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A MAGNESIUM ALLOY EXHIBITING GOOD YIELD SYMMETRY

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ABSTRACT

In the present study, a ternary Mg-3Gd-0.4Ce alloy was developed using Disintegrated Deposition Method (DMD) followed by hot extrusion. The developed alloy exhibited superior mechanical properties i.e. strength and ductility. Furthermore, the tensile yield strength of Mg-3Gd-0.4Ce, under quasi static conditions, was close to its compressive yield strength, demonstrating good yield symmetry. The mechanisms leading to its yield symmetry and the two primary factors affecting the ductility of magnesium alloys- grain size and texture- were examined through microstructural studies involving optical microscope, SEM and XRD texture analysis. Microstructure-mechanical property correlation studies were performed to understand these mechanisms.

KEYWORDS: Magnesium Alloy, Extrusion, Yield Symmetry, Microstructure.

Magnesium alloys attract intensive research efforts, primarily due to their lightweight property as well as excellent specific strength. They are vital in elevating system and energy efficiency, thus reducing fuel consumptions. Some of the key barriers inhibiting the wide applications of Mg alloys in aeronautical and automotive industries are their limited ductility, high reactivity as well as tension compression yield asymmetry. The poor ductility of Mg alloy arises from its hexagonal close-packed structure, leading to concerns in structural applications. This structure has three major slip systems, two of which that include prismatic and pyramidal slip systems are extremely difficult to be activated at room temperature. The sole slip system, basal slip, provides only two independent slip systems failing to meet the requirement of five independent slip systems for slip to occur, thus making deformation at room temperature limited [1]. Moreover, extruded Mg alloys exhibit a typical basal texture with basal planes parallel to the extrusion direction. This texture arising from secondary processing restricts basal slip at room temperature, further deteriorating its ductility. Other than its poor ductility, Mg alloys demonstrate different deformation behaviour under tension and compression [2]. For most of Mg alloys, tensile yield strength is much higher than the compressive yield strength. This yield asymmetry is attributed to texture effects as well as inherent distinct deformation mechanisms under tension and compression [3, 4]. Slip-dominant deformation occurs under tension while twinning is a predominant deformation mode under compression, i.e. twinning has a much lower activation energy compared to both basal and non-basal slips [3] under compression along extrusion direction. Relatively easier deformation by twining under compression results in lower compressive yield strength compared to deformation by slip under tension.

In order to increase ductility and reduce yield asymmetry, current research focuses on grain refinement, precipitate formation and texture modification. Grain refinement is vital for enhancing yield strength while retaining good ductility. In a study conducted by Tekumalla et al. [5], a refined grain size of 4 μm was achieved in Mg-0.4Ce. The grain refinement in the binary alloy effectively resulted in a ductility of 27%. Nevertheless, sole addition of cerium did not alter the extrusion texture in Mg-0.4Ce, in which yield asymmetry is still pronounced. Mg-Gd binary alloy system has been intensively studied for texture weakening effect by gadolinium [6]. Stanford et al. [7] concluded that micro-alloying addition of Gd weakened the extrusion texture, by retarding recrystallization, and enhancing solute segregation behavior [6, 8]. The RE-texture component with <11-21> direction parallel to the extrusion direction is developed. This alignment of large proportion of grains, favors basal slip in the tensile direction. Hence, it results in the improved ductility when tested along the extrusion direction.

In the view of the ability of cerium to refine grain size and ability of gadolinium to weaken the extrusion texture, their combined effect on the ductility and yield behavior under tension and compression was examined in this study. Microstructure and mechanical properties were analyzed in this study to validate their cumulative ability to develop a superior ternary alloy, with an increased ductility and reduced yield asymmetry.

MATERIALS AND METHODS

Magnesium turnings of 99.9% purity from ACROS Organics, USA were chosen as the matrix material. The rare earths were added in the from master alloys (Mg-30%RE) with 99% purity obtained from Sunrelier Metal Co. Limited, Pudong, Shanghai, China.

