluminum alloys, multi-element systems, which are additionally characterised by the high concentration of alloy additions.

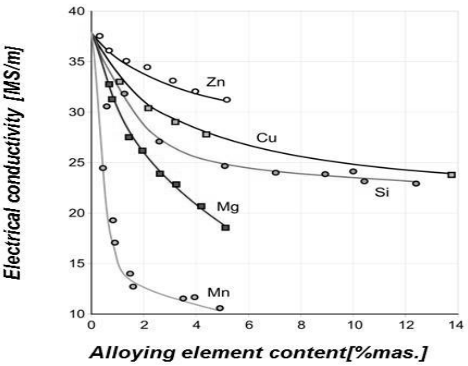

Figure 1. Electrical conductivity of as-cast binary aluminium alloys as a function of concentration of the alloying element [5]

Casting aluminium alloys have been used for many years and due to this fact a number of standards in the field are available. For instance, the European standard concerning casting aluminium alloys [6] sets out the required mechanical properties (hardness, tensile strength) with relation to the alloy temper designation. A detailed specification of the temper designation kinds applied in casting has been presented in table 1.

Table 1. Temper designations of aluminum casting alloys according [6]

Symbol	Operation type
F	As cast
O	Annealed
T1	Controlled cooling from casting and naturally aged
T4	Solution heat treated and naturally aged where applicable
T5	Controlled cooling from casting and artificially aged or over-aged
T6	Solution heat treated and fully artificially aged
T64	Solution heat treated and artificially under-aged
T7	Solution heat treated and artificially over-aged (stabilised)

In the case of electrical properties there is no specification of this kind since the standard sets out merely the conductivity ranges possible for particular alloy kinds. For example, for the AlSi7Mg (EN AC-42000) in the T6 temper, produced with the use of the gravity casting into a metal chill mould technology the minimum hardness amounts to 90 HB. However, the conductivity range concerning electrical properties set out in the standard is fairly wide and is between 19 to 25 MS/m – the temper of the material for which the particular value is available has not been specified. The above example makes it fairly clear that casting aluminium alloys are used mainly for mechanical purposes and, hence, the electrical properties of these alloys are of secondary importance.

For the new application of casting aluminium alloys (elements conducting heat or electricity) it's necessary to concentrate on the issue of the alloy chemical composition and heat treatment kind. A more detailed analysis of the issue involving the standard and the material bases such as Matweb [7] makes it possible to prepare a graphic statement of the properties (fig. 2) which demonstrates the relationship between electrical conductivity and the hardness value for the traditional casting aluminium alloys. The ordinate axis of the diagram presents the hardness value, while the axis of abscissae shows their thermal conductivity. A statement of this kind makes it possible to divide the diagram area into four basic parts, namely, above and below 70 HB as well as above and below 24 MS/m. The four parts point to the fact that majority of casting aluminium alloys are prepared for mechanical purposes since their properties classify them in the first and third part of the diagram (high mechanical and low electrical properties). From the point of view of the subject of the present paper, the most desirable materials are the ones classified in the second part of the diagram, however, as it can be seen, there are no standarised properties for the casting aluminium alloys to correspond to the classification criteria specified.

A method possible to obtain higher electrical properties of the silumins alloys has been discussed in paper [8]. The paper includes i.a. the example where higher electrical conductivity and hardness properties can be obtained for the AlSi7Mg alloy, which makes it possible to classify the alloy in the second part of the diagram.

Considering the discussion above concerning the issue which aims at obtaining non-standardised electrical properties of the casting aluminium alloys, the aim of the present paper is the analysis of the influence of the chemical composition (silicon content modification) as well as the artificial ageing operation parameters (choice of time and heating temperature) on the electrical conductivity and hardness change of three hypoeutectic silumin alloys to be used for castings for the power engineering. The tests results will comprise the specified heat treatment conditions which should be applied in order to ensure the properties characteristic for the second part of the diagram marked in fig. 2.

