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MAGNESIUM-ALLOY DIE FORGINGS FOR AUTOMOTIVE APPLICATIONS

IZKOVKI IZ MAGNEZIJEVIH ZLITIN ZA AVTOMOBILSKO INDUSTRIJO

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The paper presents an investigation of the effect of process variables and material condition on the forgeability of magnesium wrought alloys of the Mg-Al-Zn group. The experimental work included the studies of forging capabilities of the alloys in open-die forging at hot- and warm-working temperatures. Forging tests were performed for the material in both the as-cast and as-worked conditions, for two variants of the work-piece geometry. Different variants of the work piece indicated fracture-related problems in forging magnesium alloys in the warm-working temperature mode, which involved an interaction between the material composition and process variables, and the state of stress. By means of numerical calculations it was concluded that, in addition to the material condition, the favourable state of stress, provided by a closed die, could greatly improve the formability of magnesium alloys in the warm-working range.

Keywords: forging, magnesium alloys, automotive applications

Članek predstavlja preiskavo vplivov procesnih spremenljivk in materiala na kovnost magnezijevih zlitin iz skupine Mg-Al-Zn. Eksperimentalno delo je vključevalo študij sposobnosti za kovanje zlitin v odprtem orodju pri temperaturah vročega in toplega preoblikovanja. Preizkusi kovanja so bili izvršeni za material v litem stanju in za že predelan material za dve vrsti izkovkov z različno geometrijo. Različne variacije izkovkov so pokazale pri kovanju magnezijevih zlitin težavo z razpokami pri toplem preoblikovanju ter interakcijo med sestavo materiala, procesnimi spremenljivkami in stanjem napetosti. Z numeričnimi izračuni je bilo ugotovljeno, da dodatno k razmeram materiala lahko ugodno stanje napetosti, ki se ga doseže z zaprtim orodjem, močno izboljša preoblikovalnost magnezijevih zlitin v območju toplega preoblikovanja.

Ključne besede: kovanje, magnezijeve zlitine, uporaba v avtomobilski industriji

1 INTRODUCTION

The automotive industry, characterised by having the largest potential for development, is becoming an important user of magnesium materials. The use of magnesium in vehicles was, for decades, limited to the castings of complicated shapes for engines and wheels. Traditional die casting dominated for economic reasons. A possibility of using the components from magnesium materials including chassis and drives is now being considered. It turns out that it is suitable to replace the so-far used parts made of steel and aluminium with magnesium alloys. The use of magnesium alloys for the components of the chassis leads to high requirements for their strength, toughness and service life. Most of these properties are achieved by forging. The importance of using the forgings from magnesium alloys in passenger vehicles in comparison with the currently used die-cast castings is continuously increasing[1]. The use of magnesium alloys in cars depends on the price relation between aluminium and magnesium alloys. **Table 1** compares the current economic possibilities of replacing aluminium alloys with magnesium alloys, as well as the price relations expected in the years to come.

Figure 1 shows that the main market for forged components is the automotive industry. The forging industry

Table 1: Price relations between the forgings made of aluminium and magnesium alloys[1]
Tabela 1: Primerjava cen izkovkov iz aluminija in magnezijevih zlitin[1]

Price relation aluminium - magnesium	Aluminium		Magnesium – current price		Magnesium – target price	
	€/kg	€/dm^3	€/kg	€/dm^3	€/kg	€/dm^3
Basic metal	2.4	6.5	4.3	7.7	3.6	6.5
Initial blank	0.7	1.9	2.9 to 4.3	5.2 to 7.7	1.4 to 2.1	2.5 to 3.7
Forging and finishing	5–7	14.3–19.8	10–20	18–36	5–10	9–18
Total costs	8–10	23–28	17–29	31–51	10–16	1–28
Comparison with Al alloys	100 %	100 %	210–280 %	140–180 %	120–160 %	80–100 %

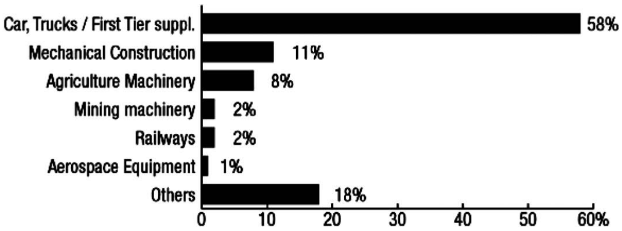

Figure 1: Customer profile of the European forging industry[2]
Slika 1: Profil porabnikov evropske industrije izkovkov[2]

is thus faced with some particular trends that relate to the developments within this sector[2].

