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EVALUATION OF THE EFFECT OF SELECTED ALLOYING ELEMENTS ON THE MECHANICAL AND ELECTRICAL ALUMINIUM PROPERTIES

OCENA WPŁYWU WYBRANYCH DODATKÓW STOPOWYCH NA WŁASNOŚCI MECHANICZNE I ELEKTRYCZNE ALUMINIUM

Modern industry expects aluminum products with new, unusual, and well-defined functional properties. Last years we are able to notice constant development of aluminium alloys. In food industry, power engineering, electrical engineering and building engineering, flat rolled products of 1XXX series aluminium alloys are used.8XXX series alloys registered in Aluminium Association during last 20 years may be used as an alternative. These alloys have very good thermal and electrical conductivity and perfect technological formability. Moreover, these materials are able to obtain by aluminium scrap recycling. Fundamental alloy additives of 8XXX series are Fe, Si, Mn, Mg, Cu and Zn. Aluminium alloying with these additives makes it possible to obtain materials with different mechanical ale electrical properties. In this paper, the analysis of alloy elements content (in 8XXX series) effect on chosen properties of material in as cast and after thermal treatment tempers has been presented.

Keywords: aluminium 8XXX, electrical conductivity, hardness, homogenization

Współczesna gospodarka oczekuje wyrobów aluminiowych o nowych, lepszych i ściśle określonych właściwościach użytkowych. W ostatnich latach obserwowany jest ciągły rozwój stopów aluminium. W przemyśle spożywczym, energetyce, elektrotechnice i w budownictwie tradycyjnie stosuje sie płaskie wyroby walcowane ze stopów aluminium serii 1XXX. Alternatywą są zarejestrowane w ostatnim dwudziestoleciu w Aluminum Association stopy serii 8XXX. Stopy te mają dobrą przewodność cieplną i elektryczną oraz znakomitą podatność do odkształcenia plastycznego. Ponadto materiały te można otrzymywać na drodze recyklingu złomu aluminiowego. Podstawowymi dodatkami stopowymi serii 8XXX są Fe, Si, Mn, Mg, Cu i Zn. Stopowanie aluminium tymi dodatkami pozwala uzyskać materiały o zróżnicowanych własnościach mechanicznych i elektrycznych. W pracy przedstawiono analizę wpływu zawartości pierwiastków stopowych obecnych w serii 8XXX na wybrane własności materiału w stanach po odlewaniu oraz po obróbce cieplnej.

1. Introduction

Rolled products made of aluminium and its alloys are increasingly manufactured using integrated technologies like "near net shape manufacturing". Continuous casting with usage of rotating cylindrical crystallizers of Twin Roll Casting (TRC) type solution becomes uncommonly popular. Effect of such line is high-quality strip at high dimensional tolerances and superb surface parameters. This strip may directly subject to cold-rolling process. Application of TRC technology allows to eliminate hot-rolling process from the manufacturing process so it makes it possible to reduce costs of infrastructure (lack of hot rolling mill) and reduce energy-consuming and material consumption indexes of the processing process while ensuring attractive technical parameters of the product. So this method is good and competitive alternative for classic methods of flat rolled products manufacturing [1-4].

TRC technology is more and more common for 1XXX and 8XXX series aluminium alloys. Both series are similar. However in 8XXX it is possible to apply higher contents of alloy additives, such as Fe, Si, Mn and (in smaller amounts) Mg, Cu and Zn [5-6]. From the utilize point of view, the identification of particular alloy additives and impurities present in 8XXX alloys influence on their usage properties is significant. 8XXX series alloys ensure exceptional connection of mechanical strength, technological formability, electrical and thermal conductivity and rheological strength of the material, so alloys from this group are used in many new applications [7]. Materials produced by TRC methods often subject to homogenization before casting in order to remove some disadvantages of the casting structure. For this reason, it is key matter to determine the quantitative effect of particular alloy additives on properties of the material after casting and after heat treatments with various cooling variants.

