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Possibilities of mechanical properties and microstructure improvement of magnesium alloys

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ABSTRACT

Purpose: Magnesium alloys are the very progressive materials whereon is due to improve their end-use properties, which . Especially, wrought Mg alloys attract attention since they have more advantageous mechanical properties than cast Mg alloys.

Design/methodology/approach: The presented article shows some specific physical-metallurgical characteristics of magnesium alloys of the AZ91 kind after hot forming. Special attention has been focused on the analysis of mutual relations existing between the deformation conditions, microstructural parameters, and the achieved mechanical properties.

Findings: The discussed topic includes namely the monitoring of the structures in the initial cast state and after the heat treatment of the T4 kind and the influence of rolling in hot state at different temperatures on this structure. The results of torsion tests of AZ91, AZ61 and AZ31 were added.

Research limitations/implications: The results of this paper evinces that a combination of ECAP technology with conventional rolling is very effective tool for improve a final properties of magnesium alloys in practical use.

Practical implications: It would be appropriate a extrusions processes for increasing of mechanical properties on their treatment by plastic deformations in a rolling mills.

Originality/value: It is explained a big consequence of the ECAP integration between classical forming techniques.

Keywords: Magnesium alloys; Rolling; Torsion test

PROPERTIES

1. Introduction

Modified Mg alloys (see Tab.1) can be processed by rolling, forging, and extrusion. Mode of processing influences development of structure and hence the resulting mechanical properties (see Tab.2). The Mg alloys crystallises in the system HTU (as all magnesium alloys with the exception of alloys with lithium), that's why its cold formability is low [1-3]. It increases significantly at the temperature around 220°C, when other slip planes apply. Formability is significantly influenced also by dynamic re-crystallisation [4,5].

In this type of alloy there are achieved higher plastic properties at temperatures of forming in the zone of homogenous solid solution. Heterogeneity of structure of alloy deteriorates formability in the same way as too coarse grain [6-7]. Grain size and resulting mechanical properties depend to a great extent on conditions of deformation (T,ε, ε′) [8,9].

Table 1.
Chemical composition (wt%) of selected magnesium alloys

Alloy	Al	Mn	Zn	Si	Cu	Ni	Fe
AZ91	8.5 -9.5	0.17 -0.3	0.45 -0.9	0.05 max	0.025 max	0.001 max	0.004 max
AZ61	5.6 -6.4	0.26 -0.50	0.20 max	0.05 max	0.008 max	0.001 max	0.004 max
AZ31	2.5 -3.5	0.2 -1.0	0.7 -1.3	0.05 max	0.03 max	-	-

2. Experimental methods

2.1. Rolling

We have verified by rolling development of structure of modified alloy AZ91 in dependence on magnitude of individual reduction passes and on temperature of rolling 420 °C. We have also monitored hardness obtained after rolling.

Initial cast structure of samples was in two states: without heat treatment (WHT) and after heat treatment T4. Heat treatment T4 comprises: heating to the temperature of 375°C/3 h and consequent heating to the temperature of 415°C/18 h followed by air cooling [10].

Both groups of samples were progressively rolled at temperatures of 420°C. The samples had shape of a prism with dimensions 150x15x10 mm. Rolling rate was approx. 0,314 m/s [11]. Strain rate varied within the interval from 1.2 – 8 s^{-1} and it was calculated from the relationship:

$$\dot{\varepsilon}_h = \frac{v_v}{l_d} \cdot \ln \frac{h_n}{h_{n-1}} \tag{1}$$

where v_v is circumferential speed of rolls,
l_d is length of the zone of deformation,

Length of the zone of deformation (l_d) influences distribution of deformation as well as state of stress in the formed sample. Average values (l_d) varied around 8 mm and they were calculated from the relationship:

$$l_d = \sqrt{R \cdot \Delta h} \tag{2}$$

where: R is radius of rolls
Δh is value of absolute reduction pass

We have measured during rolling dimensions of samples before passing and after it. In dependence on development of state of side free surface we evaluated degree of formability.

After each pass a part of the sample was cut away in order to enable investigation of structure. The remaining part was put again into the furnace with required temperature and after dwell of 15 min. another pass was carried out. We made altogether max. 7 passes. Distribution of deformations in individual passes and total deformation are shown in the Fig. 1

2.2. Torsion test

This test was performed on the torsion plastometer SETARAM. The tested samples had in the tested part diameter of 6 mm and length of 55 mm. In the course of test the bar was heated by induction in a tube made of silica glass in inert argon atmosphere. The following values were read and recorded in dependence on time:

- temperature of deformed material ,
- number of torsions,
- torque,
- axial force.

