Materials Science Forum Vol. 690 (2011) pp 202-205
Online available since 2011/Jun/14 at www.scientific.net

doi:10.4028/www.scientific.net/MSF.690.202

The relation between shear banding, microstructure and mechanical properties in Mg and Mg-Y alloys

Stefanie Sandlöbes[1, a], Igor Schestakow[1, b], Sangbong Yi[2, c], Stefan Zaefferer[1, d], Jingqui Chen[1, e], Martin Friák[1, f], Jörg Neugebauer[1, g] and Dierk Raabe[1,h]

[1]Max-Planck-Institut für Eisenforschung GmbH, Max-Planck-Str. 1, 40237 Düsseldorf, Germany

[2] Helmholtz Centre Geesthacht, Magnesium Innovation Center (MagIC), Max-Planck-Str. Geb. 47, 21502 Geesthacht, Germany

[a]s.sandloebes@mpie.de, [b]i.schestakow@mpie.de, [c]sangbong.yi@hzg.de, [d]s.zaefferer@mpie.de, [e]j.chen@mpie.de, [f]m.friak@mpie.de, [g]neugebauer@mpie.de, [h]d.raabe@mpie.de

Keywords: Mg-RE alloys, deformation, shear banding, EBSD, TEM

Abstract. The formation of deformation-induced shear bands plays an important role for the room temperature deformation of both, Mg and Mg-Y alloys, but the formation and structure of shear bands is distinctively different in the two materials. Due to limited deformation modes in pure Mg, the strain is localized in few shear bands leading to an early failure of the material during cold deformation. Contrarily, Mg-RE (RE: rare earth) alloys exhibit a high density of homogeneously distributed local shear bands during deformation at room temperature. A study of the microstructure of the shear bands by electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) at different strains was performed. These investigations give insight into the formation of shear bands and their effects on the mechanical behaviour of pure Mg and Mg-3Y. Since in pure Mg mainly extension twinning and basal <a> dislocation slip are active, high stress fields at grain resp. twin boundaries in shear bands effect fast growth of the shear bands. In Mg-RE alloys additionally contraction and secondary twinning and pyramidal <c+a> dislocation slip are active leading to the formation of microscopic shear bands which are limited to the boundary between two grains. The effects of shear bands on the mechanical behaviour of pure Mg and Mg-RE alloys are discussed with respect to their formation and growth.

Introduction

Magnesium is the lightest structural metal and exhibits a high density-to-strength ratio, but due its poor cold formability, commercial applications are limited. Already in the 1950s it was shown by Couling et al. [1] that the cold formability of magnesium can be significantly increased by adding rare earth elements (Misch-metal) in the dilute level. He reported the formation of shear bands at 30-35° to the rolling direction and explained the reported "unlimited rollability" in terms of these defects, which were suggested to act as softening regions and by this providing a lower strength and a higher room temperature ductility. Since this time numerous research studies on understanding the mechanisms of shear band formation and the increased ductility of Mg-RE alloys were performed, but until now the reason for this effect remain unclear [2-11]. In a recent study, the present authors showed that the ductility improvement in Mg-Y alloys is related to higher activities of dislocation slip, {10-11} <10-12> contraction and secondary twinning, also referred to as {10-11} {10-12} double twin [12]. It is assumed that these secondary twins trigger shear band formation [12].

Materials and experimental procedures

Cold rolling of pure Mg and Mg 3 wt-% Y was carried out on a laboratory mill with a roll diameter of 100 mm and a rolling speed of 20 rpm. The thickness reduction per pass was controlled not to exceed 4% ($\varphi < 0.05$). Samples for electron backscatter diffraction (EBSD) were prepared by sectioning and polishing the longitudinal ND-RD plane of the cold rolled material (ND: normal direction, RD: rolling direction). Mechanical grinding was followed by 1 µm diamond polishing. Samples were then electro-polished, by using the commercial electrolyte AC2 cooled to 5°C, applying a voltage of 50 V for 90 seconds. For transmission electron microscopy discs with a diameter of 3 mm parallel to the ND plane were prepared by spark erosion. The discs were mechanically grinded to 120 µm thickness and afterwards thinned by electro-polishing using an electrolyte of 3 vol.-% perchloric acid in absolute ethanol. EBSD measurements were performed on a FIB crossbeam 1540XB (Zeiss) field emission type scanning electron microscope with an acceleration voltage of 15 kV. The TEM used for the presented observations was a Philips CM 20 with a LaB6 cathode operated at an acceleration voltage of 200 kV.