It is increasingly recognised that aluminium (with a density of 2,700 kg/m^3) and magnesium (1,800 kg/m^3) are attractive alternatives to steel (7,800 kg/m^3). Notably magnesium is the lightest available engineering metal, being by 75 % lighter than steel and by 35 % lighter than aluminium[3]. To further specify this aspect, **Figure 2** gives an overview of the intrinsic weight-saving potential for some magnesium wrought alloys in comparison with the aluminium reference alloy which is in use for forgings.

Figure 2 distinguishes between some distinct modes of loading, taking into account the relevant material properties: modulus of elasticity E, yield stress YS and density ρ (for the other modes of loading, other design parameters apply). Although these data depend somewhat on the assumptions and the values of the specific property, this basic approach clearly demonstrates that benefits are anticipated for the strength-related and, in particular, for the bending-relevant parts, with a potential gain for magnesium of even 37 % over aluminium[3].

The mechanical properties of Mg can be substantially increased by alloying it with aluminium (up to w = 10 %), zinc (up to w = 6 %), manganese (up to w = 2.5 %) and zirconium (up to w = 1.5 %). Aluminium and zinc form a solid solution with magnesium. Intermetallic phases of types $Mg_{17}Al_{12}$ and $MgZn_2$ are formed when their amounts are higher. In both cases the quantity of the alloying element increases the basic mechanical properties. Manganese and magnesium form a solid solution, α-Mg. The solubility of manganese in magnesium decreases with the decreasing temperature and the α-Mn phase precipitates from the α-Mg solid solution. An addition of manganese does not influence the achieved strength characteristics, but it favourably influences the resistance to corrosion. An increase in the level of the resistance to corrosion can be explained with the fact that a thin layer of Mg-Mn oxides is formed on the surface. An addition of manganese decreases the effect of iron in magnesium. Manganese and iron form a compound of a high density, which settles at the bottom of the bath during the melting. Apart from the basic additions of these elements, an addition of tin is also used in magnesium alloys. Tin is soluble in magnesium at the temperature of 645 °C up to the amount of approximately w = 10 %. Its solubility decreases with the temperature, with a simultaneous precipitation of the β phase (Mg_2Sn). Complex Mg-Al-Mn alloys alloyed additionally with w = 5 % of Sn have good hot formability. Silicon is insoluble in magnesium. They form an intermetallic phase of the Mg_2Si type, which significantly strengthens the basic matrix[4]. Due to a significant increase in the brittleness, the amount of silicon in the alloys is under w = 0.3 %. As the alloying of magnesium alloys with zirconium refines the grains, the achieved level of mechanical properties increases and, at the same time, the resistance to corrosion decreases. The elements of rare-earth metals or thorium increase the refractoriness of magnesium alloys. Beryllium, in the amount of w = 0.005–0.012 %, decreases the oxidation of alloys during melting, casting and heat treatment[5].

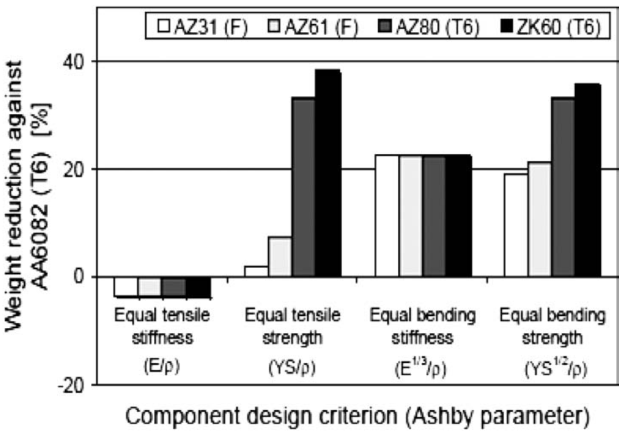

Figure 2: Mass-saving potential of magnesium over aluminium for some typical loading situations[3]
Slika 2: Možnost prihranka mase magnezija v primerjavi z aluminijem za nekatere značilne primere obremenitve[3]

One of the limitations of using the formed magnesium alloys for the production of forged parts is their low formability. For this reason, most of these materials are processed by forming at elevated temperatures, which is reflected in their strength properties. A lower forging temperature increases the precision of the forged parts, but it greatly deteriorates their formability and the material factors – the grain size, the limited number of slip systems at low temperatures and the resistance of a metal to formation of cracks, which is one of the important factors of formability.

