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DIE FORGING OF HIGH-STRENGTH MAGNESIUM ALLOYS – THE STRUCTURE AND MECHANICAL PROPERTIES IN DIFFERENT HEAT TREATMENT CONDITIONS

KUCIE MATRYCOWE WYSOKOWYTRZYMAŁYCH STOPÓW Mg – STRUKTURA I WŁAŚCIWOŚCI MECHANICZNE W RÓŻNYCH STANACH OBRÓBKI CIEPLNEJ

The object of this study was to develop parameter of the die forging process, such as feedstock temperature and to investigate her impact on the structure and mechanical properties of magnesium alloys in different heat treatment conditions. Tests were carried out on a 2,5MN maximum capacity vertical hydraulic press using forgings of sample (model) shapes. Then, based on the results obtained in previous work, research was carried out to develop for items forged from magnesium alloys the parameters of heat treatment to the T5 and T6 condition in the context of achieving possibly homogeneous and fine-grained structure and, consequently, high mechanical properties.
Keywords: magnesium alloys, die forging, mechanical properties, structure

Przedmiotem prezentowanej pracy było opracowanie parametru procesu kucia matrycowego takiego jak temperatura wsadu i jej wpływu na strukturę oraz właściwości mechaniczne stopów magnezu w różnych stanach obróbki cieplnej. Badania kucia matrycowego prowadzone były na hydraulicznej prasie pionowej o sile max. 2,5MN dla przykładowych (modelowych) kształtów odkuwek. Następnie korzystając z wyników uzyskanych w poprzednich pracach, prowadzono badania nad opracowaniem parametrów obróbki cieplnej wyrobów kutych ze stopów Mg w stanach T5 oraz T6 w kontekście uzyskania możliwie jednorodnej i drobnoziarnistej struktury a w konsekwencji czego wysokich właściwości mechanicznych.

1. Introduction

The use of wrought magnesium alloys in Poland is at present limited, but increasing number of applications for these alloys in automotive industry, aerospace and electronics is to be expected in the nearest future. Currently, most of the components made from magnesium alloys, especially in Poland, are manufactured by the casting methods, i.e. by gravity casting into metal and sand moulds, and in the pressure die casting process. By standard plastic forming, the alloys of magnesium are processed mainly at elevated temperatures. The reason is the crystalline structure of magnesium, which crystallises in a hexagonal configuration. During high-temperature deformation of metals, processes such as hardening, dynamic recovery and dynamic recrystallisation take place [1,2]. These processes are running parallel to each other in the metal subjected to deformation. Magnesium alloys have a low stacking fault energy, owing to which the dynamic recrystallisation is the leading process in the course of high temperature plastic forming. It removes the consequences of work hardening, increases ductility and reduces flow resistance [3]. Magnesium alloys can cause many problems during plastic forming, and the reason is mainly the narrow range of temperature and limited deformation rate suitable for shaping of the products [4-8]. This is particularly true in the die forging process, where the triaxial state of stress present in the process of extrusion and much more favourable for the deformed material, is available no longer [4, 9]. In this process, uniaxial or biaxial tensile stresses are often present which, combined with radial flow of material, contribute to the loss of coherence and consequently to cracking. For magnesium alloys it is essential to choose the right temperature of the die forging process and interrelate it very closely with the deformation rate. Therefore, for magnesium alloys it is preferable to use hydraulic presses for the die forging, because then the deformation rate can be controlled with adequate accuracy.

In recent years, at the Light Metals Division in Skawina of the Institute of Non-Ferrous Metals in Gliwice (IMN OML), studies have been intensified on various technologies of the plastic working of a wide range of light metals [10]. As part of the programme of research it has been planned to develop the processes of direct and indirect extrusion, die forging, multiple plastic deformation, and other methods of the plastic forming of magnesium and magnesium alloys. Interest in such products in the world is increasing, while in Poland production of this type is completely undeveloped.