Experimental results

While pure magnesium starts fracturing at the edges after 10 % thickness reduction, the Mg 3 wt-% Y alloy can be cold rolled up to a thickness reduction of 40 – 50 % before fracturing starts.

The microstructures after 10 % thickness reduction of pure Mg (a) and Mg 3 wt.-% Y (b) are illustrated in form of KAM[1] maps. The KAM values indicate local misorientations which we interpret in terms of density of geometrically necessary dislocations which itself indicates the local strain value. In pure Mg high strain appears in narrow band-like structures. All other zones exhibit only low internal misorientations. Fracturing along these shear bands start at 10 % thickness reduction in pure Mg. In contrast, the Mg 3 wt-% Y alloy forms homogeneously distributed shear bands, each of them carrying less strain than those in pure Mg.

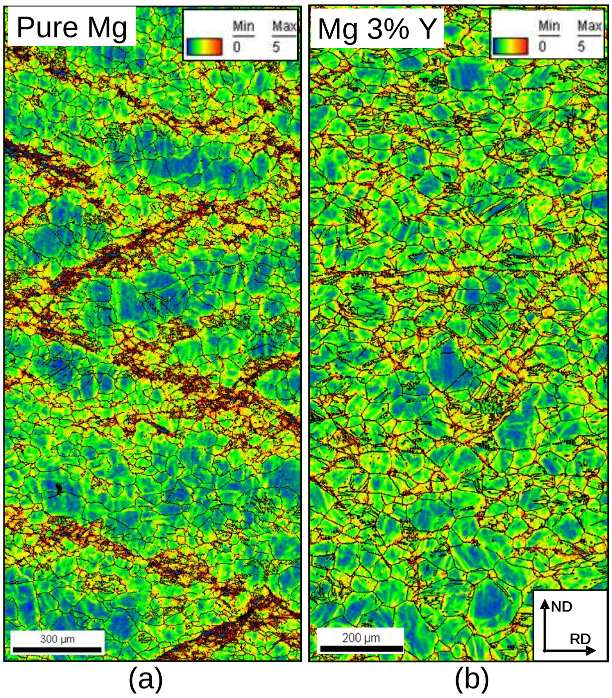

Figure 1: KAM maps of Mg (a) and Mg-3Y (b) after cold rolling up to 10 % thickness reduction

With increasing deformation the amount of local deformation bands and the strain inside them increases until most of the grains exhibit local deformation bands in Mg 3 wt-% Y (Figure 2). At the same time the interior of the grains exhibit a significantly higher homogeneously distributed strain as compared to the interior of the grains in pure Mg at the same strain level (10 % thickness reduction for pure Mg and 40 % for Mg 3 wt-% Y exhibit the same strain level [12]).

Couling et al [1] and others assumed that shear bands in Mg-RE alloys form by double twinning, but until recently no experimental evidence was found [13]. In the present study high resolution orientation microscopy by TEM on 10.6 % cold rolled Mg-3Y was performed, Figure 3. The observed shear bands consist of a large amount of narrow lamellar bands with matrix and {10-11} {10-12} secondary twin orientations. These bands rotate successively around the [11-20] axis reaching a final misorientation with respect to the surrounding matrix of about 15°, Figure 3. All shear bands observed originated from secondary twins.

[1] KAM: Kernel average misorientation, calculated as the average over all misorientation angles determined between the centre and all edge pixels in a kernel of pixels in an orientation map.

