The Influence of Chemical Composition and Parameters of Heat Treatment on the Mechanical Properties and Electrical Conductivity in Hypoeutectic Aluminium Silicon Alloys

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Abstract

The silumins are the aluminum alloys with the silicon as the main alloy addition. These are one of the most common types of casting alloys based on aluminum. They are widely used in technologies of casting such as sand casting, chill casting or pressure die casting. As their main characteristics we can include: very good castability, corrosion resistance, high mechanical properties and good thermal and electrical conductivity. Thanks to all these properties, the cast aluminum alloys have been used in various industries such as: automotive, engineering, heat exchangers or conductive elements. The last application requires a specific conditions of the process and the optimal chemical composition of the alloy, which allows to obtain high values of conductivity. The paper presents a study covering the impact of silicon content and heat treatment parameters on the electrical conductivity and mechanical properties (hardness HB) hypoeutectic silumin alloys such as AlSi11Mg, AlSi7Mg and AlSi5Mg. The aim of the study was to determine the optimal conditions for heat treatment parameters of various alloys providing to the most favorable mechanical and electrical properties.

Keywords: heat treatment, hypoeutectic aluminium silicon alloys, mechanical properties, electrical properties

1. Introduction

In the recent years, a steady growth in the demand for aluminum and aluminum alloys products has been observed. The trend is caused by the attempts to improve a number of product properties (weight, conductivity, corrosion resistance) or products prices by means of substitution for expensive metals. Apart from such economy segments as aviation, automotive, nautical, construction or engineering industries, aluminum products have been widely used in electrotechnics and electroenergetics frequently replacing copper, despite their worse electrical
properties. Aluminum in electroenergetics is mainly the traditional overhead power lines, cable veins and busbars. The current accomplishments of the aluminum industry are the enamelled wires, winding wires, electric motor impellers or construction elements of the high voltage switchgears. The final group of products comprises the ones in the form of casts used on the electrically conductive elements. In this kind of use special consideration should be given to the choice of the suitable aluminum casting alloy as well as the production technology, which will ensure the required or non-standard properties of the product, both electrical and mechanical.

There are numerous technological parameters allowing to determine casting mechanical and physical properties of products manufactured with the use of the casting technologies. The main parameters include the choice of structure modifying substances, the kinds of refining technologies, the conditions for filling the mould with liquid alloy, crystalisation and casting cooling conditions as well as the heat treatment parameters [1, 2]. However, the critical factor, which most significantly determines material properties level of the aluminum alloy, is its chemical composition. For instance, if the sole required properties of the aluminum alloy cast were its resistance properties, the additions of such elements as copper, zinc, silicon, and magnesium would straightforwardly cause a significant increase of such properties. An example of the influence of silicon and magnesium content change in the aluminum alloys on the level of mechanical properties is demonstrated in fig. 1 and 2.

![Fig. 1. Effect of Si content on the mechanical properties of AlSi casting alloy; modified (1) and unmodified (2) [3]](image1)

However, if not only resistance but also conductivity properties of the material (both thermal and electrical) are of crucial importance, then the influence of the alloy's chemical composition needs to be very closely considered regarding the expected casting properties set. In the case of electrical conductivity, both the choice of the particular kind of alloy element and its position in the aluminum structure significantly influence the level of the obtained properties. An example of particular alloying additions influence on the electrical conductivity of pure aluminum is demonstrated in fig. 3. It has to be noticed, however, that the depicted influence of alloying additions is only of demonstrative nature.

![Fig. 3. Electrical conductivity of as-cast binary aluminium alloys (containing larger amounts of the alloying additions) as a function of concentration of the alloying element [5]](image2)

Aluminum casting alloys are mainly multiple compositions with no specified correlation between the particular alloying ingredients and their influence on the alloy’s electrical properties.

