Archives of Materials Science and Engineering

Volume 71
Issue 1
January 2015
Pages 27-35

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Plastic deformation on the free surface in the vicinity of the crack in AZ magnesium alloys

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ABSTRACT

Purpose: Of this paper was to study plastic deformation of three magnesium alloys of the AZ series loaded very slowly with the aim to reveal mechanisms of plastic damage and fracture.

Design/methodology/approach: Samples of a prismatic shape were provided with the V notch and deformed in the three point bending test. The samples were only slowly loaded and the test was interrupted at the moment when the main crack passed several millimetres. The nearest neighbourhood of the crack was studied by means of the light and scanning electron microscopy.

Findings: Displays of plastic deformation on the samples free surface and an interaction of deformation bands with twins were found as the main characteristic features. Analysis of the fracture surfaces showed the influence of precipitates on the fracture properties.

Research limitations/implications: Experiments were performed only on as cast materials.

Practical implications: Technical praxis requires analysing reasons for damage of machine components, machine crashes in the traffic. Knowledge of the deformation and fracture mechanisms may contribute to solve these technical and economy problems.

Originality/value: Presented results are original; they were not published and not considered for any publication in the future.

Keywords: Magnesium alloys; Three point bending; Plastic deformation; Fracture analysis

Reference to this paper should be given in the following way:

Z. Trojanová, P. Palček, M. Chalupová, I. Hlaváčová, P. Lukáč, Plastic deformation on the free surface in the vicinity of the crack in AZ magnesium alloys, Archives of Materials Science and Engineering 71/1 (2015) 27-35.

MATERIALS

1. Introduction

Mg-Al-Zn alloys offer good combination of room temperature strength and ductility, good salt spray corrosion resistance and excellent die castability. The alloys have been widely used in the automotive and electronic industries [1-4]. Further advantages of AZ alloys are their good machinability, low cost and good recyclability. The strength of the alloys increases with increasing Al content while the ductility decreases. This is reason why the AZ91 alloy is used in the category of cast alloys, while the AZ31 alloy is considered as a successful wrought alloy. For application of load bearing components from AZ magnesium alloys in the automotive industry it is necessary to evaluate fracture properties of these alloys in various types of loading [5, 6].

Real materials contain various defects as crack, casting defects or inclusions. During loading of such materials applied stress has non-homogeneous distribution; defects serve as stress concentrators. Plastic deformation and fracture usually occurred in such weak points in the material microstructure. The main crack path may be influenced by several factors among them also by the manufacture technique [7, 8].

The purpose of this paper was to study free surface and fracture surface of samples loaded in the bending test and to reveal mechanisms of plastic deformation in the vicinity of the propagating crack and the fracture mechanism and influence of materials microstructure on these processes.

2. Experimental

Magnesium alloys AZ31, AZ63 and AZ91 were gravity cast. Chemical composition of the alloys is listed in Table 1. Dendritic microstructure is characteristic for as cast materials formed by the solid solution of Al and Zn in Mg (δ phase) and electron compound $Mg_{17}Al_{12}$ (γ phase) segregated in the interdendritic regions together with further phases containing Al, Zn, Mn and Si. Lamellar discontinuous precipitate γ + δ was observed in the vicinity of the dendrites boundaries.

Microanalysis of all three alloys showed these main results:

- Presence of the γ phase was confirmed in the AZ31 alloy, the discontinuous precipitate was observed only rarely. X-ray analysis determined particles on Si base containing Al and Mn.
- In the AZ63 alloy electron compound $Mg_{17}Al_{12}$ was found beside of discontinuous precipitate and Si particles.
- AZ91 alloy exhibit similar microstructure as AZ63 alloy, only with the different proportional representation of individual phases.

Samples (8x8x55 mm) exhibiting the V notch, were lowly loaded in the three points bending test. Microstructures of the alloys were observed using both the light microscopy (LM) and scanning electron microscope (SEM). The specimens of the alloys were slowly continuously loaded. Achieving the ultimate strength cracks were formed at the tip of the V notch. In that moment the crack release was stopped by the sudden decrease of the stress. After that morphology of the surface in the crack vicinity was observed. This procedure was repeated up to the sample fracture. Situation is schematically depicted in Fig. 1. Manifestation of plastic deformation on the sample surface and fracture surface were analysed. The grain size of alloys used in this study was 250-400 μm for AZ31 alloy, 150-200 μm for AZ63 alloy and 200-300 μm for AZ91 alloy.