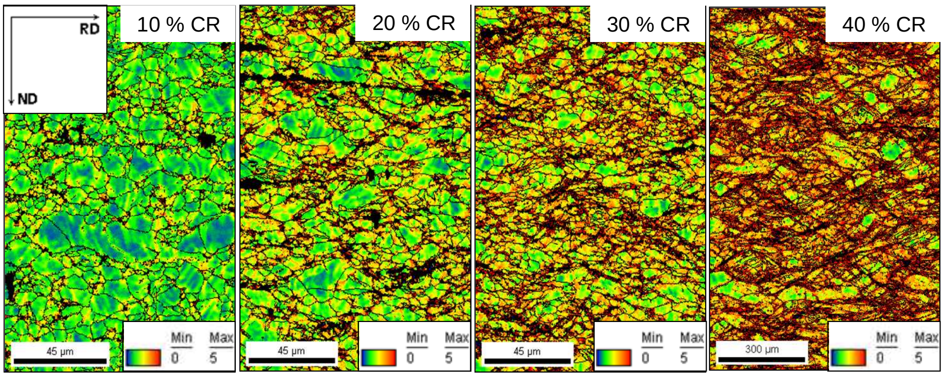

Figure 2: KAM maps of Mg-3Y after 10% (a), 20% (b), 30% (c) and 40% (d) thickness reduction

Discussion

It has been shown by TEM and by EBSD observations (see [12] for details) that in both alloys, pure Mg and Mg-Y, shear bands occur in conjunction with contraction and secondary twins. Further, it has been shown that room temperature deformation in pure Mg is limited to mainly basal <a> slip and tensile twinning, while Mg-Y shows a significantly increased activity of additional deformation modes, i.e. compression twinning, secondary twinning and pyramidal slip of <c+a> dislocations [12]. These facts lead to different shear band formation behavior in the two alloys: In pure Mg the almost exclusive slip leads to high local stress concentrations which are released by the creation of a few contraction-twin related shear bands. In MgY stress concentrations are lower due to additional non-basal slip. At the same time, easier contraction twin formation triggers the creation of more homogeneously distributed shear bands.

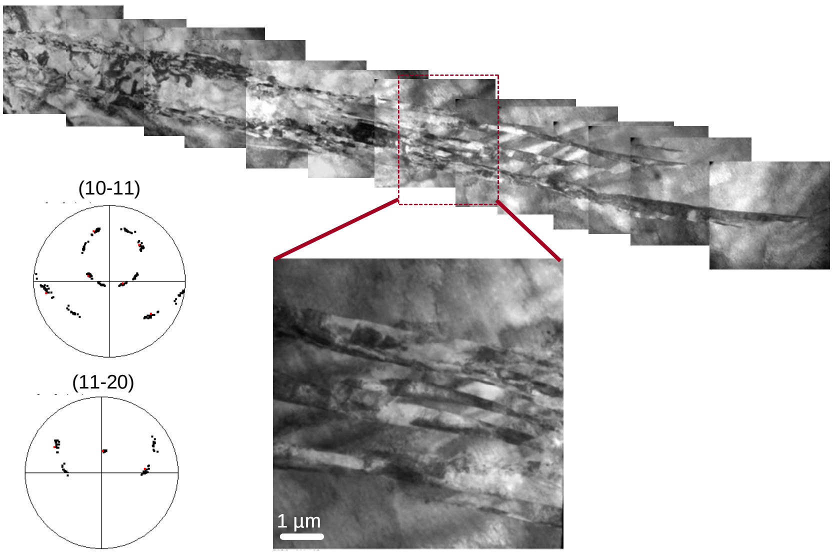

Figure 3: TEM bright-field images of a shear band in deformed Mg 3 wt-% Y; corresponding texture in form of pole figures.

In contrast to previous studies, where it was proposed that shear bands might be the reason for ductility enhancement in Mg-RE alloys (see e.g. [1]), our present study suggests that shear bands in Mg and Mg alloys act as failure mechanisms: In pure Mg the highly localized strain in shear bands causes an early exceeding of the critical strain whereas the more homogeneous distribution of strain and shear bands leads to later failure for MgY.

From our observations on shear bands in pure Mg and Mg-3Y we propose the following interpretation of shear band formation and growth in Mg and Mg-3Y (Figure 4).

