Tailoring the texture of an extruded Mg sheet through constrained groove pressing for achieving low mechanical anisotropy and high yield strength

M.M. Hoseini-Athar a,b, R. Mahmudi a,*, R. Prasath Babu b, P. Hedström b

a School of Metallurgical and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran
b Department of Materials Science and Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

ABSTRACT

Constrained groove pressing (CGP) was utilized to modify the texture and mechanical properties of extruded Mg–2Gd–3Zn sheet with typical TD (transverse direction)-split texture and pronounced mechanical anisotropy. The texture evolution sequence during CGP was studied and it was observed that a new (1211) component with basal poles rotated 15°–30° toward the extrusion direction (ED) is introduced during CGP, as a result of simultaneous activation of basal and prismatic slip and shear deformation. Finally, a non-basal ED–TD double split texture was obtained after the CGP process, resulting in significantly reduced mechanical anisotropy.

The application of magnesium alloys has been restricted due to their poor room temperature formability and inherent anisotropy originating from the hexagonal closed-packed (hcp) structure [1,2]. It is well known that Mg–rare earth (RE)–Zn alloys offer improved ductility owing to the weakened basal texture, usually formed in conventional Mg alloys, and activation of non-basal slip systems [3,4]. These alloys commonly develop a distinct texture component, known as the “TD-split” texture, with the basal poles tilted −40° toward the transverse direction (TD) [5,6]. Previous reports stated that the TD-split texture is formed due to the randomly oriented nucleation of grains at shear bands [7], and high activity of prismatic slip [8]. Regardless of the origin of formation, this type of texture can lead to a strong anisotropy in mechanical properties and much different yield strength values along various directions [9,10].

Numerous attempts have been made to modify the texture of Mg alloys, however, only a few studies have focused on tailoring the TD-split texture to reduce the mechanical anisotropy of Mg–RE–Zn alloys. Pan et al. [10] modified the TD-split texture to an even distribution of basal poles −40° around the normal direction (ND) through cross-rolling. Griffiths et al. [11] studied the effect of cold rolling strain path and subsequent annealing on texture evolution of the hot rolled ZEK100 alloy. They reported that rotating the sheet between cold rolling passes suppressed the TD-split texture, due to the prevention of shear band formation. By using a final heavy reduction rolling pass, Shi et al. [12] obtained an “oblique-line-split” texture with very low planar anisotropy, instead of the TD-split texture. These approaches are though based on conventional rolling processes, which cannot be applied when a thickness reduction is undesired. In addition, a modification of the TD-split texture is usually followed by a decrease in yield strength owing to texture softening [10]. Therefore, simultaneous texture modification and grain refinement can be a potential approach to modify texture without significant softening [13,14]. This can be achieved by constrained groove pressing (CGP) process.

As a severe plastic deformation (SPD) technique, CGP imposes significant grain refinement by repetitive corrugation and flattening of sheets without reduction in thickness [15]. Despite a few studies on microstructure and mechanical properties of CGP processed Mg alloys [16,17], there is a lack of information on the texture evolution of Mg alloys during the CGP process. Due to imposed shear strains during CGP, it is expected that the developed texture can be similar to that observed after equal channel angular pressing (ECAP), i.e. rotation of basal poles away from the pressing direction [18]. The present study investigates the effect of CGP on texture and how texture influences the mechanical properties of an extruded Mg–Gd–Zn alloy sheet after the CGP process.

