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Modification of texture and microstructure of magnesium alloy extrusions by particle-stimulated recrystallization

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Conventional magnesium alloy Mg–1Zn–0.4Zr and a modified version of the same alloy containing Nd-based rare earth mischmetal and Y were extruded at 400 °C to study dynamic recrystallization and its role in the microstructure and texture development. Second phase particles in the modified alloy seemed to generate new orientations other than the deformed orientation. Although this occurred within small volume fraction of the material, the respective recrystallizing grains grew up to considerable sizes consuming larger volumes of the extruded microstructure and dominating the bulk texture. The consequent mechanical behavior tested in plane strain compression at room temperature demonstrated improved strain hardening behavior and enhanced ambient formability relative to the conventional alloy due to well-scattered texture and prolonged activity of basal slip within a large volume of the deformed microstructure.

1. Introduction

Conventional magnesium alloys tend to develop sharp prismatic textures during extrusion that align basal planes of deformed grains parallel to the extrusion direction ED. Typically, a single $\langle 10\bar{1}0\rangle$ or double $\langle 10\bar{1}0\rangle$–$\langle 11\bar{2}0\rangle$ fiber orientations can be observed upon extrusion depending on the alloy composition and the extrusion conditions. A conventional extrusion microstructure is usually very heterogeneous with different grain shapes and sizes. It is characterized by a high fraction of large elongated grains (stripes) along the ED, surrounded by regions of fine equiaxed grains. The mechanical response of corresponding specimens tested in compression at room temperature along the extrusion direction often exhibits modest yield stress ($\sigma_y \sim 150$ MPa) and low failure strain below 15% [1]. The reason for such modest mechanical properties was attributed to significant mechanical twinning within the elongated grains and lack of basal slip. Recent studies, e.g. [2–4], have investigated the influence of rare earth (RE) addition on the extrusion texture and microstructure, and the resulting mechanical properties. They reported that for certain RE concentrations and extrusion parameters there was a shift in the orientation peak of the extrusion textures in the RE-containing alloys from $\langle 10\bar{1}0\rangle$ to new positions $\langle 11\bar{2}1\rangle$, $\langle 11\bar{2}2\rangle$ or $\langle 20\bar{2}1\rangle$ parallel to ED, which were termed "RE texture components". These texture components are well oriented for basal slip when tested in the appropriate orientation, which results in substantial increase of ductility and reduction of the tension–compression asymmetry typical for conventional wrought magnesium. The exact origin of the observed texture modification is still a subject of considerable debate, but there is literature support for *collective* mechanisms responsible including shear banding and shear band nucleation of new grains [4–6] and grain boundary pinning [2,7] that affect the boundary mobility of recrystallization nuclei and could result in new recrystallized orientations.

There are, however, other possible scenarios, where microalloying additions of RE elements to conventional magnesium alloy extrusions can significantly weaken the $\langle 10\bar{1}0\rangle$ extrusion texture, and enhance the ambient formability without generating RE texture components. The current study investigates two extruded magnesium alloys, conventional ZK10 alloy and a modified version of the same alloy, containing very low concentrations of Y and Nd-based rare earth mischmetal, with the principal objective of reviewing the role and importance of recrystallization mechanisms in dictating the evolution of extrusion texture and microstructure with and without the presence of RE elements. The incorporation of yttrium and neodymium-based RE mischmetal is intended to affect recrystallization, yielding a modified texture and microstructure that would promote stable plastic flow necessary for improved formability of the material.

By characterizing the aforementioned RE/Y-contribution to recrystallization two possible effects can be expected: (i) the resulting recrystallization texture has unique or unusual positions

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Table 1
Chemical composition of the investigated ZK10 and ZWEK1000 alloys (wt%).

Alloys	Zn (%)	Zr (%)	Nd (%)	Ce (ppm)	Gd (ppm)	Y (%)	Mg
ZK10	1.51	0.41	–	–	–	–	Rest
ZWEK1000	1.47	0.38	0.20	31	11	0.19	Rest

of maximum orientations that are distinct from the deformation orientation (RE texture) or (ii) has a close position to the maximum orientation as the deformation texture, yet with a significant drop of texture intensity and large increase of texture spread. The experimental findings of the present study will determine which effect applies to the investigated materials and rationalize the underlying mechanisms.

