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THE INFLUENCE OF EXTRUSION PROCESS PARAMETERS AND HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF HIGH-STRENGHT MAGNESIUM ALLOY

WPŁYW PARAMETRÓW PROCESU WYCISKANIA I OBRÓBKI CIEPLNEJ NA WŁAŚCIWOŚCI MECHANICZNE WYSOKOWYTRZYMAŁYCH STOPÓW MAGNEZU

The article consists test results of direct extrusion AZ80A & ZK60A magnesium alloys. Extrusion process was conducted in the temperature range 350°C-450°C at different extrusion speeds (ram speed 0.8 mm/s and 2.8 mm/s). In order to find optimum precipitation strengthening parameters the aging curves have been made. Extruded rods were characterized by mechanical properties in different tempers. Basic structure researches of magnesium alloys have been made.
Keywords: magnesium alloys, direct extrusion, mechanical properties, magnesium alloys structure

Przedstawiono wyniki badań stopów magnezu AZ80A i ZK60A w procesie współbieżnego wyciskania. Proces wyciskania prowadzono w zakresie temperatur 350°C-450°C przy różnych prędkościach wyciskania (prędkość tłoka 0,8mm/s i 2,8mm/s). W celu doboru odpowiedniego czasu starzenia wykonano krzywe umocnienia wydzieleniowego. Otrzymane pręty wyciskane scharakteryzowano pod kątem właściwości mechaniczne w różnych stanach umocnienia wydzieleniowego. Przeprowadzono podstawowe badania struktury stopów magnezu.

1. Introduction

In recent years, the world has witnessed an enormous increase in the demand for magnesium alloys. The main customers for these alloys are the automotive and electronic industries. Magnesium as an element characterised by very low density of 1.74 g/cm^3 is the lightest metal used for construction purposes. However, due to low mechanical properties of pure magnesium, common use is limited only to its alloys (cast and wrought), which due to their density (1.8 g/cm^3), very high specific strength (strength-to-specific density ratio), and good conductivity enjoy growing popularity. Good weldability and machinability of magnesium alloys makes them constantly gaining in popularity, given the ability to create lightweight, high rigidity structures.

Today, most of parts manufactured from magnesium alloys, especially in Poland, are produced by casting methods, i.e. by gravity casting into metal and sand moulds, and by pressure diecasting. Magnesium alloys are processed by plastic forming mainly at elevated temperatures [1,2,3]. This is due to the crystalline structure of magnesium, which on crystallisation forms a hexagonal arrangement. During high temperature deformation of metals, processes such as consolidation, dynamic recovery and dynamic recrystallisation occur. These processes are occurring simultaneously in the deformed metal. Magnesium alloys have low energy of the stacking fault, and therefore dynamic recrystallisation is the leading process in high temperature plastic forming [4]. It removes the effects of deformation hardening, increases ductility and reduces the flow resistance. In general, magnesium alloys processed by plastic working are characterised by significantly higher properties compared to those obtained by casting processes [10]. This results from the fact that wrought materials have more refined grains.

Nevertheless, the mechanical properties of magnesium alloys are lower than the properties of numerous aluminium alloys. Therefore it is recommended to subject to plastic forming those alloys which are expected to offer very high strength. The process most appropriate seems to be extrusion which, owing to the state of compressive stress, provides the best conditions for plastic forming.

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Currently the most popular magnesium alloys are alloys of aluminium, zinc and manganese [4,5]. Aluminium is beneficial as regards an improvement of the tensile strength and hardness. Zinc in magnesium alloys is used to improve the alloy strength at room temperature, while manganese increases the resistance to corrosion. From the phase equilibrium diagram of Mg-Al alloys follows a variable and increasing solubility of aluminium in magnesium up to a maximum content of 12.7% in the solid state to the eutectic temperature of 437°C. Therefore, these alloys are subjected to heat treatment to improve the mechanical properties by precipitation hardening (T5 and T6 condition) [6,7,8].

Magnesium alloys with manganese (MgMn) are not precipitation hardened. Manganese improves the corrosion resistance of alloys [8,9]. The precipitation-hardened MgZn alloys are classified as alloys of the highest strength (~350-400MPa). Figure 1 shows the example of a diagram illustrating the possibility of obtaining the required mechanical properties depending on the manufacturing method and condition after heat treatment.