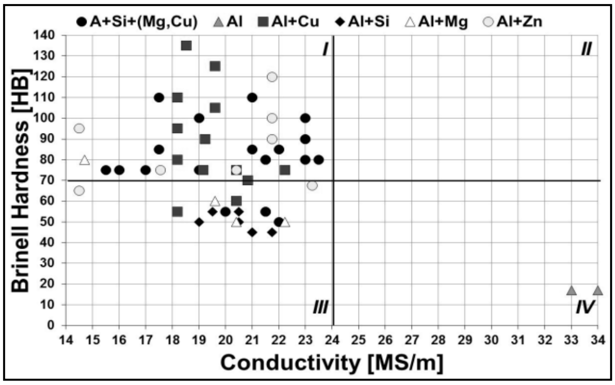

Figure 2. Statement of the electrical conductivity and hardness values for the traditional aluminium casting alloys [6,7]

2. Material and research methodology

The tested material involved three casting hypoeutectic silumins alloys with the silicon content of 7, 5.5 and 4,5 % of the mass. The exact chemical composition of the tested materials has been demonstrated in table 2. The castings for tests have been prepared in the liquid metal underwent refinement, was modified, and alloyed, and subsequently subject to gravity casting into a metal chill mould. The obtained castings, were removed from the chill mould, cooled in the open air, and then the particular heat treatment operations were carried out under the laboratory conditions. Each examined alloy was subject to supersaturation in the temperature of 535ºC for the time of 8h, then to the operation of artificial ageing which involved heating in the temperatures from 140 to 220°C and the time scope from 6 to 48 h.

Table 2. The chemical composition of the tested alloys

Alloy number	Alloy symbol	Chemical composition, % mass					
		Si	Mg	Fe	Cu	Mn	Ti
1	AlSi7Mg	6,98	0,34	0,09	0,01	0,01	0,096
2	AlSi5,5Mg	5,41	0,36	0,16	0,01	0,01	0,014
3	AlSi4,5Mg	4,53	0,36	0,09	0,01	0,01	0,048

For every kind of heat treatment, i.e. the combination of temperature and artificial ageing time, the examination of the resistance properties was carried out through the hardness test conducted with the use of the Brinell test method and alloy electrical conductivity was tested with the use of the method based on the eddy current phenomenon. The surface of the samples was polished before the measurements were performed. HB hardness test was carried out with the burden of 306,5 N using a steel ball with the diameter of 2,5 mm the WPM Leipzig HPO-250 hardness tester [9]. Electrical conductivity of the tested alloys has been measured with the use of the SIGMATEST® measuring instrument manufactured by the Foerster company using the eddy current induced in the tested material method. The measurement of the electrical properties with the use of eddy current consists in placing of the tested material in the interaction area of the time-varying magnetic field produced by a measurement probe. Subsequently, the probe processes the signals obtained from the converters, the amplitude and phase of which make it possible i.a. to detect material discontinuities or change in the electrical conductivity properties of the tested material [10]. The measuring range of the instrument is from 0,5 to 65 MS/m, during the tests, calibration of the instrument was performed according to the four electrical conductivity patterns i.e. 17,46; 22,24; 30,15 and 35,89 MS/m and the automatic temperature coefficient of resistance.

3. Tests results. Discussion

The tests results for the particular alloys have been demonstrated in the form of comprehensive diagrams of the tested property as a function of time for the selected ageing temperatures. Fig. 3 demonstrates the correspondence between the electrical conductivity change as a function of the artificial ageing time for the temperature of 140ºC over the time of 48 hours, while fig. 4 presents the hardness tests results for the analogical heat treatment conditions. Fig. 5 and 6 demonstrate the statement of the results for the electrical conductivity and hardness for the heat treatment at the temperature of 180ºC respectively. Fig. from 3 to 6 set out the results of the heat treatment for the T6 temper i.e. for the supersaturated and fully aged condition. This temper is characteristic for the materials of high resistance properties, which are represented by hardness in the present tests, as well as relatively low or average (for the temperature of 180ºC) electrical properties. In turn, in figures 7 and 8 the electrical conductivity and hardness tests results have been presented for the ageing process at the temperature of 220ºC, which refers to the materials treated to the T7 temper i.e. supersaturated and overaged. This temper is characterised by high electrical conductivity and, simultaneously, low hardness.