Alloy components with base metal may create solid solution or individual phase while simultaneously they have an effect (in various manners) on mechanical and electrical aluminium properties. This effect depends mainly on their amount and arrangement in base material. Because the systematic structure of pure metal is interfered mainly by dissolved and

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non-irregularly arranged atoms, the components that constitute solid solution will have the biggest influence on its electrical conductivity [8]. The influence of alloy elements in solid solution may be determined accordingly to the Nordheim rule. This rule shows the linear decrease of electrical conductivity in alloy elements concentration function (in matrix) and the slope depends on the type of alloy additive. In case the alloy components do not constitute (with base metal) the solid solution but the separated phase, the electrical conductivity is decreased slightly and its decrease may be determined by mixtures rule [8-10]. Similar, the hardness of materials after casting is connected mainly with the amount of alloy additives and their arrangement in the metal as well as related with grain size. This study shows the influence of Fe, Si, Mn, Mg, Cu and Zn contents on electrical conductivity and material hardness as well as analysis of changes of these properties after heat treatement which simulates homogenization process.

2. Material and research methods

99,99% pure aluminium has been selected as the material to be examined. It has been melted in specially prepared melting graphite moulds with high thermal conductance and warmed up to 720°C and next – held for 1 hour in this temperature. Various analytical samples of selected alloy additives have been introduced into such prepared liquid metal (Table 1), and then – this created alloy has been precisely mixed and left inside the furnace for 1 hour. After these actions, materials have been cooled in air pots down to the ambient temperature. Contents of additives have been selected in accordance with compositions of 8XXX series alloys, sued in various application in accordance with PN-EN 573-3:2010P standard.

TABLE 1

Content of particular alloy additives used in experiments

Cast no.	Concentration of alloying element in material [% wt]					
	Fe	Si	Mn	Mg	Cu	Zn
1	0,3	-	-	-	-	-
2	0,6	-	-	-	-	-
3	0,9	-	-	-	-	-
4	1,2	-	-	-	-	-
5	1,5	-	-	-	-	-
6	-	0,3	-	-	-	-
7	-	0,6	-	-	-	-
8	-	0,9	-	-	-	-
9	-	1,2	-	-	-	-
10	-	-	0,3	-	-	-
11	-	-	0,6	-	-	-
12	-	-	0,9	-	-	-
13	-	-	1,2	-	-	-
14	-	-	-	0,3	-	-
15	-	-	-	0,6	-	-
16	-	-	-	0,9	-	-
17	-	-	-	-	0,1	-
18	-	-	-	-	0,2	-
19	-	-	-	-	0,4	-
20	-	-	-	-	0,6	-
21	-	-	-	-	-	0,05
22	-	-	-	-	-	0,1
23	-	-	-	-	-	0,2

As an effect, casts at the mass of approximately 150 g and diameter of 40 mm with various amounts of alloy elements have been obtained. Obtained casts subjected to examinations concerning electrical conductivity and hardness. Next stage of the testing procedure was samples heat treatment in 550°C for 100 hours and rapid cooling in water in order to freeze the structure which is characteristic for high temperature (holding some alloy additives in the solution). These samples also subjected to examinations concerning electrical conductivity and hardness. The last stage of tests consisted in samples heat treated in 550°C for 100 hours and next in 250°C for 100 hours and cooling with furnace in order to release particular alloy additives in form of individual phases. In analogical way, such materials subjected to examinations concerning electrical conductivity and hardness.

3. Results and discussion of these results

Table 2 shows the selected literature data concerning the influence of selected alloy elements on the aluminium electrical conductivity [9,11,12].