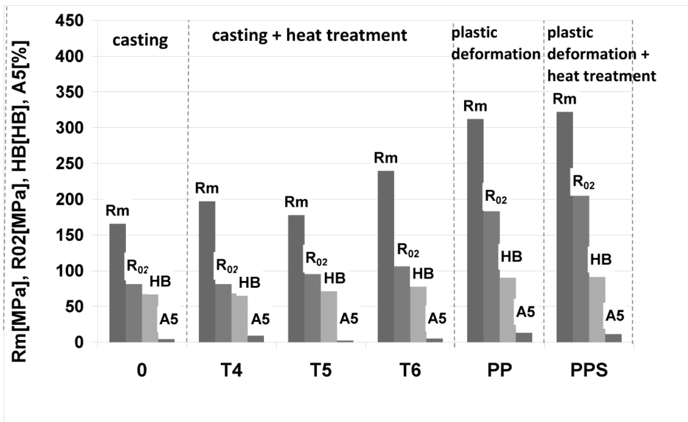

Fig. 1. Graphical representation of the mechanical properties of AZ91 alloy, depending on the process of manufacture [8]

To get the best economic results combined with the highest mechanical properties, a heat treatment (solution heat treatment) should be applied to products just upon their leaving the press ("online solution"). If alloys are subjected to aging, a precipitation-hardened product will be obtained (conditions T1, T5). It should be noted that it is the extrusion temperature that has a significant impact on the speed of recovery and recrystallisation, and on the degree of supersaturation. Therefore it is important to determine what effect the extrusion process parameters and heat treatment will have on the mechanical properties of magnesium alloys.

2. Test methods and materials

Studies of the direct extrusion process were conducted on MgAlZn (AZ80A) and MgZnZr (ZK60A) magnesium alloys belonging to the group of alloys characterized by the highest strength. The base materials were purchased from Magnesium Elektron in Manchester in the form of 100mm and 130mm diameter semi-continuously cast ingots. The chemical compositions of these alloys were presented in Table 1. Tests of direct extrusion were carried out on a laboratory stand equipped with a press of max. 0,6MN capacity using specially designed and constructed equipment. The equipment includes a container of 30mm diameter and a φ 8mm die [9]. For research purposes, from ingots of 100mm and 130mm diameters, rollers of 29mm diameter were cut out, which were later preheated to a predetermined temperature and extruded in the form of φ 8 mm rods. Due to the application of relatively high, as for magnesium alloys, preheating temperatures, rods were protected with chromate coating to minimise oxidation.

The extruded rods were subjected to multi-variant heat treatment, first, and examined for mechanical properties and structure, next.

TABLE 1

The chemical composition of ZK60A and AZ80A magnesium alloys

Alloy	Zn	Al	Si	Cu	Zr	Mn	Fe	Ni	Others	Mg
MgAlZn (AZ80A)	0,28	8,1	0,02	0,003	—	0,18	0,002	0,004	<0,30	Rest
MgZnZr (ZK60A)	5,1	—	—	—	0,56	—	—	—-	<0,30	Rest

3. Results and discussion

3.1. Extrusion process

Magnesium alloys (AZ80A and ZK60A) were extruded in direct process with extrusion ratio λ = 14, using two ram speeds, i.e. 0.8 mm/s and 2.8 mm/s. The materials were preheated from 350°C to 450°C. As a criterion in an assessment of the extruded rod quality, the surface condition was adopted, i.e. the occurrence of hot cracks, and the macro- and microstructure. The extrusion process parameters, i.e. the stock temperature, the ram speed, and the recorded maximum extrusion force with comments on the selected variant, are shown in Table 2. Figure 2 shows the example of a rod extruded from ZK60A alloy under properly selected process parameters, compared with a rod extruded from AZ80A alloy. The extrusion at mis-selected temperature and ram speed (both were too high) resulted in overheating of the material and hot-cracking.

