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PROPERTIES OF THE AZ31 MAGNESIUM ALLOY ROUND BARS OBTAINED IN DIFFERENT ROLLING PROCESSES

WŁASNOŚCI PRĘTÓW OKRĄGŁYCH ZE STOPU MAGNEZU AZ31 OTRZYMANYCH W RÓŻNYCH PROCESACH WALCOWANIA

Currently magnesium alloy bars are manufactured mainly in the extrusion process. This method has some drawbacks, which include: low process capacity, considerable energy demand, small length of finished products. Therefore it is purposeful to develop efficient methods for manufacturing of Mg alloy products in the form of bars, such methods include groove rolling and three-high skew rolling processes. Modified stretching passes provide change in material plastic flow, which contributes to the occurrence of the better distribution of stress and strain state than in the case of rolling in classical stretching passes. One of the modern method of Mg alloy bars production is rolling in a three-high skew rolling mill, which allows to set in a single pass a larger deformation compared to the rolling in the stretching passes.

The paper presents the results of experimental studies of the AZ31 round bars production in the modified stretching passes and in the three-high skew rolling mill. The study of microstructural changes, hardness and the static tensile tests were made for as-cast and ready-rolled bars in both analyzed technologies.

Keywords: three-high skew rolling mill, groove rolling, magnesium alloy, round bars, microstructure

Obecnie pręty ze stopów magnezu są wytwarzane głównie w procesie wyciskania. Metoda ta ma pewne wady, do których można m.in. zaliczyć: znaczne zapotrzebowanie na energię, ograniczona długość gotowych prętów. Dlatego celowe jest poszukiwanie bardziej wydajnych metod wytwarzania prętów ze stopów magnezu z zastosowaniem procesu walcowania w wykrojach oraz w trójwalcowych walcarkach skośnych. Zastosowanie układu wykrojów wydłużających o zmodyfikowanym kształcie wpływa na schemat plastycznego płynięcia metalu powodując bardziej równomierny rozkład odkształceń i naprężeń w porównaniu do walcowania w klasycznych układach wykrojów. Jedną z nowoczesnych metod wytwarzania prętów ze stopów Mg jest walcowanie w trójwalcowej walcarce skośnej, która umożliwia zadanie większych odkształceń w jednym przepuście w porównaniu do walcowania w wykrojach.

W artykule przedstawiono wyniki badań doświadczalnych procesu walcowania prętów ze stopu magnezu AZ31 w wykrojach modyfikowanych oraz w trójwalcowej walcarce skośnej. W ramach pracy wykonano badania mikrostrukturalne, pomiary twardości oraz statyczną próbę rozciągania dla materiału w stanie lanym oraz gotowych prętów odwalcowanych w obu technologiach.

1. Introduction

In recent years, an increase of application of magnesium alloys to structural components in aerospace and ground vehicles was observed due to its excellent properties such as low density, high strength and good stiffness. The structural components of magnesium alloy in majority are produced by casting method [1]. Casting process covered almost 90% of the total magnesium alloys production, the remaining 10% includes metal forming processes [2, 3].

Metal forming of magnesium alloys is complicated, due to the specific arrangement of atoms in crystallographic lattice that is the reason of low ductility caused by a limited number of slip planes allowed at room temperature. Magnesium belongs to the group of metals with hexagonal close packed structure (HCP) has c/a ratio close to the ideal value, and since there is insufficient amount of slip and twin systems to realize any plastic deformation at ambient temperature. Deformation is realized only by slip in the basal plane, which offers a limited number of deformation systems. Therefore, the deformation of Mg alloys are usually carried out in the temperature range of 250-400°C, where the number of operating deformation systems is higher than at ambient temperature that allows achieving desired properties in deformed material [4-6].

Currently, magnesium alloy bars of different diameters usually are manufactured in the extrusion process of cast ingots. This method has some drawbacks, which include: low process capacity, considerable energy demand, small length of finished products. However, the main drawback of this

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process is a limited capability to control process parameters, which directly influence the structure quality and mechanical properties of finished product. For these reasons, those bars after the extrusion process shall be subjected to heat treatment. Therefore it is purposeful to develop an economical and efficient technologies for manufacturing of Mg alloy products in form of bars. Such methods include groove rolling and three-high skew rolling processes, which allow the production of magnesium alloy bars of a considerable length [7, 8].