The object of the present study was to check the applicability of rods extruded on a press according to the parameters

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developed by IMN OML Skawina in further plastic forming and develop parameters of the die forging process of magnesium alloys, such as feedstock temperature and temperature of the forging tools [11]. Tests were carried out on a 2.5 MN maximum capacity vertical hydraulic press using forgings of sample (model) shapes. Then, based on the results obtained in previous work, an attempt was made to develop for items forged from magnesium alloys the parameters of heat treatment to the T5 and T6 condition in the context of achieving possibly homogeneous and fine-grained structure and, consequently, high mechanical properties.

2. Test material and methodology

Tests of die forging were conducted on Ø26mm and Ø35mm diameter rods extruded in direct process on a 5MN horizontal press available at the IMN OML Skawina. Alloys used in the tests were MgAlZn (AZ80A) and MgZnZr (ZK60A). Chemical compositions of these alloys are shown in Table 1.

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

Tests of die forging were carried out on a 2.5 MN vertical hydraulic press using a specially designed set of tools with replaceable shaping inserts (Figs.1-4). Material forged in dies to the shape of model connecting rods, making also a flat model forging to be used in preparation of samples for the static tensile test. The studies were of a physical modelling type to develop initial parameters of the die forging process, and this is why in forging, model dies were used without making forging preforms and without thorough analysis of the material flow behaviour. The photographs below show sample magnesium alloy forgings after the removal of flash (Figs. 3 and 4). In each case, to reduce friction and minimise sticking of forgings to the die, the die surfaces were lubricated with graphite. The feedstock was preheated to a temperature in the range of 350°C to 400°C, on the other hand, the tools were preheated to approximately 250°C. At temperatures kept in a lower range, failure of the material to fill the die cavity properly was sometimes observed (for example see Figs. 3 and 5). The maximum temperature of the plastic forming of the examined alloys was established at a level of 400°C, based on the results obtained in previous studies [11]. In test forging, the press ram speed in the range of 8 to 16 mm/s was applied. When the upper temperature range of the material and higher press ram speeds were applied, cracks were observed to appear in forgings (mainly for the AZ80A alloy). Therefore, in all cases, the press ram speed was limited to the value of 8mm/s. Further in this article, the results were presented only for the extreme cases of temperatures of the material before forging, i.e. 350°C and 400°C.

The resulting forgings were subjected to multi-variant heat treatment and were used for testing of the mechanical properties and structure examinations by optical microscopy and SEM.

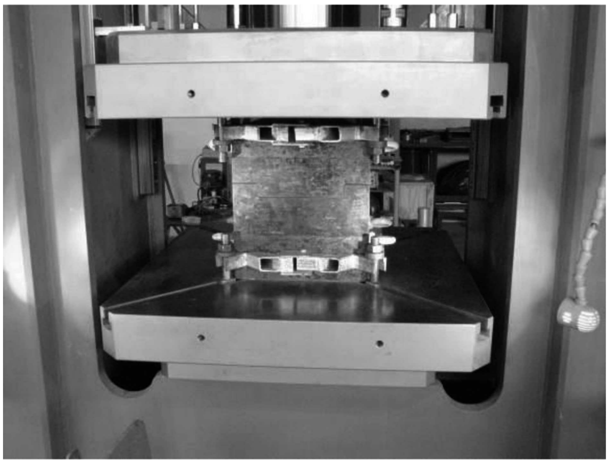


Fig. 1. A set of tools for die forging on a 2.5MN press – assembled

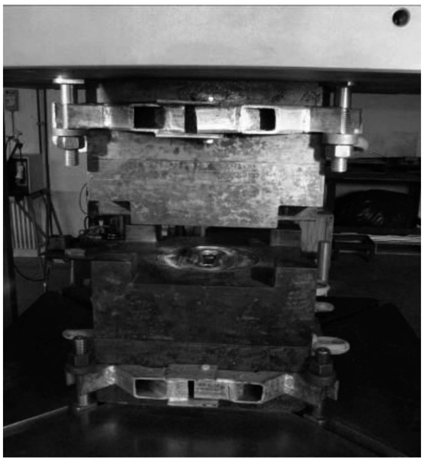


Fig. 2. A set of tools for die forging on a 2.5MN press – disassembled

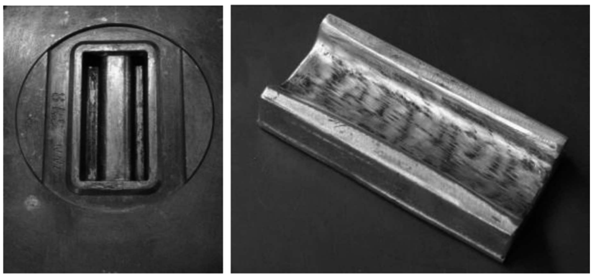


Fig. 3. Die insert to forge a flat model shape and flat model shape forged from magnesium alloy

