Compression yield behavior and corresponding microstructure characterization of Mg-1.5Sn (at.%) alloys

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Abstract
The compression yield behavior and corresponding microstructure characterization of as-cast and as-extruded Mg-1.5Sn (at.%) alloys are investigated by uniaxial compression and electron backscatter diffraction (EBSD). The as-cast and as-extruded Mg-1.5Sn alloys are uniaxially compressed at room temperature with a strain rate of $1 \times 10^{-3}$ s$^{-1}$. It shows that the extrusion obviously improves the compressive strength of Mg-1.5Sn alloys with an obvious yield plateau. A new-found micro-structure evolution and compression yield behavior of as-cast and as-extruded Mg-1.5Sn alloys are discussed in detail. The microstructure of as-extruded Mg-1.5Sn alloy is composed of refined dynamic recrystallization grains (DRXed grains) and un-dynamic recrystallization grains (unDRXed grains). The DRXed grains are beneficial to the dislocation slip and grains rotation. Meanwhile, the result shows that the $\{11-20\}$ twins grow at about 45° along the long axis of unDRXed grains regularly, which probably alleviates the accumulation of dislocations. The compression deformation mechanism is different in various strain stages, resulting in an obvious yield plateau. However, the compression yield plateau is not observed in the as-cast Mg-1.5Sn alloy with a noticeable compressive elastic and a lower strength due to its coarse and relatively uniform grains. The differences on compression behavior between as-cast and as-extruded Mg-1.5Sn alloys are discussed clearly, which can provide a theoretical basis and reference for the further development of high-strength and high-elastic Mg alloys.

1. Introduction
Mg–Sn series alloys have drawn much attention due to its increasing demand for light alloys. The classical aging behavior, mechanical property, extrusion behavior and corrosion behavior are further investigated and some classic Mg–Sn alloys were obtained. T.T. Sasaki and Mendis et al. have systemly reported the Mg–Sn alloys with elements addition and corresponding deformational behavior due to its prominent age-hardening response and strength [1–3]. The peak hardness reached to over 100 VHN in a Mg-9.8Sn-3.0Al-1.0Zn-0.1Na alloy depending on precipitation strengthening and deformation strengthening, which made a good foundation for Mg-Sn alloy study. Besides, the age-hardening response and strength property, the elastic property and deformation mechanism are emphasized, which can provide important ideas for Mg alloys with excellent comprehensive mechanical properties [4–7].

It is well known that magnesium always exhibits only limited elastic to failure, often less than 10% in tension elongation due to its HCP structure [5]. To further improve the strength and elastic property of Mg-Sn alloy, it is necessary to research its microstructure evolution and characteristics during deformation process [8, 9]. The compression curves trends and strength were determined by grain orientation and size [10], strain rate, compression temperature [11], second phase [12] and other factors. It indicated that the compression flow curves, the compressive strength and the strain hardening rate were highly affected by the initial grain orientation especially at low temperature and low strain rate. Notably, slip and twin are the two main micro-deformation modes in magnesium alloys [13]. During compression, the onset of plastic flow is accomplished
3.1. Microstructure characterization

The original billet with a chemical composition Mg-1.5Sn-0.64Ca-0.24Ag proceeds and they are eventually replaced by \((c + a)\) slip. The volume fraction of extension twinning increases steadily as the deformation proceeds [4]. Meanwhile, accumulation of dislocations on dislocation obstacles and twin boundaries is the deciding factor for the strain hardening. Profuse twins probably lead to an enhanced hardening response during compression procedure [14]. Specifically, the crystallographic slips dominate the early deformation in ND sample was demonstrated [15]. Therefore, the twinning in the late stage plays an important role on the compression yield behavior. A particularly interesting finding is related to the stress drop after yielding. It is well understood that this is due to twinning in which yielding occurs during compression [5]. The targeted researches on the compression yielding behavior of Mg-Sn alloys are scare.