Magnesium and the majority of its alloys crystallise in a hexagonal system. This system is characterised by a reduced formability, which is caused by a small number of slip mechanisms. Slips of dislocations take place in selected crystallographic planes and directions, and they are controlled by three known laws. Up to the temperature of 220 °C the only slip plane in magnesium is in the basal plane (0001) and direction $[11\bar{2}0]$. At higher temperatures the slip begins in plane $(11\bar{1}0)$ in direction $[11\bar{2}0]$. These are the planes and directions in HCP lattices that are most densely occupied by atoms. The formability increases significantly with an increase in the slip systems. The values of the critical slip stress (τ_{kr}) for pure magnesium are low. The value of the critical slip stress depends on the purity of the metal, the structure and thermodynamic conditions of deformation. The higher the purity of the metal, the lower is the magnitude of the critical slip stress. The impurities forming solid solutions with the basic metal increase τ_{kr} more intensely than the impurities that are insoluble in the basic metal[6]. If a metal and admixture form a solid solution, then the value of the critical stress increases in dependence of the difference between the magnitudes of atoms of both metals, and the difference between the electrochemical properties of both metals. The admixture elements in magnesium interact with the dislocations, increasing the critical slip stress. The influence of the admixture elements on τ_{kr} can be determined with the following equation:

$$\tau_{kr} = c^n \tag{1}$$

where c is the concentration of the admixture element and n is the exponent ($n \approx 0.5$–0.66).

The values of the critical slip stress decrease for the majority of metals with the increasing temperature. The influence of the temperature is not unequivocal in the case of magnesium and its alloys. Various slip planes can act at various temperatures. For example, at room temperature Mg alloys have only one system of slip planes. The number of active slip planes increases with an increase in the temperature, which is manifested with a rapid decrease in the slip stress. The yield strength of magnesium alloys can be approximately determined with the following equation:

$$\sigma_k = \frac{\tau_{kr}}{m} \tag{2}$$

where m is the Schmid factor ($m_{max} \approx 0.5$).

Table 2 presents the basic parameters of the technical procedure of forging magnesium alloys, as well as their mechanical and technological properties.

The basic properties of magnesium alloys depend on the achieved structural state, which is a function of the chemical composition, applied deformation and heat treatment. Recrystallisation annealing is performed at the temperature of around 350 °C. The recrystallisation of magnesium alloys strengthened by deformation starts in the temperature interval of 250–280 °C. This temperature interval depends on the degree of strain hardening. Most of the magnesium alloys alloyed with manganese or aluminium are used in the heat-treated conditions, i.e., after quenching and aging. The achieved higher strength is connected with the changed solubility of the admixture elements – Al, Zn and Zr – in dependence of the temperature. The heating before quenching is selected in such a way that the segregated intermetallic phases of types $MgZn_2$, $Mg_{17}Al_{12}$, $Mg_3Al_2Zn_2$ are dissolved in a solid solution. A homogenous oversaturated solid solution is obtained after the quenching. During aging the strengthening phases precipitate. A characteristic property of magnesium alloys is a low rate of diffusion processes and that is why the processes of the phase transformation run very slowly. During the heating before quenching the dwell times of 4–24 h are applied. Artificial aging in magnesium alloys runs within the interval from 16–24 h. The selected magnesium alloys can also be quenched by cooling them in air from the finish-forging temperature. The consequential aging performed directly from the finish-forging temperature is used without the inclusion of the previous solution annealing and quenching. The temperatures of the solution annealing of magnesium alloys vary from 380–420 °C. Controlled aging is performed at the temperatures from 200–300 °C. This procedure of heat treatment is marked as T1 and T4. To achieve the maximum level of strengthening, it is necessary to apply an aging temperature from 175–200 °C. The changes in the properties achieved by aging are smaller for magnesium alloys in comparison with aluminium alloys. An increase in the strength properties after aging is not higher than 20–35 %. However, the plastic properties of alloys decrease after aging. For these reasons the most frequently used heat treatment is the homogenisation annealing. The mechanical properties are enhanced as a result of a more homogeneous structure. An application of natural aging does not practically lead to more significant changes in the strength properties[6,7].

