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RESEARCH ON THE PRODUCTION PROCESS OF HIGH-STRENGTH PRODUCTS FROM ALUMINUM-MAGNESIUM ALLOYS FOR THEIR DIRECT PROCESSING INTO SHEETS VIA COLD ROLLING

Modern metal forming processes of non-ferrous metals, particularly aluminum and its alloys, are increasingly based on integrated technologies combining numerous operations in one process line. The subject of this paper focuses on the possibility of using materials after mould casting (simulating a continuous casting process between cylindrical crystallizers – Twin Roll Casting method) for the direct cold rolling process. As a part of this research a pilotage study on metallurgical synthesis and mould casting process of Al-Mg alloys with the magnesium contents of 5%-10%, testing their mechanical, electrical and structural properties as well as susceptibility to cold plastic deformation. This process was carried out with the measurement of strength parameters and confirmed the possibility of cold rolling alloys with a casting structure without prior hot deformation.

Keywords: aluminum alloys, twin roll casting, cold rolling, hardness

1. Introduction

The subject of this research paper is focused on the manufacturing of aluminum alloy sheets with high magnesium contents. Such alloys are currently processed with the use of casting methods for production of aircraft construction components, aircraft connectors, ship fittings, parts of vehicles exposed to impacts and often as decorative elements. There are, however, both literature and experimental premises that some aluminum-magnesium alloys (e.g. EN-AW 5059 – containing 5.5% magnesium, EN-AW 5083 – containing 4.5% magnesium) may be successfully processed using conventional casting methods followed by hot rolling process and finally cold rolling process. Materials like these in the form of sheets with thickness between 0.5 mm and 120 mm are characterized by extraordinary strength properties and ballistic resistance [1-7]. There are several possibilities concerning production of flat rolled products. Such as traditional, well-known in the literature and widely spread in the metal forming industry which includes the process of melting metal and casting of the ingots by semi-continuous method, after which the ingot is hot rolled. The next step is cold rolling and optional heat treatment in order to obtain the required properties and state of the material. There is an alternative technology which is using continuous casting via TRC method (Twin Roll Casting) and simultaneously eliminating the need for hot rolling, because the obtained material is 2-10 mm thick, which allows the direct cold rolling process [8-13].

Taking the aluminum properties, its controlling and the possibility of obtaining high mechanical properties of rolled products into consideration it should be remembered that alloy components with a base metal can form a solid solution or independent phase which directly affects the mechanical and electrical properties of aluminum in many ways. This influence depends mostly on the quantity of alloy additives and their distribution in the base material. Due to the fact that the ordered structure of the fine metal is mainly disrupted by dissolved and irregularly located atoms, the electrical conductivity is mostly affected by the components forming a solid solution with it. The influence of the alloy additives to a solid solution may be determined according to the Nordheim's rule. This rule shows a linear decrease in the electrical conductivity in terms of the concentration of the alloy additives in the matrix and the slope depends on the type of the alloy additive. In the case where alloy additives do not form a solid solution with the base metal but separate phase the electrical conductivity is reduced slightly and its decrease can be determined using the rule of mixtures. Similarly, the hardness, yield strength, ultimate tensile strength of the casted materials is primarily related to the amount of alloy additives and their distribution in the base metal and the grain size. Aside from the abovementioned methods of aluminum strengthening its mechanical properties (and thus deformation resistance) are affected by the deformation set during cold plastic working [13-16]. Solid solution, precipitation and deformation strengthening significantly affects the strength parameters of the rolling process (which in fact depend on the

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deformation resistance of the material. These parameters may be analyzed via the knowledge of the average unit pressure. One of the analytical dependencies allowing its determination is the formula proposed by Roberts [17-18]:

$$p = \sigma_{pl} e^{\frac{\mu l_d}{2h_m}} \tag{1}$$

where:

$$h_m = \frac{h_0 + h_1}{2} \tag{2}$$

- p – average (mean) material – roll pressure during rolling,
- σ – average flow stress of the material during tensile test during rolling pass,
- l_d – the length of roll – material contact during rolling pass,
- μ – coefficient of friction,
- h_m – mean height of material during rolling pass
- R – radius of roll,
- h_0 – height of material before rolling pass,
- h_1 – height of material after rolling pass.

Or another one proposed by Avitzur/Stone [19-20] which is:

$$p = \frac{2}{\sqrt{3}} \frac{e^{\frac{\mu l_d}{h_m}} - 1}{\frac{\mu l_d}{h_m}} \sigma_{pl} \tag{3}$$

In this work, the average unit pressure was determined experimentally.