After completion of test the sample microstructure was stabilised by quenching by a stream of water. Temperatures were monitored with use of pyrometer. The measured values of torque were used for calculation of tension σ from the relationship:

$$\sigma = \sqrt{\left(\frac{\sqrt{3} \cdot M}{2 \cdot \pi \cdot R^3}\right)^2 \cdot (3+p+m)^2 + \left(\frac{F}{\pi \cdot R^2}\right)^2} \tag{3}$$

where strain rate sensitivity index

$$p = \frac{N}{M} \cdot \frac{\partial M}{\partial N} = \frac{\partial \ln M}{\partial \ln N} \tag{4}$$

and strain sensitivity index

$$p = \frac{N'}{M} \cdot \frac{\partial M}{\partial N} = \frac{\partial \ln M}{\partial \ln N'} \tag{5}$$

and deformation intensity Se :

$$Se = \frac{2}{\sqrt{3}} \cdot \arcsin h \frac{2\pi R N}{3L} \tag{6}$$

Chemical composition investigated samples and structures of alloys AZ91, AZ61 and AZ 31 after torsion and quenching is shown in Table 3 and Figures 2, 3 [12].Graphic representation of the function б – Se is-Shown in Figs. 2 and 3.

Table 2.
Mechanical properties (at room temperature)

Alloy	Temper	Tensile strengh, MPa	Yield Strenght, MPa	Elong. in 50mm, %	Hardness HRB(c)	Youngs modulus, GPa	Form
AZ91	T6	230	169	3	66	45	CD
AZ61	F	310	230	16	60		WB
AZ31	F	260	200	15	49		WB
AZ31	T5	265	205	4	-		

F – as fabricated; T6 – solution heat treated and artificially aged; T5 – cooled and artificially aged

Table 3.
Chemical composition investigated samples of magnesium alloys

Alloy	Chemical composition (wt%)											
	Al	Zn	Mn	Si	Cu	Fe	Be	Zr	Sn	Ni	Pb	Ce
AZ91	8.95	0.76	0.21	0.041	0.003	0.008	0.0005	0.003	0.01	0.003	0.059	0.01
AZ61	5.92	0.49	0.15	0.037	0.003	0.007	0.0003	0.003	0.01	0.003	0.034	0.01
AZ31	2.96	0.23	0.09	0.0029	0.002	0.006	0.0001	0.003	0.01	0.002	0.013	0.01

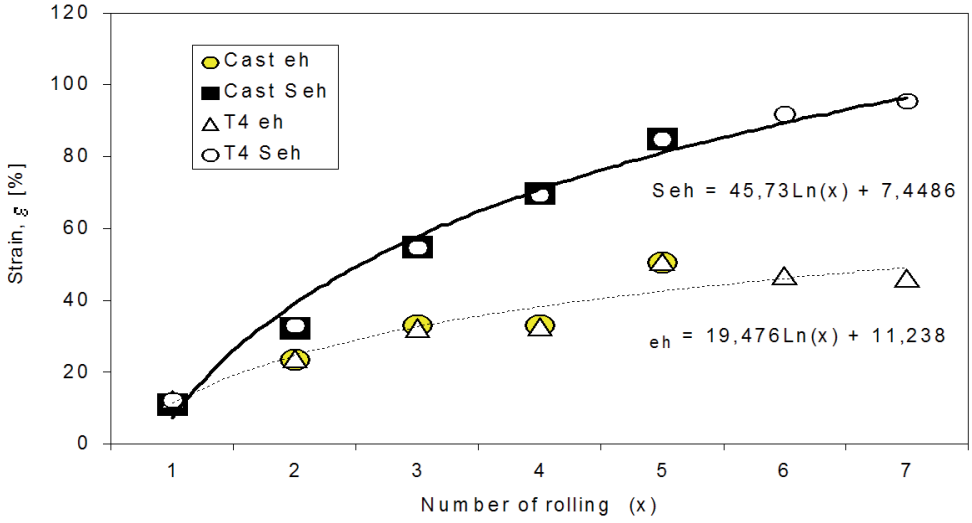


Fig. 1. Magnitude of deformation at rolling

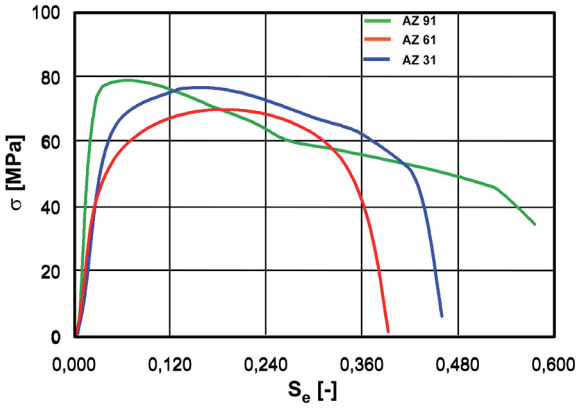


Fig. 2. Dependence of tension on deformation at torsion test for magnesium alloys of the types mentioned above without previous heat treatment (T4)