2 EXPERIMENTAL WORK

We experimentally verified the forging procedure on the piston-rod and plate forgings, the final shapes of which are illustrated in **Figure 3**. Bars with the diameter of 30 mm and the length of 178 mm were used as initial blanks for the piston-rod forgings. The flat blank for the plate forging had the following dimensions: 130 mm × 150 mm × 13 mm. The forged materials were made of magnesium alloys of types AZ31, AZ61 and AZ91. The

Table 2: Forging temperatures, mechanical and technological properties of the forgings from magnesium alloys[6]
Tabela 2: Temperature kovanja, mehanske in tehnološke lastnosti izkovkov iz magnezijevih zlitin[6]

Alloy	Forging temperatures (°C)		Mechanical properties			Technological properties	
	for forgings	for die forgings	*YS*/MPa	*UTS*/MPa	Elong. Δl/%	Weldability	Resistance to corrosion
AZ31	290–345	260–315	195	260	9.0	O	G
AZ61	315–370	290–345	180	295	12.0	G	G
AZ91	300–385	205–290	250	345	5.0	G	G

Note: O – outstanding, G – good

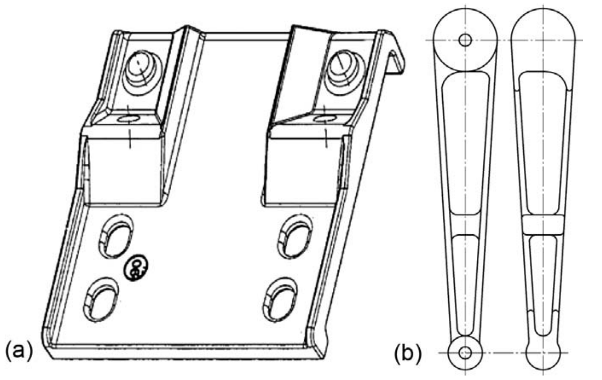

Figure 3: a) Shape of the flat-plate forging and b) shape of the piston-rod forging
Slika 3: a) Oblika izkovka plošče in b) oblika izkovka ojnice

Table 3: Chemical composition of magnesium alloys for forgings
Tabela 3: Kemijska sestava magnezijevih zlitin za kovanje

Alloy	Amounts of alloying elements in mass fractions, *w*/%						
	Al	Zn	Mn	Si	Cu	Fe	Ni
AZ31	2.50–3.50	0.20–0.80	≥ 0.200	≤ 0.100	≤ 0.05	≤ 0.005	≤ 0.005
AZ61	6.76	0.38	0.13	0.05	0.006	0.011	–
AZ91	8.76	0.73	0.22	0.05	0.010	0.011	–

Table 4: Initial parameters for forging the piston rods
Tabela 4: Začetni parametri pri kovanju ojnice

Alloy	Temperature (°C)	Mass of the blank (g)	Dimensions and shape of forgings were satisfactory (%)	Flow stress
AZ31	350	30	100	low
AZ61	320	30	97	medium
AZ91	300	30	95	high

chemical compositions of the forged alloys are presented in **Table 3**.

Forgings were used in the heat-treated as well as in the non-treated states. Before forming, the input blanks were subjected to homogenisation annealing at the temperatures of 380–420 °C. The duration of annealing was 15 h.

After the forging the samples were subjected to the heat treatment (recrystallisation annealing), which consisted of a gradual reheating of the forgings in the furnace at a rate of 20 °C per minute up to a temperature of approximately 420 °C. The forgings were left at this temperature for three hours and then cooled in water. Approximately four hours after the completion of the annealing the surfaces of the forgings were blasted with Cr-balls.

The forging of the piston-rod and plate forgings was performed in an open die on a hydraulic press MW PA 200. The samples were forged with a single strike at a temperature of 300–350 °C depending on the type of the alloy (**Table 4**). In the case of the piston-rod forging, the bleed was cut-off in the hot state, immediately after the completion of the forging.