Conducted research on the manufacturing of Al-Mg alloy strips verified the possibility of obtaining them by casting and their direct cold rolling, which in a further stage gives a real chance of obtaining such materials in the TRC process.

2.Materials and methods

Technically pure aluminum has been chosen as the base material for the research. In order to obtain specific alloys with the magnesium content of 5%, 6%, 7%, 8%, 9% and 10% the appropriate alloy additions in the form of pure Mg and a special AlTi5B1 foundry alloy have been added into the base metal (Ti content of each alloy has been 500 ppm). The first stage of the research has involved the process of aluminum melting and heating it in the crucible to the temperature of 780°C. The next step has been adding the appropriate alloy additions (Mg and Ti). Each individual alloy has been mixed thoroughly and left in the furnace for additional 20 minutes in order to homogenize the chemical composition. After this time the process of mould casting of individual materials has started. The castings have been sampled with dimensions 50 mm × 50 mm × 8 mm in order to test the hardness of the material (Vickers method) and electrical conductivity (eddy currents method) after casting. Afterwards the obtained materials have been subjected to the cold rolling process using a laboratory quarter rolling mill. Samples prepared for the cold rolling process have had the following dimensions: 100 mm x 34 mm x 8 mm. The cold rolling process have been conducted using the following rolling reduction scheme: 8 mm – 7.8 mm – 7.35 mm – 7.1 mm – 6.4 mm – 5.6 mm – 4.8 mm – 4 mm – 3.3 mm – 2.5 mm – 1.7 mm – 0.88 mm. The rolling process have been carried out with the recording of the strength parameters by using strain gauges of force attached to both rollers, the Spider device and the Catman software. In the next stage of the research the evolution of the mechanical properties in terms of the given rolling reduction have been analyzed. Structural analyses using scanning electron microscope of the casted material and material subjected to plastic deformation were conducted.

3. Results and discussion

As part of the conducted research the hardness of the mould casted materials in terms of the Mg content in the alloy have been analyzed. Based on the results of the research it can be concluded that the hardness of the materials increases with the increase of the magnesium content in the alloy (from about 70 HV 5 to about 89 HV 5) and the increase of the values is almost linear (Fig. 1). As part of the conducted work an analysis of the changes in the electrical conductivity of the tested materials in terms of the Mg content has also been carried out. As presented in Figure 2

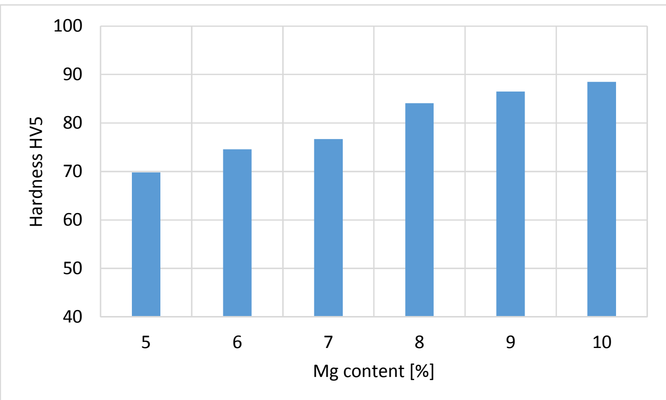


Fig. 1. The influence of the Mg alloy addition on the hardness of the material

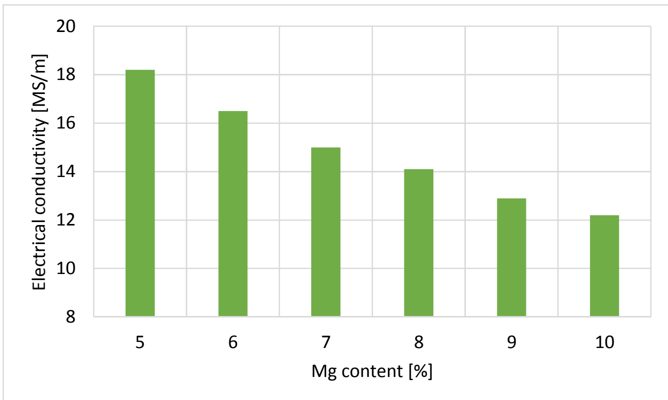


Fig. 2. The influence of the Mg alloy addition on the electrical conductivity of the material

these changes are quite significant as the electrical conductivity value decreases from 18.2 MS/m with the Mg content of 5% to 12.2 MS/m with the MG content of 10%. Such decrease is also close to linear, which may indicate that the alloy additive (Mg) is located mainly in the solid solution.