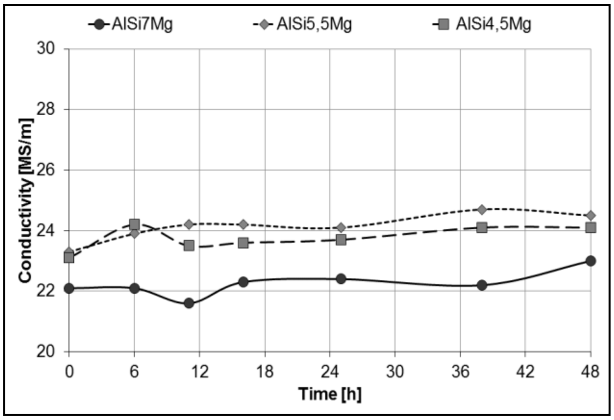

Figure 3. The electrical conductivity as a function of the artificial ageing time for 140°C (temper T6)

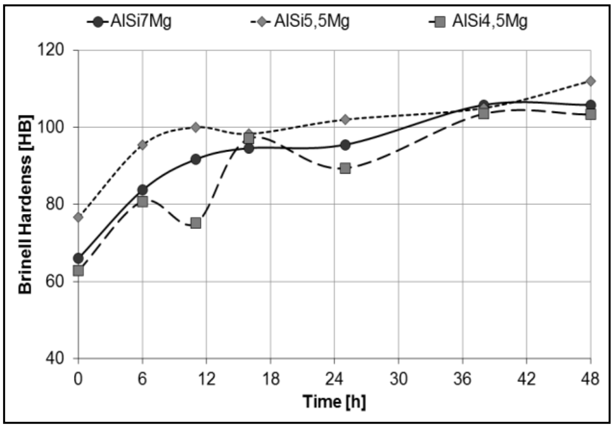

Figure 4. The Brinell hardness as a function of the artificial ageing time for 140°C (temper T6)

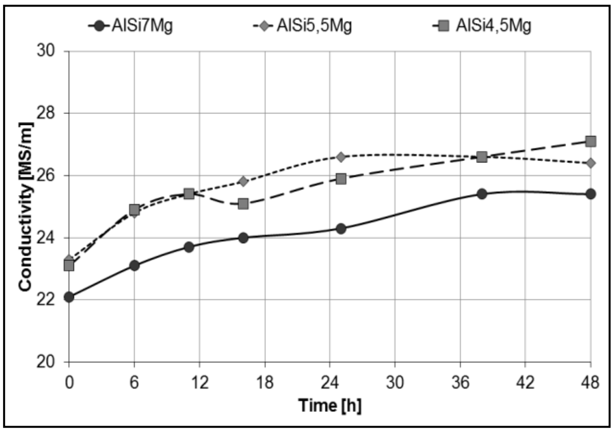

Figure 5. The electrical conductivity as a function of the artificial ageing time for 180°C (temper T6)

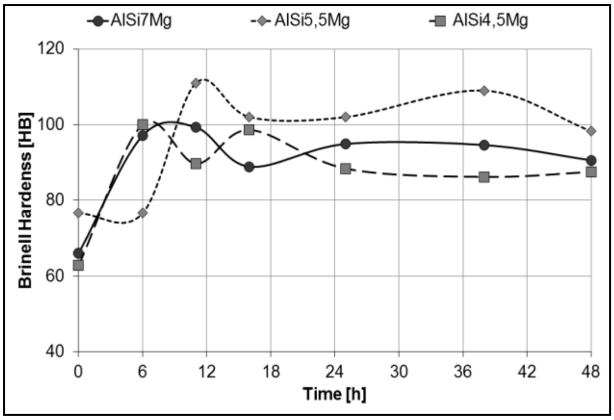

Figure 6. The Brinell hardness as a function of the artificial ageing time for 180°C (temper T6)

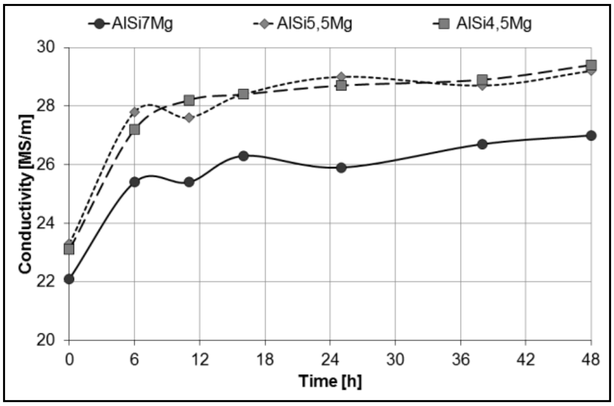

Figure 7. The electrical conductivity as a function of the artificial ageing time for 220°C (temper T6)