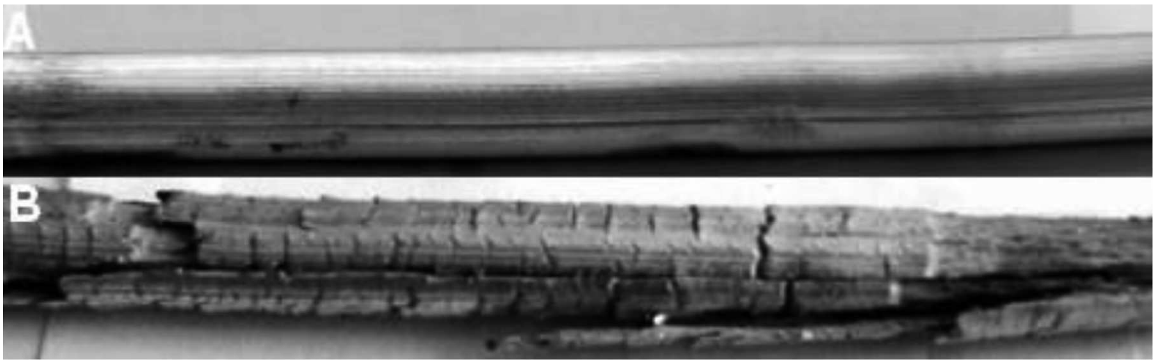

Fig. 2. Examples of extruded rods: A – ZK60A alloy (extrusion temperature 450°C, V_T = 0.8 mm/s), B – AZ80A alloy (extrusion temperature 450°C, V_T =2.8 mm/s

TABLE 2

The extrusion process parameters selected for magnesium alloys

Alloy	Billet temperature [°C]	Max. extrusion force [MN]	Results
Ram speed: V_T = 0,8 mm/s, Extrusion speed: V_W = 0,7 m/min			
AZ80A	350	0,20	+
	380	0,23	+
	420	0,16	+
	450	0,12	+
ZK60A	350	0,18	+
	380	0,17	+
	420	0,10	+
	450	0,10	+
Ram speed: V_T = 2,8 mm/s, Extrusion speed: V_W = 2,4 m/min			
AZ80A	350	0,35	+
	380	0,31	+
	420	0,28	cracking
	450	0,30	cracking
ZK60A	350	0,33	+
	380	0,32	+
	420	0,28	+
	450	0,27	cracking

Figures 3 and 4 show the examples of macrostructure and microstructure of rods extruded under the properly selected direct extrusion process parameters (from Table 2): billet temperature 450°C with the ram speed of 0.8 mm/s.

In some cases, the surface quality inspection indicated that the extrusion process parameters were correct. Only later, detailed structure examinations revealed the presence of internal hot cracks. Examples of macro- and microstructure in the extruded rod with internal hot cracks and almost invisible hot tears on the surface are shown in Figures 5 and 6.

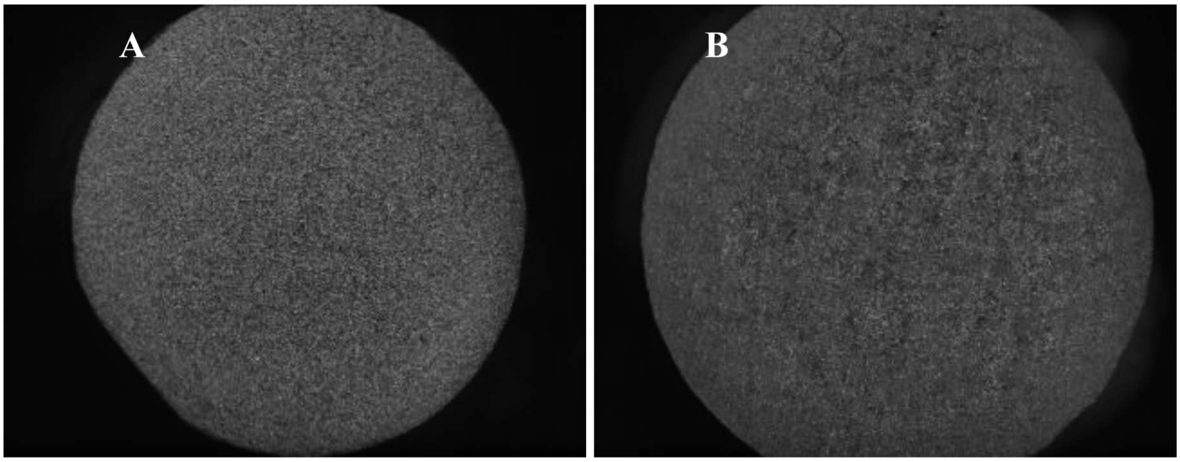

Fig. 3. Example of macrostructure in rods extruded at 450°C with the ram speed of 0.8 mm/s. A – ZK60A alloy, B – AZ80A alloy