Additionally, on the casted materials, structure analysis was performed using scanning electron microscopy as well as qualitative and quantitative analysis of chemical composition of selected areas of AlMg6 and AlMg9 alloys. The results of the analysis are presented in Figures 3-6. Based on this research it was confirmed that in the examined range of concentrations, magnesium is found mainly in the solid solution causing solid solution strengthening. Precipitations rich in magnesium located mainly at the grain boundaries and causing precipitation strengthening of the material were also observed. Figures 5-6 clearly indicate that the majority of magnesium in the alloy is in the solid solution. Considering AlMg9 alloy, about 6%-8.4% of magnesium is in the solid solution (see Fig. 6). Whereas the precipitations contain of about 30%-35% of magnesium. In addition, iron precipitations were observed in the material which is the natural impurity of the base metal.

Comprehensive research on the cold rolling process of the obtained materials have been conducted in the further stage of the work. These tests have been carried out concerning both,

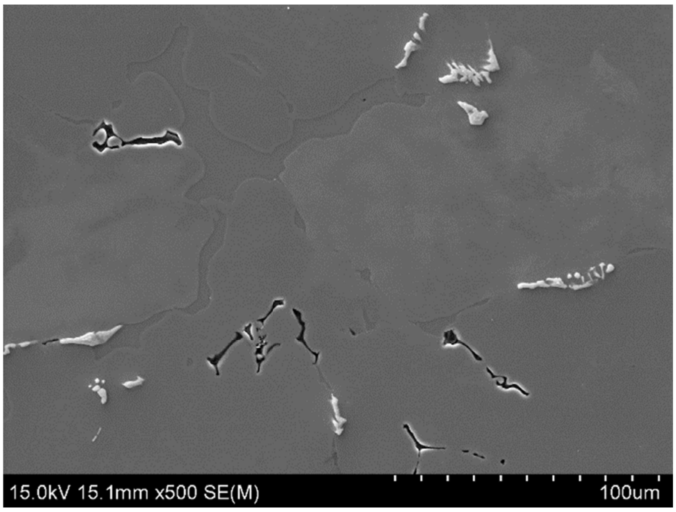


Fig. 3. Microstructure of the casted AlMg6 alloy

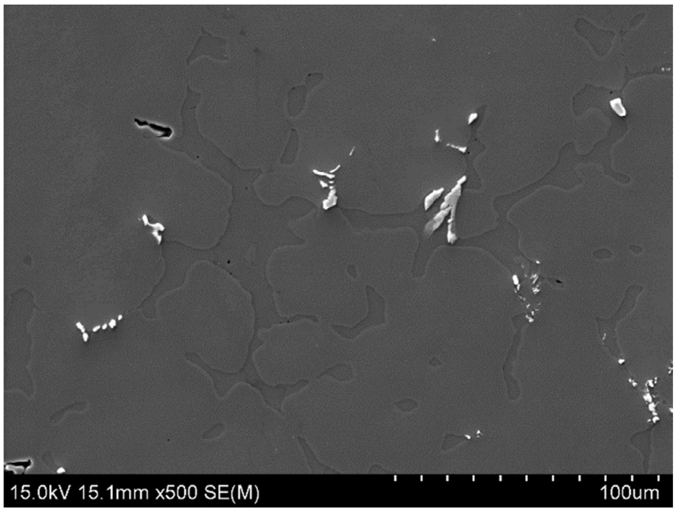


Fig. 4. Microstructure of the casted AlMg9 alloy

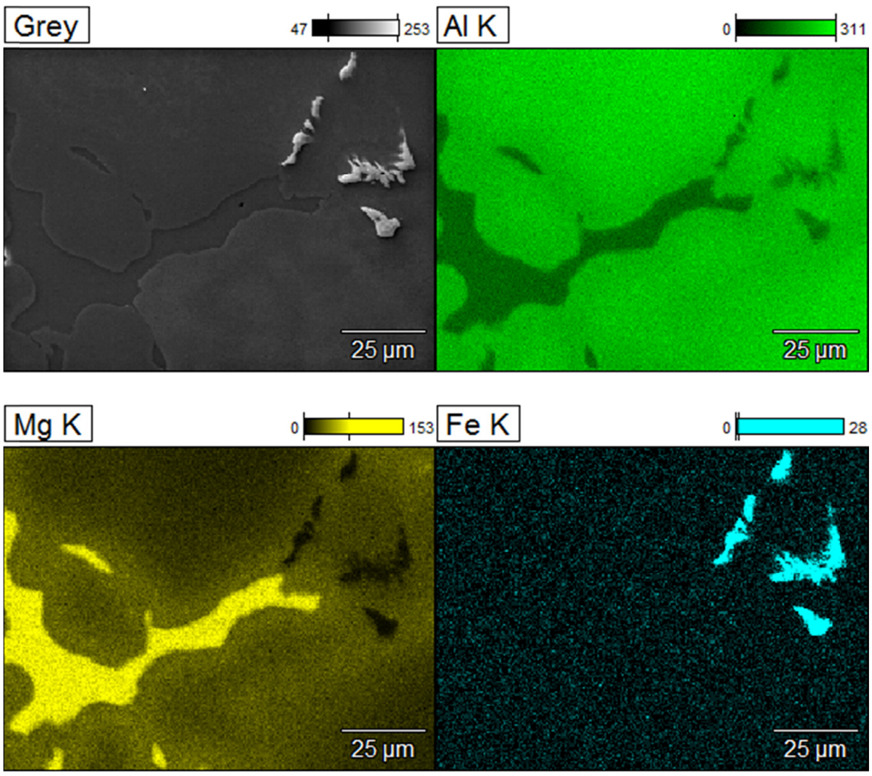