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Disintegrated Melt Deposition technique was employed to synthesize the alloy, Mg-3Gd-0.4Ce [6]. Prior to extrusion, the ingot obtained from casting was machined and soaked at 400°C for 60 min in a constant temperature furnace. Extrusion was performed on a 150 ton hydraulic press using an extrusion ratio of 20.25:1, producing rods of 8mm diameter. Specimens were cut from extruded rods for various characterization studies.

Dog bone shaped samples with 25mm gauge length and 5 mm gauge diameter were machined from extruded rods in preparation for tensile tests. Using Material Test System (MTS 810) with an extensometer of 25mm gauge length, tensile tests were conducted in accordance with ASTM test standard E8/E8M-16A at a strain rate of 1.67×10^{-4} s^{-1}. The compressive tests conforming to ASTM test method E9-09 were performed on samples using the MTS testing machine and strain rate was kept at 1.67×10^{-4} s^{-1}. During tensile and compressive testing, a minimum number of three tests were carried out to generate consistent results. For microstructure, the polished specimens were etched using the etchant: 60ml ethanol and 15ml acetic acid. The grain size of samples was analyzed using Leica DM2500M metallographic optical microscope. In order to investigate the morphological characteristics of grains, intermetallics distribution and fracture mechanisms of the samples, JEOL JSM-6010PLUS/LV Scanning Electron Microscope was used. X-ray diffraction test was used to confirm the phases as well as presence of texture through matching the bragg angles, intensity peaks and the interplanar spacing with the standard values of Mg, Gd, Ce related possible phases.

RESULTS

Structural Characterization

Optical micrographs revealed equiaxed grain morphology of Mg-3Gd-0.4Ce alloy (see Fig. 1a). The grain size was estimated to be 4μm while Mg had a grain size of about 25 μm. This indicates grain refinement in Mg-3Gd-0.4Ce alloy. The electron micrographs of Mg-3Gd-0.4Ce reveal the grain morphology and secondary phase distribution (see Fig. 1b). The secondary phases were in the form of particles, most of which were found along gain boundaries. The presence of secondary phases would be able to restrict the grain boundary movement and hinder grain growth as a result of Zener pinning effect [9]. As a consequence, the grain size was significantly reduced in Mg-3Gd-0.4Ce during dynamic recrystallization. However, due to the minimal presence of secondary phases attributed to the low alloying concentration of Gd and Ce in the ternary alloy developed in this study, the phases were not detected through XRD analysis (see Fig. 1c).