The temperature of the die tool was approximately 150–170 °C. The Acheson Dag 554/20 lubricant diluted with water at a ratio of 1 : 20 was used as a lubricating medium. The power of the stamping machine was set to 45 % and its stroke to 220 mm (the lowest possible value on the machine for such forgings).

After the forging the test samples for a metallographic analysis of the structure were taken from the forgings. The piston-rod samples were cut along the axis of symmetry in order to examine the change in the structure at individual places of the cut. The sample preparation also included their grinding, polishing and subsequent etching.

The polishing was performed in two phases. In the first phase the samples were polished on a cloth with a soft nap using a polishing suspension based on Al_2O_3. However, after the completion of the first phase of the polishing, the sample surfaces still contained a large amount of scratches and it was, therefore, necessary to start the second phase of polishing on a very fine velvet cloth with short hair. Thus polished samples were cleaned with water, rinsed in alcohol and dried by warm air. The prepared surfaces were etched in 4 % HNO_3 (Nital) in order to remove the deformed layer for its identification.

After the heat treatment, the test specimens for the determination of Brinell hardness were taken from the forgings. The hardness test was performed 10 d after the forging, prior to the heat treatment and also after the heat treatment. The load during the hardness test was 306.5 N and the diameter of the indenting ball was 2.5 mm.

Three indents were made on each sample while keeping the distance between individual indents in accordance with the ISO 6506 standard recommending at least 5 mm in order to avoid the results to be influenced by strain hardening. The samples were subjected to a load for approximately 25 seconds.

3 RESULTS AND DISCUSSIONS

The deformation behaviour and development of the structures of six alloys and two shapes of the products were verified experimentally. All the forgings were forged without any problem and with respect to technology no problem occurred during the forging of magnesium alloys. After the forging the flow stress was assessed quantitatively (**Table 5**).

Table 5: Flow stress of the formed alloys
Tabela 5: Napetost tečenja preoblikovanih zlitin

Material – shape	Average residual energy (kN)
AZ31- piston rod	5166
AZ61- piston rod	4864
AZ91- piston rod	4858
AZ31- plate	4496
AZ61- plate	4369
AZ91- plate	4285

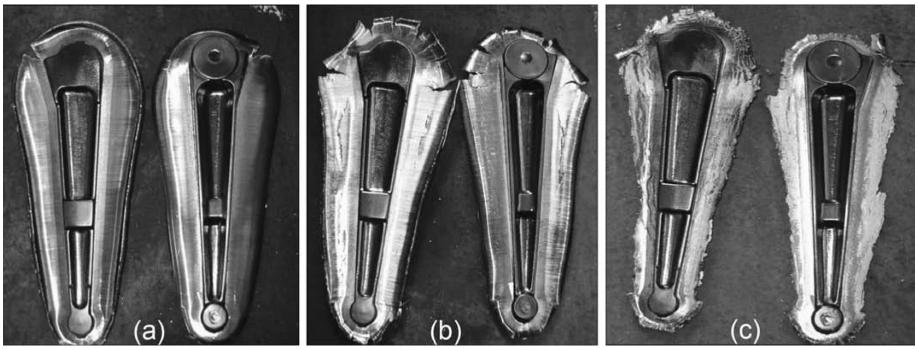

Figure 4: Shapes of the forgings from the magnesium alloys: a) AZ31, b) AZ61, c) AZ91
Slika 4: Videz izkovkov iz magnezijevih zlitin: a) AZ31, b) AZ61, c) AZ91

During the forging after a strike the energy was discharged onto the contact surfaces – it means that the forgings with the lowest residual energy had the highest flow stress. It follows from the obtained results that among the magnesium alloys the AZ91 alloy has the highest flow stress, followed progressively by AZ61 and AZ31. Some of the piston-rod forgings had a scratch on the larger diameter, which might have been related to the crack formation and such parts were investigated. The shapes of the forgings are shown in **Figure 4**.

For the preparation of the flat forging it was absolutely necessary to adapt the contact surfaces, which had to be parallel and smooth since any possible deep scratch could cause a formation of cracks. The shapes of the forgings are shown in **Figure 5**.