The objective of the paper was the analysis of the properties of AZ31 magnesium alloy bars with diameter 15 mm rolled in two methods: groove rolling in the modified stretching passes and three-high skew rolling mill. For the groove rolling process the shape of stretching passes were used as presented at work [9]. Modified shape of the stretching passes provides better handling bandwidth and ensures the uniform of the deformation on the cross-section of rolled bar compared to classically used grooves. The rolling in three-high skew rolling mill allows to obtain round bars in wide range of diameters. Round bars rolled in the three-high skew rolling mill are characterized by low ovality and high straightness. Figure 1 shows the equipment used to carrying out the rolling process: D150 two-high rolling mill, (Fig. 1a) and three-high skew rolling mill RSP 14/40, (Fig. 1b).

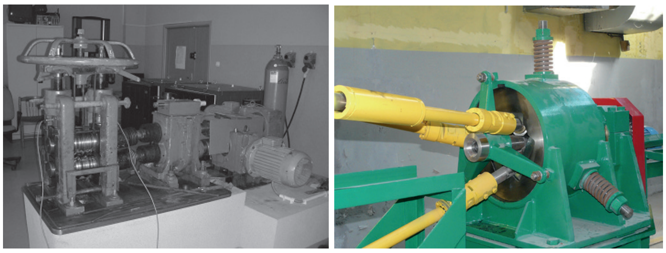

Fig. 1. The equipment used for the tests: a) D150 two-high rolling mill, b) three-high skew rolling mill RSP 14/40

The three-high skew rolling mill used for the rolling process of AZ31 magnesium bars is characterized by the roll axis inclination angle of 18°, while for conventional three-high skew rolling mills, which are used to the tubes and bars production, the maximum axis inclined angle is 16° [10]. It ensures better stability of the rolling process.

2. Materials

The stock material was AZ31 magnesium alloy widely used in various industry branches. Its chemical composition is given in Table 1 [11].

TABLE 1

Chemical composition of AZ31 magnesium alloy /%.

	Mg	Al	Zn	Mn	Si	Cu
AZ31	residual	2.5	1.0	0.12 - 0.14	0.08	0.03

In order to prepare the specimens for the rolling process from the cast slab of AZ31 magnesium alloy (Fig. 2a) the cylindrical specimens with diameter of 22.1 mm and a length of 250 mm (Fig. 2b) were made. The research performed earlier has shown that the material after casting process did not have any casting defects. Before heating the specimens were degreased and pre-sanding with an abrasive paper in order to increase friction between the metal and work rolls.

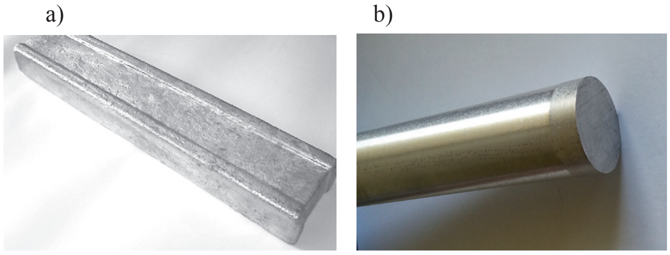

Fig. 2. AZ31 magnesium alloy: a) cast slab, b) cylindrical specimen to the rolling

3. The rolling processes

The appropriate modification of the shape of stretching passes (Fig. 3) allows larger deformations and elongations to be applied in the rolling process, compared to the case where classical stretching passes are used [12, 13]. As a result of modifying the shape of the passes, a change in the mode of material plastic flow takes place, that contributes to the occurrence of more uniform of stress and strain distribution on the cross-section of the band than in the case of rolling in classical stretching passes.

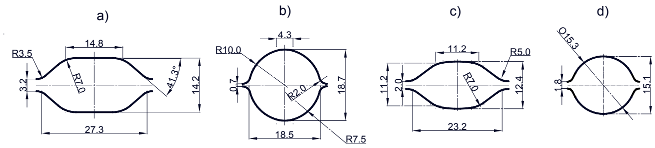

Fig. 3. Shape of grooves used during the rolling process: a) multi-radial horizontal oval, b) multi-radial vertical oval, c) multi-radial horizontal oval, d) round

The rolling process of AZ31 magnesium alloy round bars with diameter in 15 mm was carried out in four passes. The rolling speed was 0.1 m/s.

Based on the results of previous works which were carried out on three-high skew rolling mill [14, 15], round bars of AZ31 magnesium alloy with diameter of 15 mm was designed to carried out in two passes: from 22.1 mm to 18.1 mm (elongation coefficient - 1.47) and the second pass from 18.1 mm to 15.1 mm (elongation coefficient - 1.46). Developed scheme of deformation should provide stability of the rolling process, with regard to ensuring the proper length roll gap. For both passes a working rolls with diameter of 73 mm were used, the rotation speed of working rolls was 100 rpm.