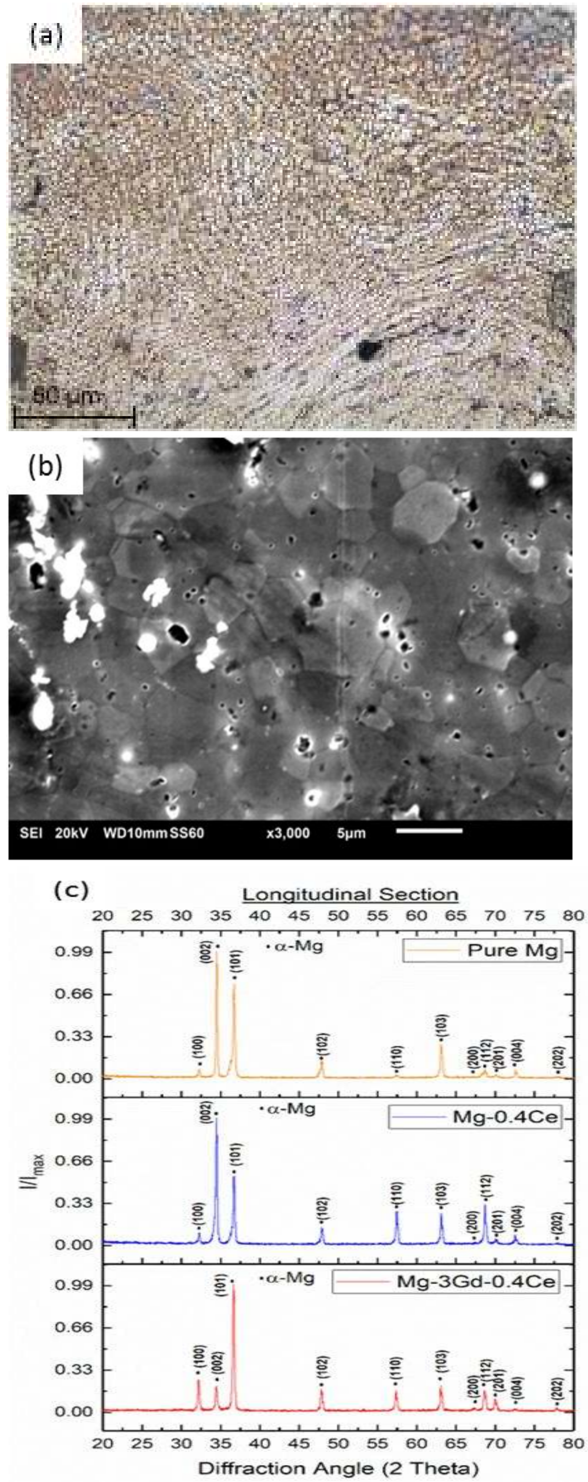
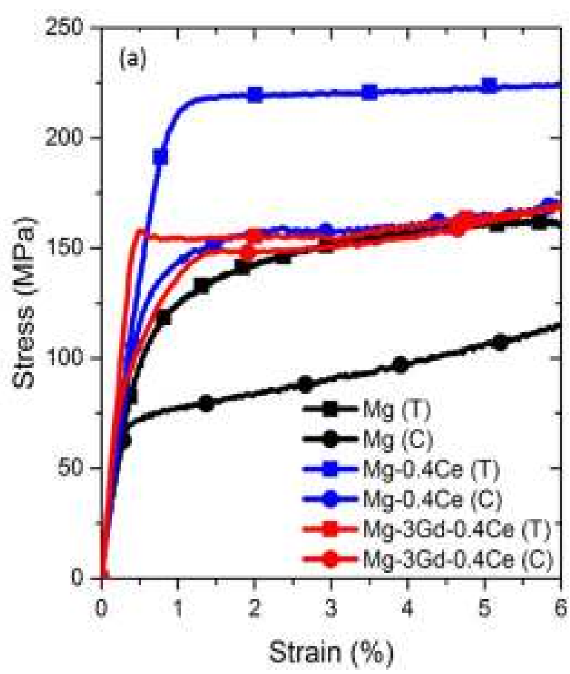


Figure 1: (a) Optical micrograph of Mg-3Gd-0.4Ce alloy; (b) Microstructure of Mg-3Gd-0.4Ce alloy; (c) XRD results of extruded samples along longitudinal section.

Mechanical Characterization

Under tensile loading, Mg-3Gd-0.4Ce has tensile yield strength 156MPa. This is 114% higher compared to pure Mg. The synthesized alloy has a fracture strain of ~35% and is more ductile than pure Mg and Mg-0.4Ce by 146% and 28%, respectively. This highlights the cumulative effect of Gd and Ce on the ductility enhancement of pure Mg. Under compressive loading, Mg-3Gd-0.4Ce has yield strength of 145 MPa which is very close to its tensile yield strength and 120% higher than that of pure Mg. A synopsis of the yield strengths are given in Fig. 2a, revealing a good yield symmetry of the Mg-3Gd-0.4Ce alloy. Its compressive fracture strain remains at ~34% which is also very close to its tensile ductility. Compared with pure Mg and Mg-0.4Ce, Mg-3Gd-0.4Ce demonstrates 48% and 36% increase in compressive fracture strain respectively. Tensile fracture studies were carried out to investigate the mode of failure. The fractography of Mg-3Gd-0.4Ce (see Fig.2b) revealed the dominant presence of dimples, indicative of ductile failure. The fracture studies further confirm the results from mechanical testing, which revealed that Mg-3Gd-0.4Ce is much more ductile than pure Mg under tension. Compressive fracture studies were performed to investigate the failure mode of the synthesized alloy under compression. Fracture surfaces are at about 45 degrees with respect to the compression test axis. Shear bands indicative of shear mode of failure were observed on the fractured surface (see Fig. 2c).



