Effects of Substitution of Y with Yb and Ce on the Microstructures and Mechanical Properties of Mg$_{88.5}$Zn$_5$Y$_{6.5}$

Hongxin Liao$^{1,2}$, Taekyung Lee$^{3}$, Jiangfeng Song$^{1,2}$, Jonghyun Kim$^{1,2,*}$ and Fusheng Pan$^{1,2,*}$

1. College of Materials Science & Engineering, Chongqing University, Chongqing 400044, China; hongxinliao@foxmail.com (H.L.); jiangfeng.song@cqu.edu.cn (J.S.)
2. National Engineering Research Center for Magnesium Alloys, Chongqing University, Chongqing 400044, China
3. School of Mechanical Engineering, Pusan National University, Busan 46241, Korea; taeklee@pnu.ac.kr
* Correspondence: joindoc@cqu.edu.cn (J.K.); fspan@cqu.edu.cn (F.P.);
Tel.: +86-186-2334-1487 (J.K.); +86-23-6730-3377 (F.P.)

Abstract: The microstructures and mechanical properties of the Mg$_{88.5}$Zn$_5$Y$_{6.5}$-RE$_X$ (RE = Yb and Ce, X = 0, 1.5, 3.0, and 4.5) (wt.%) alloys were investigated in the present study. Mg$_{88.5}$Zn$_5$Y$_{6.5}$ is composed of three phases, namely, α-Mg, long-period stacking ordered (LPSO) phases, and intermetallic compounds. The content of the LPSO phases decreased with the addition of Ce and Yb, and no LPSO phases were detected in Mg$_{88.5}$Zn$_5$Y$_{6.5}$X$_{4.5}$. The alloys containing the LPSO phases possessed a stratified microstructure and exhibited excellent mechanical properties. Mg$_{88.5}$Zn$_5$Y$_{6.5}$Ce$_{1.5}$ exhibited the highest creep resistance and mechanical strength at both room temperature and 200 °C, owing to its suitable microstructure and high thermal stability. The yield strength of Mg$_{88.5}$Zn$_5$Y$_{6.5}$Ce$_{1.5}$ at room temperature was 358 MPa. The ultimate tensile strength of Mg$_{88.5}$Zn$_5$Y$_{6.5}$Ce$_{1.5}$ at room temperature and 200 °C was 453 MPa and 360 MPa, respectively.

Keywords: Mg-Zn-Y-RE; long-period stacking ordered structure; mechanical properties; creep resistance

1. Introduction

Magnesium alloys are the lightest metallic materials that are commercially utilized in the automotive industry to lower the emission of carbon dioxide that causes global warming [1–3]. However, these alloys exhibit low mechanical strength at both room temperature and high temperature, which restricts their application [4,5]. Therefore, there have been extensive studies on the development of techniques to optimize the mechanical properties of Mg alloys. The addition of certain alloying elements has been determined to be a convenient and efficient technique to increase the strength and ductility of Mg alloys [6,7].

The Mg-RE (RE—rare earth) series alloys have attracted significant attention in recent years owing to their outstanding heat resistance and mechanical properties [8–10]. Long-period stacking ordered (LPSO) phases, which possess a special structure and excellent strengthening ability, in Mg-Zn-RE alloys have become a subject of intense research [11]. Recently, Noda et al. [12] demonstrated the excellent mechanical properties of extruded Mg$_{88.5}$Zn$_5$Y$_{6.5}$ (wt.%) at 293–773 K. Mg$_{88.5}$Zn$_5$Y$_{6.5}$ consists of three phases, namely, α-Mg, LPSO, and intermetallic compounds. The variation in the content of Zn induces changes in the volume fractions of all the phases. Kim et al. [13] reported that each RE element exerted a unique influence on the volume fractions of the LPSO phases and intermetallic compounds. As a result of the replacement of Y by different RE elements in Mg$_{88.5}$Zn$_5$Y$_s$ alloys, the alloy with Ce and La exhibits higher mechanical properties with the existence of LPSO phases, but the alloys with Nd and Sm exhibit a lower strength...
because of the disappearance of the LPSO phases. Therefore, the addition of different RE elements induces variations in their microstructures and mechanical properties. It is necessary to investigate the effect of the addition of certain RE elements on the microstructures and mechanical properties of Mg_{96.5}Zn_{5}Y_{6.5}. This will facilitate the development of inexpensive and high-strength Mg alloys.

