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Development of strength and electrical properties of Al-Si-Mg casting aluminum alloys with an Mg content of 1 wt%

Kształtowanie własności wytrzymałościowych i elektrycznych odlewniczych stopów aluminium typu Al-Si-Mg o zawartości magnezu na poziomie 1% mas.

Abstract

Silumins (i.e., alloys where the main alloy additive is silicon) are the largest casting aluminum alloy group. Materials of this kind are characterized by high strength properties, high corrosion resistance, and low density, which make it possible to use them for construction purposes. A new group of developed properties typical for casting silumins are electrical and thermal conductivity. Thermal and electrical conductivity can be optimized by the suitable selection of chemical composition of the alloy, in the process of precipitation hardening, or by means of a combination of both. The present paper includes test results of the strength and electrical properties of AlSiMg casting aluminum alloys. The alloys that were subject to testing were AlSi5Mg1, AlSi7Mg1, and AlSi11Mg1. Heat treatment included homogenization at a temperature of 535°C over a time period of 8 h, quenched, and artificial aging. The strength tests involved a Brinell hardness measurement as well as an electrical properties test involving electrical conductivity measurement tests.

Keywords: cast aluminum alloys, homogenization, quench, artificial aging, Brinell hardness, electrical conductivity

Streszczenie

Siluminy, czyli stopy aluminium z głównym dodatkiem stopowym w postaci krzemu, stanowią jedną z największych grup odlewniczych stopów aluminium. Materiały tego rodzaju charakteryzują się między innymi wysokimi własnościami wytrzymałościowymi, wysoką odpornością na działanie środowiska korozyjnego czy niskim ciężarem właściwym, co pozwala na ich stosowanie w celach konstrukcyjnych. Grupą własności odlewniczych stopów aluminium, nad którą aktualnie

trwają intensywne badania są własności elektryczne oraz, powiązane z nimi, własności cieplne. Własności te można optymalizować przez odpowiedni dobór składu chemicznego stopów, wykorzystanie zjawiska utwardzania wydzieleniowego czy też w wyniku kombinacji obu metod. Niniejsza praca opisuje wyniki badań nad kształtowaniem własności wytrzymałościowych i elektrycznych odlewniczych stopów Al-Si-Mg. W badaniach wykorzystano trzy stopy o oznaczeniach AlSi5Mg1, AlSi7Mg1 oraz AlSi11Mg1. Materiały zostały poddane operacjom obróbki cieplnej w postaci homogenizacji w temperaturze 535°C przed 8 h, przesycań do wody oraz starzeniu sztucznemu. W ramach określenia własności wytrzymałościowych wykonano pomiary twardości analizowanych stopów przy użyciu metody Brinella. Własności elektryczne określono za pomocą pomiaru przewodności elektrycznej.

Słowa kluczowe: odlewnicze stopy aluminium, homogenizacja, przesycać, starzenie sztuczne, twardość Brinella, przewodność elektryczna

1. Introduction

Aluminum alloys are used in foundry casting and, compared to other materials based on non-ferrous metals, are characterized by strength and at the same time low density, high electrical and thermal conductivity, high corrosion resistance, and very good casting properties [1]. Such a compilation of properties is allows to use Al-Si based alloys in the building and construction industries as well as the automotive and electricity industries [2].

Increasing strength and electrical properties of AlSiMg alloys is possible through the selection of the appropriate chemical composition and/or through the appropriate heat treatment in line with the further use of the element. An increase in the silicon content in the Al-Si-Mg alloys leads to an increase in casting properties (the Si additive increases the castability and solidification of the alloy and prevents hot tears or hot cracks [3]) and increases strength properties [4]. High silicon content simultaneously decreases the plastic and electrical properties of silumins alloys [5]. Another significant alloy additive for this group of materials is magnesium. A high Mg content leads to an increase in strength properties and a decrease in the plastic properties of the alloy [6]. However, magnesium is introduced mainly for the purpose of obtaining better heat-treatment effectiveness.

Casting aluminum alloys have been in use for years; for this reason, there are numerous standardized specifications in the field. For instance, the European Standardization on casting aluminum alloys [7] specifies the required mechanical properties (hardness, tensile strength) dependent on the hardening type (a detailed description of which is set out in Table 1).