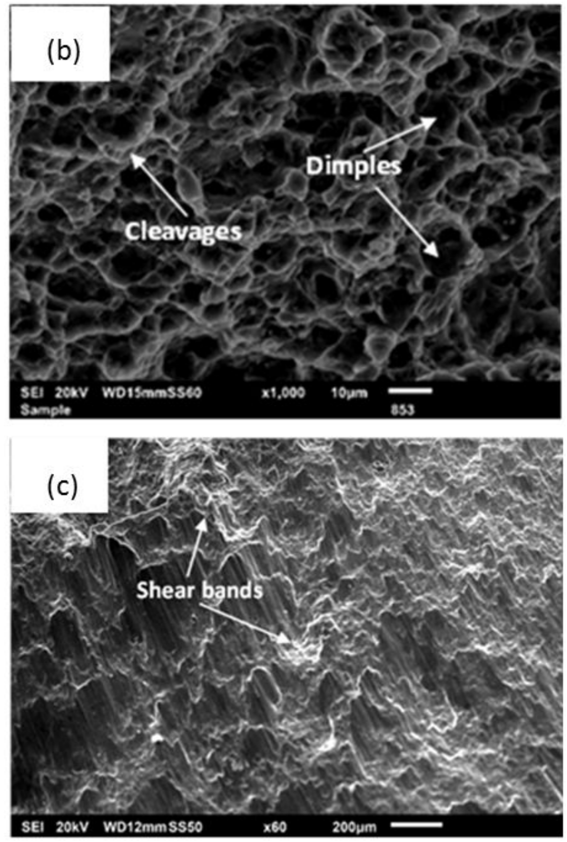


Figure 2: (a) Tension compression curves showing the yield asymmetry trend; (b) Tensile and (c) Compressive fractographies of the Mg-3Gd-0.4Ce alloy.

DISCUSSION

Effect of Gd on the texture of Mg-3Gd-0.4Ce

The effect of Gd on the texture alternation of the synthesized alloy was assessed with the aid of XRD patterns taken along longitudinal direction of extruded sample (see Fig. 1c). The diffraction angles 32°, 34° and 36° represent prismatic {100}, basal {002} and pyramidal {101} planes of HCP magnesium crystal respectively. The ratio of intensity over maximum intensity denoted by I/I_{max} at 32°, 34° and 36° for Mg, Mg-0.4Ce and Mg-3Gd-0.4Ce is listed in Table 1. The I/I_{max} ratio of Mg-3Gd-0.4Ce at 34° which corresponds to the basal texture was the lowest in comparison with Mg and Mg-0.4Ce. This is a clear indication that adding Gd leads to weakening of typical basal texture. A typical basal texture would have basal planes aligned with extrusion direction. This alignment gives rise to zero Schmid factor according to Schmid's law, thus zero critical resolved shear stress (CRSS). As a result, a strong basal texture which is commonly seen in extruded alloys would adversely affect the ductility of Mg alloys. On the other hand, Mg alloys with Gd develop RE-texture [7, 9, 10] which, in return, weakens basal texture favoring both slips and deformation twinning. Hence, a severely weakened basal texture as seen in Mg-3Gd-0.4Ce contributes to the greatly enhanced ductility of ~35%.

Table 1: Ratio of intensity to the maximum intensity at 32° ({100} prismatic plane), 34° ({002} basal plane) and 36° ({101} pyramidal plane)

Composition	I/I_{max}		
	32°	34°	36°
Mg	0.027	0.02703	0.0676
Mg-0.4Ce	0.04	0.1036	0.04
Mg-3Gd-0.4Ce	0.0709	0.0266	0.0248