Yb and Ce are representative and inexpensive RE elements that are widely utilized in traditional Mg systems. The addition of these elements optimizes the microstructures and mechanical properties of Mg alloys [14–16]. Li et al. [17] reported that the addition of Yb increased the strength of hot-extruded Mg-8Gd-1.2Zn-0.5Zr via the precipitation strengthening of the Mg-Zn-Gd-Yb phases. Ce is one of the most cost-effective RE elements, and its addition optimizes the mechanical and extrusion properties of alloys [18]. Liu et al. [19] reported that the addition of Ce optimized the mechanical properties of Mg-Zn alloys via the formation of the Mg-Zn-Ce phase. The maximum solubility of Ce in Mg is approximately 0.52 wt.% at 592 °C. Such a low solubility facilitates the precipitation of the Ce-rich phases in Mg-Ce alloys during solidification. However, the substitution of Y in Mg_{97}Zn_{3}Y_{2} with Ce induces the partial transformation of the LPSO phases to compounds, thereby optimizing the mechanical properties [13].

The results of previous studies indicate that the strengthening ability of a composite structure of LPSO phases and intermetallic compounds is higher than that of a structure of only LPSO phases. The optimization of the mechanical properties of Mg alloys via the substitution of Y with Ce and Yb is a subject of high research value. However, the correlated investigations on this subject are limited. The variations in the volume fractions of the LPSO phases and intermetallic compounds in the as-cast and as-extruded Mg alloys were investigated in this study. The tensile and creep properties of the extruded samples were tested at both room temperature and high temperature (200 °C). Finally, the effects of the substitution of Y with Ce and Yb on the microstructure and mechanical properties of Mg_{96.5}Zn_{5}Y_{6.5} were analyzed and discussed.

2. Materials and Methods

Pure Mg, Zn, Y, Yb, and Ce were subjected to high-frequency induction melting under an Ar atmosphere at 730 °C. Subsequently, the melt was poured into steel molds; thus, ingots (diameter = 45 mm) with a nominal composition of Mg_{98.5}Zn_{5}Y_{6.5}X_{RE} (RE = Yb and Ce, X = 0, 1.5, 3.0, and 4.5) (wt.%) alloys were produced. Thereafter, billets with a diameter and height of 42 and 100 mm, respectively, were cut from the cast ingots and extruded at 370 °C. The extrusion ram speed and extrusion ratio were 3.0 mm s^{-1} and 12:1, respectively.

All the samples were obtained from the middle segments of the initial ingots and the extruded samples. The microstructures of the alloys were observed by field-emission scanning electron microscopy (FE-SEM; JSM-7800F, Jeol Ltd., Tokyo, Japan) in conjunction with energy-dispersive X-ray spectroscopy (EDS) and electron backscattered diffraction (EBSD; HKL Channel 5, Oxford Instruments, Abingdon, UK). All the specimens were wet ground to a 2000 grit finish using SiC paper before each experiment. The surfaces of the specimens were polished to a 0.1 μm finish using ethanol as a lubricant for the FE-SEM and EBSD observations. The diameter and gauge length of the tensile test rods were 2.5 mm and 15 mm, respectively. The tensile tests were performed using an Instron-type tensile testing machine at room temperature and 200 °C. The rods were subjected to tensile testing (CMT5105, MTS Systems Co., Ltd., Shanghai, China) at a strain rate of 10^{-3} s^{-1}. The tensile yield strength (TYS), ultimate tensile strength (UTS), and elongation to fracture were averaged over at least three individual measurements. The phase composition, structure, and morphology were characterized by X-ray diffraction (XRD; D/ MAX-2500PC, Rigaku Corporation, Tokyo, Japan). Furthermore, transmission electron microscopy (TEM; Tecnai G2 F20, FEI Company (Thermo Fisher Scientific Inc.), Hillsboro, OR, USA) was performed at an accelerating voltage of 200 kV.
3. Results