Figure 1 presents an overview of standard strength properties in the forms of electrical conductivity and Brinell hardness [7, 8]. The majority of classic casting aluminum alloys are made for construction applications where high strength of materials is required – area I of the graph. On the other hand, only pure aluminum (which is obvious) and tin alloys are characterized by high electrical conductivity – area IV of the graph. So far, there have been no material solutions in the field of standard casting aluminum alloys that are characterized by both high strength properties and, at the same time, high electrical

conductivity – area II of the graph. Reaching the range of high hardness – high conductivity is possible through the selection of suitable chemical composition and heat treatment processes [9, 10].

Table 1. Temper designations of aluminum casting alloys according [7]

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 (stabilized)

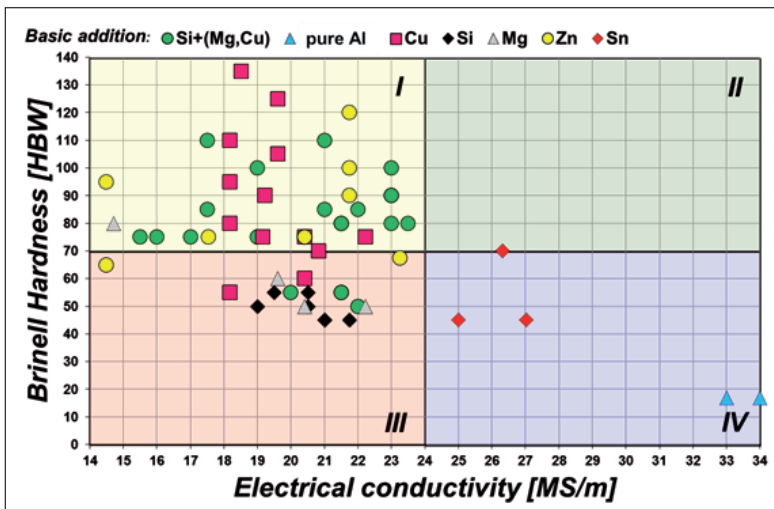


Fig. 1. Relation between Brinell hardness and electrical conductivity for traditional casting aluminum alloys [9, 10]

2. Characteristics of the tested alloys

This paper presents tests for three casting aluminum alloys with a silicon content of 5, 7 and 11 wt% as well as a magnesium content of approximately 1 wt%. The chemical composition of the tested materials is presented in Table 2. The alloys have been made through permanent mold casting and (following crystallization) cooled in the open air.

Table 2. Chemical composition of the investigated alloys

Symbol alloy	Element, wt%							
	Si	Mg	Fe	Cu	Ti	V	Cr	Al
AlSi5Mg1	5.181	0.990	0.118	0.002	0.007	0.010	0.002	remainder
AlSi7Mg1	7.234	0.947	0.130	0.002	0.007	0.009	0.002	remainder
AlSi11Mg1	11.392	1.135	0.197	0.002	0.007	0.009	0.003	remainder

Figures 2 and 3 present an overview of the strength properties (Brinell hardness) and electrical properties (electrical conductivity) of the tested alloys in the F temper.

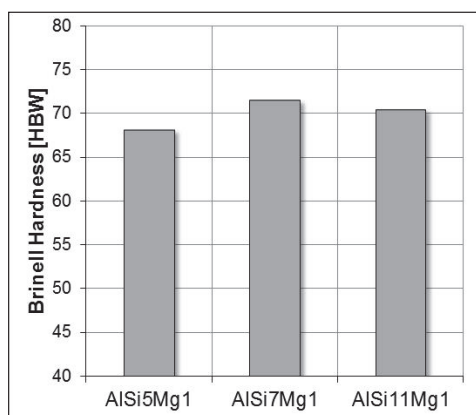


Fig. 2. Brinell hardness of the investigated materials (as cast temper)

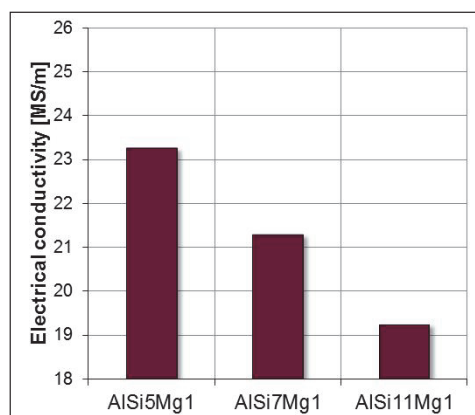


Fig. 3. Electrical conductivity of the investigated materials (as cast temper)