TABLE 2

Decrease of aluminum conductivity caused by selected chemical elements

Alloying element	The maximum solubility of aluminum in the solid state [% wt]	Decrease of the aluminium electrical conductivity in the presence of 1% of the element in the solid solution [MS/m]	Decrease of the aluminium electrical conductivity in the presence of 1% of the element outside the solid solution [MS/m]
Fe	0,052	18,66	0,81
Si	1,65	10,56	1,22
Mn	1,82	19,97	4,32
Mg	17,4	6,44	2,92
Cu	5,65	4,37	0,43
Zn	82,8	1,31	0,33

Figure 1 shows the experimental results of the influence of main elements that are alloy additives of 8XXX series 99,99% pure aluminium, used in the experiment in 20°C had the electrical conductivity of 37,92 MS/m. This result correlates well with literature data [12].

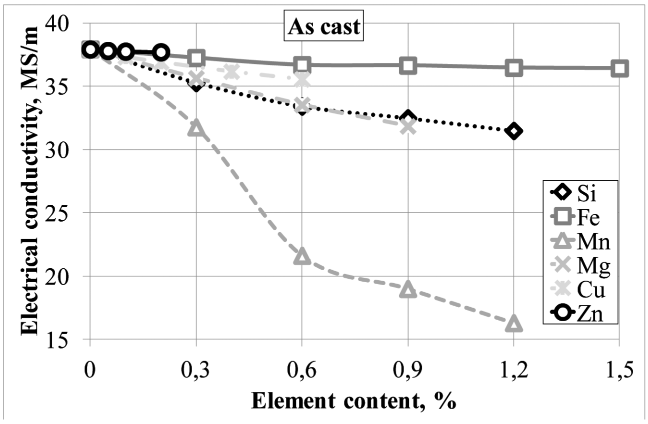

Fig. 1. Influence of selected alloy additives on the aluminium electrical conductivity, as cast temper

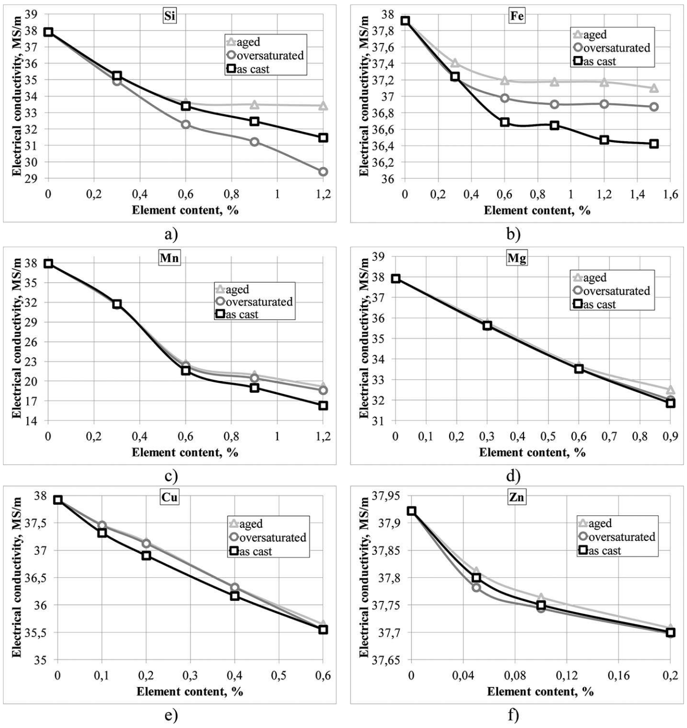

Fig. 2. Evolution of aluminium electrical properties in the function of alloy additive content, in as cast, oversaturation and aged tempers

The decrease of conductivity for examined materials in as cast temper shows the linear relation in additive concentration function. This correlates well with Nordheim rule. By analyzing the line slope angle in the Fig. 1 it can be easily observed that the smallest decrease of conductivity is a consequence of Fe and Zn activity. Next, in similar – Cu, Si and Mg. The highest degradation of electrical properties is caused by Mn. These results are similar to effects, achieved by other researchers [10] and [13].