The alloy with a nominal composition of Mg–2Gd–3Zn (wt%) was prepared by mixing pure Mg and Zn with an Mg–20 wt% Gd master alloy at 1053 K under a protective covering flux.
followed by pouring in a steel mold preheated to 623 K. After homogenization at 773 K for 10 h, the hot extrusion process with an extrusion ratio of ~6 was carried out at 653 K, and 3 mm-thick sheets were obtained. The CGP process was performed on 108 mm × 108 mm × 3 mm sheets at 573 K using dies with a groove width of 3 mm and a groove angle of 45°. The schematic representations of the CGP dies and the first two cycles of the CGP process (each cycle comprised of 4 pressings) are given in Fig. 1. Based on the die geometry, the first pressing results in an effective strain of 0.58 in the shear zones. During the second pressing, an additional strain 0.58 is exerted. By rotating 180° around ND and repeating the first and the second pressings, a uniform strain of 1.16 is obtained throughout the sheet. During CGP, the ED is perpendicular to the groove direction. Polytetrafluoroethylene (PTFE) sheet was used as lubricant.

A JEOL JSM–7800F scanning electron microscope (SEM) equipped with a Bruker e-flashXRD electron backscatter diffraction (EBSD) detector was used for microstructural and micro-textural characterization. The details of sample preparation can be found in [19]. Grain boundaries with a misorientation angle larger than 10° were defined as high angle grain boundaries. Since EBSD results were taken from only one deformation zone, macro-texture measurements were also performed on the ED–TD plane using a Rigaku Ultima IV X-ray diffraction (XRD) instrument. Tensile specimens with a gage length of 6 mm and a width of 4 mm were cut along ED, TD and 45°. A SANTAM STM-50 universal tensile testing machine was used to perform the room temperature tensile tests at an initial strain rate of 1 × 10⁻³ s⁻¹.

Fig. 2 demonstrates the EBSD orientation maps and inverse pole figures (IPFs) and XRD pole figures (PF) taken from the ED–TD plane of the studied materials. An equiaxed microstructure with a mean grain size of 9.6 µm is observed for the extruded material. After 1 cycle of CGP, partial dynamic recrystallization (DRX) results in the formation of fine DRXed grains, mostly at the grain boundaries. By further straining up to 2 cycles, complete DRX takes place, leading to a fully DRXed microstructure with a grain mean size of 4.6 µm. This clearly shows the high grain refining capability of the CGP process.

The texture data presented as PFs and IPFs in Fig. 2, reveals a typical TD-split texture (denoted as A-component) with basal poles tilted ~40° toward TD (PF in Fig. 2a) and ⟨100⟩||ED orientation (IPF in Fig. 2a) for the extruded material. Previous studies have reported that this texture component originates from the increased activity of non-basal slip, particularly prismatic slip, due to addition of Zn [6,8]. After 1 cycle of CGP, a distinct rotation of basal poles toward ED is observed (denoted as B-component), with basal poles tilted ~15°–30° toward ED and ⟨1210⟩||ED orientation. The emergence of this new component can be attributed to the simple shear deformation during CGP, similar to that observed after ECAP. During ECAP, the basal planes are inclined and realigned with the shear plane, leading to a rotation of basal poles away from the pressing direction, with a magnitude dependent on the angle of the shear plane [20,21]. Considering the 45° groove angle in CGP, it is expected that a 45° tilt away from the ND can be observed for the CGP processed specimen. However, a smaller tilt angle of ~15–30° is observed (Fig. 2). The smaller tilt angle toward ED can be due to: (i) the reverse shear during the flattening stage, compensating a portion of the deformation, and (ii) bending (instead of shear) around the die corners, changing the orientation of the shear plane. For the 2 cycle CGP processed material, the tilting toward ED is intensified and a clear ED–TD double split texture is obtained. This also results in the formation of ⟨1211⟩||ED orientation. As can be seen in Fig. 2d, the orientation of the B-component observed for the CGP processed conditions is −⟨1225⟩⟨1100⟩, which is very different from the A-component, −⟨2318⟩⟨1211⟩, observed after extrusion.