In addition, the grain size and orientation also play important roles on compressive deformation behavior at room temperature. The context of the grain size effects on mechanical twinning have been extensively discussed by Halle-Petch relationship. The twinning stress increases more rapidly with decreasing grain size than the stress to activate slip [6]. The deformation twinning and associated work hardening are observed in coarse grains and absent in the ultrafine grains of Mg alloys [14, 16, 17]. It has been argued that twinning is unfavourable in smaller grains, and twins appear more frequently in alloys with larger grains [6, 15]. Therefore, the grains size has an obvious effect on the yielding behavior of Mg alloys via controlling the twinning formation. However, at present, the twins orientation with extrusion direction were not clearly observed, which probably resulted in the compression fracture morphology. In addition, the apparent yield plateau is occurred in the compression curves the extruded alloys [9, 10, 18]. But the apparent yield plateau is not observed in the as-cast Mg alloys. This provides an effective idea for the plasticity property study of Mg-Sn alloy.

This paper is to study the effect of grain size, twining and other factors on the deformation behavior of Mg-1.5Sn-0.64Ca-0.24Ag (at. %) alloy under uniaxial compression at room temperature. Specifically, the work addresses the relationship between the yield behavior and microstructure evolution. The research on the compression yield behavior and corresponding microstructure evolution could provide important ideas for enhancing the mechanical property of Mg-Sn alloys.

2. Experimental procedures

The original billet with a chemical composition Mg-1.5Sn-0.64Ca-0.24Ag (at. %) were smelt by Mg (>99.95%), Sn (>99.9%), Ag (>99.9%) and master Mg-25Ca (wt. %) alloys. All the materials and steel crucible should be dried at 200 °C for 20 min before the melting started. Firstly, the Mg-25Ca master alloys were put into the bottom of the pit furnace and the high purity magnesium was put above. The metals were heated to melt and pure Sn and Ag were put into the liquid with the protection of 99 % CO2 mixture gas [16, 19]. Then, the melt was held at 740 °C for 10 min to obtain a uniform alloy, which was stirred at the same time. Finally, when the temperature was reduced to 700 °C and the slag was removed, the melt was slowly poured into a permanent metallic mold (Φ 60 mm × L 250 mm), which was preheated to ~200 °C to keep dry.

Figures 1(a) and (b) show the heat treatment, extrusion and compression cycles for as-cast and as-extruded specimens. The as-cast alloys were homogenized at 400 °C for 16 h with the protection of a Ar atmosphere followed by water quenching [13]. The cylindrical solution treated alloy with a diameter of 25 mm and a height of 30 mm was extruded into a bar with a diameter of 4.2 mm at 320 °C [5]. The samples for compression experiment were cut into a bar with a diameter of 4 mm and a height of 8 mm, which was compressed by universal testing machine with a strain rate of 1 × 10 \(^{-3}\) s \(^{-1}\) to obtain compression property and status [5, 20]. The schematic diagram of the extrusion and compression process is shown in figure 1(c). The morphology analysis was characterized by Electron Backscatter Diffraction (EBSD). The EBSD examined samples includes as-cast (with 7% engineering strain) and extruded alloy (with 0% and 7% engineering strain) and scanned with a step of 0.5 mm at room temperature. The flow chart of as-cast and as-extruded samples is shown in figure 1 [13].

3. Results

3.1. Microstructure characterization

stress distribution maps ((a)–(b): as-cast alloy with 7% engineering strain, (c)–(d): as-extruded alloy with 0% engineering strain and e–f: as-extruded alloy with 7% engineering strain).

Figure 2 and table 1 show the microstructure of as-cast alloy with 7% engineering strain and as-extruded alloy with 0% and 7% engineering strain. Figure 2(a) shows the as-cast alloy with 7% engineering strain mainly composed of randomly sub-structured grains and a few irregular twins in the grain internal. The activated twins are preferred to be distributed irregularly in the as-cast Mg-7Sn alloys as previous report [21]. After extrusion treatment, the microstructure of as-extruded alloy with 0% engineering strain was mainly composed of DRXed and sub-structured grains with few deformed grains as shown in figure 2(c), which was similar with previous
Figure 1. Heat treatment cycles for (a) as-cast and (b) as-extruded specimen and (c) schematic diagram of the extrusion and compression process.