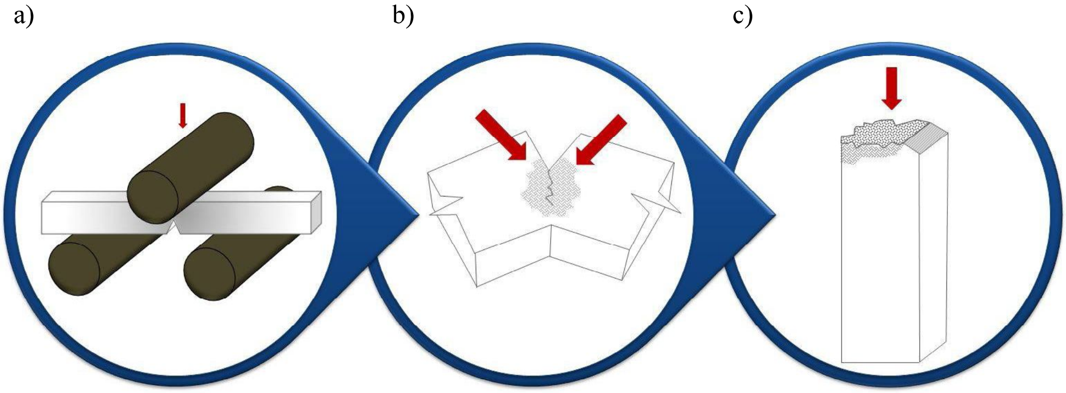

Fig. 1. Schematic drawn of experimental steps: a) three points bending test, b) surface morphology in the crack vicinity, c) fractographic analysis

Table 1.
Chemical composition of alloys

Alloy	Concentration of solute elements in wt.%								
	Al	Zn	Mn	Si	Fe	Ca	Cu	P	Mg
AZ31	2.98	0.655	0.202	0.067	0.0073	0.0017	0.00045	0.0024	balance
AZ63	5.37	2.75	0.368	0.0141	0.0059	0.00046	0.0020	0.0039	balance
AZ91	8.61	0.776	0.229	0.0369	0.0331	0.00031	0.0129	0.0063	balance

3. Experimental results

3.1. AZ31 alloy

In the first stage of the three points bending the main crack was formed. In its vicinity the brittle failure of intermetallic phases was observed due to their different response to the mechanical loading (higher hardness, high strength, low ductility). Secondary cracks formed in the adjacent area of the main crack are documented in Fig. 2a. Small cracks are visible in the left upper corner of the micrograph. Such secondary cracks are formed in the weak areas of the microstructure, in this case of the γ phase. Plastic deformation on the free surface is evident in the vicinity of the secondary crack (Fig. 2b) and in two adjacent grains (Fig. 3a). Strain bands were formed due to dislocation motion during the loading. The slip lines on the surface have different orientation limited by the grain boundaries. In the crack vicinity only grains with the favourable orientation are deformed.

The observed slip lines exhibit different density and orientation. It is caused by the non-uniform action of the loading stress, different grain orientation or possible presence of various inclusions. Slip planes in the deformation bands exhibited in some cases waved character which is very probably caused by activities in secondary slip systems.

Beside of deformation bands realised by the dislocation motion, twins and twin steps were observed at the free sample surface as it can be seen in Fig. 3b where interactions of the twin steps with the strain bands are evident. High stress concentrations necessary for the twin nucleation may arise in the vicinity of the crack tip. In some cases the propagating crack changes its direction and the stressed grains act on the originally twined grain. Secondary twins may arise due to this mechanism, as shown in Fig. 3b.