Figure 1 shows the XRD patterns of the Mg$_{88.5}$Zn$_5$Y$_{6.5}$-xRE$_x$ alloys. Mg$_{88.5}$Zn$_5$Y$_{6.5}$ comprised α-Mg, Mg$_2$ZnY (LPSO phase), and Mg$_3$ZnY$_2$ (intermetallic compound). The intensity of the peaks of the LPSO phases decreased with the increase in the content of Yb and Ce. The peaks of the LPSO phases were absent in the XRD pattern of Mg$_{88.5}$Zn$_5$Y$_{2.0}$Yb$_{4.5}$. The primary second phases in Mg$_{88.5}$Zn$_5$Y$_{3.5}$Yb$_{3.0}$ and Mg$_{88.5}$Zn$_5$Y$_{2.0}$Yb$_{4.5}$ were Mg$_2$Yb and Mg$_3$ZnY$_2$. The intensity of the peak of Mg$_2$Yb increased with the increase in the Yb content. The substitution of Y with Ce induced the disappearance of the peaks of Mg$_3$ZnY$_2$ and the appearance of the peaks of Mg$_3$Ce. The intensity of the peaks of Mg$_3$Ce increased with the increase in the Ce content.

![Figure 1. XRD patterns of the Mg-Zn-Y-Ce and Mg-Zn-Y-Yb alloys.](image)

Figures 2 and 3 show the SEM micrographs of the as-cast Mg$_{88.5}$Zn$_5$Y$_{6.5}$-xRE$_x$ alloys. The light and dark gray phases denote the LPSO phases and intermetallic compounds (marked by an arrow), respectively. A coarse dendritic structure was formed by the continuous network of the LPSO phases and intermetallic compounds. The volume fraction of the LPSO phases decreased significantly with the increase in the Yb and Ce content. The LPSO phases were not detected in Mg$_{88.5}$Zn$_5$Y$_{2.0}$Yb$_{4.5}$, and this result was consistent with the XRD analysis. The XRD data indicated that the Mg$_3$ZnY$_2$ phases constituted the compounds in Mg$_{88.5}$Zn$_5$Y$_{6.5}$. The Mg$_2$Yb phases were the primary constituents of the compounds in the Mg-Zn-Y-Yb alloys, while the Mg$_3$ZnY$_2$ and Mg$_3$Ce phases were the primarily constituents of the compounds in the Mg-Zn-Y-Ce alloys.
Figures 2 and 3 show the SEM micrographs of the as-cast alloys: (a) Mg$_{88.5}$Zn$_5$Y$_6.5$; (b) Mg$_{88.5}$Zn$_5$Y$_5$Yb$_{1.5}$; (c) Mg$_{88.5}$Zn$_5$Y$_3$Yb$_{3.0}$; (d) Mg$_{88.5}$Zn$_5$Y$_2$Yb$_{4.5}$.

Figures 4 and 5 show the SEM micrographs of the extruded alloys along the extrusion direction. Although the volume fractions of the LPSO phases and intermetallic compounds remained unchanged, there was a significant variation in the morphology. The LPSO phases exhibited a transformation from a net-like to rod-like morphology, and they were uniformly distributed along the extrusion direction in all the samples. The compounds exhibited a morphological transformation from bulk to granular (particles) during extrusion. Furthermore, only the particles of Mg$_2$Yb were detected in
Mg$_{88.5}$Zn$_{5.0}$Y$_{2.0}$. These observations were consistent for the XRD and SEM analyses of the as-cast alloys.

**Figure 4.** SEM microstructure of the extruded alloys: (a) Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$; (b) Mg$_{88.5}$Zn$_{5.0}$Y$_{5.0}$Yb$_{1.5}$; (c) Mg$_{88.5}$Zn$_{5.0}$Y$_{3.5}$Ce$_{3.0}$; (d) Mg$_{88.5}$Zn$_{5.0}$Y$_{2.0}$Ce$_{4.5}$.