Figure 2. EBSD results of: (a), (c), (e) inverse pole figure map, (b), (d), (f) corresponding residual.
Table 1. The microstructure and compressive property parameters of different alloys

| Alloys         | DRXed | Sub-structured | Deformed | Average grain size (μm) | Compressive strength (MPa) | Compressive elastic (%) | m_{ε=0.08} | Maximum intensity of texture |
|----------------|-------|----------------|----------|-------------------------|---------------------------|-------------------------|-------------|-----------------------------|
| As-cast        | 1.3   | 93.3           | 5.4      | 56.76 ± 9.43            | 281.05                    | 22.9                    | 0.75        | 10.53                       |
| As-extruded    | 34.9  | 54.6           | 10.5     | 6.77 ± 0.48             | 545.81                    | 12.9                    | 0.68        | 14.74                       |
| Com-extruded   | 41.9  | 42.9           | 15.2     | 6.53 ± 0.61             | —                         | —                       | —           | 13.08                       |
It can be found that the long axis of deformed grains was parallel to the extrusion direction. Furthermore, after compression procedure with 7% engineering strain, the twins that grew at 45° along the compression direction regularly was newly found in the com-extruded alloy as shown in figure 2(e), which probably plays an important role on the compression and fracture behavior of as-extruded Mg-1.5Sn alloy. In addition, it can be found from figures 2(b), (d) and (f) that the residual stress distribution after extrusion or compression was obviously affected by the grains size. It can be found that the finer grains were, the larger stress is distributed. According to this, it can be inferred that a stronger stress concentration was easily induced in the area with refined grains, which probably resulted in the different compression deformation mechanisms in refined grains and coarse grains areas [22, 23].

3.2. The compression flow curves

Figure 3 shows the true stress-strain flow curves of as-cast and as-extruded alloys, where the maximum compressive strength and compressive strain to fracture are designated as compressive strength (MPa) and compressive elastic (%), following previous reports [24, 25]. The stress-strain curve of as-cast alloy is smooth before failure. But the stress-strain curve of as-extruded alloys can be divided into three stages: initial steep increase, followed by a short plateau and a rapid increasing stage until it levels off. Similar trends were also revealed in previous studies [26, 27]. The as-extruded alloy shows a higher compressive strength and a higher deformation rate \(\frac{d\varepsilon}{d\sigma}\) [28]. However, the compressive elastic abnormally declined with the decrease of average grains size [5, 6]. It is known that the initial grains of as-cast was uniform and relatively coarser than that of as-extruded alloy. But the initial microstructure of as-extruded alloy was composed of coarse deformed grains and fine DRXed grains. The differences of compression flow curves and the reasons were discussed in detail below.

4. Discussions

The relationship between the compression behavior and corresponding microstructure has been reported. The compression deformation was closely related to the grains size, texture and twins types. When finest grain size was about 0.8–2.0 μm, the deformation mode transformed from that dominated by twinning to that by slip. With larger grains (>3 μm), yielding occurred by twinning followed by significant strain hardening [17]. This can be explained by the mature Hall-Petch formula: \(\sigma_y = \sigma_0 + k_d^{-1/2}\) (where \(\sigma_y\) is the yield strengths, \(\sigma_0, k\) are the constants and d is the grain size), which was further demonstrated that \(k_t\) (k for twinning) was usually much larger than \(k_s\) (k for slip) [29]. It requires to satisfy the mechanical equilibrium: \(\sigma_{yt} = \sigma_{ys}\), same as: \(\sigma_0 + k_t d_t^{-1/2} = \sigma_0 + k_s d_s^{-1/2}\). Therefore, it can be concluded that the grains size dominated by twinning was obviously larger than that dominated by slip. Karel Tesa also indicated that the total elongations to fracture in compression decreased with a more serious deformation, which can be attributed to that the intense twinning caused a rapid work hardening after yielding [25]. And the early stage of deformation mechanism was crystallographic slips and rotation of fine grains [8, 30], which resulted in the early elastic deformation stage with a higher deformation rate \(\frac{d\varepsilon}{d\sigma}\). And the twinning in coarse grains induced the late plastic deformation stage. It is strange that the as-cast alloy with a larger average grain size obtains a superior compressive elastic. This may be
due to stress concentration by dislocation pile-ups observed at twin boundaries in the as-extruded Mg-Sn alloys [5]. The strain rate sensitivity index (m) was used to describe the materials workability and calculated by [8]:

