Materials Letters 190 (2017) 86–89

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/mlblue

Evolution of dislocation density during compression of a Mg-Zn-Y alloy with long period stacking ordered structure

K. Máthis [a], G. Farkas [a], G. Garcés [b], J. Gubicza [c,*]

[a] Department of Physics of Materials, Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, 121 16 Praha 2, Czech Republic
[b] Department of Physical Metallurgy, CENIM-CSIC, Avenida Gregorio del Amo 8, E-28040 Madrid, Spain
[c] Department of Materials Physics, Faculty of Science, Eötvös Loránd University, Pázmány P. sétány 1/A, H-1117 Budapest, Hungary

ARTICLE INFO

Article history:
Received 27 November 2016
Received in revised form 20 December 2016
Accepted 2 January 2017
Available online 3 January 2017

Keywords:
Mg-Zn-Y alloy
Long period stacking ordered (LPSO) structure
Texture
Compression
Dislocation density
Kinking

ABSTRACT

An extruded Mg-Zn-Y alloy with long period stacking ordered (LPSO) structure was compressed in two different loading directions. The LPSO phase in the initial extruded material exhibited strong texture and elongated grain morphology which resulted in different dislocation densities and plastic behaviors during compression parallel and perpendicular to the extrusion direction.

1. Introduction

The new environmental policies implemented worldwide significantly increased the interest in magnesium alloys with high strength-to-density ratio. Magnesium alloys with long-period stacking-ordered (LPSO) phase have been found as promising materials, which can fulfil this requirement [1,2]. Particularly, the Mg-Zn-Y alloys have been extensively studied, in which rhombohedral (R) 18R or hexagonal (H) 14H structure of the LPSO phase have been observed [3]. During the casting process first the 18R structure formed, which can be transformed into 14H after sufficiently long heat treatment [4]. The main advantage of this class of materials is that besides the good ductility they have superb mechanical strength in the range of 350–600 MPa. Many studies pointed out that the mechanical properties depend on the LSPO phase content and the load direction with respect to the orientation of the LPSO phase [5]. In addition, significant tension-compression asymmetry was found by Garces et al. [6]. It was revealed that basal dislocation slip in both LPSO and magnesium phases has a key role in the deformation mechanisms [2,3,5].

The investigation of the evolution of the dislocation structure during deformation is a difficult task owing to the high dislocation density. The existing studies were performed by HRTEM, which gives valuable results, but it characterizes only a small volume of the samples. Furthermore, according to our knowledge, in LPSO alloys a complex investigation of the dislocation structure in both the LPSO and Mg phases was not performed yet. In this work, X-ray line profile analysis (XLPA) is used for revealing the dislocation density in extruded 97% Mg–2% Y–1% Zn (at.%) alloy, deformed by compression at room temperature. A statistically relevant dataset about the dislocation density in both LPSO and Mg phases was obtained for two different mutual orientations of the loading axis and the extrusion direction.

2. Material and methods

An LPSO alloy with a composition of 97% Mg–2% Y–1% Zn (at.%) was cast in a resistance melting furnace. The as-cast material was subsequently extruded at 400 °C using an extrusion ratio of 18:1 and a rectangular profile of 4×20 mm^2. Samples with dimensions of $4 \times 4 \times 8$ mm^3 were cut parallel to the extrusion (ED) and transverse (TD) directions for compression tests. The compression experiments were performed at room temperature and an initial strain rate of 10^{-3} s^{-1} up to the strain of 10%.

The dislocation structures in the Mg phase of both extruded and compressed specimens were studied by XLPA. The surface of the samples was mechanically polished and etched. The diffraction

* Corresponding author.
E-mail address: jeno.gubicza@ttk.elte.hu (J. Gubicza).

http://dx.doi.org/10.1016/j.matlet.2017.01.006
0167-577X/

peaks were measured on the surfaces lying parallel to the compression direction by a high-resolution rotating anode diffractometer (type: RA-MultiMax9, manufacturer: Rigaku) using CuKα1 radiation with a wavelength of $\lambda = 0.15406$ nm. The line profiles were evaluated for crystallite size, dislocation density and twin fault probability by the Convolutional Multiple Whole Profile (CMWP) fitting procedure [7]. As in the present materials the crystallite size was larger than the detection limit (~800 nm), the CMWP fitting method gave only the dislocation density and the twin fault probability. For all X-ray diffraction patterns the best fit was obtained when $\{10\bar{1}2\}$ twin faults were assumed in the evaluation procedure. This observation suggests that there is an abundance of $\{10\bar{1}2\}$ twin faults in the samples, therefore only this twin boundary type was included in the CMWP procedure.

