Review Article

Influence of Grain Size and Texture on the Yield Strength of Mg Alloys Processed by Severe Plastic Deformation

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Severe plastic deformation (SPD) has been widely employed to refine the grain size of Mg alloys, with the main objective to improve the strength and ductility of Mg alloys, since the well-known Hall-Petch equation suggests that a decreased grain size leads to an increased yield strength. However, the yield strength of Mg alloys processed by SPD is often decreased even though the grain size is effectively reduced. The abnormal flow behavior in Mg alloys processed by SPD has attracted great attention although this mechanism is still unclear, due to its complex and extensive influence factors. In this paper, the relationships between the processing conditions, grain refinement, and mechanical properties of the SPD treated Mg alloys are reviewed, with the emphasis on the effects of grain size and texture on the yield strength.

1. Introduction

The use of magnesium alloys in industrial fields, such as the automotive and bicycle industries, has gained much attention due to their energy-efficient properties which include low density and high specific strength. However, the application of magnesium alloy is greatly limited for its relatively low strength and plasticity. An effective way to improve the mechanical properties of magnesium alloy is to refine the grains [1, 2]. For the polycrystalline materials, the yield stress σ_y varies with average grain size d according to Hall-Petch relationship ($\sigma_y = \sigma_0 + k_y \cdot d^{-1/2}$, where σ_0 is a friction stress required to move dislocations and k_y is the stress concentration factor). At room temperature, the Hall-Petch slope k_y value for pure magnesium is quite higher than that of pure aluminum, so it is much more effective to enhance the strength of Mg alloys by simply refining the grain size [3].

Severe plastic deformation (SPD) has been a widely used method to fabricate ultrafine grained metals and alloys, by introducing an ultralarge plastic strain into a bulk metal without any significant change in the overall dimensions

[4, 5]. Among the various SPD techniques, equal channel angular pressing (ECAP) and cyclic extrusion and compression (CEC) are attractive due to their characteristics of processing the relatively large bulk samples [5–9]. Up to now, ECAP processing has received the most attention from researchers than other SPD processes, including CEC. However, CEC seems to be more promising for industrial applications due to its continuous process. Moreover, it is very suitable for refining grains of hard-to-deform metals, for example, magnesium alloys, since it imposes three-dimensional compression stresses during processing [10].

It has been widely proved that the microstructures of Mg alloys can be dramatically refined by the ECAP and CEC processes [1, 2, 6, 10–14]. Nevertheless, the ECAP and CEC processed Mg alloys often showed a decreased yield strength even though grain size is effectively reduced, and this abnormal result has been attributed to the effect of the texture that developed during ECAP and CEC processing [6, 15–23]. However, researchers still report an increase in yield strength of fine-grained Mg alloys processed by ECAP and CEC [13, 24–32]. These discrepancies indicate that the effects of ECAP

FIGURE 1: Schematic illustration of the ECAP process [33].

FIGURE 2: Schematic illustration of the CEC facility and procedures: (a) initial state, (b) extruding by Ram A, (c) end of Ram A involvement, (d) reverse extruding employing Ram B, (e) end of Ram B involvement, and (f) final extrusion to obtain a rod [6].

FIGURE 3: Grain size of Mg alloys as a function of the accumulated strains of (a) CEC and (b) ECAP.

and CEC processes on the mechanical properties of Mg alloy are complicated. In this paper, the relationships among the processing conditions, grain refinement, and mechanical properties of the Mg alloys processed by ECAP and CEC are discussed, with the emphasis on the effects of grain size and texture on the yield strength.

2. The Principle of ECAP and CEC

The process of ECAP was first introduced by Segal and his coworkers in the 1970s and 1980s [40]. Figure 1 shows a schematic illustration of a section through the ECAP facility [33], with the die consisting of two channels, equal in cross-section. The ECAP is conducted by pressing the sample through the die using a plunger. The strain accumulated in ECAP is given by the expression [41]

$$\varepsilon_N = \frac{N}{\sqrt{3}} \left[2\cot\left(\frac{\phi}{2} + \frac{\psi}{2}\right) + \psi\operatorname{cosec}\left(\frac{\phi}{2} + \frac{\psi}{2}\right) \right], \quad (1)$$

where N is the number of passes through the die, ϕ is the angle of intersection of two channels, and ψ is the angle subtended by the arc of curvature at the outer point of intersection. When $\phi = 90^\circ$ and $\psi = 0^\circ$, the strain of ~ 1 is introduced into the sample in each pass through the die.