Fig. 4. Die insert to forge a model of connecting rod and model of connecting rod forged from magnesium alloy

Heat treatment of forged models was carried out to obtain the following two conditions:

– T5 (cooled from an elevated temperature of the forming process and then artificially aged),
– T6 (solution heat treated in furnace, and then artificially aged).

To obtain the T5 condition, the as-forged material was immediately cooled in water "on-line" from the forming process temperature and then artificially aged. On the other hand, the T6 condition was obtained by cooling the material after the forging process "in the air", then reheating forgings in furnace and subjecting them to solution heat treatment at a pre-established temperature, followed by water quenching and artificial aging. The temperature and time of the solution heat treatment and aging were determined from the results of the experiments made in the previous phase of the project [11]. Detailed parameters of the heat treatment are given in Table 2.

TABLE 2
Parameters of the heat treatment of magnesium alloy forgings

Alloy	Temper	Solutioning parameters	Aging parameters
ZK60A	**T5**	„on line"	175°C/12h
AZ80A			
ZK60A	**T6**	430°C/2h	
AZ80A			

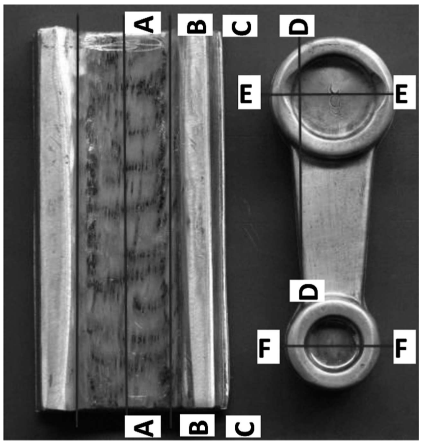


Fig. 5. View of magnesium alloy forgings with marked lines where samples were cut out

TABLE 3
Macrostructures obtained on different cross-sections of the connecting rod forged from ZK60A alloy; as-forged (F) and heat treated to the T5 and T6 condition

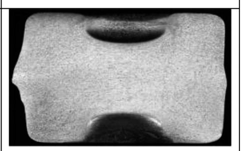
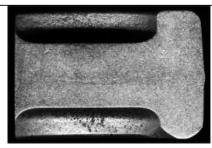
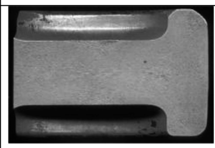
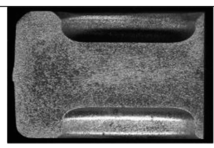
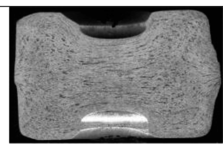
Temper F	Temper T5	
cross-sections F	cross-sections E	cross-sections D
		
Temper T6		
cross-sections E	cross-sections D	
		

TABLE 4
Macrostructures obtained on different cross-sections of the connecting rod forged from AZ80A alloy; as-forged (F) and heat treated to the T5 and T6 condition

Temper F	Temper T5	
cross-sections F	cross-sections E	cross-sections D
		
Temper T6		
cross-sections E	cross-sections D	
		

3. Analysis of structure and mechanical properties of model forgings

To determine the mechanical properties and hardness of the obtained forgings, samples were prepared for further studies. The forged flat model served for the preparation of standard samples for the mechanical testing. Cutting of the forging is schematically shown in sections A-C in Figure 5. Because of greater variations in the nature of the section (different degrees of plastic deformation), structure was examined only in forgings of the model connecting rod. Schematic diagram of cutting out samples for macro-and microstructure examinations is shown in sections D-F in Figure 5. Tables 3 and 4 show macrostructures obtained on different cross-sections of the model connecting rod forged in the examined magnesium alloys.