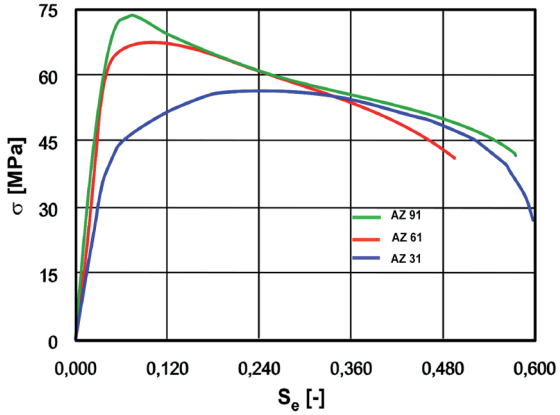
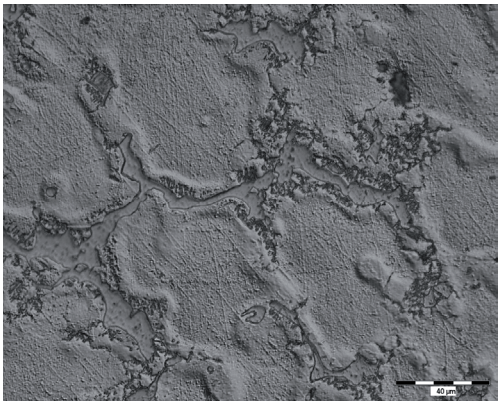


Fig. 3. Dependence of tension on deformation at torsion test for magnesium alloys of the types mentioned above after previous heat treatment (T4)

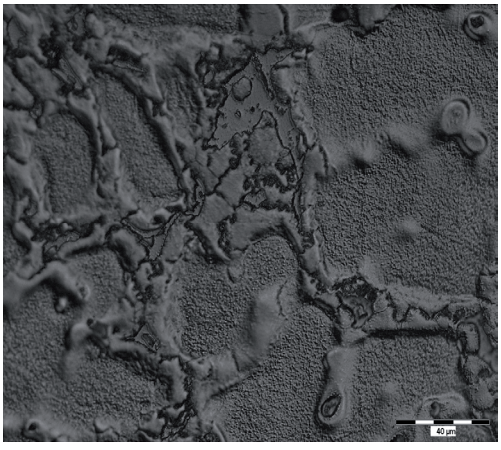
3. Results and discussion

Structure of the alloy AZ91 before deformation in initial state as cast and after heat treatment T4 is shown in the Fig. 6.Microstructure in the as cast state consists of majority phase (solid solution of aluminium in magnesium) and of 2 types of other minority phases (Fig. 5, 6a).

AZ91



AZ61



AZ31

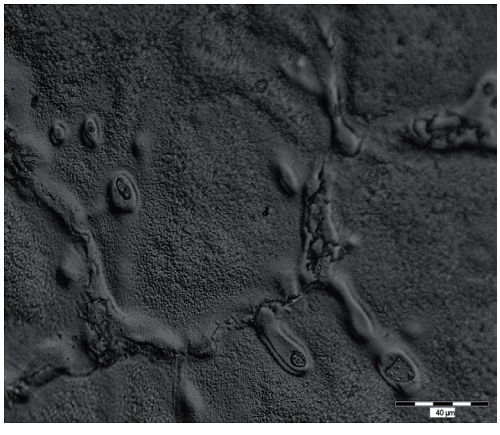
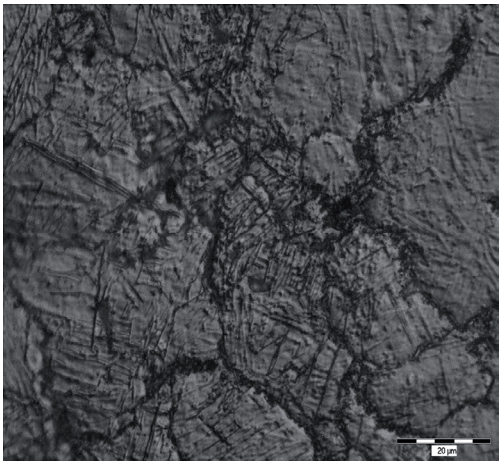
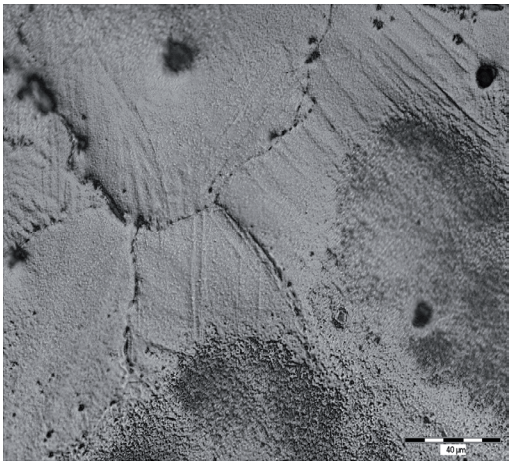