The mechanical properties of the extruded alloys at room temperature and 200 °C are presented in Figures 6 and 7, respectively. Mg$_{88.5}$Zn$_{5.0}$ exhibited a TYS, UTS, and elongation of approximately 375 MPa, 425 MPa, and 5.2%, respectively. There was an initial increase and a subsequent decrease in the mechanical strength with the increase in the Yb and Ce content. This indicated that the substitution of Y with an optimal concentration of Yb and
Ce increased the strength of the alloys. Mg$_{88.5}$Zn$_5$Y$_5$Ce$_{1.5}$ exhibited the highest strength, while Mg$_{88.5}$Zn$_5$Y$_2$Yb$_{4.5}$ exhibited the lowest strength and the highest elongation. The strength and elongation at 200 °C were significantly lower and higher, respectively, than those at room temperature. Mg$_{88.5}$Zn$_5$Y$_5$Ce$_{1.5}$ exhibited the maximum strength at 200 °C with a TYS and UTS of 330 MPa and 360 MPa, respectively. It was observed that Mg$_{88.5}$Zn$_5$Y$_5$Ce$_{1.5}$ exhibited the highest strength at both room temperature and 200 °C.

Figure 6. Mechanical properties of the extruded alloys at room temperature: (a) Mg-Zn-Y-Ce alloys; (b) Mg-Zn-Y-Yb alloys.
The creep curves for the extruded alloys were obtained at 200 °C and 150 MPa and are presented in Figure 8. The curves depicted the first and second stages of creep deformation [20]. The effects of Yb and Ce on the creep rate of Mg85Zn5Y6.5 were discernible from the figure. There was an initial increase and a subsequent decrease in the creep resistance of the Mg-Zn-Y-RE alloys with the increase in the Yb and Ce content. The creep resistances of only Mg85Zn5Y5Ce1.5 and Mg85Zn5Y5Yb1.5 were higher than the creep resistance of Mg85Zn5Y6.5. It was concluded that the creep resistance of the Mg-Zn-Y-Ce alloys was higher than that of the Mg-Zn-Y-Yb alloys.
Figure 8. Creep curves of the extruded alloys: (a) Mg-Zn-Y-Ce alloys, and (b) Mg-Zn-Y-Yb alloys, as measured at 200 °C and 150 MPa.

The mechanical properties and creep resistance of Mg88.5Zn5Y5.0Ce1.5 were superior to those of the other alloys. EBSD analyses were performed to compare the crystallographic features of the extruded Mg88.5Zn5Y6.5 and Mg88.5Zn5Y5.0Ce1.5, and the results are presented in Figure 9a,b. The color variation denotes the grain orientation, and the black grains denote the LPSO phases. A part of the worked α-Mg region, with coarse grains, and the dynamically recrystallized (DRXed) α-Mg region, with fine grains, existed in Mg88.5Zn5Y6.5 and Mg88.5Zn5Y5.0Ce1.5. Mg88.5Zn5Y6.5 and Mg88.5Zn5Y5.0Ce1.5 exhibited an increase in the grain size after heat treatment at 400 °C for 1 h. Furthermore, the heat treatment induced static recrystallization in Mg88.5Zn5Y6.5 and Mg88.5Zn5Y5.0Ce1.5, thereby resulting in the transformation of all the worked α-Mg grains to recrystallized grains [21]. Therefore, no worked α-Mg regions were detected in the heat-treated alloys, and the microstructure became uniform. The grains in Mg88.5Zn5Y5.0Ce1.5 were finer than those in Mg88.5Zn5Y6.5, for both the as-extruded and heat-treated states [22].
Figure 9. Inverse pole figure (IPF) maps of extruded (a) Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>6.5</sub> and (b) Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>5.0</sub>Ce<sub>1.5</sub>; heat-treated (c) Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>6.5</sub> and (d) Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>5.0</sub>Ce<sub>1.5</sub>.