$$m = \frac{\partial \ln \sigma}{\partial \ln \varepsilon}$$

Where $\sigma$ is the flow stress and $\varepsilon$ is the strain rate. The $m_{\varepsilon=0.08}$ values were shown in table 1 and the as-cast alloy shows a higher m value, easily leading to a locally homogeneous deformation. Therefore, the compression fracture was lately achieved and a superior compressive elastic was obtained in as-cast alloys. In conclusion, the higher strength with a noticeable compressive elastic of as-extruded alloy simultaneously depend on the smaller average value and greater consistency of grain size.

Interestingly, an obvious yield plateau was only observed in the as-extruded alloy. The reason can be concluded as follows: (1) the transformation of deformation mechanism was occurred in different compression stages of as-extruded alloy. In the early stage, non-basal slips are more desired to be activated in fine DRXed grains undergo homogeneous deformation and the twinning is restricted [31]. The twins were activated gradually due to the increase of stress [25]. However, the grains size of as-cast alloy was uniform and slips were main deformation mechanism, which resulted in no yield plateau. (2) the roles of deformation twinning in the compression strain hardening response mainly contains the following aspects: (i) The twin boundaries play an important role on barriers to dislocation motion and then lead to the further work hardening [32]; (ii) twin-induced grain refinement causes Hall-Petch hardening response. Therefore, it can be concluded that deformation twinning during compression cause an obvious strain hardening response, resulted in a rapid increase in the compression strain-stress curves of as-extruded alloy [19, 33].

As to the twins, it is worth noticing that [11–20] tension twins at angle 86°, {10–11} contraction twinning at angle 55° and {11–20}–{10–11} double twining at angle 34.8° and low angle grain boundary (LAGB) (2°–15°) were dominated [34]. According to the peak of 86.3°, 6.05°, 54.95° and others in figure 4(a), it can be concluded that various twins and low angle grain boundary (LAGB) existed in the as-cast alloy with 7% engineering strain. However, only low angle grain boundary (LAGB) (2°–15°) and some unrepresentative peaks in the as-extruded alloy with 0% engineering strain. And only [11-20] tension twins with little other peaks were obviously found in the as-extruded alloy with 7% engineering strain as shown in figure 4(c) [11, 26]. This result confirmed that {11-20} tension twins was one of the main compression deformation mechanisms of as-extruded Mg-1.5Sn (Ca,Ag) alloy.

To further verify the grain orientation and twin types, the inverse pole figures of the investigated alloys were shown in figure 5. Figure 5(a) shows that a strong (0001) fiber texture with maximum intensity of 10.53 and

![Figure 4. Evolutions of the misorientation angle distributions (MAD) of (a) as-cast alloy with 7% engineering strain, (b) as-extruded alloy with 0% engineering strain and (c) as-extruded alloy with 7% engineering strain.](image-url)
other textures were observed in the compressed as-cast alloy, which was probably related to the large-scale reorientation due to $\{11-20\}$ twinning [34]. However, figure 5(b) shows a maximum intensity (14.74) peak between $[10]$ and $[11-20]$ area in the as-extruded alloy, which indicated the c-axis of most grains are mainly distributed on the radial direction (RD) plane with a concentration along the RD for all samples, which is a typical grain orientations distribution characteristic of the extrusion [35]. Figure 5(c) shows that the extrusion treatment resulted in a strong $(0001)$ fiber texture with maximum intensity of 13.8 while weakened the intensity peak distributed between $[10]$ and $[11-20]$ area. It is certain that the texture development is strongly associated with the twinning and subsequent DRX process during extrusion [36].