Due to sharp basal textures in pure Magnesium, the Schmid factor for basal <a> slip is low under plane strain compression (fig 4(a)). We assume that the resulting high stress fields locally exceed the activation energy for compression and subsequent secondary twinning, providing a <c> deformation component. These twins are favourable oriented for basal <a> slip leading to a pile-up of dislocations at the twin boundaries (fig 4(b)). This pile-up causes high stress fields which trigger the formation of further twins (fig 4(c)).

In Mg-3Y the activation of <c+a> dislocation slip, compression and secondary twinning is much easier. Therefore frequent formation of homogeneously distributed local shear bands occurs, where each shear band carries less strain than the shear bands in pure Mg. *Ab initio* calculations aiming at a quantitative analysis of the underlying atomistic mechanisms and processes are ongoing [14].

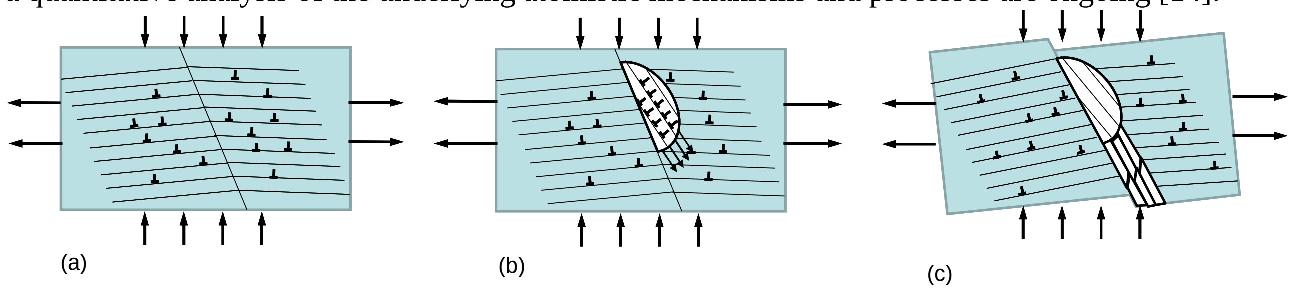

Figure 4: Proposed model for shear band formation in pure Mg and Mg-Y alloys

Conclusions

Y-alloyed Mg shows a significantly increased room temperature ductility compared to pure Mg. In the case of pure Mg strain localization in few shear bands causes early material failure. The observed strain localization is caused by limited deformation mechanisms during room temperature deformation to almost exclusively basal slip and extension twinning. In the Mg-Y alloy the formation of homogeneously distributed local shear bands was observed, which is caused by enhanced activities of further deformation mechanisms including <c+a> slip and contraction and secondary twinning. By this the sensitivity of the material to failure is considerably reduced.

Acknowledgement

The authors gratefully acknowledge the Deutsche Forschungsgemeinschaft (DFG) for financial grant in the project „Verständnis der Duktilität von RE-Mg Legierungen“ (YI103/1-1, ZA278/6-1).

References

[1] S.L. Couling, J.F. Pashak, L. Sturkey: Trans ASM Vol. 51 (1959), p. 94-107

[2] S.R. Agnew, M.H. Yoo, C.N. Tome: Acta Mater. Vol. 49 (2001), p. 4277-4289

[3] S.R. Agnew, J.A. Horton, M.H. Yoo: Metall Mater Trans A Vol. 33 (2002), p. 851-858

[4] J. Bohlen, M.R. Nürnberg, J.W. Senn, D. Letzig, S.R. Agnew: Acta Mater. Vol. 55 (2007), p. 2101-2112

[5] Y. Chino, M. Kado, M. Mabuchi: Acta Mater. Vol. 56 (2008), p. 387-394

[6] Y. Chino, M. Kado, M. Mabuchi: Mater Sci Eng A Vol. 494 (2008), p. 343-349

[7] B. Li, E. Ma: Acta Mater. Vol. 57 (2009), p. 1734-1743

[8] B. Li, E. Ma: Philos Mag. Vol. 89, (2009), p. 1223-1235

[9] B. Li, P.F. Yan, M.L. Sui, E. Ma: Acta Mater. Vol. 58 (2010), p. 173-179

[10] R.K. Mishra, A.K. Gupta, P.R. Rao, A.K. Sachdev, A.M. Kumar, A.A. Luo: Scripta Mater. Vol. 59 (2008), p. 562-565