The metallographic investigation of the samples was performed in the initial state, after the heat treatment and, finally, after the forging and heat treatment. The analysis of the microstructure was focused on the formation of the cracks that were highlighted during the technological production of the forgings and the individual phenomena associated with the forming of magnesium alloys (dynamic recrystallisation, twinning, growth and shape of grains).

In the initial state, the microstructures of magnesium alloys AZ31, AZ61 and AZ91 contained the majority phase (a solid solution of aluminium in magnesium) and two types of the minority phase. The first type of the

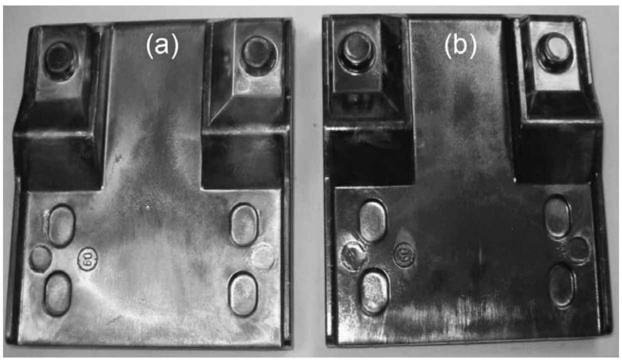

Figure 5: Shapes of the forgings from the magnesium alloys: a) AZ31, b) AZ61
Slika 5: Videz izkovkov iz magnezijevih zlitin: a) AZ31, b) AZ61

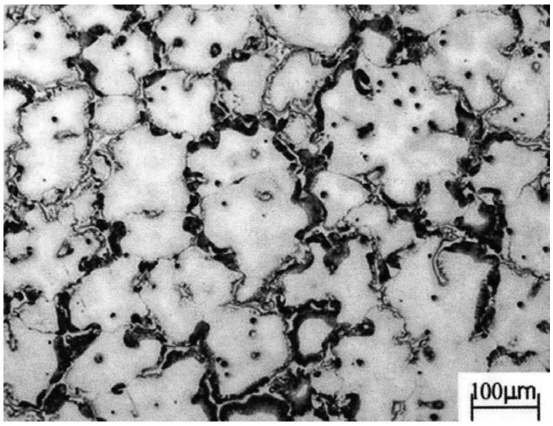

Figure 6: Microstructure of alloy AZ91 in the as-cast state, a cross-section
Slika 6: Strjevalna mikrostruktura zlitine AZ91; prečni prerez

minority phase consisted of relatively massive particles of $Mg_{17}Al_{12}$, while the second type consisted of fine, needle-like particles of the same phase present in the vicinity of the grain boundaries (**Figure 6**).

The objective of the homogenisation annealing was to remove the segregation heterogeneities of the admixture elements. During the homogenisation annealing the

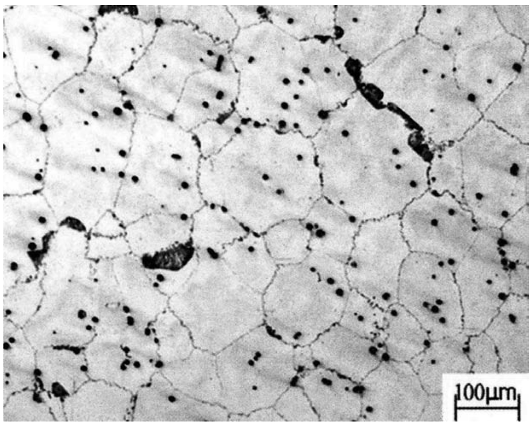

Figure 7: Microstructure of the AZ91 alloy after the homogenisation annealing, a cross-section
Slika 7: Mikrostruktura zlitine AZ91 po homogenizacijskem žarjenju; prečni prerez