3. Program and testing methods

The tested materials were subject to heat treatment operations in the form of solution heat treatment, which resulted in the T4 temper (solution heat treatment conditions: 535°C/8 h – material cooled down with water at a temperature of 25°C). Next, the alloys underwent an artificial aging operation at a temperature range of 140 to 240°C in a time period of 24 h. For all of the variants of the heat treatment operation, Brinell hardness and electrical conductivity were carried out. The hardness tests were performed on an HPO-250 WPM Leipzig hardness tester. Electrical conductivity of the tested alloys was measured with a SIGMATEST® measuring device, using the eddy currents method induced in the tested material. Each of the measuring points presented in the paper is an arithmetic mean of at least three measurements in the case of Brinell hardness and at least ten measurements in the case of electrical conductivity.

4. Test results

The test results for the AlSi5Mg1 alloy are presented below. Figure 4 shows the alloy microstructures for the T6 temper. Brinell hardness over an artificial aging time is shown in Figure 5. Figure 6 presents the results of the electrical conductivity measurements.

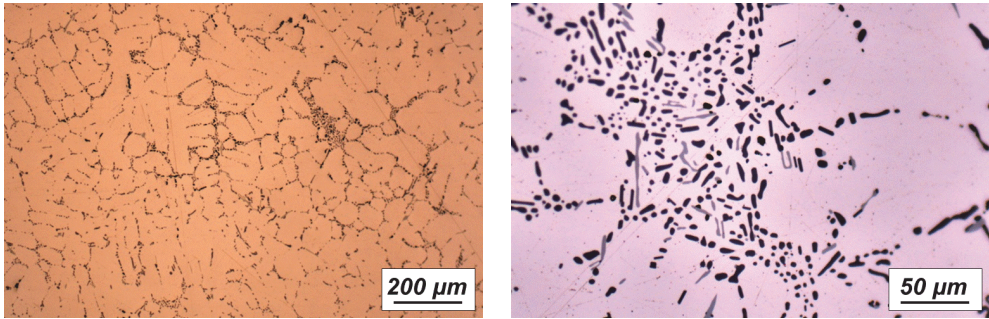


Fig. 4. Microstructures of the AlSi5Mg1 alloy for the T6 temper

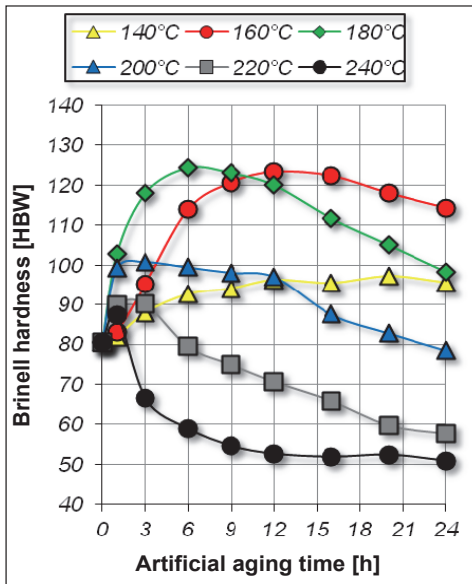


Fig. 5. Brinell hardness versus temperature and time of artificial aging for AlSi5Mg1 alloy

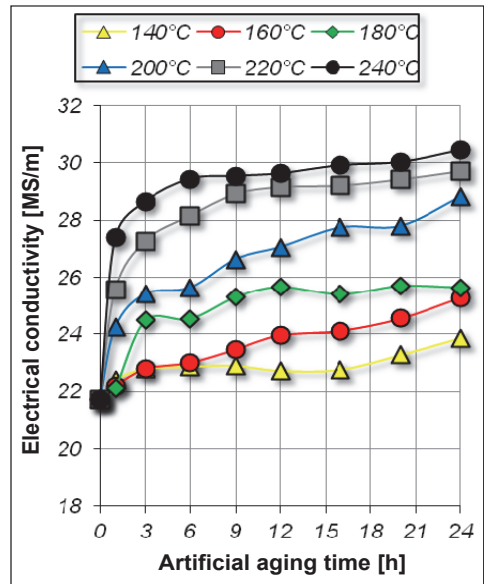


Fig. 6. Electrical conductivity versus temperature and time of artificial aging for AlSi5Mg1 alloy

The maximum hardness for the AlSi5Mg1 alloy was observed in the case of artificial aging at a temperature of 180°C for 6 h, and this amounted to 124.33 HBW (an increase of over 70% as compared to the properties of the T4 temper). Lowering the artificial

aging temperature to 160°C extended the time needed to obtain the maximum hardness (123.33 HBW), but further lowering of the temperature would not make it possible to carry out the heat treatment effectively from the point of view of the strength properties – the maximum hardness level for aging at a temperature of 140°C in the tested time is 97.13 HBW. In the case of a temperature of 200°C, the maximum Brinell hardness was obtained for a time of 3 h (100.83 HBW – an increase of nearly 33% as compared to the T4 temper).