Figure 10 shows the TEM micrographs of the extruded Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>5.0</sub>Ce<sub>1.5</sub>. Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>5.0</sub>Ce<sub>1.5</sub> primarily comprised α-Mg grains, intermetallic compounds, and LPSO phases. The rod-like LPSO phases were distributed within the grains (Figure 10a). Furthermore, two types of compounds were detected in the alloy; one was distributed in the form of particles at the grain boundaries, while the other existed as blocks within the α-Mg matrix and between the LPSO phases.

Figure 10. TEM micrographs of the extruded Mg<sub>88.5</sub>Zn<sub>5.0</sub>Y<sub>5.0</sub>Ce<sub>1.5</sub>: (a) morphology of LPSO phases and (b) morphology of compounds.

4. Discussion

Figure 11 shows the calculated volume fractions of α-Mg, the LPSO phases, and intermetallic compounds in the Mg-Zn-Y-RE alloys. MgZn<sub>5</sub>Y<sub>6.5</sub> comprised 31.5 and 2.8 vol.% of the LPSO phases and intermetallic compounds, respectively. The content of the LPSO phases decreased from 24.4 to 5.2% with the increase in the Ce content from 1.5 to 4.5%. The addition of Yb also decreased the content of the LPSO phases, and no LPSO phases were detected in MgZnY<sub>2.0</sub>Yb<sub>4.5</sub>. The criteria for the formation of LPSO phases in the Mg-Zn-RE alloys are as follows [23]:

1. High solid solubility limit in Mg alloys.
2. Negative mixing enthalpy between Mg-RE and Zn-RE.
3. HCP structure at room temperature.
4. Higher atomic size of the RE atoms as compared to that of Mg.

Figure 11. Volume fraction of the α-Mg, LPSO phases, and compounds in Mg-Zn-Y-RE alloys.

The negative mixing enthalpy between Mg-RE and Zn-RE as well as the difference in the atomic sizes of Mg, Zn, and RE were similar for the addition of Ce and Yb. However, the solid solubility limits of Ce and Yb in magnesium are 0.66 and 3.3 wt.%, respectively, at the eutectic temperature [14]. The high solid solubility limit of Yb lowered the volume fraction of the intermetallic compounds in the Mg-Zn-Y-Yb alloy; however, the effect on the volume fraction of the LPSO phases was negligible at a Yb content of 1.5 and 3.0 wt.%. Therefore, the volume fraction of the LPSO phases in the Mg-Zn-Y-Yb alloys was higher than that of the LPSO phases in the Mg-Zn-Y-Ce alloys. The LPSO phases were absent in Mg$_{88.5}$Zn$_{5.0}$Y$_{5.0}$Yb$_{1.5}$. The XRD analysis indicated that Zn and Y formed a compound, Mg$_3$Zn$_2$Y$_2$, instead of the LPSO phases. The underlying reason for this phenomenon needs further research.