In addition, the regularities of twins distribution in the microstructure were also observed in the as-extruded alloy. Figure 6(a) shows that all the twins grown at about 45° along the compression direction regularly was newly found in as-extruded alloy, which probably resulted in the micro-behavior of compression fracture. The schematic diagram for hexagonal close-packed crystal critical with resolved shear stress (CRSS) was also provided in figure 6(b). The red arrow and orange lines mean the long axis of deformed grains and the long axis of twins, respectively, as shown in figure 6(a). The optimal growth direction of twins can be explained by the critical shearing stress of hexagonal close-packed crystal [23, 37], which probably resulted in preferred growth direction of twins. This regular twins activation and refined grains rotation were the main reasons to transform the texture before and after compression, contributing to a further compression strain hardening [20]. Therefore, the yield plateau preferred to occur in the as-extruded Mg-1.5Sn (Ca,Ag) alloy due to above reasons. This study provides a theoretical basis and reference for the further research on the stress-strain behavior of Mg alloys. As future research scope, the Mg-Sn alloy with an obvious yield plateau is expected to obtain high strength and high elastic simultaneously via controlling the grains size and orientation.

Figure 5. Inverse Pole Figures (IPF) of: (a) as-cast alloy with 7% engineering strain, (b) as-extruded alloy with 0% engineering strain and (c) as-extruded alloy with 7% engineering strain.
5. Conclusions

The compressive property and corresponding microstructure characteristics of as-cast and as-extruded Mg-1.5Sn-0.64Ca-0.24Ag (at. %) alloys were investigated and conclusions can be drawn as follows:

(1) Extrusion treatment plays an important role on the compressive properties of Mg-1.5Sn-0.64Ca-0.24Ag (at. %) alloys. The as-extruded alloy obtains a noticeable compressive strength (545.81 MPa) with a relatively low compressive elastic (12.9%) compared with those of as-cast alloy. The strength improvement is mainly attributed to the grain refinement and the formation of twins. However, the texture and the size differences between DRXed grain and unDRXed grains result in a relatively low compressive elastic.

(2) The compression curve shapes of as-cast and as-extruded alloys are obviously different. An obvious yield plateau is only observed in the as-extruded alloy. The compression hardening is ascribed to the activation of \{11-20\} tension twins and rotation of reﬁned grains. The compression deformation mechanism was different in various compression stages due to the different grain sizes and grain orientations, resulted in an obvious yield plateau.

(3) Interestingly, the microstructure of as-extruded alloy with 7% compression engineering strain shows \{11-20\} tension twins that grew at 45° along the compression direction regularly was newly found in the unDRXed grains.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors have no conflict of interest.

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References

[1] Elsayed F R, Sasaki T T, Ohkubo T, Takahashi H, Xu W, Kamado S and Hono K 2013 Effect of extrusion conditions on microstructure and mechanical properties of microalloyed Mg–Sn–Al–Zn alloys Materials Science and Engineering: A 588 318–28

[2] Elsayed F R, Sasaki T T, Mendis C L, Ohkubo T and Hono K 2013 Compositional optimization of Mg–Sn–Al alloys for higher age hardening response Materials Science and Engineering: A 566 22–9

[3] Mendis C L, Bettles C J, Gibson M A and Hutchinson C R 2006 Materials science and engineering: a An Enhanced Age Hardening Response in Mg–Sn Based Alloys Containing Zr 435–436 163–71

[4] Kula A, Jia X, Mishra R K and Niewczas M 2017 Flow stress and work hardening of Mg–Y alloys Int. J. Plant. 92 96–121