3. Results and discussion

The extruded microstructure is shown in the backscattered electron image of Fig. 1a. The extrusion process resulted in elongated LPSO grains in ED, having bright contrast in Fig. 1a. Its volume fraction was estimated as 19% by metallographic analysis. Fig. 1b and c show that the material has a strong texture in which the basal planes of the Mg phase are lying parallel to ED. The basal planes of the LPSO phase are also oriented parallel to the extrusion direction.

The density of dislocations in the Mg phase of the extruded sample was $\sim 1.5 \times 10^{14}$ m^{-2}. In addition, a relatively high probability of $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ twin faults (~0.38%) was also observed. The stress-strain curves for ED and TD are shown in Fig. 2. The proof stress for sample ED (~350 MPa) is almost 100 MPa higher than that for specimen TD. Furthermore, a characteristic plateau after macroscopic yield can be observed in ED. In contrast, in TD the sample continuously hardened during compression.

The influence of the sample orientation can also be observed in the evolution of the dislocation density in Mg phase. For both samples, the dislocation density increased by about one order of magnitude during compression (Fig. 3). This large enhancement in the dislocation density in Mg phase is due to the hindering effect of LPSO phase on dislocation annihilation. However, in TD the dislocation density is almost double of that in ED. For the LPSO phase we could not evaluate the dislocation density quantitatively as the CMWP method is not elaborated for rhombohedral crystals and the anisotropic elastic constants of LPSO phase are not known. However, the increase of the full width at half maximum (FWHM) values in Fig. 4 due to compression suggests refinement of the microstructure and/or increase in the dislocation density.

The different deformation behaviors and dislocation density evolutions in ED and TD directions (see Fig. 2) can be correlated to the crystallographic texture of both phases and the elongated shape of LPSO phase. In LPSO phase, similarly to the magnesium phase, the dislocation slip in the close-packed planes (basal slip)