The CEC processing was proposed by Richert et al. [42], which is performed by pushing a sample from one cylindrical chamber with a diameter D into the second chamber with the same dimensions, through a die having a smaller diameter d , as illustrated in Figure 2 [6]. This will form one “cycle” of the CEC process. During the final extrusion cycle, the opposite ram is removed in order to release the rod. The equivalent

strain ε generated in the specimen after N cycles of CEC processing is given by the following equation [10, 42]:

$$\varepsilon = 2N \ln \frac{D^2}{d^2} - \ln \frac{D^2}{d^2} = 2(2N - 1) \ln \frac{D}{d}. \quad (2)$$

3. Microstructures of ECAP and CEC Processed Mg Alloys

3.1. Grain Refinement. Figure 3 shows the grain refinement of Mg alloys processed by ECAP [22, 38, 43] and CEC [6, 10, 13, 14, 37]. The average grain sizes were measured primarily by the linear intercept method. It can be seen that both the ECAP and CEC are efficient grain refinement methods for Mg alloys. Grain refinement takes place mainly during early stage of ECAP and CEC, and the grain size decreases slowly with further increasing strain till a balance occurs between the grain refinement and grain growth. Compared with the ECAP processed (ECAPed) Mg alloys, the CEC processed (CECed) Mg alloys exhibit a finer grain size, under the similar deformation conditions of accumulated strain and temperature. This may be due to the CEC processing which introduces a large hydrostatic compressive stress into the alloy [10]. In addition, the finer microstructures can be achieved by a lower deformation temperature.

Table 1 summarizes the data on grain refinement and yield strength for Mg alloys after ECAP and CEC processing. It can be seen that ultrafine grained Mg alloys with the grain size below $1 \mu\text{m}$ can be produced by ECAP and CEC processing. Moreover, the finer the initial grain size is, the finer the final grain size will be. However, even though the grain size is reduced effectively, some CECed [6, 10, 37] and ECAPed [18, 21, 22, 29, 34–36, 38] Mg alloys showed a decreased yield

TABLE 1: Summary of the grain size and yield strength of Mg alloys processed by ECAP and CEC.

Material	Processing	Strain (pass number)	Deformation temp./°C	Initial $d/\mu\text{m}$	Final $d/\mu\text{m}$	Initial $\sigma_{0.2}/\text{MPa}$	Final $\sigma_{0.2}/\text{MPa}$	Ref.
AZ31	Ex + ECAP + AN	8	200	~15	~15	~220	~110	Mukai et al. [18]
	Ex + ECAP	6	200	0.7	0.7	265	217	Lin et al. [34]
	Cast + ECAP	4	200	380	1~3	120	210	Janecek et al. [26]
	Ex + ECAP	4	200~320	48.3	2.5	200.5	180.3	H. K. Kim and W. J. Kim [35]
	Ex + ECAP(B_C)	4.4	250	11	5	201	93	Seipp et al. [36]
	Ex + ECAP(C)	8.8	250	11	5.5	201	72	
	Ex + ECAP(B_C)	(6P)	280	24	4.8	202	110	Kim and Jeong [21]
	Ex + ECAP(A)				1.9	221		
	Ex + ECAP(B_C)	(4P)	200	7	1.8	142	138	Ding et al. [17]
	Ex + ECAP(C)			1.7		118		
AZ31	Ex + CEC	10.5	300	25	1.77	189	140	Chen et al. [37]
				20.2	1.6	136	109.2	
	AZ31 - 0.6RE			17.2	1.3	~146	129.8	
	AZ31 - 0.6Ca	4	200	13.7	1.9	~160	148.2	Masoudpanah and Mahmudi [38]
	AZ31 - 0.3RE - 0.3Ca			15.1	1.2	~150	134.6	
AZ31				29	2.5	111.7	117.5	
	AZ31 + 0.3TiAl			19	2.1	115.5	121.1	
	AZ31 + 0.6TiAl	~4	220	16	2.0	120.2	125.3	Torbati-Sarraaf and Mahmudi [27]
	AZ31 + 1.0TiAl			14	1.9	124.2	126.4	
				24.4	8.4	215	154	
AZ61	Ex + ECAP(B_C)			>400	23	154	125	Kim et al. [22]
	Ex + AN + ECAP(B_C)	8	275	>400	22	154	163	
	Ex + AN + ECAP(A)							
AZ91	Rolling + ECAP	2	200	100	17	145	240	Yamashita et al. [24]
	Ex + CEC	6	230	15.2	1.4	248	215	Lin et al. [6]
	Ex + CEC	12	350	~20	~1.5	238	192	Lin et al. [10]
Mg-0.9% Al				17			141	
	Rolling + ECAP	2	200	100	48	57	73.5	Yamashita et al. [24]
			400	78			97	
Mg-Ni-Y-RE	Ex + ECAP	(1P)	310	<1		295	363	Eddahbi et al. [28]
			370	1.4			340	
	Ex + ECAP(A)			1.3			246	
Mg-5.25 Zn-0.6Ca	Ex + ECAP(B_C)	4.2	250	4.3	0.7	178	180	Tong et al. [29]
	Ex + ECAP(C)			0.8			131	
Mg-10Gd-2Y-0.5Zr	Ex + CEC	21.9	450	18	<1	225	270	Peng et al. [13]
	Ex + CEC	12.2	350	18	1.3	225	321	Lin [39]
Mg-Zn-Y-Nd	Ex + CEC	4	250	10~15	~1	183	185	Wu et al. [31]
Mg-Nd-Zn-Zr	Ex + CEC	12	350	5~20	~1	~172	~280	Zhang et al. [30]

Note. A: route A, B_C : route B_C , C: route C, Ex: extrusion, P: pass, AN: anneal, d : grain size, and $\sigma_{0.2}$: yield stress.