Procedure of rolling AZ31 round bars for both rolling processes was similar. Prior to rolling, the stock was heated up to a temperature of 400°C in a chamber furnace, and rolled in the designed system of passes. After each rolling pass, templates were taken, and the remaining part of the band was heated up in the furnace to the initial temperature and rolled in the next pass. The templates were scanned and, using a CAD

TABLE 2

Parameters of experiential rolling process of AZ31 round bars

No. of pass	Groove rolling process				Three-high skew rolling			
	Dimensions [mm]		Cross-section area [mm^2]	Elongation	Dimensions [mm]		Cross-section area [mm^2]	Elongation
	height	width			height	width		
-	22.1	22.1	383.4	-	22.1	22.1	383.4	-
1	14.2	25.9	312.3	1.23	18.2	18.2	261.5	1.47
2	18.7	18.3	254.6	1.23	15.1	15.1	178.4	1.46
3	12.4	22.2	209.5	1.22				
4	15.2	15.0	179.8	1.16				

computer program, geometry measurements were made and the band cross-sectional areas were determined.

Figure 4 presents AZ31 round bars rolled in both rolling processes. As it can be noticed in Fig. 4 on the surface of the AZ31 round bars rolled in three-high skew rolling mill can be observed characteristic "thread" lines, which correspond to the twisting the band during the rolling in roll gap.

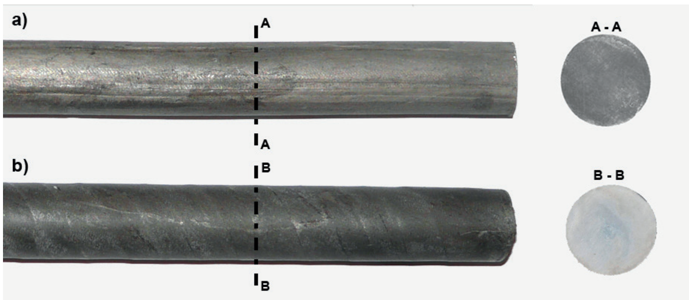

Fig. 4. Shape of the AZ31 magnesium alloy bars: a) modifed streatching passes, b) three-high skew rolling mill

As it can be noticed, Fig. 4 and in the Table 2, AZ31 magnesium alloy round bars rolled in the three-high skew rolling mill are more straight and have lower ovality on the cross-section in compassion to round bars rolled in modified stretching passes. However, both straightness as well as ovality of rolled bars in blanks can be improved either by adjusting the blanks and the use of rolling equipment, in which does not were in the used D150 two-high rolling mill. The use of the three-high skew rolling mill to round bars rolling process allowed to reduce the number of passes required to made finished product by half.

4. Microstructure, microhardness and tensile tests

The structural examinations of the cast billet and the finished bars were carried out within the study. Specimens for observations with an optical microscope were etched in a reagent with the following composition: 10 ml $C_2H_4O_2$, 6g $C_6H_3N3O_7$ and 100 ml C_2H_5OH. The specimens were taken from cross section and longitudinal section of the rolled bars. As the rolling process may lead to the formation of an inhomogeneous structure on the finished product, the analysis of the microstructure of finished bars was made in the central and in the edge zone of rolled bars. The microstructure of the stock, i.e. the AZ31 alloy in an as-cast condition, is shown in Figure 5. Analyzing the structure of the alloy material it can be found that the structure is heterogeneous. There can be found a large grains with extensive substructure within the grains boundary (Figs. 5c and 5d). There can be observed a substructure inside analysed large grain which can be caused by not full dynamic recystalisation during the bars rolling process.

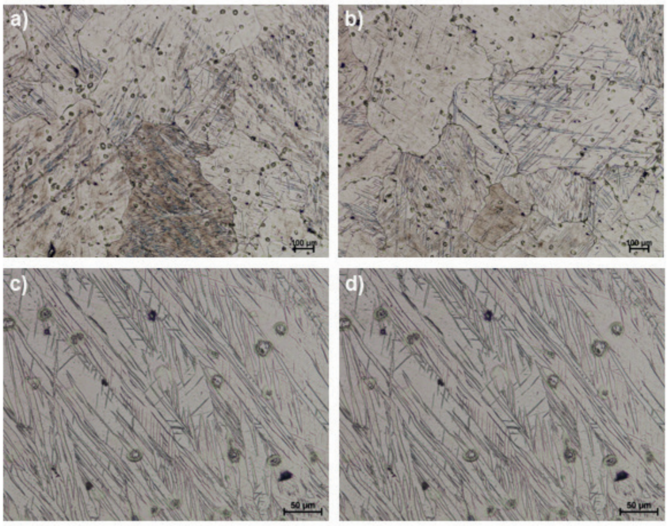

Fig. 5. Microstructure of AZ31 magnesium alloy cast billet used for rolling: a) cross section - central zone at magnification 50x, b) cross section - subsurface zone at magnification 50x, c) longitudinal section - central zone at magnification 200x, d) longitudinal - subsurface zone at magnification 200x