For better demonstration of the texture evolution during CGP, ED–ND cross-sectional orientation maps, IPFs and EBSD PFs after extrusion and the first and the second pressings are presented in Fig. 3. It should be noted that the EBSD PFs were obtained from only one shear zone. For the extruded material (Fig. 3a), the basal poles are perpendicular to the ED with the ⟨1000⟩||ED, and ND is oriented ~30°–40° away from the (0002). Comparing Figs. 3a–c clearly shows that the A-component present in the extruded sample is transformed to the B-component through a sequential texture evolution, schematically demonstrated in Fig. 3d. According to the texture results, during the groove pressing, the basal poles are rotated away from TD toward ND, evolving into the A’-component with −⟨1210⟩ − ⟨1211⟩||ED and a narrow distribution of the basal poles around ND (ND IPF in Fig. 3b). This is accompanied by a 30° rotation from ⟨1100⟩ (Fig. 3a) to ⟨1210⟩ (Fig. 3b), which is schematically shown in the IPF in Fig. 3d.

The intragranular misorientation axis (IGMA) was analyzed to elucidate the active slip modes, considering grain boundaries with misorientations in the range of 2°–5° [22]. More details on IGMA analysis can be found in [23]. The result for the groove pressed specimen presented in Fig. 3b shows that IGMA is concentrated around both ⟨uvw⟩0 and ⟨0001⟩. IGMA along ⟨uvw⟩0 is an indicator of the activity of basal and pyramidal II slip systems, while lattice rotation around ⟨0001⟩ suggests the contribution of prismatic slip mode [22]. Therefore, it is inferred that the A’-component is evolved through combined rotation around the ⟨1100⟩ and ⟨0001⟩ axes, as a result of basal and prismatic slips. Transformation to A’ is followed by an ~15°–45° rotation of basal poles away from ND toward ED. This is the typical simple shear texture, in which the basal poles are gradually rotated and realigned with the macroscopic shear plane. Similar texture components have been
previously reported after ECAP, which is also associated with simple shear deformation [24]. During the shear deformation, maximum rotation is observed when the Burgers vector of the active slip system is perpendicular to the shear direction [20]. Since this is not the case for most grains here, a broad distribution of rotation angles is achieved.

During the second pressing, which flattens the grooved sheet, reverse shear takes place, in which the shear plane remains the same but the shear direction is reversed. As a result of reverse shear, the tilt angle might be slightly reduced to 15°–30° (Fig. 3c), accompanied by the reappearance of the A-component with lower intensity. Slip in a reverse direction, caused by the reverse shear, can lead to reverse motion of dislocations, resulting in a reduction in the intensity of the B-component. It should be mentioned that there was no substantial difference in the texture of the deformed and recrystallized grains, i.e. the recrystallized grains inherit the deformed texture. Similar results indicating that the recrystallization texture of Mg alloy is close to the deformation texture (with some weakening) have been previously reported [24].

Although the above sequence explains the formation of the B-component, only one part of the B-component demonstrated in Fig. 2 is evolved during the first and the second pressings. Fig. 1 suggests that the shear direction in the neighboring zones can be opposite. As a result, the third and the fourth pressings result in the same sequential texture evolution, but in the opposite direction, while the zones deformed during the first and the second pressings preserve the evolved texture. Since XRD PFs include several deformation zones, an ED–TD double split texture, i.e. both parts of the B-component, is observed in the PFs shown in Figs. 2b and c. By continuing the CGP process to 2 cycles, the higher magnitude of imposed strain intensifies the B-component, leading to a more pronounced (1211) orientation, as shown in Fig. 3d.