The tested material after the forging process (F condition) and rapid cooling from the temperature of plastic forming and artificial aging (T5 condition) was characterised by fine-grained structure. However, after re-heating to the temperature of solution heat treatment and aging (T6 condition), examinations of forged macrostructure revealed the grain growth caused by recrystallisation. This situation has occurred in both alloys tested. The growing grains showed the material flow lines in samples of the connecting rod models (Tables 3-4).

Next, microstructure of the ZK60A and AZ80A alloys was examined in as-forged condition and after heat treatment to different states using light microscopy and scanning electron microscopy with EDS analysis. The obtained results are shown in Figures 6-13.

3.1. ZK60A alloy

The structure of alloy reveals the presence of lenticular zirconium-rich areas (about 1.5 wt.%). Borders of these areas are additionally enriched in zinc (Fig. 6 and 7), and there are fine zinc-zirconium precipitates (Fig. 8). These phases precipitate during either hot plastic forming or heat treatment.

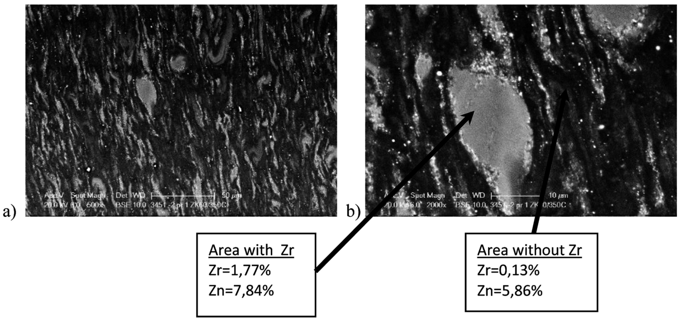


Fig. 6. SEM microstructure of ZK60A alloy forged at 400°C, T5 temper (a – mag. ×500, b – mag. ×2000) with the EDS chemical analysis in microregions

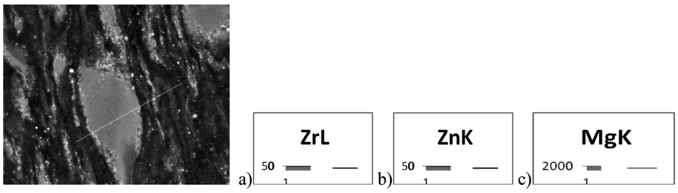


Fig. 7. The linear EDS analysis of elements – Zr (a), Zn (b), and Mg (c)

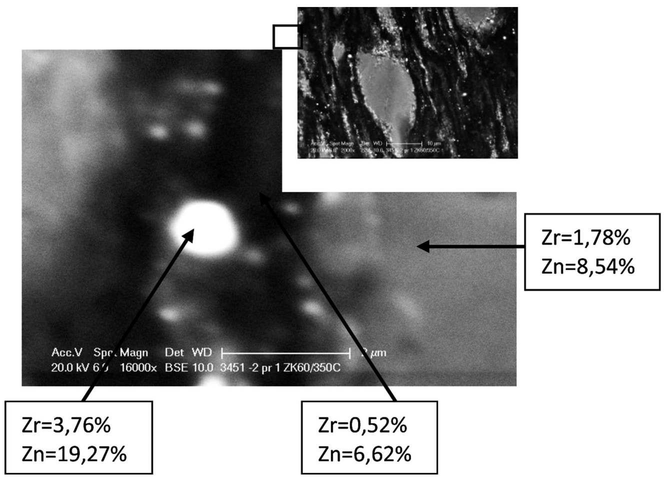


Fig. 8. EDS chemical analysis in microregions (ZK60A alloy forged at 400°C, T5 temper).

As a result of plastic forming (extrusion or forging) or heat treatment (solutioning), at the temperature of 350°C, the recrystallisation of zirconium-free areas has occurred (Fig. 9b). Areas rich in zirconium do not recrystallise at this temperature, since zirconium in these alloys increases the recrystallisation temperature. Heating to the temperature of solution heat treatment, i.e. to 430°C (T6 condition), has resulted in complete recrystallisation of the material (fig. 9c), i.e. including the grains with and without the zirconium particles, causing local large variations in the grain size (Fig. 9d), and hence lower mechanical properties (Tables 5, 6). Large variations in the size of recrystallised grains were due to the fact that in the areas with zirconium-free grains, the growth of grains took place earlier during recrystallisation, while in the grains with zirconium, zirconium acted as a grain refiner, and grains in those areas were finer after recrystallisation.