As previously mentioned, the degradation of aluminium electrical properties depends to a large extent on the amount of alloy additives and their arrangement in the base. This is reflected by relations specified in Fig. 2a – 2f.

Si influence on the conductivity significantly depends on the condition of the material (Fig. 2a), because Si may be located inside the solid solution (after homogenization and fast cooling to water) or beyond the solid solution (after homogenization slow cooling with oven and heated in 250°C). It is worth to observe that after heating in 250°C, some minor part of Si is still present in solid solution. At this temperature, solvus line of Al-Si phase diagram shows the solubility of approximately 0,04% of Si so the majority of silicon is located in the separated phase. Difference in the value of electrical conductivity for particular states is starting when silicon solidifies in aluminium at the level of 0,3% and when it is 1,2% of content it shows decrease respectively for: as cast state – 6,44 MS/m, after homogenization and fast cooling to water – 8,51 MS/m, after homogenization, slow cooling and heating in250°C – 4,49 MS/m. These values are slightly smaller than literature data mentioned in Table 1.

Fe effect on electrical conductivity (Fig. 2b) slightly depends on the condition of the material. Fe solubility in Al in solid state is very small (0,052%) and observed differences may be related to the evolution of non-equlibrium AlFe phases chemical composition and change their volume fraction in the material. Linear decrease of the conductivity for each of three examined tempers occurs within the Fe content of up to 0,3%. At higher concentrations, line slope is smaller and their dependence on the material condition is more visible. Al-Fe alloy after casting and Fe solidification in amount of 1,5% shows the conductivity which is nearly 1,5 MS/m lower than for pure base metal. Appropriate thermal treatment allows to limit the negative influence of Fe on the aluminium conductivity down to the value of approximately 0,82 MS/m at the concentration of 1,5%.

The third of the most common alloy additives from 8XXX series is manganese. As it results from the relation, presented in the Fig. 2c and Table 1, it significantly impacts the aluminium conductivity decrease. Mn concentration in the amount of 1,2% in Al-Mn alloy causes the conductivity decrease by 19,7 – 21,6 MS/m. When analyzing the experimental and literature data and also the Al-Mn phase diagram it is possible to conclude that within the examined scope of concentrations, manganese stays mainly in solid solution and applied actions of heat treatement result in transferring some minor part of alloy additive to the separated phase. It can be observed within the scope of concentrations from 0,6% to 1,2%.

Magnesium shows high solubility in aluminium (up to 17,4%) and that is why the measurements of electrical conductivity shown nearly perfect, linear decrease of this parameter, in accordance with Nordheim rule (Fig. 2d). Conductivity decrease by 6 MS/m at the concentration of 0,9% perfectly corresponds with data presented in [9] and [11]. The process of long-term heating of Al-Mg0,9 alloy in 250°C results in insignificant increase of its conductivity by 0,5 MS/m in comparison to the material in as cast temper.

The similar linear dependence of Cu additive influence on the aluminium conductivity can be observed in Al-Cu alloys, within the frames of concentrations from 0-0,6% Cu (fig. 2e). This decrease equals approximately 2,3 MS/m and this practically does not depend on the material condition because of the quite high Cu solubility in aluminium which equals 5,65%.

Zinc appears in 8XXX series alloys but in very small amounts. And its maximal concentration is assumed as 0,2%. In this scope, it causes only small decrease of the electrical conductivity (similarly to Fe) and it stays (in total) in the solid solution. This results from Al-Zn phase diagram.

The Vickers hardness method has been selected as the representative amount for the analysis of alloy additives influence on mechanical properties. Particular examined additives have an influence (at various extents) on the aluminium hardening. Fig. 3 and Table 3 shows the influence of selected alloy additives content on the aluminium Vickers hardness in as cast and heat treated tempers. The hardness grows linearly together with the increase of alloy elements content and it depends on the type of alloy chemical element. Observed increase of hardness is the smallest for materials containing Fe and Zn. It happens independently from the material condition.