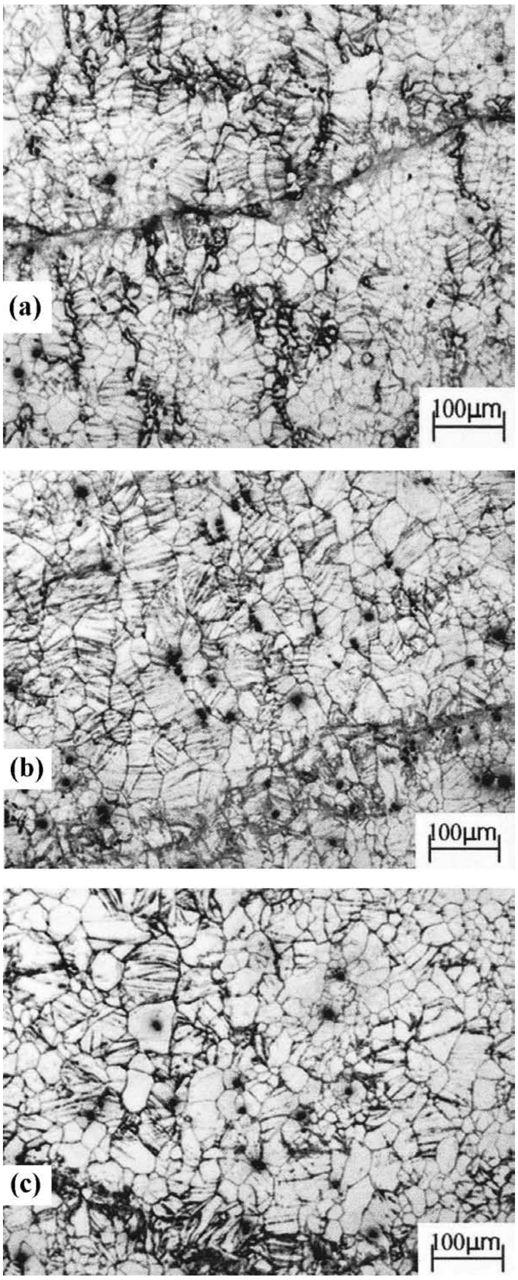

Figure 8: Microstructures of the alloys: a) AZ31, b) AZ61 and c) AZ91 after the forging, a cross-section

Slika 8: Mikrostrukture zlitin: a) AZ31, b) AZ61 in c) AZ91, po kovanju; prečni prerez

segregated phases on the grain boundaries dissolved in the basic matrix and the chemical composition of the alloy was more homogenous (**Figure 7**). This improved the formability and enhanced the level of mechanical properties.

The structures of the forged piston rods made of alloys AZ31 and AZ61 did not show any defects that could cause a subsequent failure of the components. The grains of both alloys were stretched in the direction of the intensive flow of the material, i.e., in the longitudinal direction of the forging. In alloy AZ61 a dynamic recrystallisation took place, which started at the boundaries of the original grains, being supported by a sufficiently large number of precipitates of $Mg_{17}Al_{12}$ and by the created twins. The recrystallisation gradually expanded toward the centre of the basic grains. The piston rod made of alloy AZ91 had its central part without any significant failures; however, its peripheral parts were characterised by the cracks that penetrated deeper into the sample. In this alloy a dynamic recrystallisation on the grain boundaries took place, but there was insufficient time for its propagation into the entire volume (**Figure 8**).

With respect to the flat blank for plate forging, the best forging over the entire cross-section was achieved with the AZ31 alloy that showed no cracks. The AZ61 alloy contained no cracks in the central part of the component, but under the surface some cavities were formed, which could cause a failure of the given component during the subsequent use.

The most damaged microstructure was found for alloy AZ91, where cracks were present right under the surface in all the areas, penetrating deeper into the component and, in some cases, they appeared on the surface as well. It was evident from the metallographic investigation that the cracks were preferentially formed on the grain boundaries, particularly in the presence of phase $Mg_{17}Al_{12}$ or in the places where this phase was dissolved. The grains of all the forged alloys were considerably stretched in the direction of the bleed groove and in alloy AZ91 they led to a formation of a crack over the entire component.