[5] Grtnerová V, Singh A, Iger A and Mukai T 2017 Deformation behavior of ultra-fine-grained Mg-0.3at% Al alloy in compression J. Alloys Compd. 726 651–7

[6] Kula A, Silva C J and Niewczas M 2017 Grain size effect on deformation behaviour of Mg–Sc alloys J. Alloys Compd. 727 642–57

[7] Cheng J, Mu Y L, Zu G Y and Yao Q H 2017 Impact toughness and fractography in Mg–Y alloy Mater. Des. 123 64–8

[8] Hou M J, Zhang H, Fan J F, Zhang Q, Wang L F, Deng H B and Xu B S 2018 Microstructure evolution and deformation behaviors of AZ31 Mg alloy with different grain orientation during uniaxial compression J. Alloys Compd. 741 514–26

[9] Lei W W and Zhang H 2020 Analysis of microstructural evolution and compressive properties for pure Mg after room-temperature ECAP Mater. Lett. 271 127178

[10] Zhao L, Zhang M N, Wang H J, Shi B and Jin P P 2020 Effects of initial grain size and orientation on the twin behavior in ZK60 Mg alloy Mater. Struct. 167 110496

[11] Malik A, Wang Y G, Wu C H, Nazer F, Ahmed B, Khan M A and Wang M J 2020 Constitutive analysis, twinning, recrystallization, and crack in fine-grained ZK61 Mg alloy during high strain rate compression over a wide range of temperatures Materials Science & Engineering A 771 138469

[12] Ma X L, Jiao Q, Kecses L J, El-Awdy J A and Weihs T P 2020 Effect of basal precipitates on extension twinning and pyramidal slip: a micro-mechanical and electron microscopy study of a MgAl binary alloy Acta Mater. 189 35–46

[13] Gui Y W, Gui B Y J, Bian H K, Li Q A, Ouyang L X and Chiba A 2021 Role of twin and {10–12} twin on the crystal plasticity in Mg–RE alloy during deformation process at room temperature Journal of Materials Science & Technology 80 279–96

[14] Trojanova Z, Droz Z, Halmová K, Džučan J, Škraban T, Minárik P, Németh G and Lukác P 2021 Strain hardening in an AZ31 alloy Unpublished to rotary swaging Materials. 14 157

[15] Barnett M 2008 A rationale for the strong dependence of mechanical twinning on grain size Script materials 59 696–8

[16] Malik A, Wang Y W, Nazer F, Khan M A, Sajid M, Jamali S and Wang M J 2021 Deformation behavior of Mg–Zn–Zr magnesium alloy on the basis of macro-texture and fine-grain size under tension and compression loading along various directions J. Alloys Compd. 858 152769

[17] Li J Z, Xu W, Xu X L, Ding H and Xia K N 2011 Effects of grain size on compressive behaviour in ultrafine grained pure Mg processed by channel angular pressing at room temperature Materials Science and Engineering A 528 5993–8

[18] Park S H, Jung J, Kim Y M and You B S 2015 A new high-strength extruded Mg-8Al-4Sn-2Zn alloy Mater. Lett. 139 35–8

[19] Mao L H, Liu C M, Yan Y C, Chen T, Jiang S N and Chen Z Y 2021 Loading mode dependence of {10–12} twin variant selection in a rolled Mg–Al–Zn alloy J. Mater. Eng. Perform. 12 1–10

[20] Li Y, Hou P J, Wu Z G, Feng Z L, Ren Y and Choo H 2021 Dynamic recrystallization of a wrought magnesium alloy: grain size and texture maps and their application for mechanical behavior predictions Mater. Des. 202 109562

[21] Li B J, Wang S, Gui N and Guo F 2021 Twinning and dynamic recrystallization of Mg-7Sn-3Zn alloy under high strain rate hot compression Materials Science & Engineering A 809 140896