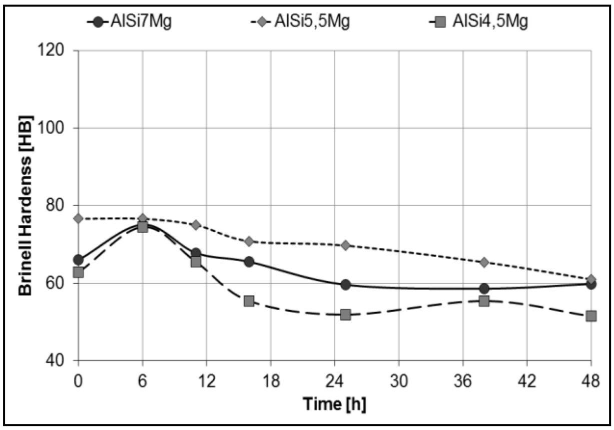

Figure 8. The Brinell hardness as a function of the artificial ageing time for 220°C (temper T6)

The summary of the hardness and electrical conductivity results for the tested alloys in the obtained tempers i.e. T4, T6 and T7 has been presented in figures 9 and 10 respectively. The model for the T6 temper typical properties is here understood as obtained through heating the alloys in the temperature of 180ºC for 25h, while for the T7 temper – through heating for 25h in the temperature of 220ºC. As it can be seen, both the rise of heating temperature and of its time lead to the electrical conductivity increase among all the alloys tested. However, the observed tendency doesn't apply to the hardness properties. The maximum hardness of the materials was obtained preparing the materials for the T6 temper. The overaged alloys are typically of lower hardness as compared with the properties of the supersaturated material i.e. in the T4 temper. As it can bee seen, reducing the content of silicon from 7% of the mass to 5,5% of the mass led to significant increase of the electrical conductivity, especially in the T6 and T7 tempers. However, further reduction of the silicon addition content to the level of 4,5% of the mass leads to minimal decrease of the electrical properties. In turn, in the case of hardness the highest values were obtained for the AlSi5,5Mg alloy in the T6 temper, which is due to the higher content of iron and significant reduction of the titanium addition as compared with the two remaining alloys.

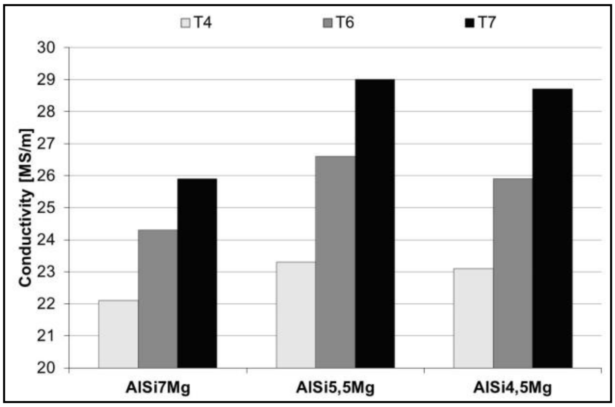

Figure 9. Summary of the electrical conductivity results for alloys in tempers T4, T6 and T7

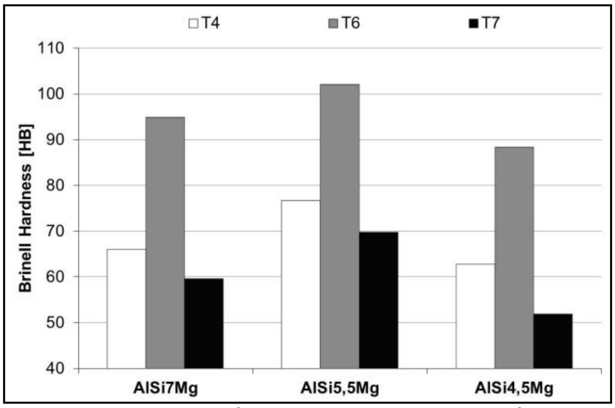

Figure 10. Summary of the Brinell hardness results for alloys in tempers T4, T6 and T7