![Fig. 3. Electrical conductivity of binary aluminium alloys (containing larger amounts of the alloying additions) as a function of concentration of the alloying element [5]](image3)

Despite the fact that aluminum casting alloys have been used for years and they are subject to vast amount of standardisation, there is still no exact data concerning their electrical properties. The main focus of the standards concerns alloys’ mechanical properties, the parameters of which are specified following the casting technology and the heat treatment conditions, while the conductive properties are provided exclusively in the form of an approximate amount. For instance, Table 1 demonstrates the chemical composition and Table 2 – the requirements concerning the particular material options i.e. AlSi7Mg0,3 (EN AC-42100) and AlSi11 (EN AC-44000) following the European standardisation concerning aluminum casting alloys [6]. The AlSi5Mg alloy is not included in the standardisation.
Hosen mainly due to their ing a steel ball with the diameter of 2.5 mm. The tests influence of alloys' chemical composition (silicon was considered of secondary importance. The new applications of aluminum casting alloys (conductive elements) require thus concentrating on the issue of the influence of alloys' chemical composition, their production technology as well as the heat treatment conditions on the possibility of modifying their electrical and thermal conductivity.

The preliminary analysis of the data concerning cast aluminum alloys' electrical conductivity comprising material property databases such as Matweb [7] has made it possible to prepare the diagram (Figure 4) demonstrating the correspondence between the physical properties (conductivity) and the mechanical properties (hardness) for the traditional aluminum casting alloys. The ordinate axis of the diagram presents the HB hardness value of particular alloys, while the axis of abscissas shows their electrical conductivity. Such statement makes it possible to divide the area of the diagram into four basic parts (according to the application), i.e. above and below 70 HB as well as above and below 24 MS/m. The demonstrated criterion qualifies the majority of aluminum casting alloys as materials designated for mechanical use since the mechanical properties feature in the first and third area of the diagram, however, as it can be observed, there are no standardised aluminum casting alloys demonstrating such non-standardised properties.

Table 1. Chemical composition of the AlSi7Mg0,3 and AlSi11 alloy [6]

<table>
<thead>
<tr>
<th>Alloy designation</th>
<th>Chemical symbols</th>
<th>Si</th>
<th>Mg</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AC AlSi11</td>
<td>EN AC 4400</td>
<td>10,0-11,8</td>
<td>0,45</td>
<td>0,19</td>
<td>0,05</td>
<td>0,10</td>
<td>0,07</td>
<td>0,15</td>
</tr>
<tr>
<td>EN AC AlSi7Mg0,3</td>
<td>EN AC 42100</td>
<td>6,5-7,5</td>
<td>0,25-0,45</td>
<td>0,19</td>
<td>0,05</td>
<td>0,1</td>
<td>0,07</td>
<td>0,25</td>
</tr>
</tbody>
</table>

Table 2. Properties of the AlSi7Mg0,3 and AlSi11 alloy [6]

<table>
<thead>
<tr>
<th>Alloy designation</th>
<th>Casting technology</th>
<th>Temper</th>
<th>HB, min</th>
<th>Electrical conductivity, MS/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AC AlSi11</td>
<td>Sand casting</td>
<td>F</td>
<td>40</td>
<td>18 - 24</td>
</tr>
<tr>
<td></td>
<td>Chill casting</td>
<td>F</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>EN AC AlSi7Mg0,3</td>
<td>Sand casting</td>
<td>T6</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chill casting</td>
<td>T6</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Investment casting</td>
<td>T6</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>

The discussion above concerning the issue which aims at obtaining non-standardised electrical properties of the aluminum casting alloys, the aim of the present paper is the analysis and assessment of the influence of the chemical composition (silicon content modification) as well as the artificial aging operation parameters (choice of time and heating temperature) on the electrical conductivity and hardness change among the selected hypoeutectic silumins to be used for castings for the electroenergetics. It will constitute the basis for drawing up the alloy selection criteria as well as their heat treatment conditions which will ensure optimal electrical and mechanical properties for the material properties to reach the fourth area presented in Figure 4.

2. Material and research methodology

The research involved three aluminum casting alloys from the group of hypoeutectic silumins with the silicon content of 11, 7, and 5 % of the mass the exact chemical composition of which has been demonstrated in Table 2. The castings for examination have been produced in the ZM WSK Rzeszów establishment in such a way that the liquid metal underwent refinement, modification, and alloying, and then gravity casting into a metal chill mould. The obtained castings, were removed from the chill mould, cooled in the open air, and then the heat treatment operation was carried out under the laboratory conditions. Each examined alloy was subject to supersaturation in the temperature of 535°C for the time of 8h, then to the operation of artificial ageing which involved the temperatures from 180 to 220°C and the time scope from 1 to 24 h.

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 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 induced in the tested material [8].