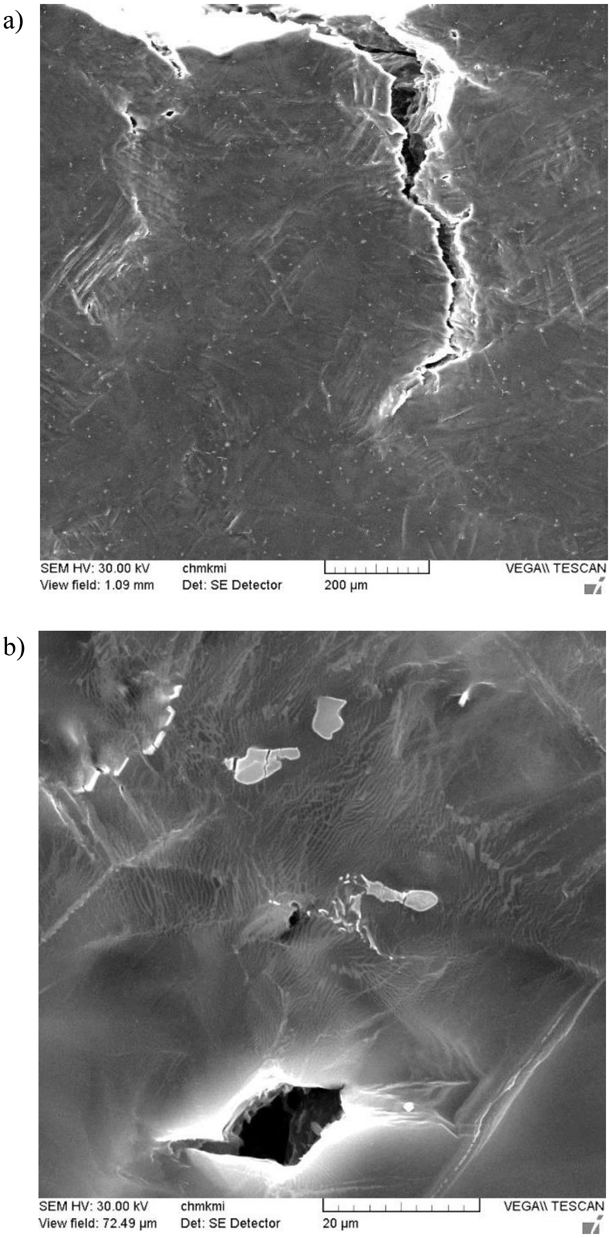

Fig. 2. The main crack propagating from the V notch (a), secondary cracks formed in the vicinity of the γ phase (b)

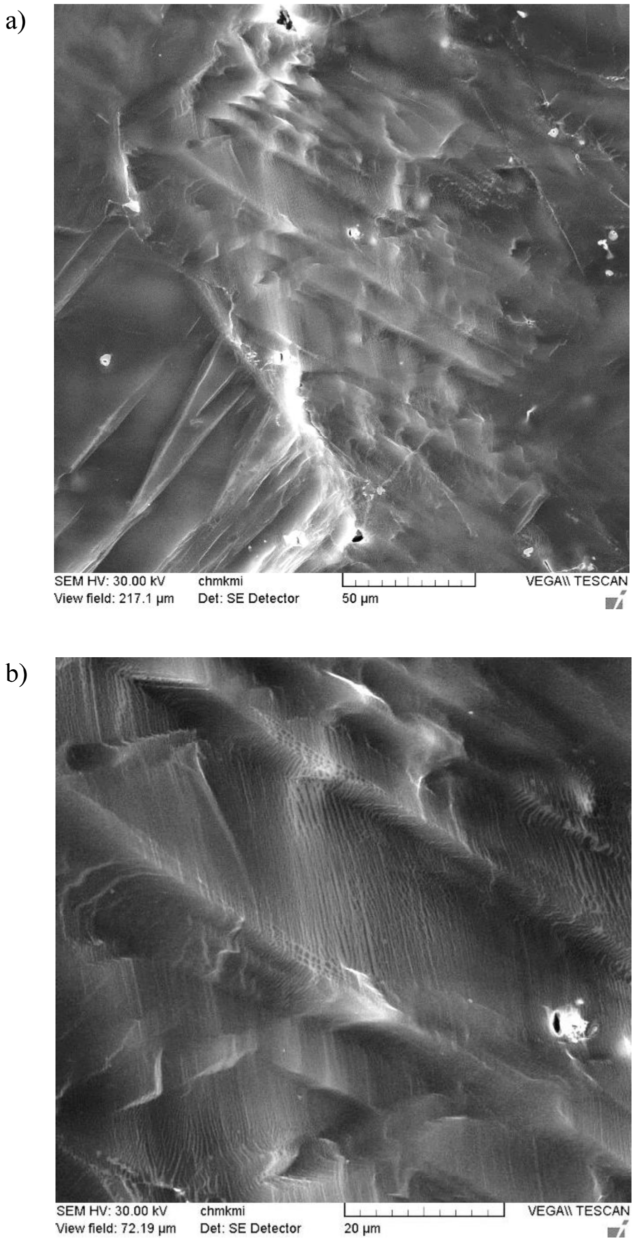

Fig. 3. Plastic deformation on the sample surface: deformation bands in two grains with the different orientation (a), deformation twins (b)

The fracture surface depicted in Fig. 4 has a character of the trans-crystalline ductile failure with the dimples (Fig. 4a) or groove (Fig. 4b) morphology. Shear fracture micro-mechanism is usually found in materials with the H12 lattice structure. For the surface morphology, the orientation of basal planes in respect to the fracture surface (or plastic deformation plane) is relevant. If the fracture surface is oriented parallel to the basal planes, the morphology of the fracture surface has a groove character. When basal planes are oriented perpendicular to the fracture surface then mainly the dimple morphology is observed. Both morphology types were found on the fracture surface, as shown in Fig. 4, due to various orientations of grains.