In Figure 6 is shown the microstructure of the round bars rolled in modiffied streaching passes. Rolling in the modified passes according to the assumed scheme of deformation allowed to decrease grain size in all the observed cross and longitudinal section. In the microstructure of all examined areas, fine recrystallized grains surrounded by larger grains were observed. Analyzing the microstructure of the material after the rolling process can be seen fragmented areas of grain (average size is approximately 5 μm), but also appears areas not deformed as much (grain size is about 50 μm). As it can be noticed for both logitudinal and cross directions (Fig. 6), shape and size of grains in rolled bars are similar. For applied scheme of rolling in modified grooves the rolling process allowed, to observe heterogeneous fragmentation of structure.

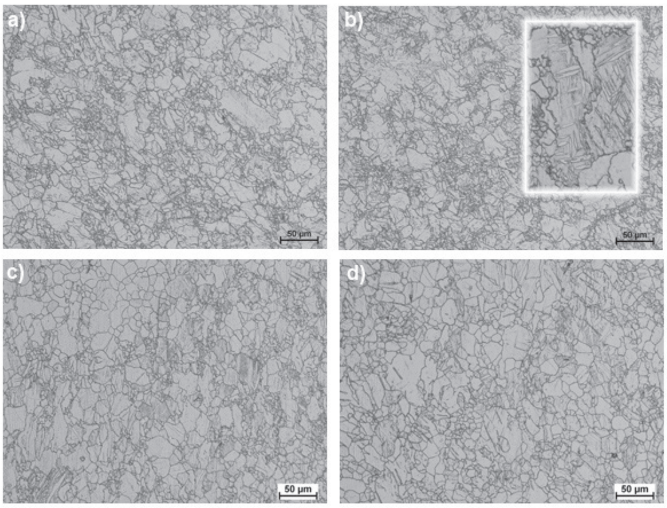

Fig. 6. Microstructure of AZ31 magnesium alloy round bars after rolling in modified grooves at magnification 200x: a) cross section - central zone, b) cross section - subsurface zone, c) longitudinal section - central zone, d) longitudinal - subsurface zone.

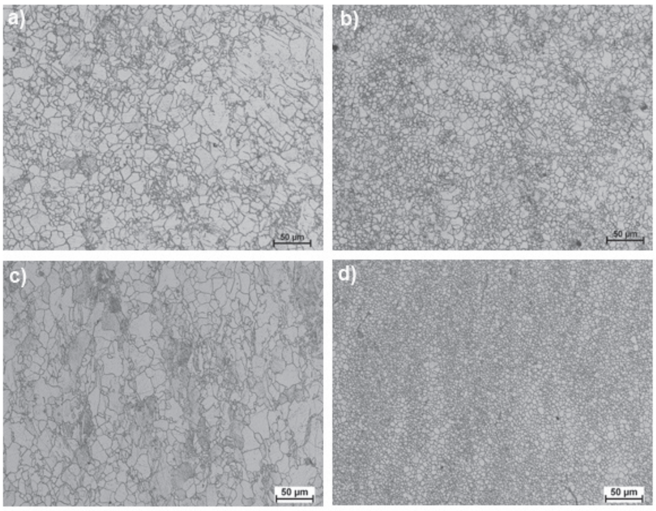

Fig. 7. Microstructure of AZ31 alloy round bars after the rolling in the three-high skew rolling mill at magnification 200x: a) cross section - central zone, b) cross section - subsurface zone, c) longitudinal section - central zone, d) longitudinal - subsurface zone

In Figure 7 is shown the microstructure of the round bars rolled in the three-high skew rolling mill. After the rolling process it can be seen that a greater refinement of the structure takes place in the subsurface zone for both directions of the rolled bar (Figs. 7b and 7d). The average grain size after the rolling is about 4.5 µm. The refinement of the structure can be seen particularly in longitudinal section (Fig. 7d). Grain visible in the core of the bar are much larger, than the subsurface zone (Fig. 7c). Grains observed in the longitudinal section in the central zone are slightly elongated in comparison to grains in the subsurface zone. Determined average grain size in central zone is about 10 µm. In Fig. 6b is shown a magnification of the characteristic grain structure observed in the cross-section of AZ31 bars rolled in the modified streaching passes.