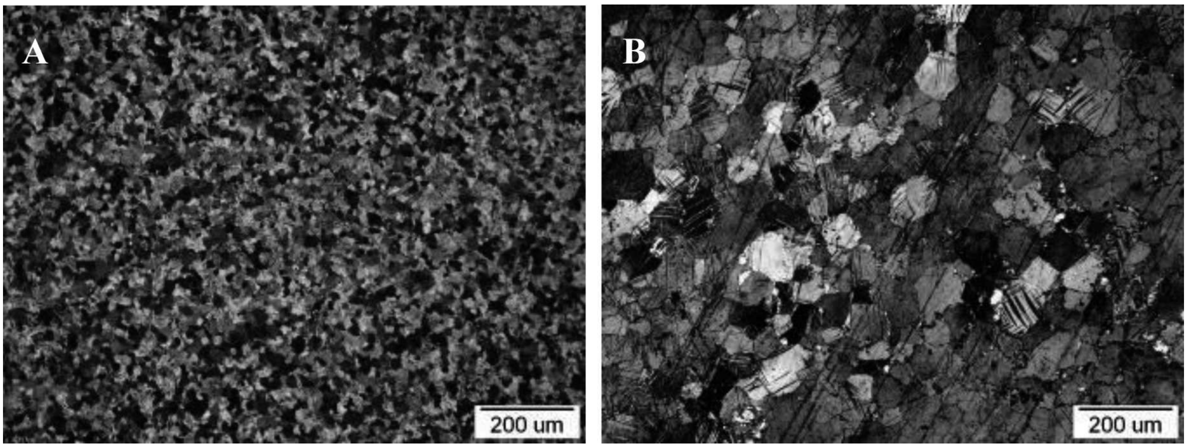

Fig. 4. Example of microstructure in rods extruded at 450°C with the ram speed of 0.8 mm/s. A – ZK60A alloy, B – AZ80A alloy

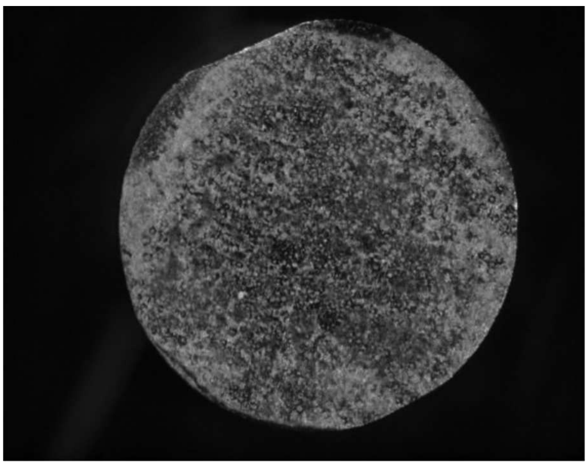

Fig. 5. Example of macrostructure in rod extruded at 420°C with the ram speed of 2.8 mm/s showing visible internal cracks, AZ80A alloy

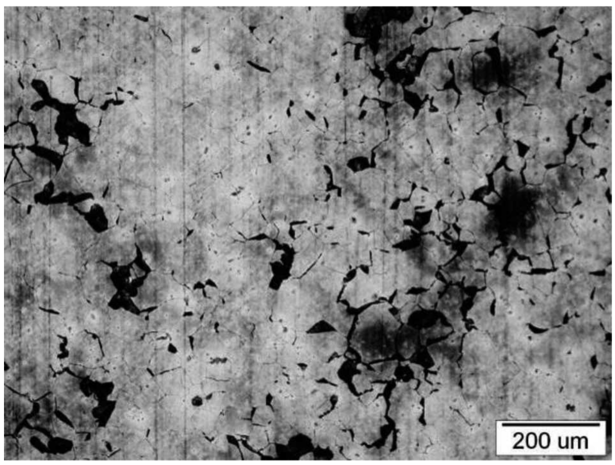

Fig. 6. Example of microstructure in rod extruded at 420°C with the ram speed of 2.8 mm/s, showing internal discontinuities, AZ80A alloy