Fig. 4. Alloys AZ91, AZ61, AZ31 without heat treatment, after torsion test (Nomarski contrast)

AZ91



AZ61



AZ31

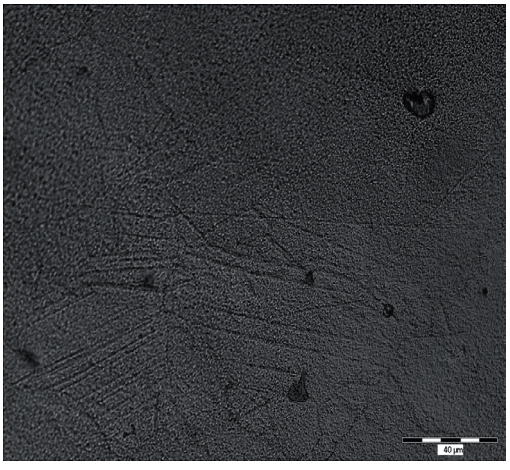


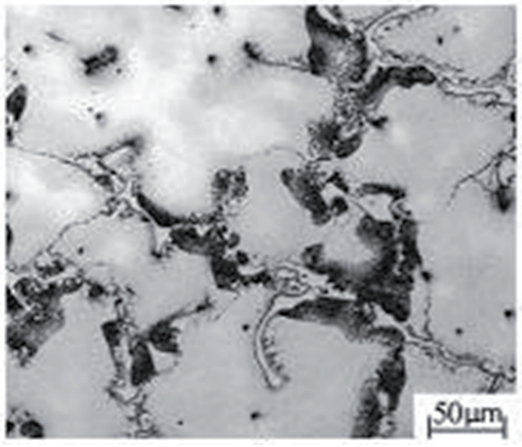
Fig. 5. Alloys AZ91, AZ61, AZ31 after heat treatment (T4), after torsion test (Nomarski contrast)

The first type is formed by comparatively massive particles of the phase $Mg_{17}Al_{12}$, or $Mg_{17}(Al,Zn)_{12}$. The second type shows fine needle-shaped or granular particles of the same phase, occurring in the very proximity of grain boundaries of majority phase. Described type of microstructure is not quite in conformity with binary equilibrium diagram Al – Mg. Structure of the alloy is normally related to thermodynamic and kinetic aspects of solidification and cooling [13].

After application of heat treatment T4 precipitates and compact phases largely dissolve. During air cooling there does not occur repeated precipitation from solid solution in greater extent and resulting structure is formed by over-saturated solid solution on the basis of magnesium, as well as by non-dissolved small residues from the massive phase $Mg_{17}(Al, Zn)_{12}$, (Fig. 6b).

Figures 7 and 8 show structures in longitudinal direction after the first, third and sixth passes for both initial states.

a)



b)