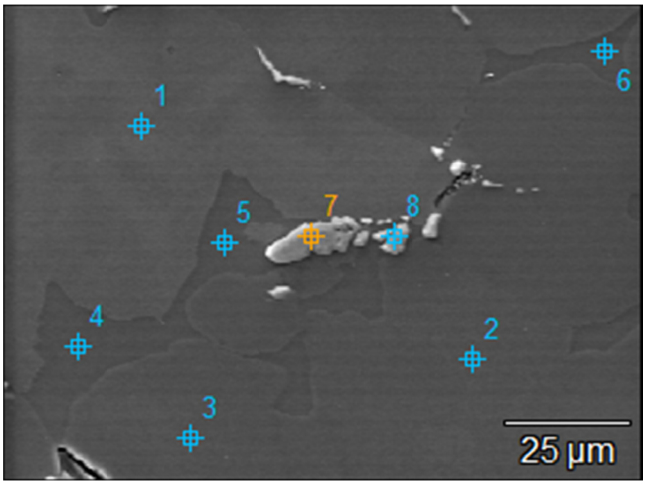


Fig. 5. Qualitative analysis of the chemical composition of the matrix and precipitations occurring in the casted AlMg6 alloy



Point of measurement	Mg [wt.%]	Al [wt.%]	Fe [wt.%]
1	5,95	94,05	—
2	5,94	94,06	—
3	8,37	91,63	—
4	34,98	65,02	—
5	31,00	69,00	—
6	35.19	64,81	—
7	1,82	65,34	32,84
8	1,22	64,23	34,55

Fig. 6. Quantitative analysis of the matrix and precipitations occurring in the casted AlMg9 alloy

the Mg alloy addition and the temperature of the rolling process which ranged from 20° to 200°C. What should be kept in mind is that the rolled material has been in the casting state, i.e. with no prior universally used in the production of sheets hot rolling process. During each of the rolling passes strength parameters have been registered and subsequently converted into the average unit pressure of the rolling process. Figures 7-10 show the dependences of the average unit pressure in terms of the given strain for AlMg5, AlMg6, AlMg7 and AlMg8. As can be seen in each case, the average unit pressure increases in the next rolling pass which indicates the deformation strengthening of the examined materials. Generally, the increase of the Mg content

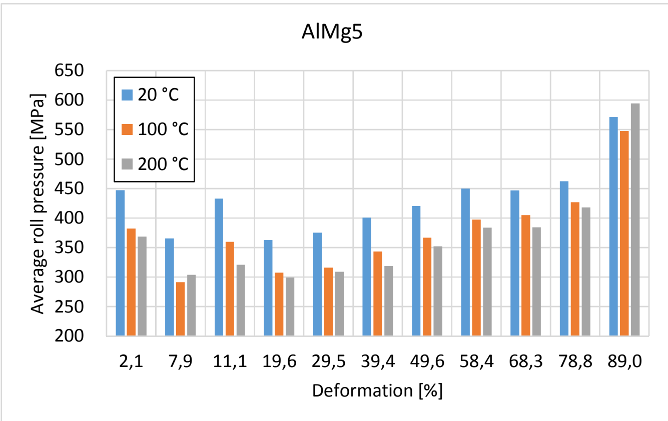


Fig. 7. The influence of the temperature and given strain during the cold rolling of AlMg5 in terms of an average unit pressure