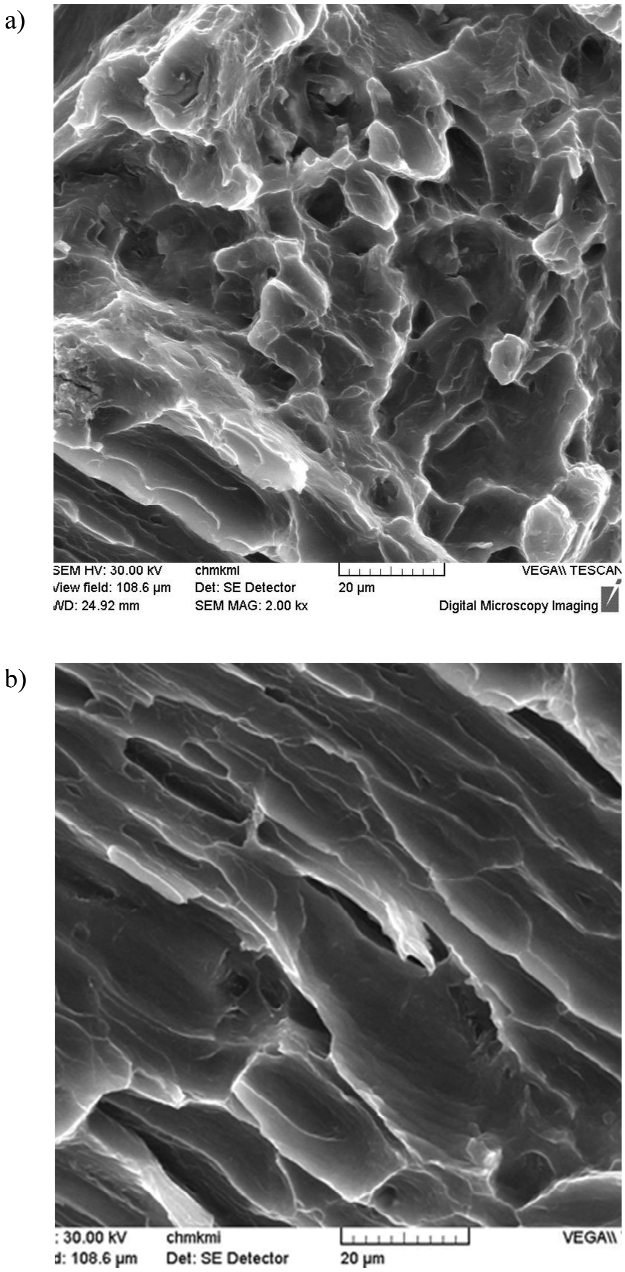

Fig. 4. The fracture surface in the AZ31 alloy with the dimple (a) and groove (b) morphology

3.2. AZ63 alloy

Discontinuous precipitates (DP) are the typical feature in the microstructure of the as cast state [9]. The slip mechanism was observed on the sample surfaces of AZ31 alloy.

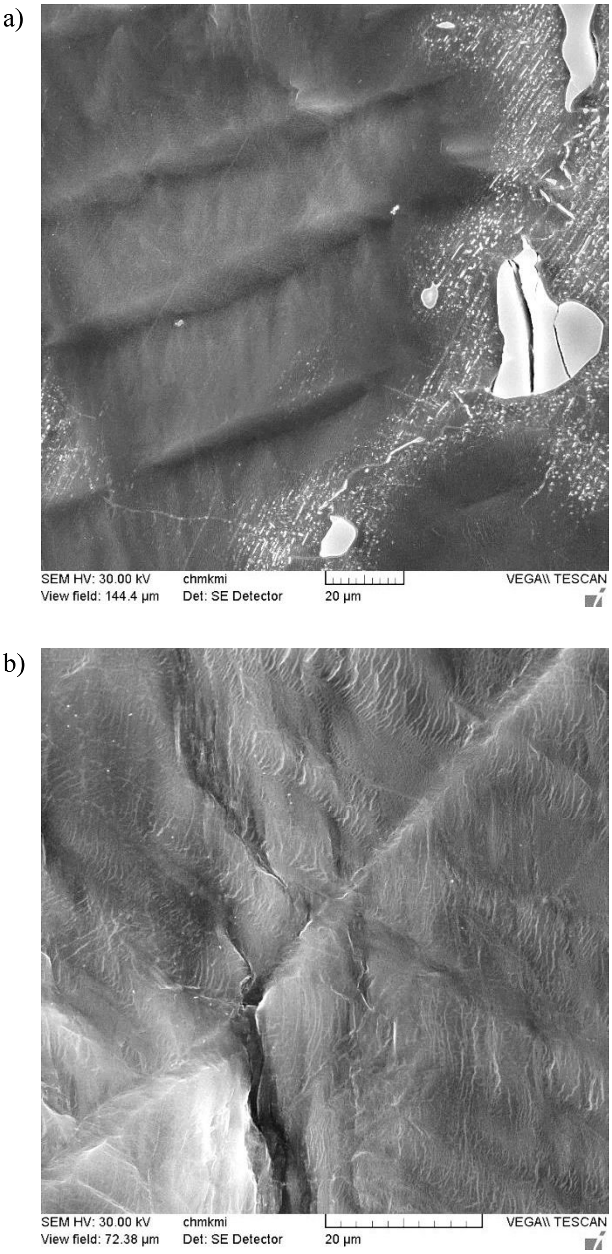

Fig. 5. Plastic deformation in the AZ63 alloy: brittle fracture of the γ phase (a) and combination of twins with fine slip lines (b)