After the annealing, a complete recrystallisation of the grains occurred in the sample made of alloy AZ91. The grains contained acicular particles, spread over the entire grains. In alloy AZ61, the recrystallised grains were present only on the borders of the original grains, but they did not spread throughout the entire volume. The chemical composition, i.e., the amount of aluminium, had a great influence on these processes. The secondary phases, and zinc- and aluminium-based

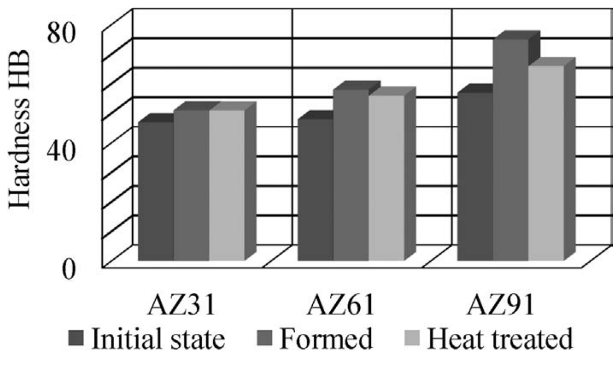

Figure 9: Hardness values of the piston-rod forgings in the initial state, after the forming and after the heat treatment

Slika 9: Trdota izkovka ojnice v začetnem stanju, po kovanju in po toplotni obdelavi

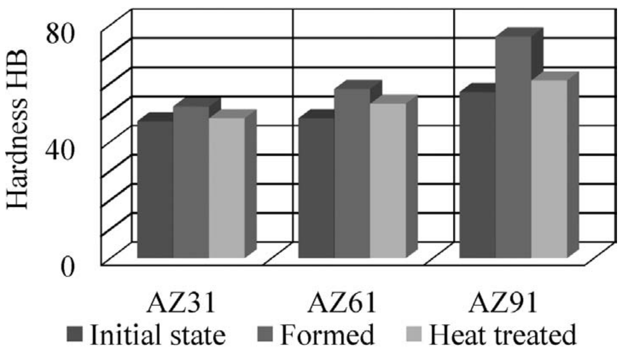

Figure 10: Hardness values of the plate forgings in the initial state, after the forming and after the heat treatment

Slika 10: Trdota izkovka plošče v začetnem stanju, po kovanju in po toplotni obdelavi

precipitates dissolved during the heat treatment in the basic matrix.

The mechanical properties of the forgings and their evolution in dependence of the heat treatment were verified with a hardness test. For all the investigated magnesium alloys in the initial state, the Brinell hardness values were measured after the forming and after the heat treatment, and they were averaged for individual alloys. The resulting hardness values are represented in **Figures 9** and **10**.

It follows from the results of the hardness tests that the heat treatment and forming had considerable influences on the hardness of magnesium alloys. The aluminium amount in the material is another factor, influencing the hardness. The material hardness decreases with the decreasing aluminium amount in the material (**Table 3, Figures 9** and **10**). During the forming the hardness of alloy AZ91 increased considerably – even by 19 HB. The hardness of alloy AZ61 increased by 10 HB. The weakest influence of the forming on the hardness value was found for alloy AZ31. After the heat treatment the hardness of alloy AZ91 dropped considerably, which was caused by the recrystallisation, taking place during the heat treatment. The heat treatment had no significant impact on the resulting hardness of alloys AZ31 and AZ61.

4 CONCLUSIONS

The deformation behaviour of alloys AZ31, AZ61 and AZ91 during die forging was experimentally verified. The influences of the forging technology and homogenisation annealing on the structures and properties of the forgings were compared. The influences of the heat treatment and the forming temperature on the final structure and mechanical properties were evaluated. It follows from the obtained results that the aluminium amount in the material as well as the heat treatment and forming had considerable influences on the hardness of the magnesium alloys. The initial structures used in the tests were in the as-cast form, which probably caused the formation of cracks in the alloys with higher aluminium amounts (AZ61, AZ91).

The results confirmed the suitability of applying heat treatment before forging. This procedure enabled us to obtain the forgings with a more homogeneous structure. After the application of forming some micro-cracks and voids were detected in the magnesium alloys of AZ61 and AZ91. The cracks were located just under the surface and they penetrated deeper into the material. In alloy AZ91 the micro-cracks were formed throughout the entire volume and the initiations of these micro-cracks were preferentially on the grain boundaries, mainly in the area of particles $Mg_{17}Al_{12}$. From the structural point of view, alloy AZ31, in which no structural defects were detected, was found satisfactory. The highest strength and hardness were obtained with alloy AZ91. It follows from the obtained results that with the increasing aluminium amount the hardness of forged magnesium alloys increases as well.

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