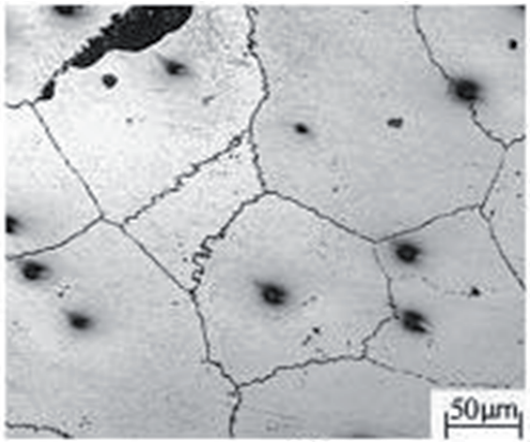
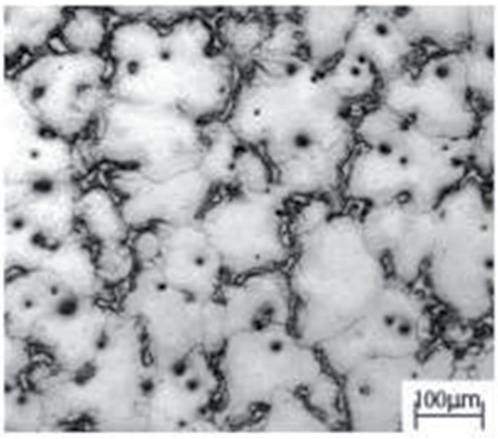
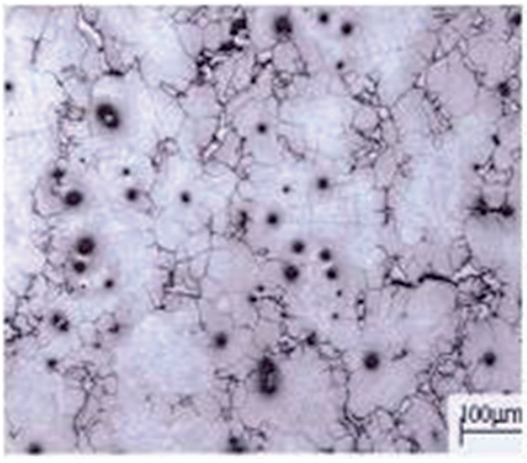


Fig. 6. Structure of initial samples: (a) without heat treatment, (b) after heat treatment T4

a)



b)



c)

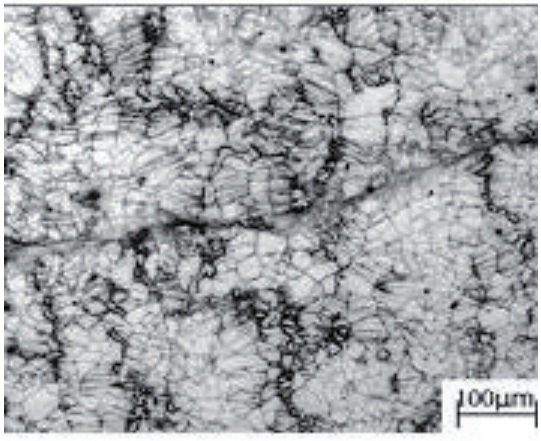
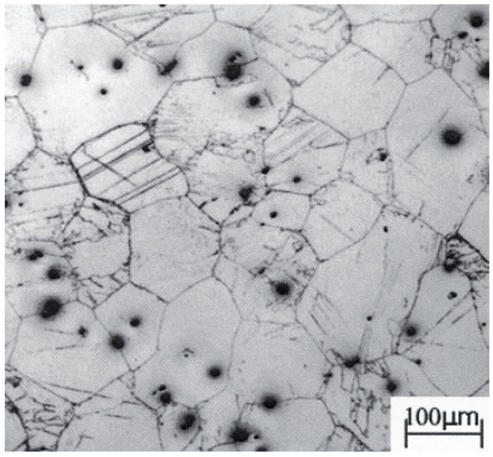
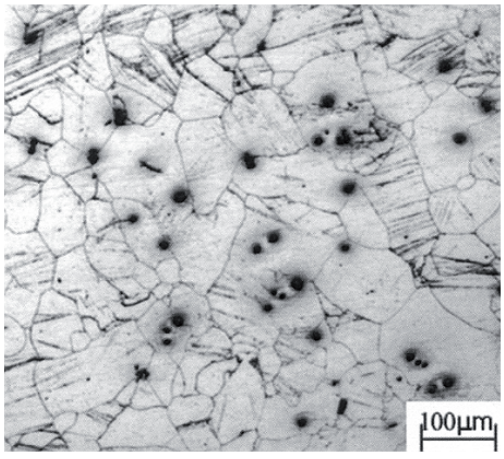


Fig. 7. Development of structure of the alloy without heat treatment after the first, third and sixth pass

a)



b)



c)

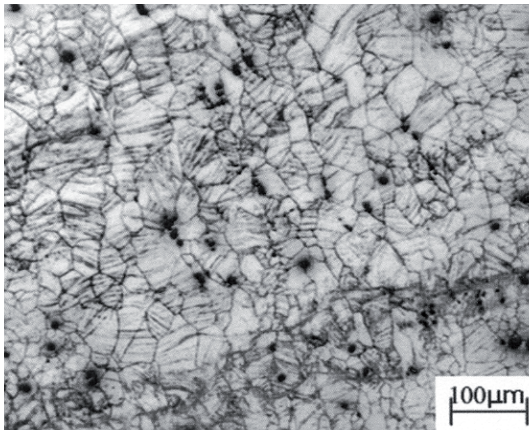


Fig. 8. Development of structure of alloy with heat treatment (T4) after the first, third and sixth pass

It is evident from the Figures 7 and 8, that plastic deformation and re-crystallisation run differently for initial state without heat treatment and for the state after heat treatment T4.