Abundant occurrence of the DP influenced the display of plastic deformation. Lamellae in the DP look as a natural obstacle for the development of plastic deformation. Brittle fracture of particles of the γ phase (Fig. 5a) was observed. From Fig. 5a is obvious that the plastic deformation in the DP was very weak. Combination of the glide deformation with twinning is obvious from Fig. 5b - twins of two systems are accommodated by the tiny slip lines.

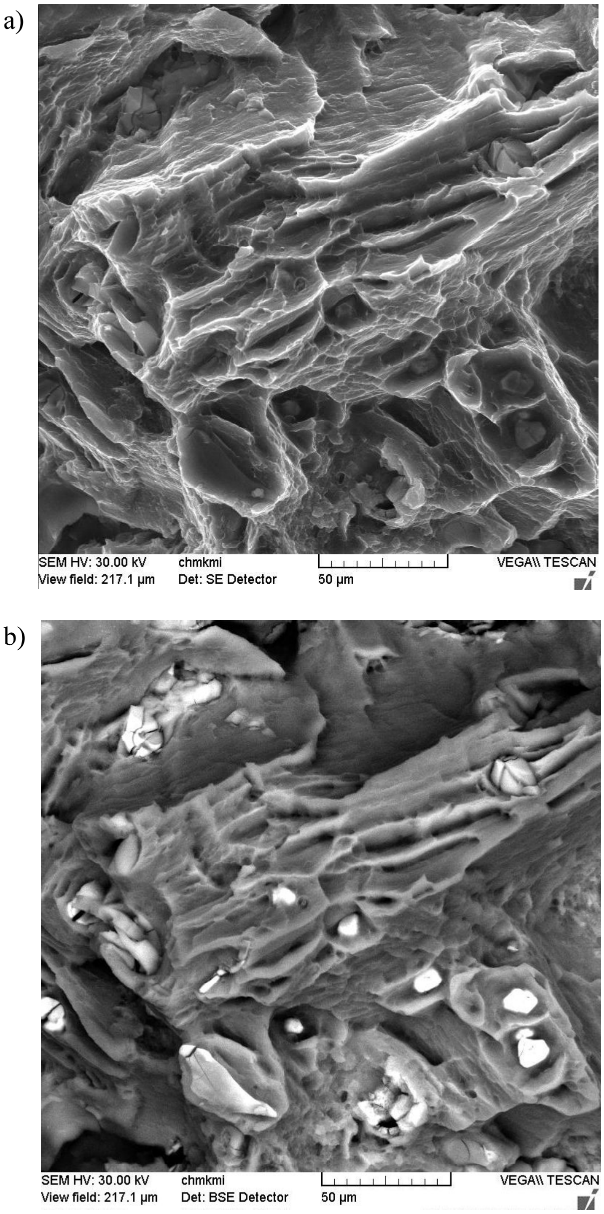

Fig. 6. Trans-crystalline ductile failure in the AZ63 alloy: dimple morphology (a) and the same place depicted in the second electron image showing inclusions in the dimples bottom (b)