[11] S. Ando, H. Tonda: Materials Science Forum, Vol. 350-351 (2000), p. 43-48

[12] S. Sandlöbes, S. Zaefferer, I. Schestakow, S. Yi, R. Gonzales-Martinez: Acta Mater. Vol. 59 (2011), p. 429-439

[13] M.R: Barnett, M.D. Nave, C.J. Bettles: Mater Sci Eng A Vol. 386 (2004), p. 205-211

[14] S. Sandlöbes, M. Friák, A. Dick, S. Zaefferer, D. Raabe, J. Neugebauer *(manuscript in preparation).*

Light Metals Technology V
10.4028/www.scientific.net/MSF.690

The Relation between Shear Banding, Microstructure and Mechanical Properties in Mg and Mg-Y Alloys
10.4028/www.scientific.net/MSF.690.202

DOI References

[2] S.R. Agnew, M.H. Yoo, C.N. Tome: Acta Mater. Vol. 49 (2001), pp.4277-4289.
doi:10.1016/S1359-6454(01)00297-X
[4] J. Bohlen, M.R. Nürnberg, J.W. Senn, D. Letzig, S.R. Agnew: Acta Mater. Vol. 55 (2007), pp.2101-2112.
doi:10.1016/j.actamat.2006.11.013
[5] Y. Chino, M. Kado, M. Mabuchi: Acta Mater. Vol. 56 (2008), pp.387-394.
doi:10.1016/j.actamat.2007.09.036
[6] Y. Chino, M. Kado, M. Mabuchi: Mater Sci Eng A Vol. 494 (2008), pp.343-349.
doi:10.1016/j.msea.2008.04.059
[9] B. Li, P.F. Yan, M.L. Sui, E. Ma: Acta Mater. Vol. 58 (2010), pp.173-179.
doi:10.1016/j.actamat.2009.08.066
[10] R.K. Mishra, A.K. Gupta, P.R. Rao, A.K. Sachdev, A.M. Kumar, A.A. Luo: Scripta Mater. Vol. 59 (2008), pp.562-565.
doi:10.1016/j.scriptamat.2008.05.019
[11] S. Ando, H. Tonda: Materials Science Forum, Vol. 350-351 (2000), pp.43-48.
doi:10.4028/www.scientific.net/MSF.350-351.43
[13] M. R: Barnett, M.D. Nave, C.J. Bettles: Mater Sci Eng A Vol. 386 (2004), pp.205-211.
doi:10.1016/j.msea.2004.07.030
[2] S.R. Agnew, M.H. Yoo, C.N. Tome: Acta Mater. Vol. 49 (2001), pp.4277-4289.
doi:10.1016/S1359-6454(01)00297-X
[4] J. Bohlen, M.R. Nürnberg, J.W. Senn, D. Letzig, S.R. Agnew: Acta Mater. Vol. 55 (2007), pp.2101-2112.
doi:10.1016/j.actamat.2006.11.013
[5] Y. Chino, M. Kado, M. Mabuchi: Acta Mater. Vol. 56 (2008), pp.387-394.
doi:10.1016/j.actamat.2007.09.036
[6] Y. Chino, M. Kado, M. Mabuchi: Mater Sci Eng A Vol. 494 (2008), pp.343-349.
doi:10.1016/j.msea.2008.04.059
[9] B. Li, P.F. Yan, M.L. Sui, E. Ma: Acta Mater. Vol. 58 (2010), pp.173-179.
doi:10.1016/j.actamat.2009.08.066
[10] R.K. Mishra, A.K. Gupta, P.R. Rao, A.K. Sachdev, A.M. Kumar, A.A. Luo: Scripta Mater. Vol. 59 (2008), pp.562-565.
doi:10.1016/j.scriptamat.2008.05.019
[11] S. Ando, H. Tonda: Materials Science Forum, Vol. 350-351 (2000), pp.43-48.
doi:10.4028/www.scientific.net/MSF.350-351.43
[13] M. R: Barnett, M.D. Nave, C.J. Bettles: Mater Sci Eng A Vol. 386 (2004), pp.205-211.
doi:10.1016/j.msea.2004.07.030