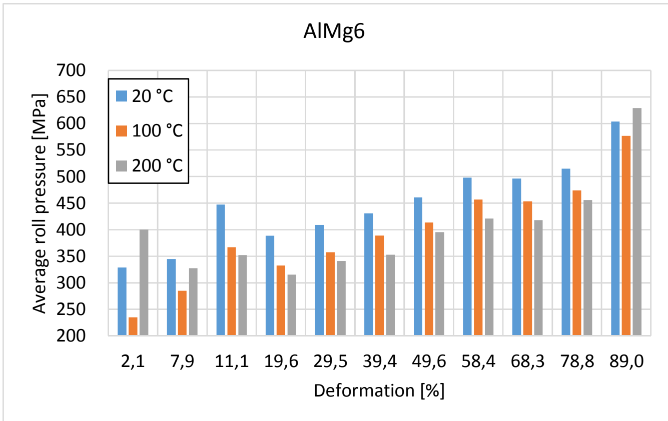


Fig. 8. The influence of the temperature and given strain during the cold rolling of AlMg6 in terms of an average unit pressure

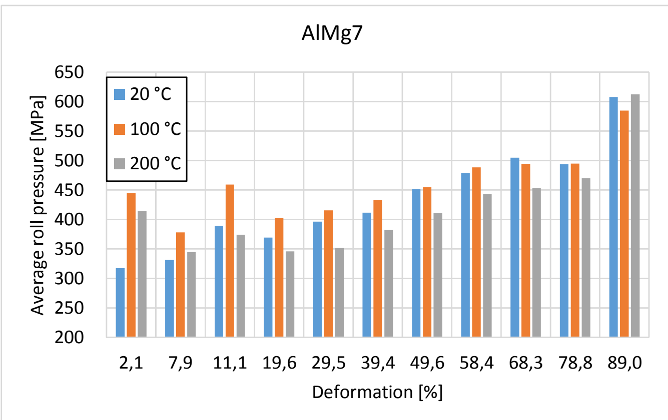


Fig. 9. The influence of the temperature and given strain during the cold rolling of AlMg7 in terms of an average unit pressure

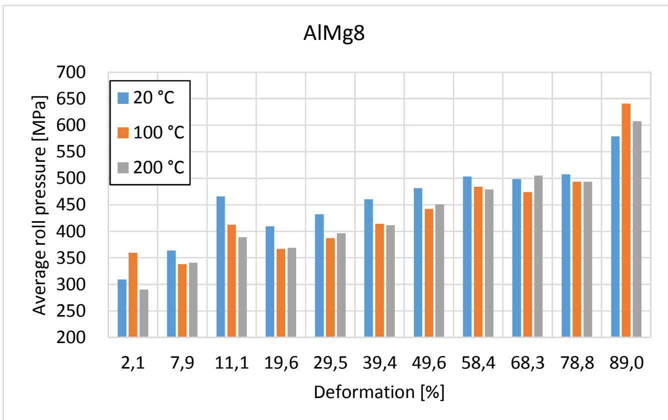


Fig. 10. The influence of the temperature and given strain during the cold rolling of AlMg8 in terms of an average unit pressure

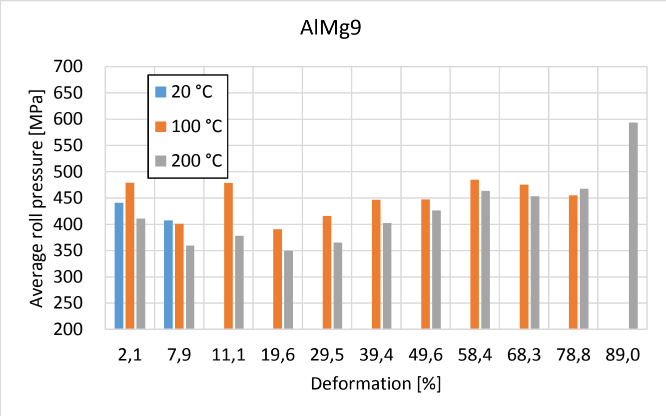


Fig. 11. The influence of the temperature and given strain during the cold rolling of AlMg9 in terms of an average unit pressure