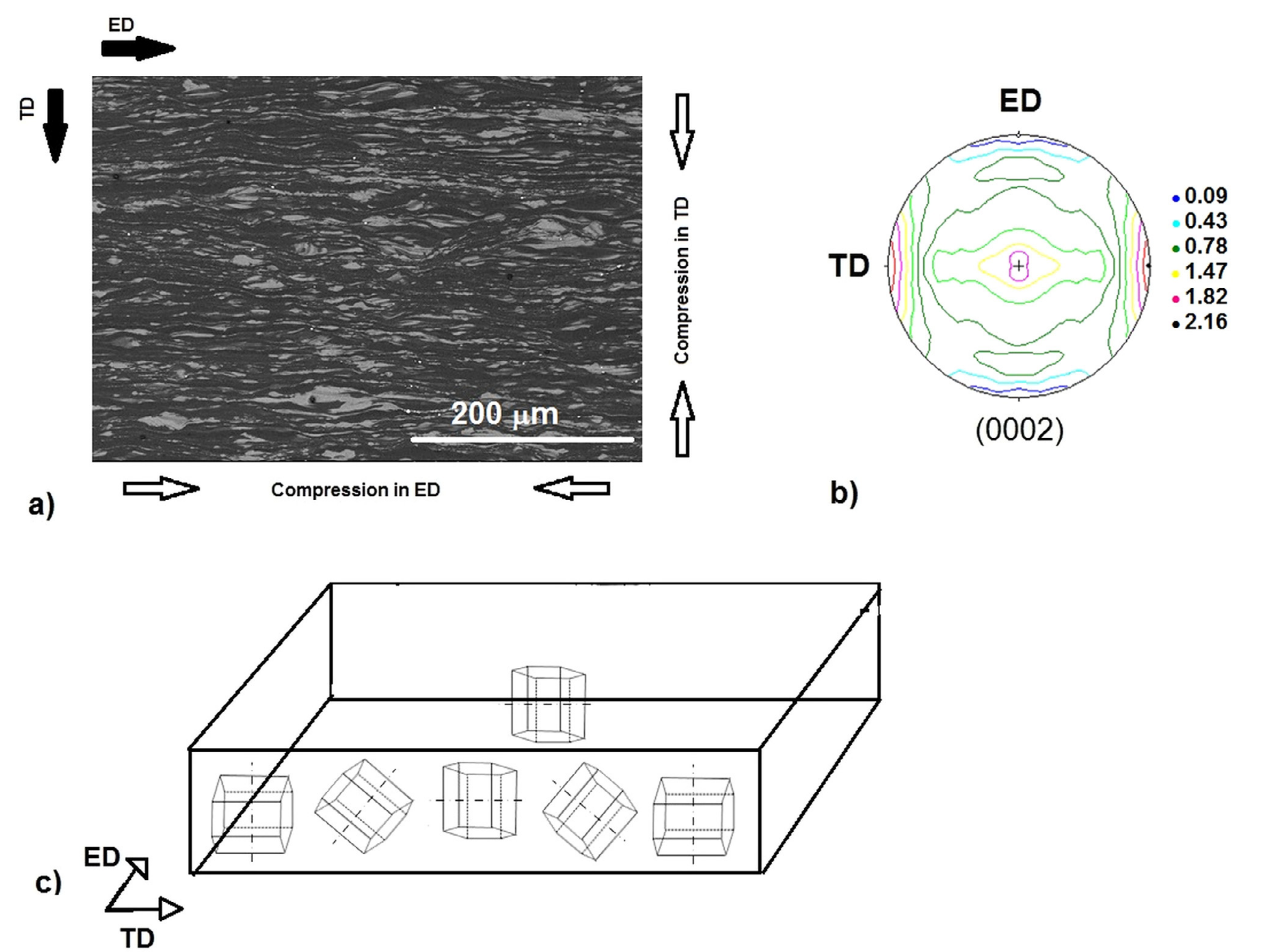

Fig. 1. (a) Microstructure of the extruded material; (b) (0002) pole figure for the extruded state; (c) schematic showing typical grain orientations.

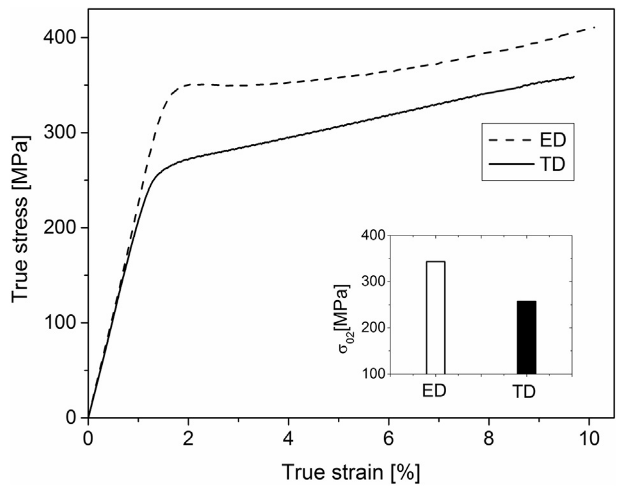

Fig. 2. True stress – true strain curves for loading directions ED and TD. The proof stress values for ED and TD are indicated in the diagram at the right bottom corner of the figure.

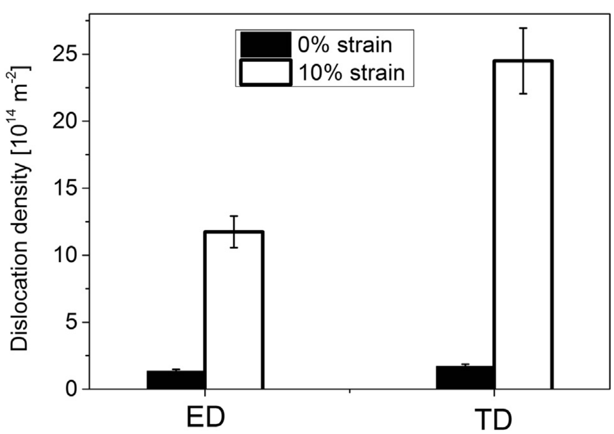

Fig. 3. Change of the dislocation density in the Mg phase due to compression up to the strain of 10%.

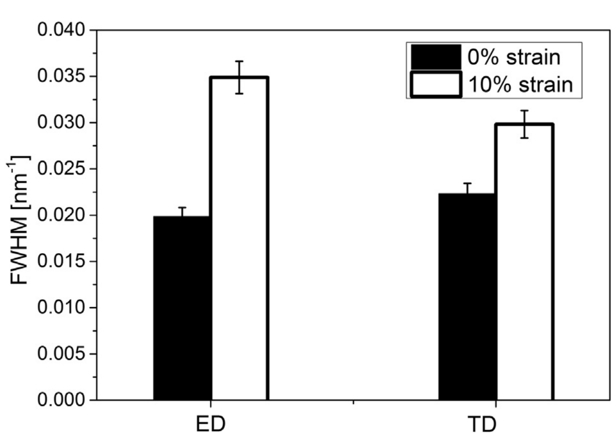

Fig. 4. Increase of the FWHM for reflection $4\bar{2}\bar{2}5$ of the LPSO phase due to 10% compression in ED and TD.

is the easiest slip mode [5]. Due to the texture, the LPSO phase was not favorably oriented for basal slip during compression in ED. In addition, the nucleation of $\{10\bar{1}2\}$ $\langle10\bar{1}1\rangle$ twins was also hindered due to the stacking sequence of close-packed planes and the irregular arrangement of Zn and Y atoms in the LPSO phase [3]. As a consequence, the deformation occurs primarily by the formation of the kink bands which mechanism requires accumulation of high density of dislocations [8]. Moreover, these dislocations might form kink bands walls [9], therefore the kinking process could lead to a significant increment of dislocation density and a fragmentation of the microstructure due to kink walls. Both effects result in a strong increase of FWHM during compression in ED, in accordance with our XLPA results.