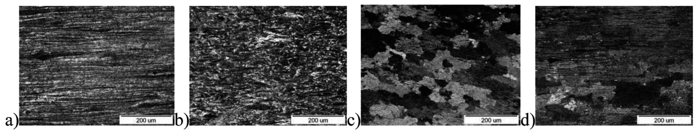


Fig. 9. Microstructures showing the grain size in ZK60A alloy forged at 350°C and heat treated to various conditions, a) T5 –non-recrystallised structure, b) T5 partially recrystallised structure c) T6 (solutioning at 430°C) – completely recrystallised structure, d) T6 with local large grain size variations

The results of structure examinations were confirmed by the mechanical properties determined in static tensile test (Tables 5,6). The mechanical properties of forgings were higher for the T5 condition, because the resulting material was only partially recrystallised (Fig. 9 a, b). Aging has no longer had any effect on the recrystallisation process, only on the decomposition of the solid solution and precipitation of fine-dispersed phases of Mg-Zn and Zn-Zr, which resulted in a slight increase of the properties.

3.2. AZ80A alloy

Forging of AZ80A alloy at the temperature of 350°C with the following heat treatment to the T6 condition, i.e. solutioning at 430°C for 2 hours and aging at 175°C for 16 hours, resulted in recrystallisation of the structure and formation of material with non-homogeneous grain size (Fig. 10).

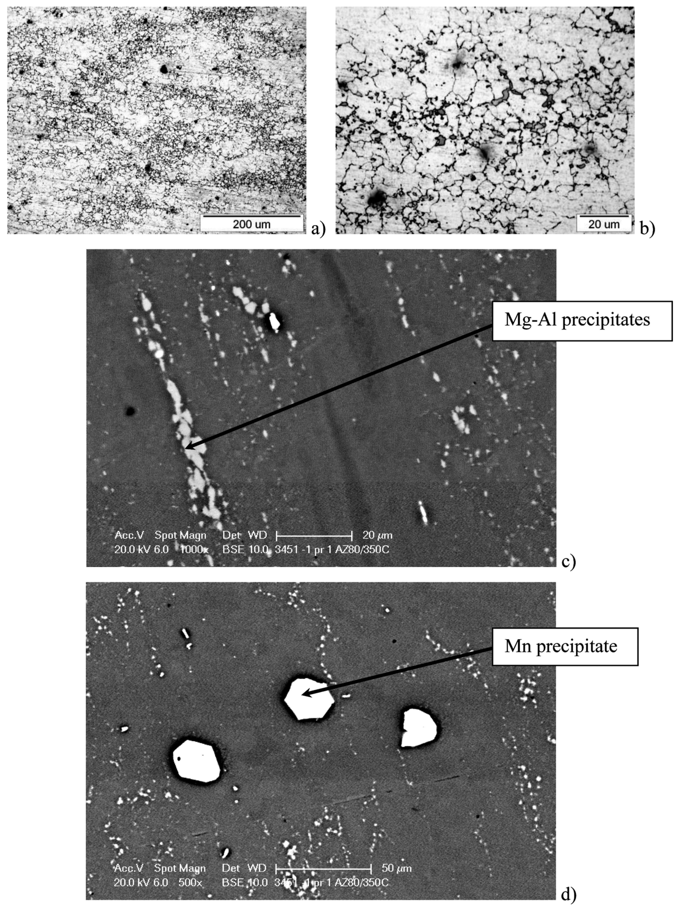


Fig. 10. Microstructure obtained in the forging process carried out at 350°C with the following heat treatment to the T6 condition; examinations by light microscopy (a, b) and scanning electron microscopy with the chemical analysis in microregions (c, d)

Heat treatment to the T6 condition has hardly changed the material properties. Hardness increased from 71 to 78.5 HB (Table 6).