The extrusion tests have showed that for both alloys it is possible to use the temperature of the extruded material ranging from 350°C to 450°C when the process is run with an extrusion ratio of λ = 14 at the ram speed of 0.8 mm/s corresponding to the extrusion speed (rod speed leaving the die) of 0.7 m/min.

Higher temperature of extrusion is beneficial as it enables reducing the process power and is essential for the rod solutioning heat treatment in an "on-line" system, i.e. on the press handling equipment (the treatment to T5 temper). For higher ram speed of 2.8 mm/s, which corresponds to the extrusion speed (rod speed leaving the die) of 2.4 m/min, in AZ80A alloy at a temperature of 420°C, cracks began to show in the surface, while at a temperature of 450°C, the rod was breaking. For the same speed, the ZK60A alloy rod was also breaking at 450°C. It is thus important for the AZ80A alloy to preheat the material to a temperature not exceeding 380-400°C and 400-420°C for the ZK60A alloy. Such temperatures, however, cannot provide optimum parameters for the "on-line" solutioning heat treatment process carried out on the press handling equipment. Therefore, in further research, the rods were extruded from both alloys preheated previously to 450°C and applying the ram speed Vt=0.8 mm/s.

3.2. Heat treatment

Magnesium alloys are usually heat treated to conditions T6 (solution heat treatment and artificial aging) and T5 (solution heat treatment from the temperature of plastic forming and artificial aging), the latter one being used more widely and yielding higher mechanical properties. Due to insufficient information in literature on the parameters of solution heat treatment and aging, a series of studies was carried out to select the best time-and-temperature regime. For condition T6, the following parameters were adopted from the literature: solution heat treatment temperature of 460°C for both magnesium alloys and aging temperature of 175°C [5,8,14].

To determine the optimum aging time, the precipitation hardening curves were plotted for both alloys for the variant of solutioning heat treatment in a furnace and from the temperature of plastic forming (rods were extruded into water). The resulting curves are shown in Figures 7 and 8.

From the plotted hardening curves it follows that hardness of the ZK60A alloy gets its maximum value with the aging time of 12 hours and then decreases for both variants of the solution heat treatment. On the other hand, AZ80A alloy subjected to the heat treatment variant for condition T6, i.e. with additional heating in the solution heat treatment furnace obtains its maximum hardness after 8 hours of artificial aging at 175°C, and only then the hardness decreases. This may be due to the excessively high temperature of aging that has been adopted for this alloy because different literature sources give different reference data. In the case of solution heat treatment from the temperature of plastic forming, the AZ80A alloy reaches its maximum hardness after a time similar to ZK60A alloy, i.e. after 12 hours. Both alloys get hardness higher in the case of heat treatment to condition T5.

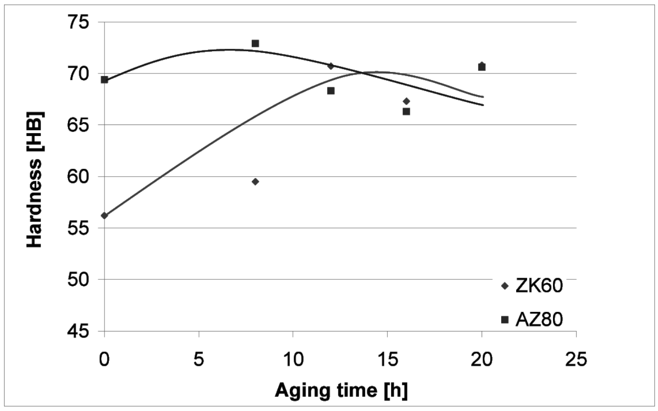

Fig. 7. The hardening curve plotted for ZK60A and AZ80A alloys after solution heat treatment in furnace (condition T6)