Since the triggering of kinking needs high applied stress, our material can be considered as a short-fiber reinforced metal matrix composite, where the LPSO fibers are aligned in ED (cf. Fig. 1a). According to Lilholt [10], the load transfer from the matrix to the reinforcing phase is more effective if the fibers are aligned in the compression direction. This explains the higher yield strength for ED. After reaching a certain stress value, kinking process takes place in this direction. Furthermore, massive extension twinning is expected in the magnesium phase [11]. Both mechanisms might contribute to the stress plateau observed for the compression in ED (see Fig. 2).

In TD the load transfer mechanism is less effective, i.e., the magnesium phase has to bear a larger portion of load. Consequently, this phase is more deformed and the dislocation density is higher than in ED (Fig. 3). Unlike for ED, in sample TD there are LPSO crystallites for which the *c*-axis is not perpendicular to the compression direction (see Fig. 1c). Therefore, basal slip can be activated in many LPSO crystallites during compression in TD without formation of kink bands, as the stress necessary for basal slip in LPSO phase is significantly lower than that for kinking [5]. Finally, it is obvious from Fig. 1c that in TD there are less grains favorably oriented for extension twinning in Mg phase and basal slip can be easily activated which increases the dislocation density.

4. Conclusions

The evolution of the dislocation density in extruded 97% Mg – 2% Y – 1% Zn LPSO alloy during compression in two different directions was investigated. The following conclusions were drawn:

1. The extruded initial material exhibited strong texture in both Mg and LPSO phases in which the close-packed planes were parallel to ED. In addition, the LPSO grains were elongated in ED which yielded a higher compressive proof stress in ED than in TD.
2. After 10% deformation the dislocation density in Mg phase increased by one order of magnitude. The dislocation density in TD was significantly higher owing to the less effective load transfer from the Mg phase to the LPSO grains with elongated morphology in ED.
3. A higher dislocation density and/or a finer microstructure in the LPSO phase were developed during compression in ED than in TD due to kinking. Owing to texture, dislocation slip in close-packed planes can be activated in many LPSO crystallites during compression in TD.

Acknowledgement

The authors are grateful for the support of the Czech Science Foundation under the contract no. 16-12075S, the Hungarian Scientific Research Fund, OTKA, Grant no. K-109021 and the Spanish Ministry of Economy and Competitiveness under project number MAT2012-34135.

References

[1] Y. Kawamura, M. Yamasaki, Formation and mechanical properties of Mg97Zn(1)RE(2) alloys with long-period stacking ordered structure, Mater. Trans. 48 (11) (2007) 2986–2992.
[2] J.F. Nie, Y.M. Zhu, A.J. Morton, On the structure transformation and deformation of long-period stacking ordered phases in Mg-Y-Zn alloys, Metall. Mater. Trans. A 45 (8) (2014) 3338–3348.
[3] D. Egusa, E. Abe, The structure of long period stacking/order Mg-Zn-RE phases with extended non-stoichiometry ranges, Acta Mater. 60 (1) (2012) 166–178.
[4] Y.M. Zhu, A.J. Morton, J.F. Nie, Growth and transformation mechanisms of 18R and 14H in Mg-Y-Zn alloys, Acta Mater. 60 (19) (2012) 6562–6572.
[5] K. Hagihara, N. Yokotani, Y. Umakoshi, Plastic deformation behavior of Mg12YZn with 18R long-period stacking ordered structure, Intermetallics 18 (2) (2010) 267–276.
[6] G. Garces, M.A. Munoz-Morris, D.G. Morris, J.A. Jimenez, P. Perez, P. Adeva, The role of extrusion texture on strength and its anisotropy in a Mg-base alloy composed of the long-period-structural-order phase, Intermetallics 55 (2014) 167–176.
[7] G. Ribárik, T. Ungár, J. Gubicza, MWP-fit: a program for multiple whole-profile fitting of diffraction peak profiles by ab initio theoretical functions, J. Appl. Crystallogr. 34 (2001) 669–676.
[8] J.B. Hess, C.S. Barrett, Structure and nature of kink bands in zinc, Am. Inst. Min. Metall. Eng. 185 (9) (1949) 599–606.
[9] K. Higashida, J. Takamura, N. Narita, The formation of deformation bands in FCC crystals, Mater. Sci. Eng. 81 (1–2) (1986) 239–258.
[10] H. Lilholt, Aspects of deformation of metal matrix composites, Mater. Sci. Eng. A 135 (1991) 161–171.
[11] D. Drozdenko, J. Bohlen, S. Yi, P. Minarik, F. Chmelik, P. Dobron, Investigating a twinning-detwinning process in wrought Mg alloys by the acoustic emission technique, Acta Mater. 110 (2016) 103–113.