During forming of samples in as cast state without heat treatment we have observed at lower amounts of deformation spheroidization of fine phases [14] in the area of grains and their progressive dissolving (Fig. 7a). In these areas, which form limited bright zones, re-crystallisation started at higher amounts of deformation (from 25 % of deformation, i.e. after the second pass) – see Fig. 7b. Re-crystallisation was accomplished already at the 5th pass (Fig. 7c). Re-crystallisation begins in the areas of grains at the places, where we formerly observed the phase $Mg_{17}Al_{12,}$ or $Mg_{17}(Al, Zn)_{12}$.

During forming of samples after T4 the structural changes were effected by somewhat different mechanism, (Fig. 8). Re-crystallisation started sooner than in samples without heat treatment – already after 10 % of deformation (Fig. 7b). Volume of re-crystallised grains achieved at 30 % of deformation (3rd pass) almost 100 % [15, 16]. We have observed at the same time intensive precipitation of fine phases both in the zone of grains and in the zone of slip bands in grains. The highest amounts of deformation were connected with formation of elongated grains and occurrence of slip bands. These phenomena were less distinct in samples without heat treatment. We have determined higher formability in samples after heat treatment T4.

Assessment of results of torsion test has confirmed influence of heat treatment, which decreased the values of resistance to deformation. At the same time the magnitude of deformation before destruction of the sample has increased.

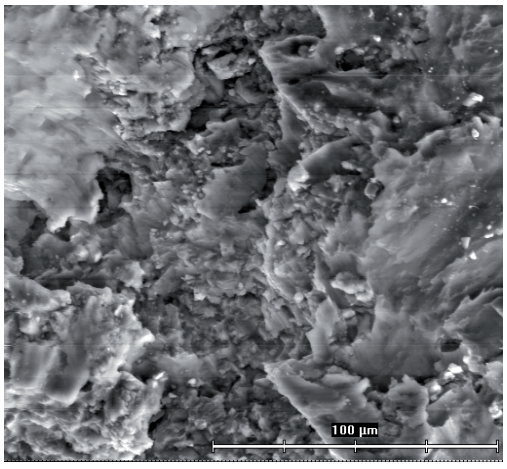
In comparison with other types of alloys the alloy AZ91 manifested (in as-cast state and also after application of T4) the highest σ and deformation [17]. It is worth mentioning that there has occurred an increased strengthening of the alloy AZ31 [18] after application of heat treatment (in as-cast state the strengthening achieved the value similar to that of AZ91).

In all samples there are visible traces of deformation twins. In the alloys AZ31 and AZ91 new grains were formed by dynamic re-crystallisation (Fig. 5). Fractured surfaces on both states demonstrate differences resulting from different deformation behaviour, when in the state after T4 there are visible in all alloys the dots after plastic fracture (Fig.10). The alloy AZ31 is in the state without heat treatment, character of the fractured surface is different (Fig. 9).

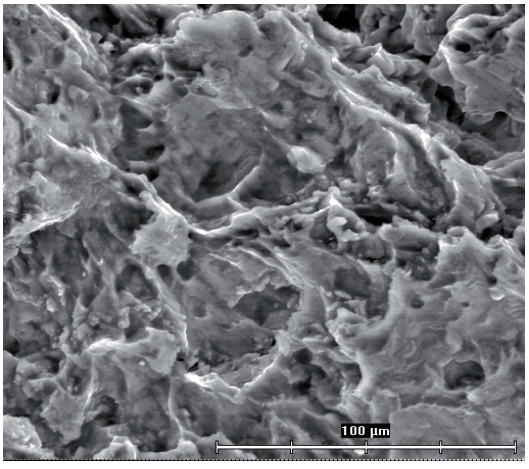
4. Conclusions

We have verified experimentally development of structure at forming of the modified Mg alloys at temperatures of 420^{o}C. Mechanism of deformation and range of re-crystallisation depends on type of initial microstructure and on its homogeneity. In samples without heat treatment there occurs in the area of grain boundaries dissolving of minority phases and partial re-crystallisation, particularly at higher deformations. Deformation of re-crystallised grains is limited, but even at the highest amounts of deformation we have usually not observed formation of slip bands or creation of fibrous structure. Scope of re-crystallisation is significantly smaller than in samples after heat treatment T4.