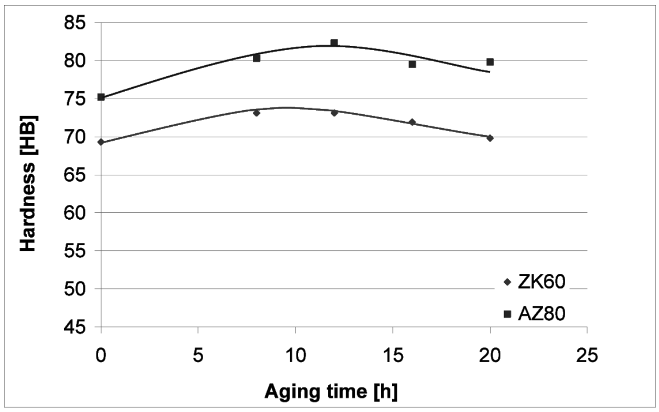

Fig. 8. The hardening curve plotted for ZK60A and AZ80A alloys after solution heat treatment in furnace (condition T6)

3.3. Mechanical properties

The mechanical properties of the investigated alloys were determined in a static tensile test (sizes of samples: diameter 8mm, base longht 50mm). Rods extruded from magnesium alloys AZ80A and ZK60A were heat treated applying parameters described and selected under Section 3.2. Tables 3 and 4 contain the results of mechanical testing of alloys extruded at the maximum possible temperature, i.e. at 450°C (V_T =0.8mm/s), and brought to different conditions after heat treatment.

TABLE 3
Mechanical properties from the tensile test for ZK60A alloy

No.	Temper	$R_{P0,2}$ [MPa]	R_m [MPa]	A [%]
1	extruded	250	321	16,4
2	T6	262	312	11,6
3	T1	258	329	15,9
4	T5	293	341	18,6

TABLE 4
Mechanical properties from the tensile test for AZ80A alloy

No.	Temper	$R_{P0,2}$ [MPa]	R_m [MPa]	A [%]
1	extruded	237	312	10,4
2	T6	216	302	8,9
3	T1	210	329	13,4
4	T5	275	343	8,9

According to the assumptions adopted and previous results of the hardness tests, both magnesium alloys obtained in the T5 temper higher mechanical properties. The obtained values are largely due to the grain growth after re-heating in furnace, which results in deterioration of the mechanical properties. Differences in grain size for the examined cases of ZK60A alloy are shown in Figures 9 and 10, while for the AZ80A alloy they are shown in Figures 11 and 12.

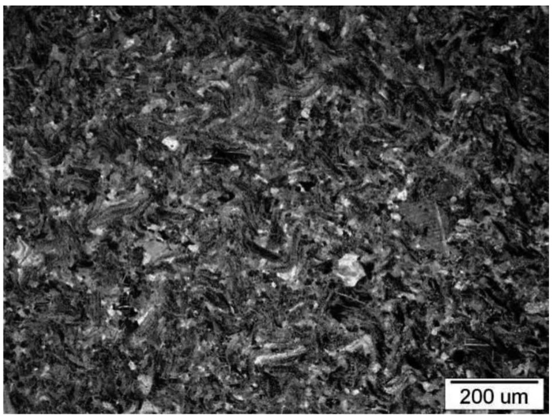

Fig. 9. Grain size in the rod extruded from ZK60A alloy at 450°C, the ram speed of 0.8 mm/s, solution heat treatment from the extrusion process temperature, condition T5

According to literature data, the heat treatment of magnesium alloys should start at a lower temperature of 250°C-300°C, gradually increased next to the point of solution. The time required to preheat the material from the initial temperature to the required temperature of the heat treatment depends on the chemical composition of this material, and on the size, weight and thickness of the product. For some magnesium alloys it is very important to ensure the shortest possible "jumping" from the initial temperature to the required temperature of the heat treatment, mainly to avoid the formation of "coarse" grains [11,12,15,16,17]. Studies on the heat treatment of magnesium alloys will continue under the project within which the above described tests have been carried out.