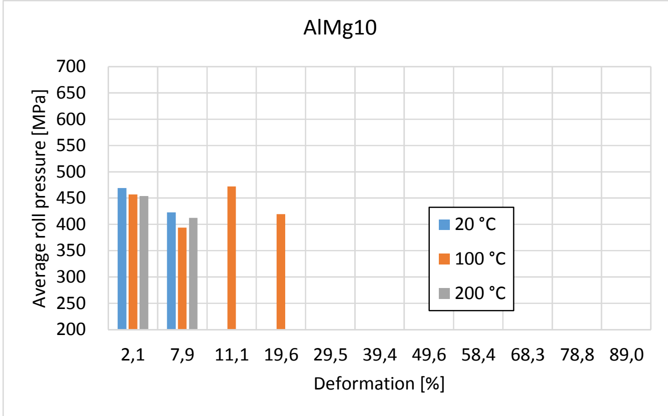


Fig. 12. The influence of the temperature and given strain during the cold rolling of AlMg10 in terms of an average unit pressure

in the alloy increases the average unit pressure in the rolling process (which is consistent with the analytical dependencies that bind the average unit pressure in the rolling process with the deformation resistance of the material proposed by both Roberts and Avitzur/Stone). However, considering the chemical compositions presented in Figures 7-10 the differences are not that high. Additionally, it is worth mentioning that the increase of the temperature of the rolled material slightly decreases the registered strength parameters during the process. At this stage it should also be emphasized that for Al-Mg alloys with the Mg content of 5-8% no technological problems during the cold rolling process have occurred and the obtained sheets have been characterized with high surface quality.

Figures 11 and 12 show the dependence of the average unit pressure in terms of the given strain of AlMg9 and AlMg10. Similarly to the other materials in these cases an increase in the strength parameters has also been observed when the Mg content in the alloy increased as well as a decrease in the average unit pressure along with the increase of the material temperature during rolling. However, it should be noted that these two alloys have caused technological problem during rolling. Considering AlMg10 alloy the obtained strips have been rolled with a total rolling reduction of 19.6% and at this stage the cracking of the rolled material, both in the longitudinal and cross-sectional direction, have occurred. The result has been slightly better in the case of AlMg9 alloy. After heating the material to 200°C the rolling with the rolling reduction of 89% has been possible. Lowering the materials temperature to 100°C allowed to conduct the rolling with the rolling reduction of 78.8% and in the case of the ambient temperature it has only been 7.9%

Fig. 13 and 14 show cracks (both longitudinal and cross-sectional) occurring in AlMg9 and AlMg10 materials subjected to the cold rolling process. These cracks are brittle and are located in the areas with high magnesium contents, although the preheating of the material caused the transfer of a large part of magnesium from precipitates to the solid solution.

During the conducted research on the rolling process of the AlMg alloy sheets after each rolling pass the obtained material has been sampled to test the hardness using the Vickers method in order to determine the curves of strengthening of particular alloys. As may be seen in Figures 15-20 each of the tested materials shows the tendency to deformation strengthening and the

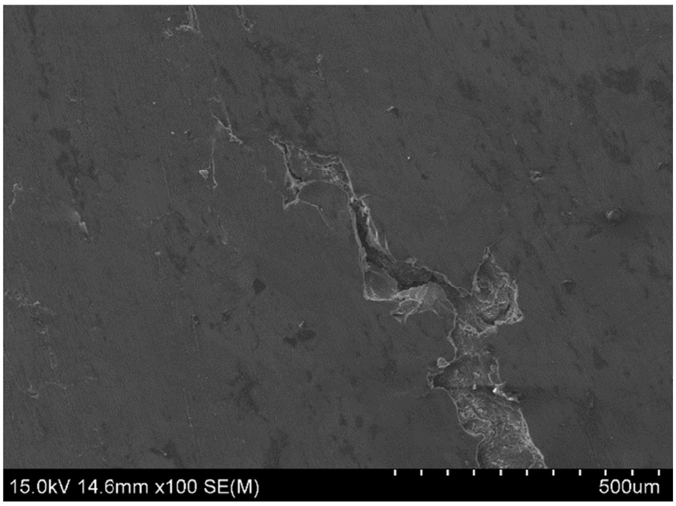


Fig. 13. The view of the surface crack in the cross-sectional direction of the AlMg9 alloy sheet subjected to 78.8% deformation