FIGURE 4: Typical {0002} and {10-10} pole figures of Mg alloys processed by (a) conventional extrusion [9], (b) CEC [9], and (c) ECAP (route B_c) [17].

strength. On the other hand, the other references in Table 1 report an increase in the yield strength. These abnormal results have been attributed to the combined effect of the texture modification and grain refinement caused by ECAP and CEC processing, but the mechanism is still under debate due to the complex and extensive influence factors.

3.2. Texture Evolution. For Mg alloys, a strong texture is always present after forming due to its HCP structure with limited nonbasal slip activities. Different textures are expected to result from different processing routes with different strain paths. Figure 4 shows the typical {0002} and {10-10} pole figures of conventional extruded ZK60 alloy [9],

4-cycle CECed ZK60 alloy [9], and 4-pass ECAPed AZ31 alloy (route B_c) [17], and Figure 5 shows the schematic illustration of the dominant texture in the extruded CEC and ECAP conditions. It has been reported that the deformation texture type of Mg alloys is mainly determined by the characteristics of the plastic deformation process [44]. The extruded Mg alloys always exhibit an ED//{10-10} fiber texture, in which the {0002} basal plane is parallel to the extrusion direction [6, 10]. After CEC and ECAP deformation, the basal planes are mainly inclined about $\sim 30^\circ$ [10] and $\sim 45^\circ$ [17, 45] to the extrusion axis, respectively, which are more favorable conditions for basal slip activity and resulting in a decrease in the yield strength.

FIGURE 5: Schematic showing the dominant texture in the extruded ECAP and CEC conditions.

FIGURE 6: Grain size dependencies of yield strength of Mg alloys processed by (a) CEC and (b) ECAP.

4. Yield Strength of the ECAP and CEC Processed Mg Alloys

Figure 6 shows the grain size dependencies of yield strength of Mg alloys processed by CEC [6, 10, 13, 37, 46] and ECAP [22, 23, 35, 38, 47]. It can be seen that almost all ECAPed and CECed Mg alloys exhibit a decrease in yield strength, especially in the early stage of ECAP and CEC deformation. With further decrease in the grain size, the yield strength starts to increase. The abnormal decrease in yield strength of the SPD refined Mg alloys has been attributed to the modification of the texture. It is known that the grains of as-extruded Mg alloy in a “hard” orientation with low Schmid factor, that is, the basal plane slip, are difficult to be activated. After ECAP and CEC, the grains orientations are more favorable for basal slip activity and resulting in a decrease in the yield strength. It is understood that the texture softening, caused by texture change, overwhelms the strengthening due to grain refinement at the early stage of ECAP and CEC deformation.

With further increase in deformation strain, grain refinement strengthening overwhelms the texture softening, and then the yield strength starts to increase.

Additionally, as shown in Figure 6(a), even though having a similar texture type with other CECed Mg alloys, the CECed GW102K alloy exhibits a monotonically increasing yield strength. The opposite relationships between grain size and yield strength of the CECed Mg alloys can be ascribed to the different texture intensity. Peng et al. [13] showed that the texture intensity of the CECed GW102K alloy is much lower than that of the CECed ZK60 alloy.

It has been reported that the annealing treatment produces almost no change on the texture of the ECAPed Mg alloy [16, 21, 46, 48]. So, the SPD processed (SPDed) Mg alloys with different grain sizes but with similar texture can be prepared by the SPD process and post-SPD annealing. In Figure 7, the yield stress is plotted against $d^{-1/2}$ for the SPD + annealed Mg alloys, based on the Hall-Petch relationship, to examine the grain size effect on the SPDed

FIGURE 7: Grain size dependencies of yield strength of Mg alloy after SPD process and annealing.

Mg alloys. It can be seen that the strength of the SPDed Mg alloys increases with the decrease of grain size, which is in agreement with the standard Hall-Petch relationship (a positive slope in the plot of yield stress versus $d^{-1/2}$). The standard positive strength dependence on the grain size for Mg alloys, with the similar texture, supports that the softening of SPDed Mg alloys (a negative slope) which are typically observed despite the significant grain refinement, is due to the texture modification where the rotation of basal planes occurs towards the orientation for easier slip [21]. Thus, it can be concluded that the yield strength of the SPDed Mg alloy is determined by the competition of grain size strengthening effect and texture softening effect, and the texture softening depends on the texture type and texture intensity.

5. Summary and Conclusions

- (1) Both the ECAP and CEC are efficient grain refinement methods for Mg alloys, and grain refinement takes place mainly during early stage of ECAP and CEC. Compared with the ECAPed Mg alloys, the CECed Mg alloys exhibit a finer grain size, under similar deformation conditions of accumulated strain and temperature.
- (2) The yield strength of ECAPed and CECed Mg alloys is determined by the competition of grain size strengthening effect and texture softening effect, and the texture softening depends on the texture type and texture intensity.
- (3) A standard positive Hall-Petch relation can be obtained in the ECAPed and CECed alloys when texture is constant.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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