In the case of the AlSi5Mg1 alloy following heat treatment of the T6/T7 temper, two groups of curves for electrical conductivity over an artificial aging time were observed: curves exceeding the 26 MS/m (temperatures of 200–240°C), and curves equal with the temperatures in which the level of 26 MS/m was obtained in the analyzed scope of artificial aging times (temperatures of 140–180°C). In the case of the first group of curves, the maximum points for the particular temperatures of artificial aging reached a level of approximately 30.5 MS/m for a temperature of 240°C (an increase of approx. 40% as compared to the T4 temper) and approx. 30 MS/m for a temperature of 220°C (an increase of approx. 33% as compared to the T4 temper). In the case of the other group of curves, the maximum electrical conductivity level was also reached for artificial aging for 24 h and for temperatures of 180°C and 160°C, amounting to approx. 26 and 25 MS/m respectively. In the case of the lowest temperature (140°C) and 24 h of aging, an electrical conductivity level of over 24 MS/m was not crossed.

Another group of results are the analyses concerning research into the AlSi7Mg1 alloy heat treatment. Figure 7 presents the microstructures of this material in the T6 temper. Figures 8 and 9 show the measurement results for Brinell hardness and electrical conductivity (respectively) for various parameters of the artificial aging operation.

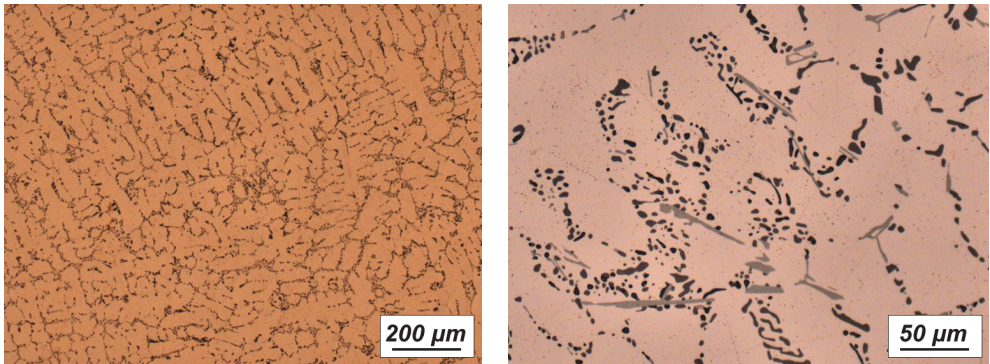


Fig. 7. Microstructures of the AlSi7Mg1 alloy for the T6 temper

Looking at the artificial aging curves for the AlSi7Mg1 alloy, it can be observed that the highest obtained levels of Brinell hardness for the particular annealing temperatures were: 126 HBW for artificial aging at a temperature of 160°C for 12 h (an increase in hard-

ness by approx. 52% as compared to the T4 temper), 126.67 HBW for artificial aging at a temperature of 180°C for 6 h (an increase by approx. 53%), and for temperatures of 200°C, 220°C, and 240°C, respectively, for the artificial aging for 1 h: 117.33 (an increase of approx. 42%), 113.33 (an increase of approx. 37%), and 85.6 HBW (an increase of approx. 4%). For a temperature of 140°C, the highest hardness was obtained for the longest artificial aging time, and this level amounted to 108.63 HBW (i.e., an increase of approx. 31% as compared to the T4 temper for the AlSi7Mg1 alloy).