Also hardness measurements for all analyzed cases were made. The microhardness of the as-cast AZ31 magnesium alloy was µHV0.1 = 55. For both variants of rolled round bars measurements were made on the cross and longitudinal sections (Table 3).

Analyzing the data presented in Table 3 can be seen an anisotropy of microhardness determined for bars rolled in the three-high skew rolling mill for both directions. Decreasing the grain size and microhardness distribution are closely related to the distribution of strain intensity during the rolling process. As shown in the work [14] during the rolling in the three-high skew rolling mill distribution of strain intensity on the cross and longitudinal sections is a centric where the highest strain intensity values are observed within the external material zone, and the lowest are located in the central zone. The difference observed in microhardness between cross and longitudinal sections of the AZ31 bars rolled in modified stretching passes, may be the result of the characteristic magnesium structure observed in Fig. 6b. The substructure that forms inside the grains causes increase of the microhardness on the cross section.

The last stage of the research was static tensile test made on the testing machine Zwick Z/100, for specimens that were taken from rolling feedstock and bars after both rolling processes. The differences of microstructure and microhardness was verified by static tensile tests which were made for finished bars rolled in both processes. Figure 8 shows the average results obtained in the static tensile test. Table 4 presents the determined value of the yield strength - **YS**, ultimate tensile strength - **UTS** and ductility factor **YS/UTS**.

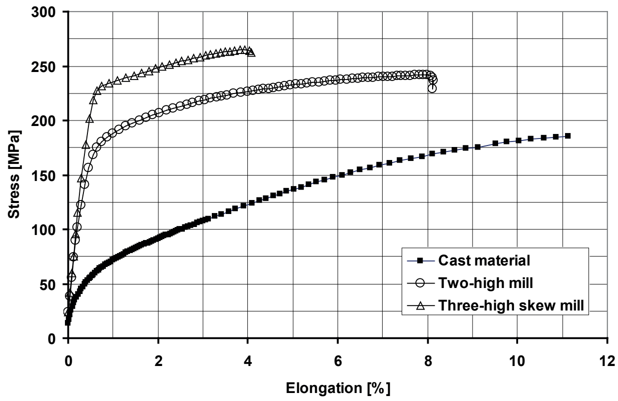

Fig. 8. Results of tensile tests

TABLE 3

Microhardness of AZ31 round bars

	Microhardness µHV$_{0.1}$			
	Groove rolling process		**Three-high skew rolling mill**	
	Axis zone	Surface zone	Axis zone	Surface zone
Cross section	87.2	86.9	58.0	65.6
Longitudinal section	62.5	62.3	55.6	63.4

Based on the data presented in Fig. 8 and in Table 4 for both cases of rolling values of ultimate tensile strength increase and plasticity range decrease comparing to as-cast material. Moreover AZ31 round bars rolled in the three-high skew rolling mill are characterized by greater value of ultimate tensile strength in comparison to bars rolled in stretching passes. However, round bars rolled in stretching passes were characterized by better ductility than bars rolled in three-high skew rolling mill (Fig. 8). The difference in ductility factor - YS/UTS values for both rolled bars may be the result of different grain size and microhardness values in round bars rolled in three-high skew rolling mill. For the round bars rolled in modified stretching passes grain size and microhardnes are more uniform, which should result in improving yield strength of the final product.

TABLE 4

Parameters determined in static tensile tests for AZ31 alloy round bars

	YS [MPa]	UTS [MPa]	YS/UTS
Cast material	**107.6**	**166.8**	**0.64**
AZ31 bar rolled in modified passes	169.9	239.4	0.71
AZ31 bar rolled in three-high skew rolling mill	229.2	263.5	0.87

5. Summary

From the investigation carried out it can be found that:

- both presented in this work methods of rolling round bars from AZ31 magnesium alloy allow to obtain a finished product that provide established dimensional tolerances;
- rolling on the three-high skew rolling mill allows to realize the process with higher elongation in a single pass;
- AZ31 round bars rolled in three-high skew rolling mill have smaller ovality and are more straight compared to round bars rolled in modified stretching passes;
- round bars rolled in the three-high skew rolling mill are characterized by anisotropy of properties that comes from the different grain size in both the cross and longitudinal directions, which is also reflected in not uniform distribution of microhardness;
- after rolling for both cases the value of ultimate tensile strength increase and plasticity range decrease comparing to as-cast material;
- bars rolled in three-high skew rolling mill are characterized by greater value of ultimate tensile strength in comparison to bars rolled in stretching passes;
- AZ31 round bars rolled in stretching passes were characterized by better ductility than bars rolled in three-high skew rolling mill.

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