As demonstrated in the above summaries of the tests results, apart from the modification of silicon content, the properties of the heat treated material are significantly influenced by the amount of the titanium addition. Fig. 11 demonstrates the diagram of the silicon and titanium content dependence, on the basis of which it can be stated that the titanium content is significantly reduced in the case of AlSi5,5Mg alloy, which most probably resulted in this particular alloy obtaining the most beneficial set of properties.

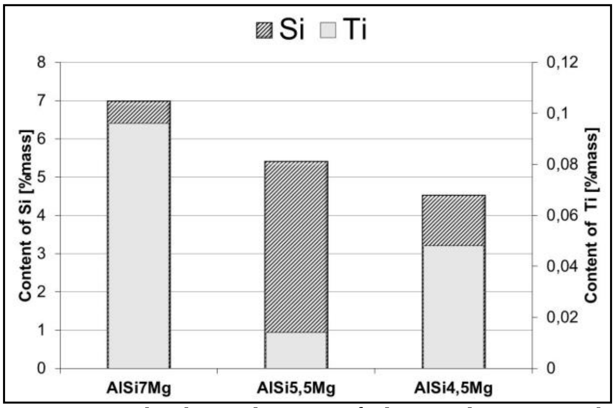

Figure 11. The chemical content of silicon and titanium in the tested alloys

Fig. 12 presents a summary of the conducted tests and it's analogical to the one presented in fig. 1, the statement of the hardness and electrical conductivity relationship for the tested alloys. It needs to be pointed out that reaching the second part (high hardness and high conductivity) is possible mainly due to the modification of the heat treatment parameters in the form of time and heat treatment temperature the alloy is subject to. Modification of the chemical composition through reducing the content of silicon and titanium – the AlSi5,5Mg alloy – made it possible for the material properties to be classified on the border of part two i.e. to obtain the assumed level of electrical properties as well as minimum level of resistance properties.

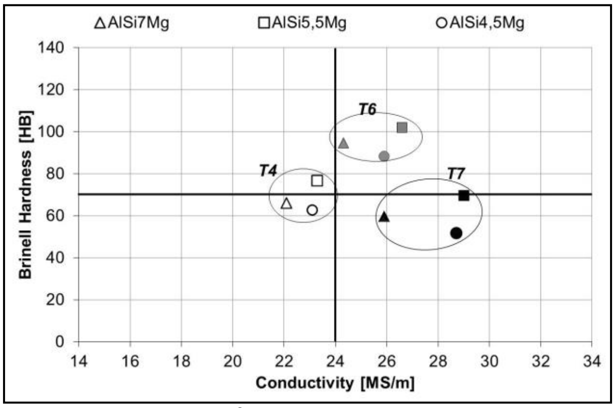

Figure 12. Summary of the electrical conductivity and hardness values for tested alloys in tempers T4, T6 and T7

4. Conclusions

The performed tests allow the following conclusions to be drawn:

-The hypoeutetic silumin alloys with the silicon content of 7 to 4,5% and magnesium content of approximately 0,3 respond very well to heat treatment consisting in supersaturation and artificial ageing or overageing

-Artificial ageing in the temperatures of 140ºC and 180ºC following the operation of supersaturation make it possible to obtain the maximum hardness level for the tested alloys. In the case of the AlSi5,5Mg alloy the level amounts to over 110 HB, which was obtained for the temperature of 180 ºC.

-Rising the artificial ageing temperature from 140 and 180 to 220ºC resulted in overageing of the tested alloys (reaching T7 temper), and, consequently, caused lowering of the resistance properties and, simultaneously, obtaining the maximum level of electrical conductivity.

-The AlSi5,5Mg alloy proved optimal due to its both resistance and electrical properties. Such beneficial properties of the alloy are seen to be possible to obtain due to its chemical composition (titanium content). Due to this fact, in the case of castings manufactured for electrical purposes the content of heavy elements such as Mn, Ti, Cr, V should be reduced.

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