AZ91



AZ61



AZ31

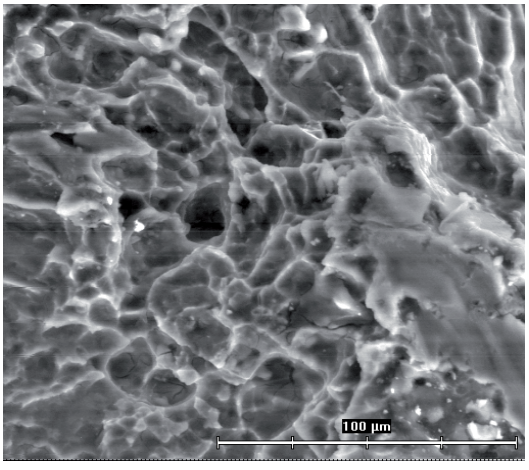
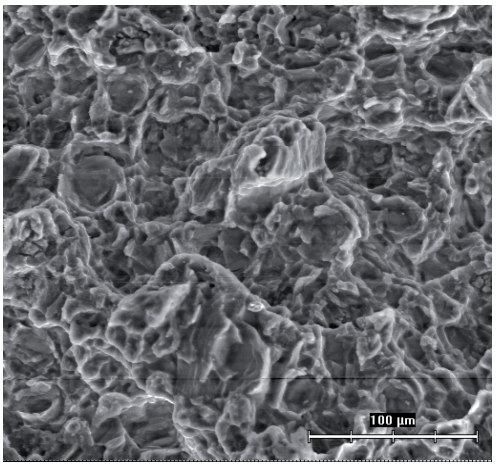
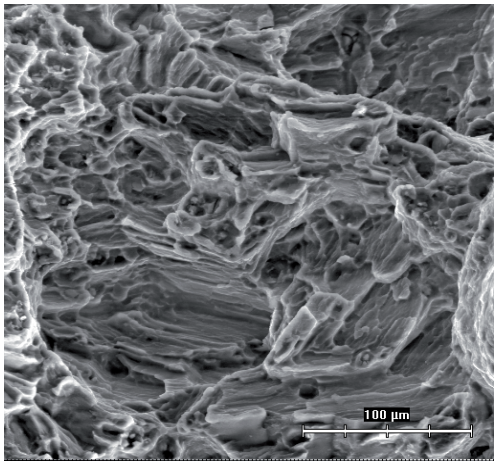


Fig. 9. Fractured surfaces of investigated alloys without application of T4 after torsion test

AZ91



AZ61



AZ31

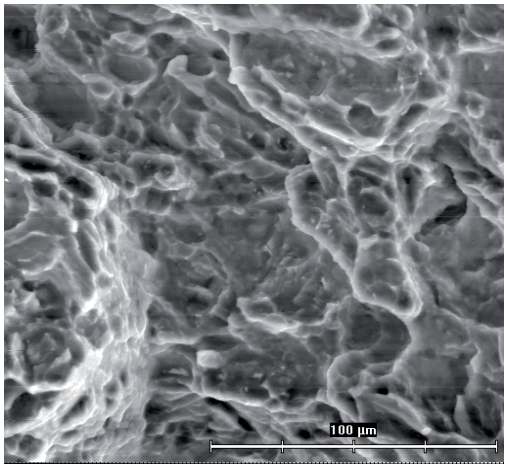


Fig. 10. Fractured surfaces of investigated alloys after application of T4 after torsion test

Re-crystallisation in samples after heat treatment T4 occurs in greater extent than in samples without heat treatment, practically after the first pass. At higher deformations there are formed slip bands, in which there occurs intensive precipitation of fine phases. There occurs also creation of fibrous microstructure. At higher deformations micro-cracks are formed, particularly on side surfaces. In samples without heat treatment these first cracks have been observed after the 3rd pass, while in samples after heat treatment T4 they have been observed only after the 5th pass [19, 20].

Apart from basic slip mechanism of plastic deformation in all three alloys there are visible traces of deformation twins, particularly in the alloys AZ31 and AZ91. There also occurs dynamic re-crystallisation. On the fractured surfaces there are evident differences resulting from different deformation of alloys formed after heat treatment T4.

Acknowledgements

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Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005 in Gliwice-Zakopane, Poland on 6th-9th December 2005.