Forging of AZ80A alloy at the temperature of 400°C resulted in the formation of recrystallised structure with very fine grains (Fig. 11).

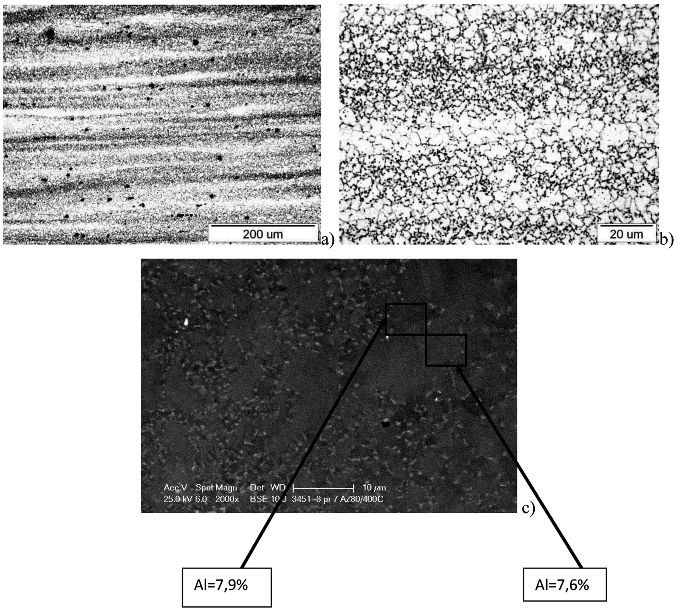


Fig. 11. Microstructure obtained in the forging process carried out at 400°C; examinations by light microscopy (a, b) and scanning electron microscopy with the chemical analysis in microregions (c)

The following heat treatment to the T6 condition (solution heat treatment in furnace) carried out on the AZ80A alloy has caused considerable grain growth (Fig. 12), and therefore a drop of mechanical properties.

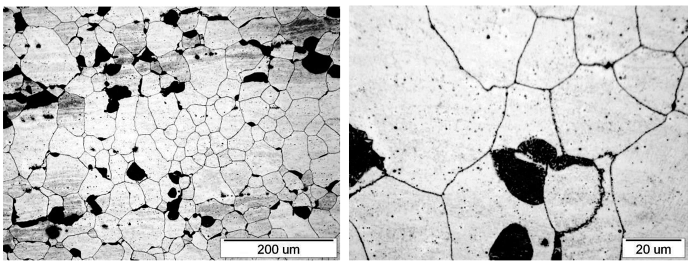


Fig. 12. Microstructure obtained in the forging process carried out at 400°C with the following heat treatment to the T6 condition, i.e. solutioning at 430°C for 2 hours and aging at 175°C for 6 hours; examinations by light microscopy

Forging at the temperature of 400°C followed by solution heat treatment from the temperature of the plastic forming and aging (T5 condition) has made the homogeneous and fine-grained structure obtained by forging remain unchanged during aging (Fig. 13); the decomposition of the solid solution increased the mechanical properties. Due to this, forgings in this state achieved the highest properties (Tables 5-6).

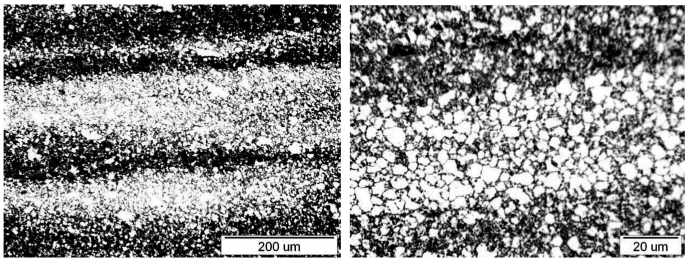


Fig. 13. Microstructure obtained in the forging process carried out at 400°C with the following heat-treatment to the T5 condition; examinations by light microscopy

3.3. Mechanical properties of ZK60A and AZ80A alloys

The results of mechanical tests carried out on forgings made at the extreme temperatures of 350 ÷400°C with the following heat treatment to the T5 and T6 condition are shown in Tables 5 and 6.