The surface of the samples was polished before the tests 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 tests were performed on the hardness tester WPM Leipzig HPO-250 model.
Table 2. Chemical composition of the examined alloys

<table>
<thead>
<tr>
<th>Alloy symbol</th>
<th>Designed silicon content [%]</th>
<th>Chemical composition, % mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi11Mg0.3</td>
<td>11</td>
<td>11,2 Si, 0,3 Mg, 0,1 Fe, 0,01 Cu, 0,02 Mn, 0,12 Ti+Zr</td>
</tr>
<tr>
<td>AlSi7Mg0.3</td>
<td>7</td>
<td>7,3 Si, 0,4 Mg, 0,1 Fe, 0,1 Cu, 0,1 Mn, 0,1 Ti+Zr</td>
</tr>
<tr>
<td>AlSi5Mg0.3</td>
<td>5</td>
<td>4,85 Si, 0,36 Mg, 0,12 Fe, 0,01 Cu, 0,001 Mn, 0,001 Ti+Zr</td>
</tr>
</tbody>
</table>

Electrical conductivity of the tested alloys has been measured with the use of the SIGMATEST® measuring instrument manufactured by the Foerster company. 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

Tests results for the selected heat treatment temperatures have been presented for the particular alloys in the form of comprehensive diagrams of the tested property in relation to the ageing time. Fig. 5 presents the HB hardness tests results in relation to the alloy artificial ageing time in the temperature of 180 °C. Electrical conductivity tests results for this temperature have been presented in Fig. 6. Another selected heat treatment temperature is 200 °C and Fig. 7 presents HB hardness change results, while Fig. 8 demonstrates the conductivity change dependence. The final case of heat treatment temperature choice analysed is 220 °C. The change results concerning the tested properties in relation to time for this temperature have been presented in Fig. 9, which shows HB hardness and Fig. 10, presenting electrical conductivity change.

Fig. 5. The Brinell hardness as a function of the artificial ageing time for 180 °C

Fig. 6. The electrical conductivity as a function of the artificial ageing time for 180 °C

Fig. 7. The Brinell hardness as a function of the artificial ageing time for 200 °C

Fig. 8. The electrical conductivity as a function of the artificial ageing time for 200 °C

All the alloys reach plateau at the temperature of 180°C, characteristic of the T6 condition, the level of which remains practically constant in the ageing time analysed. The rise of the ageing temperature causes the hardening effect to appear faster, however, the effect diminishes and the extended testing time shows that each of the alloys display increasingly worse mechanical properties thus reaching the T7 condition (becomes over-aged). The electrical conductivity curves, however, (Fig. 6, 8, and 10) are of a slightly different character as related to the ageing time. Following the rise of the temperature and lengthening of the ageing time, it can be observed that the electrical conductivity values gradually improve and stabilize for each of the tested materials.
In the case of AlSi7Mg0.3 and AlSi11Mg0.3 alloys the maximum conductivity level amounts to approximately 23 MS/m and is reached already at the temperature of 200°C. However, in the case of the AlSi5Mg0.3 alloy, electrical conductivity stabilisation (at the level of 30 MS/m) is not obtained until the temperature of 220°C. Irrespective of the nature of the electrical conductivity change of the tested materials in relation to the time and temperature, it can be observed that the obtained electrical conductivity results do not demonstrate the expected connection concerning the silicon content in the alloy, which would be implied by Fig. 1. The AlSi7Mg0.3 and AlSi11Mg0.3 alloys with distinct silicon content at the level of 4% differ insignificantly in terms of conductivity, the difference amounting to 1 MS/m on average (mas 2 MS/m), while the AlSi5Mg0.3 and AlSi7Mg0.3 alloys with distinct silicon content by approximately 2% differ in terms of conductivity at the level of 4 to 6 MS/m. This difference concerning the electrical properties of the alloys can be attributed to their chemical composition. As shown in Table 2, alloys with the silicon content of 7 and 11% contain approximately 0.1% of titanium, hence, approximately 100 times more than in the case of the AlSi5Mg0.3 alloy (0.001 % Ti). Taking into consideration titanium influence on the electrical properties of aluminum, it can be stated that it could have caused the significant decrease of the electrical properties of the tested AlSi7Mg0.3 and AlSi11Mg0.3 alloys. Hence, in the case of the aluminum casting alloys, which are required to possess non-standard electrical properties, presence of the element should be limited and this applies also to other elements having a similar effect e.g. Cr, Mn and V.