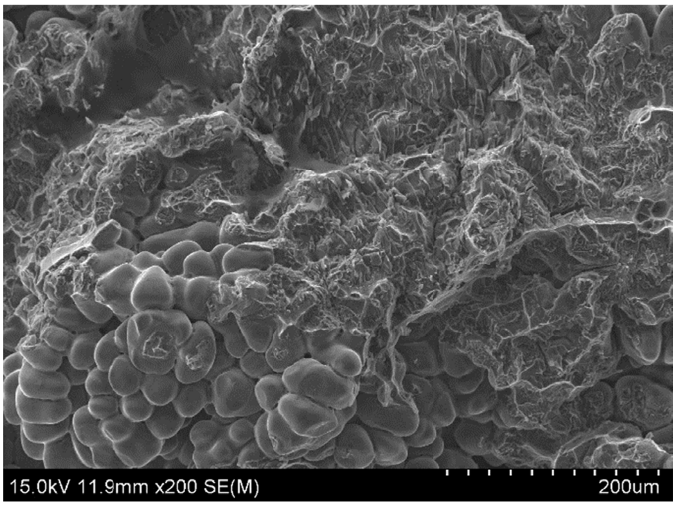


Fig. 14. The view of the longitudinal fracture of the AlMg10 alloy sheet subjected to 19.6% deformation

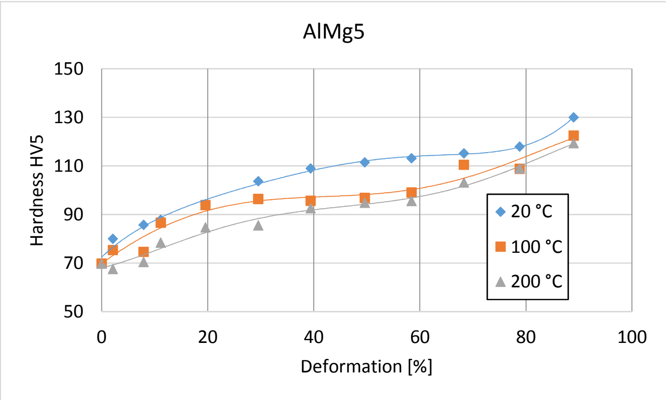


Fig. 15. The evolution of the AlMg5 hardness in terms of the cold rolling temperature and the given deformation

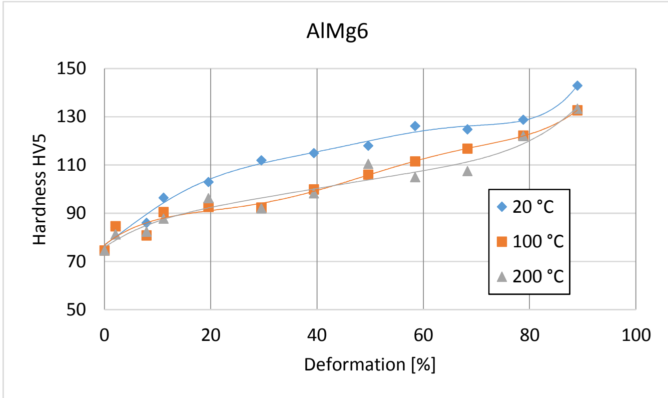


Fig. 16. The evolution of the AlMg6 hardness in terms of the cold rolling temperature and the given deformation

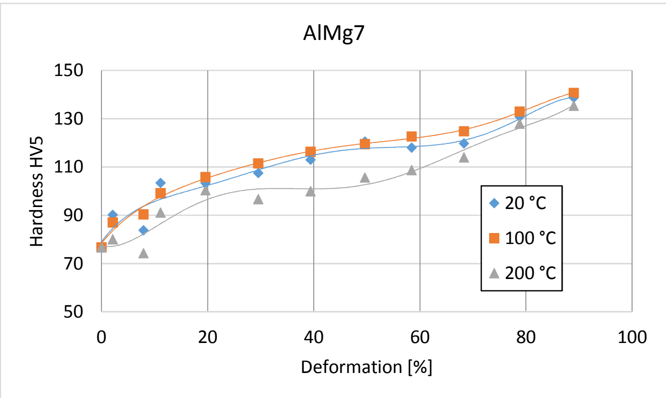


Fig. 17. The evolution of the AlMg7 hardness in terms of the cold rolling temperature and the given deformation