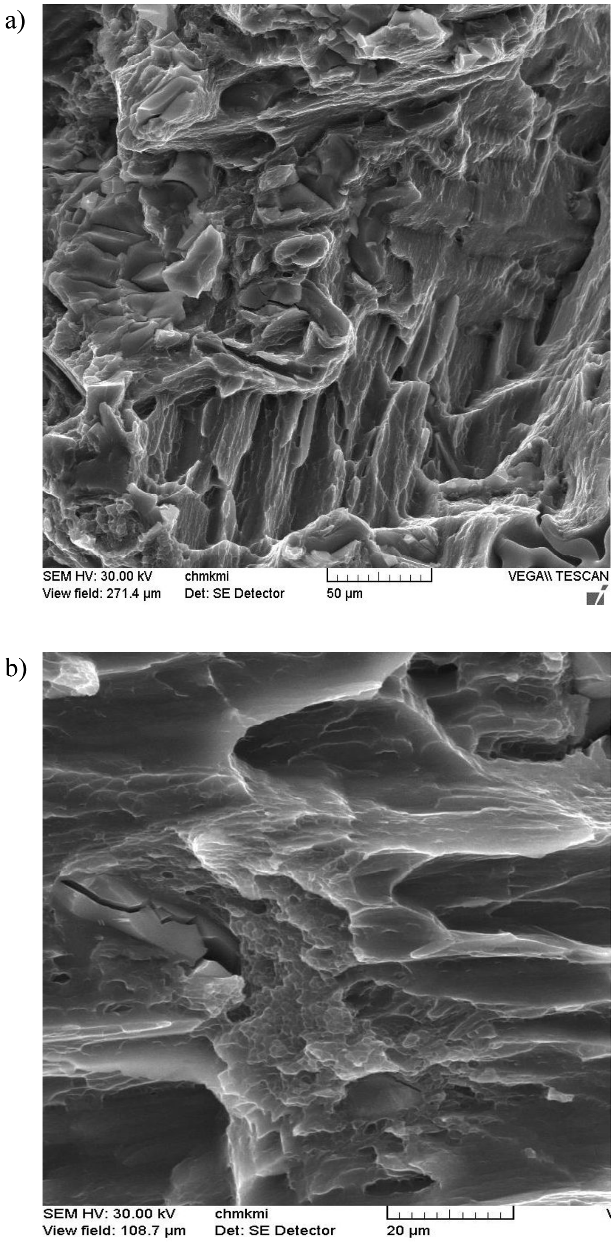

Fig. 7. Fracture surface of the AZ63 alloy: bands formed by the twinning (a), brittle failure in the γ phase and ductile fracture of the DP (b)

Fracture of AZ63 alloy has the trans-crystalline ductile mode characterised by relatively deep dimples (Fig. 6a). Big dimples were initiated by inclusions that are well visible in Fig. 6b. X-ray microanalysis showed that these inclusions have different character (Mn particles, AlMn complexes).

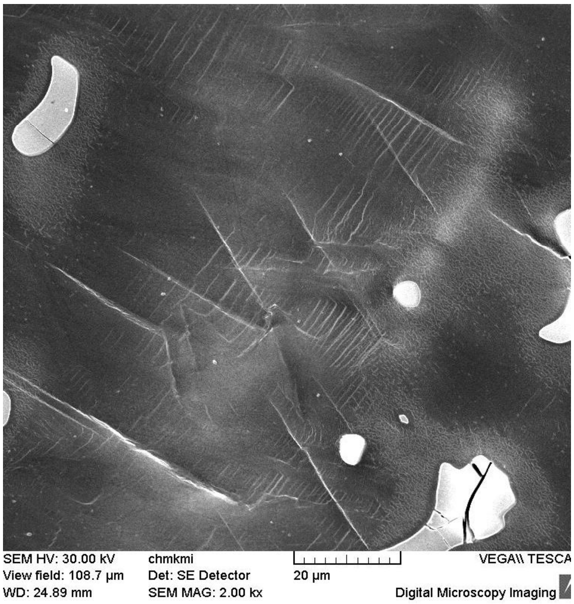

Fig. 8. Plastic deformation on the free surface of the AZ91 alloy: fractured particles and mechanical twins

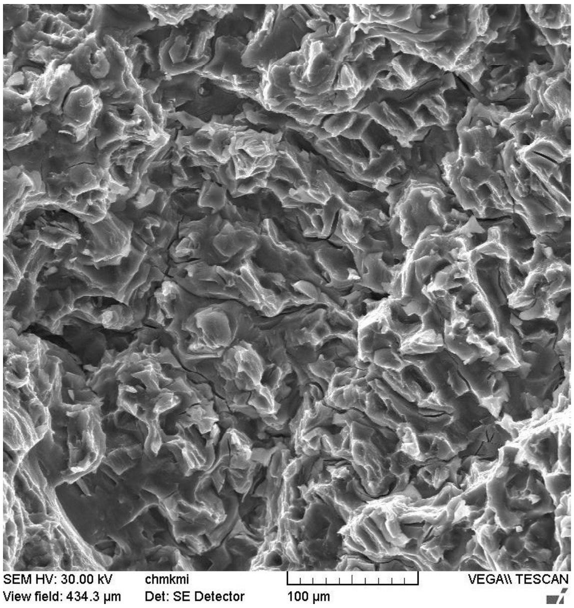

Fig. 9. Fracture surface of the AZ91 alloy

The fracture of the AZ63 alloy was partially inter-crystalline. Bands on the fracture surface similar to facets were formed by the twinning deformation (Fig. 7a). Grains, in which basal planes were oriented parallel to the applied stress, were damaged by a combination of the shear failure in basal planes and ductile failure with the dimple morphology oriented perpendicular to the basal planes. Smooth ductile facets were formed during failure parallel to the basal planes realised by the shear mechanism. On the other hand, during the failure perpendicular to the basal planes ductile steps with groove morphology were formed. Brittle failure of the continuous precipitates and ductile failure of the DP with the small dimples is documented in Fig. 7b.