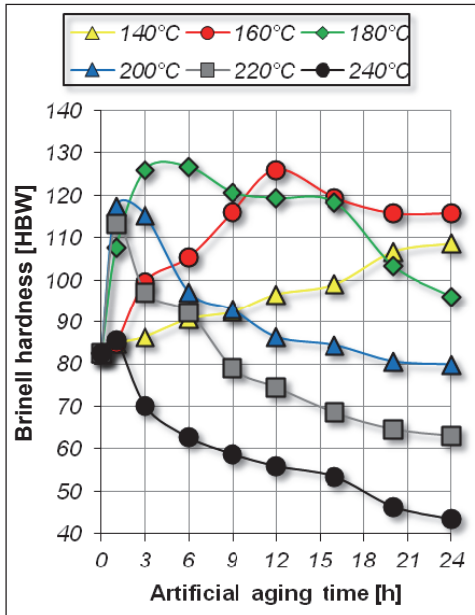


Fig. 8. Brinell hardness versus temperature and time of artificial aging for AlSi7Mg1 alloy

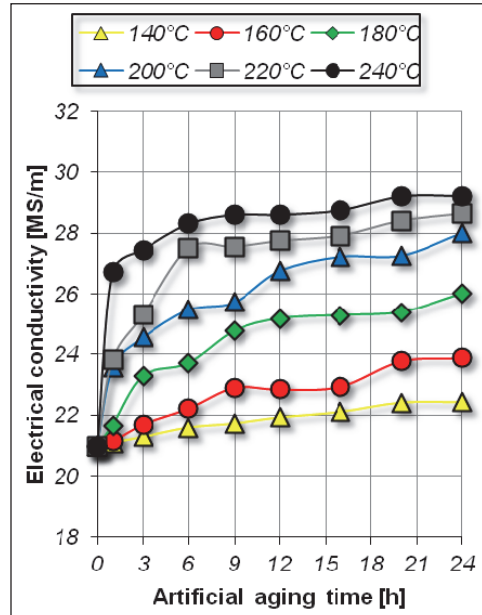


Fig. 9. Electrical conductivity versus temperature and time of artificial aging for AlSi7Mg1 alloy

The maximum electrical conductivity level for the AlSi7Mg1 alloy was obtained after annealing at a temperature of 240°C for 24h (29.23 MS/m). In both cases of artificial aging at temperatures of 240°C and 220°C after 9 h of annealing, the area of maximum electrical conductivity was obtained (respectively, ranges of 28.3–29.3 MS/m and 27.5–28.6 MS/m) where, together with an increase in the time of the process, the level of electrical properties rose slightly. For artificial aging at temperatures of 200°C and 180°C, the level of high and stable electrical properties was obtained after as much as 12 h and involved ranges of 26.7–28 MS/m and 25.20–26 MS/m respectively, which are the maximum points for these temperatures allowed to obtain electrical conductivity higher than the conductivity obtained for the T4 temper by 32 and 23%. At a temperature of 140°C, electrical properties after 24 h of annealing increased by only 6.5%.

The last alloy discussed in the paper is the AlSi11Mg1 material. Microstructures of this material are presented in Figure 10 (T6 temper). An overview of the Brinell hardness and electrical conductivity results is presented in Figures 11 and 12.

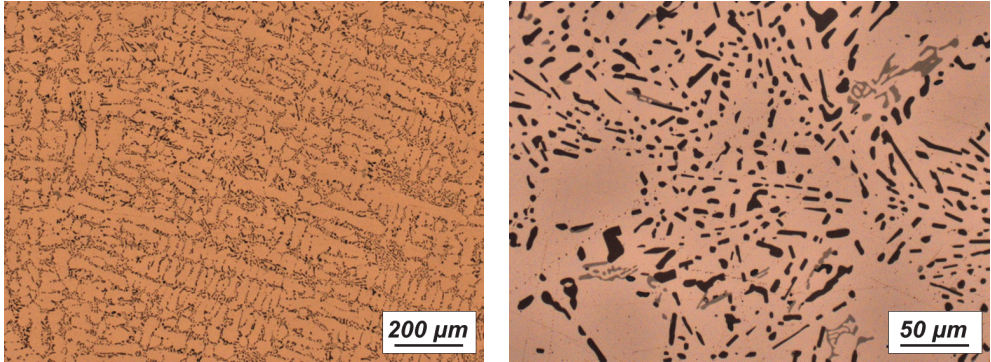


Fig. 10. Microstructures of the AlSi11Mg1 alloy for the T6 temper

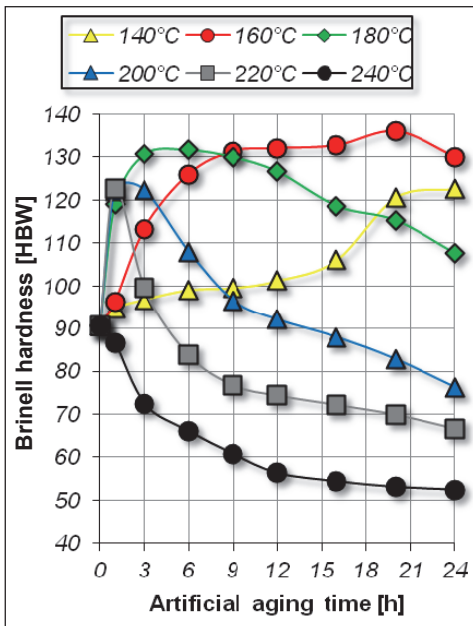


Fig. 11. Brinell hardness versus temperature and time of artificial aging for AlSi11Mg1 alloy