TABLE 3

Estimated increase of aluminium hardness caused by 1% addition selected chemical elements in different tempers

Alloying element	ΔHV5/1% – as cast	ΔHV5/1% – homogenized and fast cooled to water	ΔHV5/1% – homogenized, slow cooled and heated in 250°C
Si	11,54	11,81	12,98
Fe	4,16	1,92	2,27
Mn	14,26	13,4	13,34
Mg	18,6	16,95	16,15
Cu	18,33	10,36	8,32
Zn	8,29	2,68	2,81

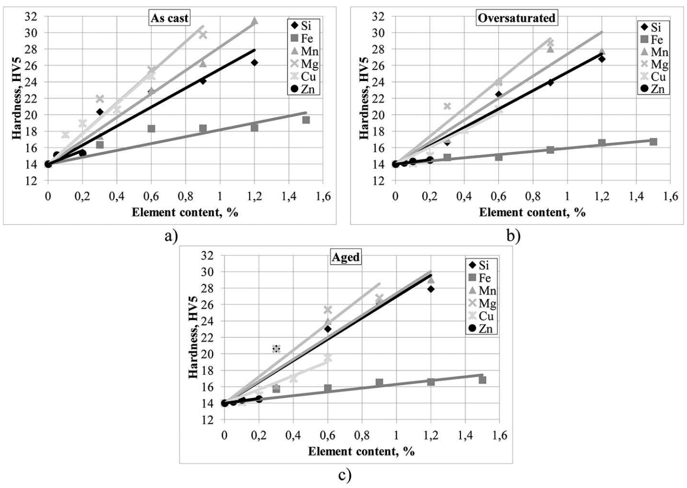

Fig. 3. Evolution of aluminium hardness in the function of alloy additive content, in different tempers

Definitely, the highest hardening is the result of adding magnesium into the aluminium. The concentration of this metal in amount of 1,2% causes more than two times higher mechanical properties. Such amount of additive most probably causes the solution hardening and its extent depends (in not large extent) on the thermal treatment processes. In case of Al-Cu alloys, we observe significantly higher effect of material hardening in as cast state than after heat treatment. Al-Mn alloy shows noticeable change of hardening level during thermal treatment. Fast cooling after homogenization the decrease the strengthening effect. In examined concentrations scope, manganese stays mainly in the solid solution. Long-term heating treatment in 250°C results in possible pass of not large portion of alloy additive to the separate phase and this results in higher level of alloy strengthening. Definitely, the biggest changes in strengthening level are noticeable in Al-Si alloys. The increase of hardness for homogenized and fast cooled materials with Si additive is lower in comparison to materials after homogenization, slow cooling and heating in 250°C. It results from the smaller influence of solution hardening in opposition to the bigger second phase hardening.

4. Conclusions

The analysis of the results of experimental tests for the Fe, Si, Mn, Mg, Cu and Zn contents influence on the electrical conductivity and aluminium hardness has been carried out. Relation between the electrical conductivity and the content of alloy chemical elements is quasi-linear. Within the tested scope of concentrations, the conductivity of Al-Si alloys (which is significantly changed during the heat treatement processes) depends on the condition of the material. So we are able to conclude that homogenization treatments (that are often practiced after casting with TRC method) will result in changes of silicon content in solid solution and in phases – especially in AlFeSi. Fe influence on electrical conductivity is insignificant. The biggest degradation of electrical properties is caused by manganese which may (for different conditions of cooling after homogenization) show a trend consisting in passing from solid solution into the separated phases at high concentrations in aluminium.

Material hardening as a result of introducing alloy additives also shows a trend which is similar to the linear tendency. For the selected chemical elements (excepting Fe) this is mainly a solution hardening but in materials characterized by silicone addition, it is also possible to notice the hardening with the second phase.

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