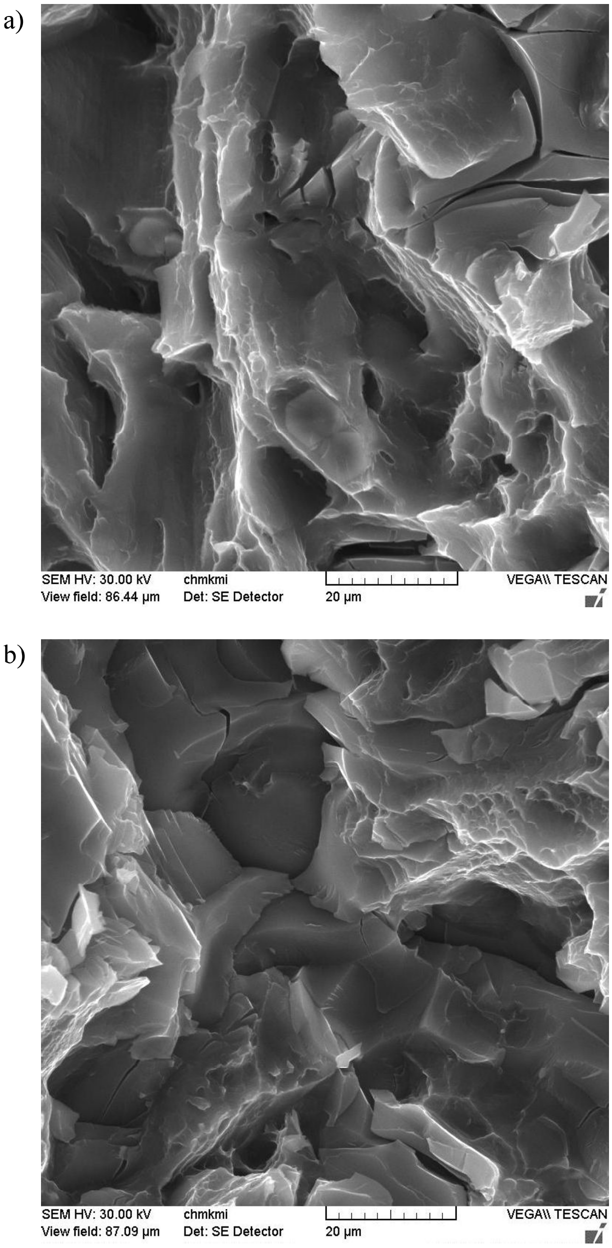

Fig. 10. Fracture surface of the AZ91 alloy: intercept particles at the bottom of dimples (a), interface cleavage between the matrix and the γ phase, and DP damage (b)

3.3. AZ91 alloy

The observed display of plastic deformation on the free surface of AZ91 alloy is weaker compared with the alloys containing smaller Al content. A possible reason for the non-significant plastic deformation is very probably deformation of the secondary phases inside of microstructure, which consumes a big portion of energy for the formation of new surfaces. Brittle fracture of the γ phase particles and deformation twins are evident in Fig. 8.

The fracture surface of the AZ91 alloy has trans-crystalline ductile character with the non-typical dimple morphology as it is shown in Fig. 9. The dimples formed on the fracture surface are shallow without significant reshaped ridges. The observed presence of second phase particles at the bottom of dimples is demonstrated in Fig. 10a. Observation of more details showed a cleavage between the matrix and the second phase particles (Fig. 10b). Fine and relatively deep dimples (obvious in Fig. 10b) are very probably damaged DP.