[22] Jiang M G, Xu C, Yan H, Fan G H, Nakata T, Lao C S, Chen R S, Kamado S, Han H E and Lu B H 2018 Unveiling the formation of basal texture variations based on twinning and dynamic recrystallization in AZ31 magnesium alloy during extrusion Acta Mater. 157 53–71

[23] Paramatmuni C and Dunne F P E 2020 Twin nucleation and variant selection in Mg alloys: an integrated crystal plasticity modelling and experimental approach Int. J. Plast. 135 102775

[24] Chai Y F, He C, Jiang B, Fua J, Jiang Z Y, Yang Q S, Sheng H R, Huang G S, Zhang D F and Fan P S 2020 Influence of minor Ce additions on the microstructure and mechanical properties of Mg-1.0Sn-0.6Ca alloy Journal of Materials Science & Technology 37 26–37

[25] Tesa K, Somekawa H and Endo T 2020 Development of texture and grain size in Mg–Al–Sn–Zn alloys containing stable quasicrystalline i-phase and its effect on tensile and compression strength J. Alloys Compd. 849 156340

[26] Wan Y J, Zeng Y, Zeng Q, Song B, Huang D X F, Qian X Y and Jiang B 2021 Simultaneously improved strength and toughness of a Mg–Sn alloy through abundant prismatic lath–shaped precipitates Materials Science & Engineering A 811 141087

[27] Guo W M, Li N, Zhou J X, Liu L, Tian L N, Chen L Z, Zai F and Ding N 2021 Flow Curve and microstructure analysis of a ZK60 magnesium alloy during hot compression tests Metallography, Microstructure, and Analysis 10 46–54

[28] Hoseini-Athar M M, Mahmudi R, Prasath Babu R and Hedstrom P 2020 Microstructure, texture, and strain-hardening behavior of extruded Mg–Gd–Zn alloys Materials Science & Engineering A 772 138833

[29] Meyers M A, Vohringer O and Lubarda V A 2001 The onset of twinning in metals: a constitutive description Acta Mater. 49 4025–39

[30] Zhang M N, Wang J H, Zhu Y P, Zhang L and Jin P P 2020 Ex-situ EBSD analysis of hot deformation behavior and microstructural evolution of Mg-1Al-6Y alloy via uniaxial compression Materials Science & Engineering A 775 138978

[31] Hu F P, Zhao S J, Gu G L, Ma Z D, Wei G B, Yang Y, Peng X D and Xie W D 2020 Strong and ductile Mg-0.4Al alloy with minor Mn addition achieved by conventional extrusion Materials Science & Engineering A 795 139926

[32] Guerza-Soualah F, Hanna A, Azeddine H, Helbert B A, Brisset F, Baudin T and Bradi D 2020 The deformation and recrystallization behaviour of an Mg–Dy alloy processed by plane strain compression Materials Today Communications. 24 101239

[33] Carneiro L, Calbertson D, Zhu X Y, Yu Q and Jiang Y 2021 Twinning characteristics in rolled AZ31B magnesium alloy under three stress states Mater. Struct. 175 110100

[34] Hradilová M, Montielleit F, Fraczkiewicz A, Desrayaud C and Leček P 2013 Effect of Ca–addition on dynamic recrystallization of Mg–Zn alloy during hot deformation Materials Science & Engineering A 580 217–26

[35] Barnett M R, Keshavarz B, Beer A G and Atwell D 2004 Influence of grain size on the compressive deformation of wrought Mg-3Al-1Zn Acta Mater. 52 5093–103

[36] Che X, Dong B B, Wang Q, Liu K, Meng M, Gao Z, Ma J, Yang F L and Zhang Z M 2021 The effect of processing parameters on the microstructure and texture evolution of a cup-shaped AZ80 Mg alloy sample manufactured by the rotating backward extrusion J. Alloys Compd. 854 156264

[37] Wang J Y, Molina-Aldareguia J M and LLorca J 2020 Effect of AI content on the critical resolved shear stress for twin nucleation and growth in Mg alloys Acta Mater. 188 215–27