In order to investigate the effect of the texture on mechanical properties and yield anisotropy, tensile tests were performed along ED, 45° and TD. Fig. 4 shows the engineering stress-strain curves and the Schmid factor (SF) distribution for the basal slip. The results are summarized in Table 1. As can be seen, the tensile

**Table 1**

<table>
<thead>
<tr>
<th>Condition</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>εy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED 45° TD</td>
<td>ED 45° TD</td>
<td>ED 45° TD</td>
</tr>
<tr>
<td>Extruded</td>
<td>172 133 121</td>
<td>263 248 231</td>
<td>35 37 46</td>
</tr>
<tr>
<td>CGP–1 cycle</td>
<td>185 146 136</td>
<td>280 269 270</td>
<td>30 33 34</td>
</tr>
<tr>
<td>CGP–2 cycles</td>
<td>189 205 198</td>
<td>283 274 273</td>
<td>32 33 34</td>
</tr>
</tbody>
</table>
Fig. 3. EBSD orientation maps (ED–ND), inverse pole figures, EBSD pole figures and selected intragranular misorientation axis (IGMA) map after (a) extrusion, (b) 1st pressing, and (c) 2nd pressing. (d) Texture evolution during the 1st and the 2nd pressings.

curves of the extruded material exhibit a pronounced difference in terms of yield strength and elongation in different directions. For instance, a high yield strength of 172 MPa and a low elongation of 34% along ED are in contrast with a much lower yield strength of 121 MPa and a high elongation of 47% along TD. After the 2 cycles of CGP, the yield anisotropy is clearly reduced, so that the difference between the yield strength along ED and TD decreases from 51 MPa to 9 MPa and the difference in elongation values decreases from 13% to 1%. The difference in the yield strength is due to the particular texture observed for each specimen, influencing the SF value for the basal slip. For the extruded specimen, the TD-split texture results in much higher SF values along TD compared to ED, as shown in Fig. 4b. For this texture component, the basal poles are perpendicular to ED, leading to low SF values. Therefore, a much higher yield strength is observed along ED. Yan et al. [25] have also reported yield differences of 37 MPa and 65 MPa for Mg–1Gd–1Zn and Mg–1Gd–2Zn alloys with TD-split texture, respectively. After the CGP process, the B-component with basal poles tilted toward ED is formed, increasing the SF value along ED. For the 2 cycle CGP processed specimen, the SF distribution along various directions are rather similar, leading to a less significant yield strength anisotropy.

As reported earlier, the development of the shear-type texture usually increases the SF value, leading to a significant decrease in the yield strength through texture softening [26]. Considering the yield strength values along ED, it is observed that despite an in-
crease in the SF value due to CGP, the yield strength has not substantially dropped. This is due to the grain boundary strengthening caused by grain refinement during CGP. Based on the Hall-Petch relationship, a 5 μm decrease in grain size after 2 cycles of CGP, results in ~40–50 MPa increase in the yield strength (considering a Hall-Petch coefficient of ~0.28–0.32 MN.m \(^{-3/2}\) for Mg alloys [27]). Therefore, it can be expected that texture softening is mostly compensated by grain refinement, as only a 17 MPa increase in yield strength (along ED) is observed after 2 cycles of CGP. On the other hand, the yield strength values along TD indicate an increase in the yield strength from 121 MPa for the extruded specimen to 198 MPa for the 2 cycle CGP processed specimen due to grain refinement and slight texture hardening (caused by a small decrease in SF). The decreased yield anisotropy obtained by the CGP process here is as promising as that achieved by cross-rolling for the Mg–2Gd–2Zn alloy [10]. In addition, the ECAP process, previously used for reducing anisotropy, is not usually suitable for sheets [28]. Therefore, the CGP process can be a good choice for the modification of the texture and mechanical properties of the Mg sheets.

In summary, texture evolution during the CGP process of the Mg–2Gd–3Zn alloy was investigated by EBSD analysis and a relation between texture and mechanical properties was established. It was observed that the CGP process results in significant grain refinement, and the initial TD-split texture in the extruded sheet is transformed into an ED–TD double split texture through a distinct texture evolution sequence. This texture component is formed due to the shear deformation. The particular ED–TD double split texture leads to a more uniform distribution of Schmid factor values, decreasing the mechanical anisotropy. The suggested process can be used to alleviate the significant mechanical anisotropy, usually observed in Mg–RE–Zn alloys with TD-split texture.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**