Effect of Gd on the yield asymmetry of Mg-3Gd-0.4Ce

The plastic flow characteristics of Mg alloys under tension and compression is very different. Mg alloys usually possess much lower compressive yield compared to tensile yield strength. The stark difference in the yield behavior is attributed to the typical strong basal texture which is developed after extrusion process as well as a high c/a ratio [11]. Under tension, the primary deformation mechanism for Mg alloys is basal slip plus non-basal slip while the mechanism switches to basal-slip plus twinning under compression. A strong basal texture renders much lower activation energy for twinning in comparison with slip, which is the underlying reason for the yield asymmetry of Mg alloys. The ratio of compressive yield strength to the tensile yield strength of Mg-3Gd-0.4Ce and other Mg alloys is present in Table 2. The ratio for Mg-3Gd-0.4Ce is 0.93. This is much higher than 0.7 of Mg-0.4Ce, indicating that good yield symmetry is attained in Mg-3Gd-0.4Ce. Mg and Mg-0.4Ce still demonstrate a typical basal dominant texture [11], but the strength of this basal texture becomes the weakest in Mg-3Gd-0.4Ce. In addition, the synthesized alloy exhibits a distinct prismatic dominant texture. A shift from typical basal dominant texture to prismatic dominant texture with the addition of Gd is credited for the reduced yield asymmetry in Mg-3Gd-0.4Ce.

Table 2: Tension-compression yield asymmetry values

Composition	CYS (MPa)	TYS (MPa)	CYS/TYS
Mg-0.4Ce	144	206	0.70
Mg-3Gd-0.4Ce	145	156	0.93

CONCLUSION

A ternary Mg-3Gd-0.4Ce alloy was successfully synthesized using disintegrated melt deposition technique. The synergistic effect of Rare Earths- Gd and Ce- on both mechanical and microstructural properties of Mg was investigated. The following conclusions are drawn from this study:

1. Mg-3Gd-0.4Ce had tensile yield strength of 156 MPa, which is 114% higher than pure Mg. It exhibited a superior tensile ductility ~35%.
2. Mg-3Gd-0.4Ce had compressive yield strength of 145 MPa, which is 120% higher than pure Mg. Its compressive ductility was retained at ~34%.
3. Good yield symmetry was found in Mg-3Gd-0.4Ce with the ratio of compressive yield strength to tensile yield strength close to unity.
4. Presence of Gd significantly weakened the basal texture. A shift from basal dominant texture to prismatic dominant texture was found in Mg-3Gd-0.4Ce.
5. The improvement in ductility was attributed to the weakened basal texture, reduced grain sizes, minimal presence of secondary phases as well as large volume of twins.

REFERENCES

Koike, J., et al., The activity of non-basal slip systems and dynamic recovery at room temperature in fine-grained AZ31B magnesium alloys. Acta Materialia, 2003. 51(7): p. 2055-2065.

Barnett, M., et al., Texture selection mechanisms in uniaxially extruded magnesium alloys. Scripta materialia, 2010. 63(7): p. 721-724.

Zhang, D., et al., Deformation Twinning (Update) $. Ref. Modul. Mater. Sci. Eng., 2015: p. 1-24.

Park, S.H., et al., Tension–compression yield asymmetry in as-cast magnesium alloy. Journal of Alloys and Compounds, 2014. 617: p. 277-280.

Tekumalla, S., et al., Influence of Cerium on the Deformation and Corrosion of Magnesium. Journal of Engineering Materials and Technology, 2016. 138(3): p. 031011.

Hirsch, J. and T. Al-Samman, Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications. Acta Materialia, 2013. 61(3): p. 818-843.

Stanford, N. and M. Barnett, The origin of “rare earth” texture development in extruded Mg-based alloys and its effect on tensile ductility. Materials Science and Engineering: A, 2008. 496(1): p. 399-408.

Stanford, N., et al., Solute segregation and texture modification in an extruded magnesium alloy containing gadolinium. Scripta Materialia, 2011. 65(10): p. 919-921.

Cherukuri, B., et al., The influence of trace boron addition on grain growth kinetics of the beta phase in the beta titanium alloy Ti–15Mo–2.6Nb–3Al–0.2Si. Scripta Materialia, 2009. 60(7): p. 496-499.

Lv, B., et al., The effect of addition of Nd and Ce on the microstructure and mechanical properties of ZM21 Mg alloy. Journal of Magnesium and Alloys, 2013. 1(1): p. 94-100.

Yang, W., S. Tekumalla, and M. Gupta, Cumulative Effect of Strength Enhancer—Lanthanum and Ductility Enhancer—Cerium on Mechanical Response of Magnesium. Metals, 2017. 7(7): p. 241.