In order to summarise the analysis of the obtained tests results, the diagrams presenting the hardness results (Fig. 11) and the electrical conductivity results (Fig. 12) with the hardness conditions i.e. W, T6 and T7 specified [6] have been prepared for the particular alloys. Following this, it has been stated that the best hardness properties for the tested alloys have been obtained with the heat treatment resulting in the T6 condition. However, obtaining the non-standard electrical conductivity properties required the change of the heat treatment parameters so as to reach an optimal compromise between the mechanical and electrical properties of the tested alloys. The best electrical properties were obtained for the longer ageing time scopes which correspond to the so called condition of being over-aged (T7).

Fig. 11. Summary of the Brinell hardness results for alloys in tempers W, T6 and T7

Fig. 12. Summary of the electrical conductivity results for alloys in tempers W, T6 and T7

Fig. 13 presents a summary of the conducted tests and it’s analogical to the one presented in Fig. 4, the statement of the HB hardness and electrical conductivity relationship for the tested alloys. As mentioned earlier, the most beneficial area, considering both electrical and hardness properties, is area II. We can see that the only material to reach this area is the AlSi5Mg alloy. Apart from the lowered silicon content, it’s titanium content is also low (Table 2), which might have resulted in the exceptionally good electrical properties of the alloy due to the significant influence of titanium on aluminum conductivity.

4. Conclusions

On the basis of the analysis of the obtained tests results of the AlSiMg aluminum casting alloys, the following conclusions have been drawn:
- The hypoeutetic silumin alloys with the silicon content of 11 to 5 mass % and Mg content of approximately 0.3 mass % respond very well to heat treatment comprising supersaturation and artificial ageing.
Considering the hardness properties (reaching T6 condition), it should be assumed that the best heat treatment parameters for the tested alloys are the temperature of 180ºC and the ageing time of 2 to 8 h.

The mechanical properties curves for the alloys, the coefficient of the artificial ageing processes employed (in the tested temperature scope), display considerable similarities due to the occurrence of the same phases and hardening mechanisms.

The choice of the best heat treatment parameters for the tested alloys, considering electrical conductivity properties, entails a separate consideration of the chemical composition of the given alloy.

The obtained electrical conductivity curves, resulting from the ageing processes, demonstrate a significant influence on the obtained properties not so much of the alloy’s silicon content but rather its titanium content.

The best compromise between the mechanical and electrical properties of the tested alloys requires reaching an appropriate condition of being over-aged (T7 condition) each time.

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**Badania nad wpływem składu chemicznego oraz parametrów obróbki cieplnej na własności mechaniczne i elektryczne stopów aluminium z grupy siluminów podeutektycznych**

**Streszczenie**

Siluminy, czyli stopy aluminium z głównym dodatkiem w postaci krzemu, są jednymi z najczęściej stosowanych typów stopów odlewniczych na bazie aluminium. Są one wykorzystywane w szeregu technologii odlewniczych takich jak: odlewanie piaskowe, kokilowe czy odlewanie nisko lub wysoko ciśnieniowe. Do podstawowych własności tej grupy stopów możemy zaliczyć bardzo dobra lejlność, odporność na działanie środowiska korozjnego, wysokie własności mechaniczne oraz dobra przewodność cieplna i elektryczna. Dzięki tym własnościom, główne zastosowanie odlewów z siluminów to przemysł samochodowy, maszynowy, elementy konstrukcyjne, wymienniki ciepła czy elementy przewodzące prąd elektryczny. Ta ostatnia aplikacja wymaga zapewnienia szczególnych warunków procesu technologicznego oraz odpowiedniego składu chemicznego stopu, tak aby uzyskać wysokie wartości przewodnictwa. W pracy przedstawiono badania obejmujące wpływ zawartości krzemu oraz parametrów obróbki cieplnej na przewodność elektryczną i własności mechaniczne (twardeść HB) siluminów podeutektycznych typu AlSi11Mg, AlSi7Mg oraz AlSi5Mg. Celem badań było określenie optymalnych warunków obróbki cieplnej poszczególnych stopów umożliwiających uzyskanie najkorzystniejszych własności mechanicznych i elektrycznych.