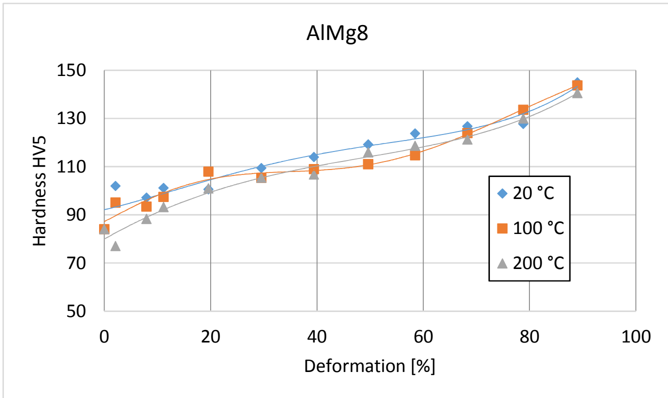


Fig. 18. The evolution of the AlMg8 hardness in terms of the cold rolling temperature and the given deformation

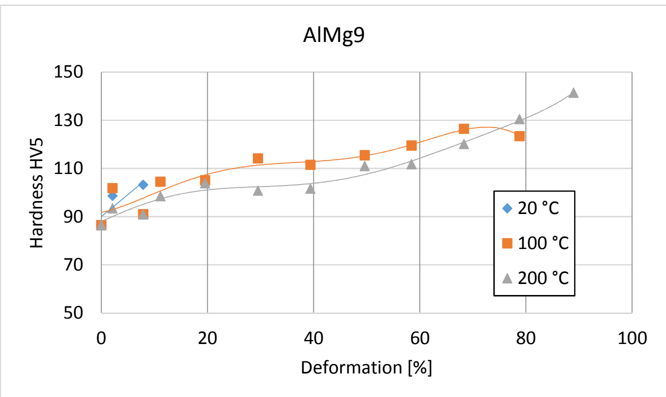


Fig. 19. The evolution of the AlMg9 hardness in terms of the cold rolling temperature and the given deformation

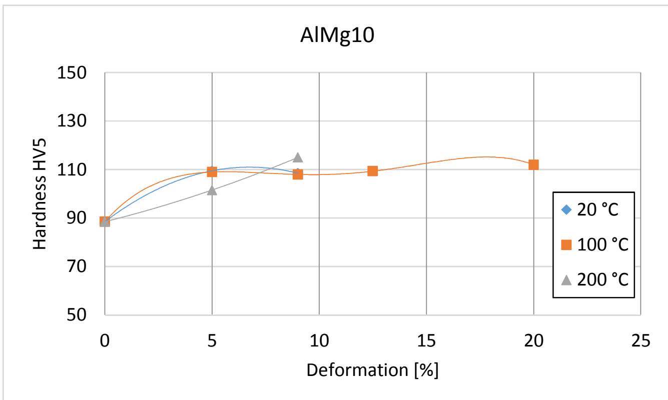


Fig. 20. The evolution of the AlMg10 hardness in terms of the cold rolling temperature and the given deformation

increase in hardness is close to linear (which is in accordance with the conducted analysis of the changes in the strength parameters of the rolling process).

Taking the presented in Figs 15-20 strengthening curves into account it can be unequivocally stated that the highest hardness values of the materials have been recorded for the samples subjected to the rolling process at the ambient temperature (20°C), however, the differences between the hardness values at various temperature parameters for all examined samples are in the range of 5-10 HV5 so increasing the rolling temperature which facilitates the process does not significantly affect the final mechanical properties of the obtained sheet.

4. Conclusions

As part of this study research on the metallurgical synthesis, mould casting and direct cold rolling of high-strength aluminum alloys with magnesium content of 5%, 6%, 7%, 8%, 9% and 10% have been conducted. Based on the conducted research it can be stated that the metallurgical synthesis and casting process has been carried out correctly as the obtained materials have been characterized with the assumed chemical composition and homogeneous both hardness and electrical conductivity along the volume of the cast. On the basis of the tests carried out on the cast materials it has been proved that the hardness of the materials increases with the increase in the magnesium content in the alloy and this increase has taken on almost linear characteristic. On the other hand the electrical conductivity has been decreasing as the Mg content increased. These results indicate that the obtained group of alloys is most likely characterized mainly by the location of alloy additives in a solid solution. Analysis of the material using scanning electron microscopy also revealed a number of precipitates rich in magnesium. The casted material subjected to the cold rolling process has not shown technological problems in the range of chemical compositions containing from 5% to 8% magnesium. Considering samples with the higher contents of said alloy addition, numerous defects such as cracks both longitudinal and cross-sectional have been observed mostly at the areas with high magnesium content. The tested materials have shown the tendency to solid solution and precipitation strengthening as well as strain hardening after cold rolling process which has been confirmed by the curves of changes in the average unit pressure and the strengthening curves represented by hardness and structural analysis using scanning electron microscope.

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