TABLE 5

Static tensile test – the results obtained after heat treatment

Alloy	Forging temperature [°C]	Temper	Rm [MPa]	$R_{P0,2}$ [MPa]	A [%]
ZK60A	350	T5	325	282	15,3
ZK60A		T6	292	231	11,6
AZ80A		T5	348	285	9,6
AZ80A		T6	350	261	9,8
ZK60A	400	T5	318	278	14,4
ZK60A		T6	290	226	10,3
AZ80A		T5	366	293	11
AZ80A		T6	333	241	9,4

TABLE 6

Hardness of the examined alloys after heat treatment

Alloy	Forging temperature [°C]	Temper	Hardness before heat treatment [HB]	Hardness heat after treatment [HB]
ZK60A	350	T5	66	74
ZK60A		T6	66	65
AZ80A		T5	66	86
AZ80A		T6	72	79
ZK60A	400	T5	65	72
ZK60A		T6	62	71,5
AZ80A		T5	68	86
AZ80A		T6	74	75

The obtained results allow concluding that for both alloys the T5 condition at the same forging temperature enables obtaining higher mechanical properties than the T6 condition. Only in the case of AZ80A alloy, at the forging temperature of 350°C, the strength was the same for both conditions (still with the yield strength higher for the T5 condition). This indicates that the temperature of plastic forming at which this alloy was forged, i.e. 350°C, was too low to get proper solutioning of the material allowing the achievement of high strength. At the same time, forgings from the ZK60A alloy were characterised by higher ductility in the T5 condition. For AZ80A alloy, this difference was not so pronounced. The conducted heat treatment also resulted in increased hardness of samples in the T5 condition for both alloys tested. Alloys in the T6 condition showed either small changes in the level of hardness or no change at all.

4. Conclusions

1. Hot forging tests have proved the possibility to shape the finished and semi-finished products in AZ80A and ZK60A magnesium alloys. The ready forgings had good outer surface, free from the defects like cracks and cold shuts, and proper macrostructure.
2. Forgings made at the temperature of 350°C had the structure non-recrystallised or partially recrystallised, while forgings made at the temperature of 400°C had the structure fully recrystallised. In the case of re-heating for the heat treatment to the T6 condition, the structure in terms of the grain size was not homogeneous.
3. Both AZ80A and ZK60A alloys acquire higher mechanical properties in the case of solution heat treatment from the temperature of the plastic forming (forging) and artificial aging, i.e. in the T5 condition and not in the T6 condition (that is, after re-heating in furnace for the solution heat treatment).
4. The AZ80A alloy achieves the highest mechanical properties in the T5 condition when forging is conducted at a higher temperature of 400°C.

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REFERENCES

[1] E.F. Volkova, Met Sci Heat Treat+ **48**, 508-512 (2006).
[2] L. Cizek, M. Greger, L. Pawlica, L.A. Dobrzański, T. Tański, J Mater Process Tech. **157-158**, 466-471 (2007).
[3] ASM Specialty Handbook, Magnesium and Magnesium Alloys, ASM International Materials Park, (2004).
[4] W. Pachla, A. Mazur, J. Skiba, M. Kulczyk, S. Przybysz, Arch Metall Mater. **57**, 485-493 (2012).
[5] J. Michalczyk, T. Bajor, Arch Metall Mater. **56**, 533-541 (2011).
[6] R.Ye. Lapovok, M.R. Bernett, C.H.J. Davies, J Mater Process Tech. **146**, 408-414 (2004).
[7] L. Liu, H. Zhou, Q. Wang, Y. Zhu, W. Ding, Advanced in Technology of Materials and Materials Processing Journal **6**, 158-165 (2004).
[8] M. Shahzad, L. Wagner, Mater Sci Eng. **506**, 141-147 (2009).
[9] P. Skubisz, J. Sińczak, Arch Metall Mater. **5**, 329-336 (2007).
[10] J. Senderski, M. Lech-Grega, B. Płonka, Arch Metall Mater. **56**, 475-486 (2011).
[11] B. Płonka, J. Kut, P. Korczak, M. Lech-Grega, M. Rajda, Arch Metall Mater. **57**, 619-626 (2012).

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