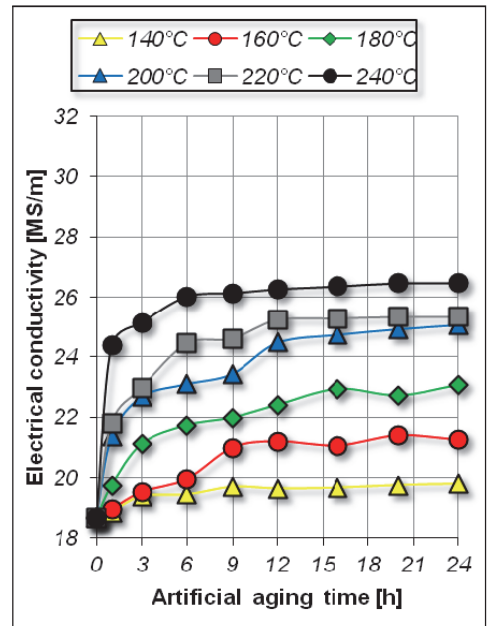


Fig. 12. Electrical conductivity versus temperature and time of artificial aging for AlSi11Mg1 alloy

A further increase of silicon content to a level of approx. 11% mass allowed us to raise the maximum Brinell hardness value to a level of 136 HBW after artificial aging at a temperature of 160°C for 20 h (an increase of approx. 50% as compared to the T4

temper). Raising the temperature to 180°C made it possible to obtain a level of 130 HBW already after 3 h of artificial aging, which (in the case of artificial aging at a temperature of 160°C) was possible after as long as 9 h. A further increase in the temperature for the process to be carried out has no beneficial effect on the strength properties in the form of Brinell hardness: at a temperature of 200°C following reaching the maximum point for approx. 122 HBW after a time of 1–3 h, a steady drop in hardness was observed of approx. 76 HBW after 24h. A similar level of maximum hardness was observed for a temperature of 220°C and 1h aging; however, in this case, the material was artificially aged faster and reached a lower value (approx. 66 HBW after 24 h). In the case of artificial aging at a temperature of 140°C, an increase in Brinell hardness to a level of slightly over 120 HBW was observed after aging longer than 16 h.

The maximum electrical conductivity obtained for AlSi11Mg1 amounted to approx. 26.5 MS/m (an increase of approx. 42% as compared to the T4 temper). A satisfactory level of electrical conductivity was also obtained for artificial aging at temperatures of 220°C and 200°C. The level of 24 MS/m in these cases was exceeded after 6 and 12h, respectively. In the case of a temperature of 180°C, the maximum hardness level following artificial aging for 24 h was approx. 23 MS/m. For lower temperatures 140–160°C, the artificial aging curves did not exceed a level of 22 MS/m.

5. Conclusions

The conducted tests and analyses led to the following conclusions:

- The AlSi5Mg1, AlSi7Mg1, and AlSi11Mg1 alloys in the F and T4 state display average strength properties and electrical properties from the viewpoint of their further application.
- The parameters of the artificial aging operation for which both high Brinell hardness (over 70 HBW) and high electrical conductivity (over 24 MS/m) was obtained are:
 - for the AlSi5Mg1 alloy: 160°C/16–24 h, 180–200°C/3–24 h, 220°C/1–12 h, 240°C/1 h;
 - for the AlSi7Mg1 alloy: 180°C/9–24 h, 200°C/3–24 h, 220°C/1–3 h;
 - for the AlSi11Mg1 alloy: 200°C/12–4 h, 220°C/6–16, 240°C/1–3.
- An increase in the silicon content in the alloy leads to its increase in hardness with a simultaneous degradation of its electrical conductivity.
- The eutectic of silicon becomes slightly oval following artificial aging as compared to the structure obtained for the T4 temper.

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