References

[1] H. Baker, ASM Specialty Handbook. Magnesium and Magnesium Alloys, ed. Avedesian, ASM International, The Materials Information Society, USA 1999.
[2] J. Kielbus, T. Rzychon, R. Cibis, Microstructure of AM50 die casting magnesium alloy, Journal of Achievements in Mechanical and Matenals Engineering18 (2006) 135-138.
[3] M. Yong, A. Clegg, Procese optimisation for a squeeze cast magnesium alloy, Journal of Materials Processing Technology 145 (2004) 134-141.
[4] X. Ming-Xu, Z. Hong-Xing, Y. Sen, L. Jian-Guo, Recrystallization of preformed AZ91 D magnesium alloys in the semisolid state, Materials and Design 26 (2005) 343-349.
[5] R.M. Wang, A. Eliezer, E. Gutman, Microstructures and dislocations in the stressed AZ91 D magnesium alloys, Materials Science and Engineering A344 (2002) 279-287.
[6] N.V. Ravi Kumar, J.J. Blandin, C. Desrayaud, F. Montheillet, M. Suéry, Grain refinement in AZ91 magnesium alloy during thermomechanical processing, Materials and Engineering A359 (2003) 150-157.
[7] J. Kielbus, Structure and mechanical properties of casting MSR-B magnesium alloy, Journal of Achievements in Mechanical and Materials Engineering 18 (2006) 131-134.
[8] T. Haga, H. Watari, S. Kumai, High speed roll casting of Mg alloy strip by a vertical type twin roll caster, Journal of Achievements in Mechanical and Materials Engineering 15 (2006) 186-192.
[9] H. Watari, R. Paisarn, T. Haga, K. Noda, K. Davey, N. Koga, Development of manufacturing process of wrought magnesium alloy sheets by twin roll casting, Journal of Achievements in Mechanical and Materials Engineering 20 (2007) 515-518.
[10] L.A. Dobrzański, T. Tański, L. Čížek, Heat treatment impact on the structure of die-cast magnesium alloys. Journal of Achievements in Mechanical and Materials Engineering 20 (2007) 431-434.
[11] M. Greger, L. Čížek, Z. Muskalski, Magnesium and alloys for forming, Scientific International Conferences FORMING ´04, Vysoké Tatry 2004, 75-79.
[12] M. Greger, R. Kocich, L. Čížek, Forging and rolling of magnesium alloy AZ61. Journal of Achievements in Mechanical and Materials Engineering 20 (2007) 447-450.
[13] L.A. Dobrzański, T. Tański, L. Čížek, Influence of modification with chemical elements on structure of magnesium casting alloys, Proceedings of the 13th Scientific International Conferences Achievements in Mechanical and Materials Engineering AMME'2005, Gliwice-Wisła, 2005, 199-202.
[14] P. Palček, P. Lukáč, M. Chalupová, Z. Trojanová, Influence of temperature on fracture characteristics selected magnesium alloys, Conference "Degradation of structural materials '2005", Těrchová - Biely Potok, 2005, Publication in Materiálove Inžinierstvo (Materials Engineering) 3, 2005, 7-10 (in Slovak).
[15] L.A. Dobrzański, T. Tański, L. Čížek, Influence of Al addition on microstructure of die casting magnesium alloys, Journal of Achievements in Materials and Manufacturing Engineering 19 (2006) 49-55.
[16] K. Ishikawaa, H. Watanabea, T. Mukaib, High strain deformation behavior of an AZ91 magnesium alloy at eleva temperatures, Materials Letters 59 (2005) 1511-1515.
[17] C. Yan, L. Ye, Y.W. Mai, Effect of constraint on tensile behavior of an AZ91 magnesium alloy, Materials Letters 58 (2004) 3219-3221.
[18] K. Iwanaga, H. Tashiro, H. Okamoto, K. Shimizu, Improvement of formability from room temperature to warm temperature in AZ31 magnesium alloy, Journal of Materials Processing Technology 155-156 (2004) 1313-1316.
[19] M. Greger, R. Kocich, L. Čížek, L. Kander, Ultrafine grain formation during equal channel angular extrusion in an Al-Mg-Si alloy, Journal of Achievements in Materials and Manufacturing Engineering 15 (2006) 181-185.
[20] M. Greger, R. Kocich, L. Čížek, LA. Dobrzański, I. Juřička, Mechanical properties and microstructure of Mg-Al alloys after forming, Proceedings of the 11th International Scientific Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005, Gliwice-Zakopane, 2005, (CD ROM).