4. Discussion

Whereas the slip deformation mechanism is dominant in a tensile test, deformation twinning in the deformation zone adjacent to the crack tip is significant in the three point bending fracture tests. This is due to non-homogeneous stress field in the vicinity of the main crack containing both the tensile and compressive stress components. Plastic deformation on the free surface in the AZ31 alloy subjected to the three points bending occurred by the slip and twinning. Straining in grains adjacent to the main crack starting from the V notch activated dislocation motion in the basal slip system. The critical resolved shear stress for basal slip of <a> dislocations with the Burgers vector of $\frac{1}{3}\langle 11\bar{2}0\rangle$ at room temperature is much lower than the critical stress for prismatic and pyramidal systems with <a> and <c+a> dislocations as well as for mechanical twinning [10,11]. One may assume that the moving basal dislocations are stored in individual grains, which leads to the subsequent strain hardening. It should be mentioned that Mg exhibits with a reasonably strong Hall–Petch grain size sensitivity of $k_y \sim 0.22$ MPa $m^{1/2}$ [12-14], which indicates that dislocation pile-ups formed in one grain may easily evoke an activity of dislocation sources in the surrounding grains. Hardening due to storage of dislocations in individual grains maintains the strain hardening. Strain bands visible on the sample surface have different orientation. This is caused by the mechanical twinning. The activation of the main twinning system $\{10\bar{1}2\}$ causes a misorientation of 86.3° between the twinned and the untwined lattice [11]. Twins orientation is influenced by different factors as grain boundaries, inclusions, density and distribution of second phase particles. The observed fracture surface is a result of various effects such as the slowly increased load, energy storage, dislocation motion, change of the grains orientation and/or the crack propagation direction. Shear micro mechanism may be significant for fracture of hexagonal magnesium alloys at lower temperatures. In this case the fracture surface morphology is determined by the orientation of basal planes in respect to the load direction. The dimple morphology is observed when the basal planes are oriented perpendicular to the fracture surface. When the basal panes are parallel to the fracture plane, the surface dimples are elongated into shallow grooves. From the macroscopic point of view, the samples of AZ31 and AZ63 alloys fractured by the same ductile trans-crystalline mode (trans granular associated with ductile dimples). Microscopic analysis revealed that the fracture surface of AZ63 alloy contains also regions with the inter-crystalline damage that has exclusively arisen by the shear mechanism. It should be mentioned that due to high degree of plastic deformation, smooth ductile facets were formed in grains that were suitable oriented with respect to the basal planes (i.e. parallel orientation to the loading direction). On the other hand, trans-crystalline ductile steps with the groove morphology were observed if the basal planes were oriented perpendicular to the load direction. In AZ31 alloy the damaged discontinuous precipitates can be also observed on the fracture surface with the fine dimple morphology.

The observed manifestation of plastic deformation on the sample surface of AZ91 alloy was significantly weaker than that in the AZ31 and AZ63 alloys containing lover content of Al. The different fracture behavior may be very probably caused by lower ductility of the AZ91 alloy due to a higher content of intermetallic particles present in the matrix. Coherent stresses in the vicinity of particles influence the yield stress and also mobility of dislocations. Stored dislocation at the matrix/particle interface accelerated debonding and cleavage at the interface, which was really observed. Brittle fracture of the intermetallic particles is the typical feature of the fracture surface. Damage of the DPs in the AZ91 sample resulted into fine deep dimples.

5. Conclusions and outlook

Analysis of the experimental data obtained during slow loading in the three point bending test of three magnesium alloys express the following main results:

- The surface plastic deformation was realised mainly by the twinning mechanism, in a low degree also by the dislocation motion.
- In the AZ91 alloy only weak imprints of plastic deformation were observed at the sample surface.
- Discontinuous precipitates in the AZ63 alloy prevent the fracture propagation.
- Character of the fracture surface morphology depends on the grains orientation.
- The fracture surfaces are formed predominantly by the ductile trans-crystalline failure with the dimple and groove morphology.
- The dimple morphology is characterised by the shallow uniaxial dimples formed into the hexagon shape. The groove morphology exhibited dimples elongated into flat elliptic grooves.
- In some cases the ductile facets were observed at the fracture surface as a consequence of the trans-crystalline failure.
- Fracture morphology in the discontinuous precipitates regions exhibited fine shallow dimples giving evidence about the ductile failure.
- Intermetallic compounds of the γ phase exhibited only the brittle fracture; in some cases interface cleavage was observed.

Analysis of the experimental results showed that microstructural and casting defects play an important role for the fracture development during the loading in the three point bending test. Homogenisation of the microstructure may significantly influence the fracture properties of these materials. Such a homogenisation may be performed either using adequate thermal treatment or thermomechanical treatment. For the Mg alloys of the AZ series usually T4 or T6 tempers are used [15]. Such thermal treatment can improves mechanical properties and it is standardly applied in the technological praxis. New data concerning to thermally treated alloys are attractive from both theoretical and practical point of view. Materials subjected to severe plastic deformation (for example, equal channel angular pressing - ECAP, accumulative roll bonding - CRB, high pressure torsion - HPT and so on) may exhibit not only the refined microstructure but also unusual mechanical properties. Data concerning to the cracks propagation and fracture properties of such materials are of the highest interest. Effect of RE additions on the deformation behaviour and fracture mechanism should be also investigated.

Acknowledgements

The authors are grateful for the support offered by the Czech and Slovak authorities under the Exchange Programme 7AMB14SK190/SK-CZ-2013-0076. Z.T. and P.L. thank to the Czech Science Foundation GACR for the financial support by the grant 107-15/11879S. P.P. and M.C. are grateful Ministry of Education and Academy of Science of the Slovak Republic for the support by the project VEGA No. 1/0683/15 and European Union-the Project ITMS: 26110230117.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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