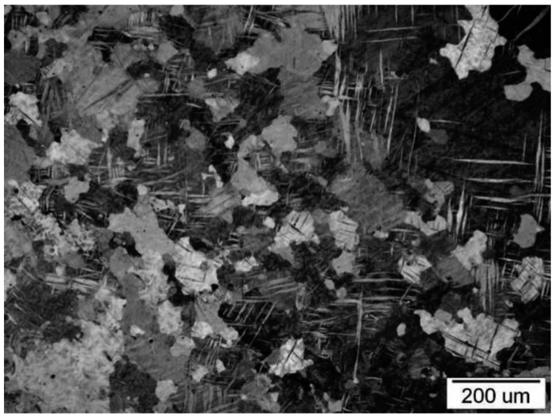

Fig. 10. Grain size in the rod extruded from ZK60A alloy at 450°C, the ram speed of 0.8 mm/s, additional preheating in furnace and solution heat treatment, condition T6

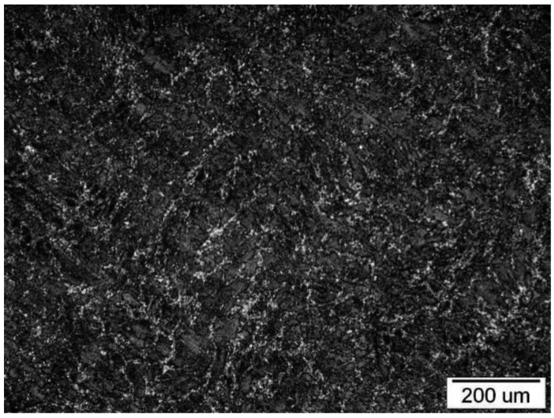

Fig. 11. Grain size in the rod extruded from AZ80A alloy at 450°C, the ram speed of 0.8 mm/s, solution heat treatment from the extrusion process temperature, condition T5

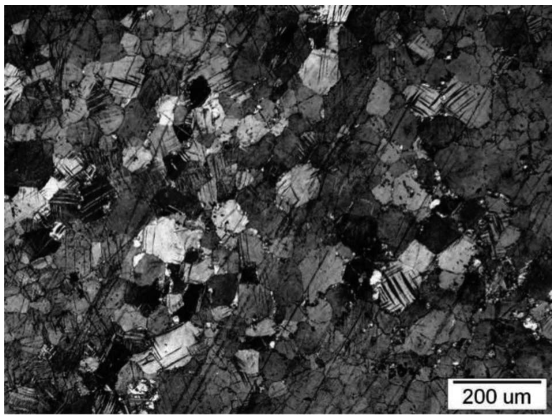

Fig. 12. Grain size in the rod extruded from AZ80A alloy at 450°C, the ram speed of 0.8 mm/s, additional preheating in furnace and solution heat treatment, condition T6

4. Summary

1. With the extrusion ratio $\lambda = 14$ and the ram speed equal to 0.8 mm/s, the AZ80A and ZK60A alloys can be extruded at temperatures in the range of 350°C-450°C, while with the ram speed of 2.8 mm/s, the temperature should be kept at 380°C and at 400°C for AZ80A alloy and ZK60A alloy, respectively.
2. Due to a lower extrusion force and the solution heat treatment immediately after extrusion, resulting in fine-grained structure and higher mechanical properties, the process of direct extrusion should be carried out at a maximum allowable temperature.
3. In the case of the solution heat treatment of rods extruded at 460°C or from a sufficiently high temperature of the plastic forming (for the extrusion process it is above 420°C), for both alloys the aging process at 175°C should be carried out within the time limit of up to 12 hours, possibly in the case of AZ80A alloy (condition T6) for 8 hours only.
4. Magnesium alloys AZ80A and ZK60A in condition T5 are characterised by higher mechanical properties than in the condition T6, i.e. after re-heating and solution heat treatment in the furnace.
5. The, developed and tested in laboratory, parameters of the direct extrusion process of magnesium alloys will serve as a basis for tests and development of parameters for the pilot-scale studies. Semi-industrial tests will be carried out on a direct-indirect press of maximum 5MN capacity installed and operating at IMN OML Skawina.

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