2. Experiments

The chemical composition of the investigated alloys is given in Table 1. The alloy rods were uniaxially hot extruded at 400 °C and an extrusion velocity of 1 mm/min. The extrusion ratio and the final extruded rod diameter were $R=9$ and $d=50$ mm, respectively. Rectangular specimens 14 mm (LD) × 10 mm (TD) × 6 mm (CD) were cut from the extruded rods with the longitudinal direction LD parallel to the extrusion direction ED, and tested in plane strain compression (PSC) in a channel-die at room temperature and $10^{-3}\,s^{-1}$ constant strain rate to examine the ambient formability of the two extruded materials (CD: compression direction; TD: transverse direction). Metallographic sample preparation was carried out by conventional grinding and diamond polishing. For electron backscatter diffraction (EBSD) measurements the specimens were additionally electro-polished at 2 V for 45 min using a 5:3 solution of ethanol and orthophosphoric acid. X-ray textures were determined by measuring incomplete pole figures ($5^\circ \le \alpha \le 75^\circ$) using Co K$\alpha$ radiation at 40 kV and 30 mA. A set of six measured pole figures ($\{10\bar{1}0\}$, (0002), $\{10\bar{1}1\}$, $\{10\bar{1}2\}$, $\{11\bar{2}0\}$ and $\{10\bar{1}3\}$) was used to calculate the orientation distribution function (ODF) using the MTEX toolbox [8]. EBSD orientation measurements using Channel 5 data acquisition software was carried out in a scanning electron microscope (SEM) equipped with a field emission gun. Texture measurements in the PSC specimens were performed on the LD–TD plane parallel to the extrusion direction at $\varepsilon=0$ (starting condition) and $\varepsilon_f=-0.22$ (fracture). The textures in the current study are represented by means of recalculated (0002) pole figures with respect to the extrusion geometry with LD=ED, CD=RD, TD=RD; RD: radial direction.

3. Results and discussion

3.1. Extrusion microstructures

Fig. 1a and b shows representative EBSD micrographs of the extrusion microstructures of both ZK10 and ZWEK1000 alloys in terms of inverse pole figure (IPF) maps. The corresponding misorientation angle distributions (MAD) of grain boundaries are shown in Fig. 1c and d. Obviously, the addition of Nd-mischmetal and Y affects the recrystallization behavior of the alloy resulting in a different extrusion microstructure with respect to grain morphology and orientation relative to that of the ZK10 alloy. The most striking feature is that the large elongated grains in the ZK10 alloy were replaced by coarse equiaxed grains in the RE/Y-containing alloy. The fraction of fine equiaxed grains (smaller than 10 μm) was comparable in both alloys. The favorable modification of the extrusion microstructure in the ZWEK1000 alloy correlated well with the peak shift of misorientation angles from low angle to high angle boundaries, shown in Fig. 1c and d. In the extruded ZK10 alloy the highest misorientation peak was located at 5°, corresponding to predominant proportion of recovered subgrain structures within the unrecrystallized elongated grains. By contrast, the highest misorientation peak in the ZWEK1000 extruded alloy was associated with high angle boundaries at 30°, referring to a common 30° [0001] misorientation relationship during growth of recrystallized grains in hexagonal materials (e.g. [9–11]). In addition to enhanced recrystallization at the expense of deformation structure there was a pronounced increase in the range of orientations of growing recrystallizing grains diverging the recrystallization texture from the sharp $\langle 10\bar{1}0 \rangle \parallel$ ED orientation that dictated the traditional extrusion texture in the ZK10 alloy.

3.2. Ambient formability during PSC tests

The variation of stress and strain of both extruded alloys during subsequent PSC deformation at room temperature and $10^{-3}\,s^{-1}$ strain rate is shown in Fig. 2. The term true strain refers to a logarithmic strain defined by $\varepsilon_t=\ln(1+\varepsilon)$. Surprisingly, the mechanical response of the two materials indicated a very similar flow behavior despite different extrusion microstructures. Both flow curves exhibited significant hardening with increasing deformation strain, attaining a maximum at different strain values followed by short work softening and localized shear failure (see insets in Fig. 2) at different strains ($\varepsilon_f \sim -0.012$ for ZK10 and $\varepsilon_f \sim -0.022$ for ZWEK1000). The ZWEK1000 alloy was expected to yield at lower stresses as a result of PSN texture softening that disposes more grains favorable for basal slip. However, the interaction of dislocations with second phase particles and RE/Y solutes during plastic deformation seemed to keep the yield strength of the alloy similar to that of the original alloy ZK10.

3.3. PSC texture development and the role of basal slip

The PSC texture development for the ZWEK1000 specimen is shown in Fig. 3 by the starting (extruded) condition and upon PSC deformation to failure. It might be somewhat confusing that the extrusion texture in Fig. 3a does not show a typical (0002) fiber at the equator but this is due to the current choice of projection plane, with ED at the top of the projection and not in the center. Either way, the characteristic alignment of basal planes with the primary flow direction during extrusion is not affected by the choice of projection plane, and thus, the basal poles (c-axes) in the current (0002) pole figure appear aligned perpendicular to the extrusion direction ED. However, and as indicated earlier in Fig. 1, the addition of RE and Y to the ZK10 alloy alters the common type of the extrusion texture and its strength. For a typical extrusion texture, one would expect a continuous (0002) fiber distributed homogeneously between RD–RD. Instead, the (0002) fiber shown in Fig. 3a seemed to contain a "localized" component E and a "scatter" component S. The latter is characterized by a vast angular spread of basal poles from the position of E component with maximum intensity toward the center of the pole figure. Another impact of RE/Y addition is the weakening of the – usually sharp – $\langle 10\bar{1}0 \rangle \parallel$ ED component in the prismatic pole figure by reducing its intensity to four multiples of random (Fig. 3a).

The extrusion texture described above provided a good basis for subsequent PSC deformation at room temperature since the basal poles of the scatter component were well-oriented for deformation by basal slip when the compression direction CD was set perpendicular to ED (compression was applied