According to the IPF maps (Figure 9), the average grain size of both the Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$ and Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$Ce$_{1.5}$ alloys is 1.5 μm. In fact, the average grain size of all the alloys is almost the same, and this result excluded the effect of grain size on the strength, so the major factor to effect of mechanical properties is the second phases. Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$Yb$_{1.5}$ and Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$Ce$_{1.5}$ possessed a networked and stratified structure of LPSO phases and intermetallic compounds (Figures 4 and 5). This structure was responsible for the high strength of these alloys. The mechanical strengths of Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$Yb$_{1.5}$ and Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$Ce$_{1.5}$ were higher than the mechanical strength of Mg$_{88.5}$Zn$_{5.0}$Y$_{6.5}$ at both room temperature and 200 °C. A curve of the variation in the tensile yield strength with the volume fraction of the LPSO phases was plotted (Figure 12) to elucidate the effect of the Yb and Ce content on the mechanical properties of Mg-Zn-Y-RE alloys. There was a marked increase in the TYS, with the increase in the content of the LPSO phase. The LPSO phases exhibit a unique mode of plastic deformation, known as kink deformation [24]. The deformation models of the LPSO phases and α-Mg are significantly different. Therefore, the deformation of the LPSO phases in the grains is incompatible with that of α-Mg. Consequently, the alloys containing the LPSO phases exhibit high strength [25]. Multiple researchers have reported that alloys containing the LPSO phases exhibit an extremely high strength [26,27]. The variation in the mechanical properties was primarily attributed to the volume fraction of the LPSO phases.
As shown in Figure 9, the worked Mg grains that existed in the Mg$_{88.5}$Zn$_{5}$Y$_{5}$Ce$_{1.5}$ and Mg$_{88.5}$Zn$_{5}$Y$_{6.5}$ alloys disappeared after the heat treatment at 400 °C for 1 h. This result indicated the presence of deformed storage energy inside the grains after extrusion. The heat treatment enabled the deformed storage energy to become the driving force for recrystallization nucleation. This induced the transformation of the worked Mg grains to recrystallized grains through a particulate-stimulated nucleation mechanism. The high-volume fraction of LPSO phases results in a significant stress transferred from the Mg matrix to the LPSO phases, which is much higher than the compounds [28]. Therefore, the Mg$_{88.5}$Zn$_{5}$Y$_{5}$Ce$_{1.5}$ alloy with low LPSO phases have much more strain energy to induce recrystallization than the MgZn$_{5}$Y$_{6.5}$ alloy, and leads to a finer grain size after heat treatment. The thermal stability of Mg$_{88.5}$Zn$_{5}$Y$_{5}$Ce$_{1.5}$ was higher than that of Mg$_{88.5}$Zn$_{5}$Y$_{6.5}$ at high temperature, and Mg$_{88.5}$Zn$_{5}$Y$_{5}$Ce$_{1.5}$ exhibited a high strength and creep resistance at 200 °C. The creep resistance of Mg$_{88.5}$Zn$_{5}$Y$_{5}$Yb$_{1.5}$ was higher than that of Mg$_{88.5}$Zn$_{5}$Y$_{6.5}$. There was a decrease in the creep resistance with the increase in the content of Yb that substituted Y. The creep resistance of Mg$_{88.5}$Zn$_{5}$Y$_{2}$Yb$_{4.5}$ was markedly low, owing to the absence of the LPSO phases, thereby confirming the efficacy of the LPSO phases for increasing the creep resistance.

The Mg-Zn-Y-RE alloys were classified into Type A and Type B (Figure 13). The LPSO phases were formed in the Mg$_{88.5}$Zn$_{5}$Y$_{5.5}$Ce$_{0.5}$ alloys during solidification, and the volume fraction of the LPSO phases decreased with the increase in the Ce content (Type A). The variation rule for the Mg$_{88.5}$Zn$_{5}$Y$_{6.5}$Yb$_{4.5}$ alloys was the same as that for the Mg$_{88.5}$Zn$_{5}$Y$_{6.5}$Ce$_{0.5}$ alloys; however, the LPSO phases disappeared at a Yb content of 4.5 wt.% (Type B). Mg$_{88.5}$Zn$_{5}$Y$_{2}$Yb$_{4.5}$ did not contain the LPSO phases; therefore, it exhibited a low strength, low creep resistance, and high elongation.
5. Conclusions

The microstructures and mechanical properties of the Mg-Zn-Y-RE alloys were investigated in this study. The results can be summarized as follows:

(1) When the content of Ce and Yb in the Mg-Zn-Y-RE alloys increased, the content of the LPSO phases decreased during solidification. When the content of Y was low, the content of the LPSO phases in Mg_{88.5}Zn_{5}Y_{2.0} was also low. Furthermore, the LPSO phases did not exist in Mg_{88.5}Zn_{5}Y_{2.0}Yb_{4.5}.

(2) The alloys that contained the LPSO phases exhibited a higher strength, higher creep resistance, and lower elongation than those exhibited by the alloys that did not contain the LPSO phases.

(3) The creep resistance and the mechanical properties of Mg_{88.5}Zn_{5}Y_{5.0}Ce_{1.5} were superior to those of the other alloys at both room temperature and 200 °C. This was attributed to the suitable microstructure and high thermal stability of Mg_{88.5}Zn_{5}Y_{5.0}Ce_{1.5}.

Author Contributions: H.L., writing—original draft, data analysis, investigation and methodology; T.L., data analysis, supervision; J.S., data analysis, investigation and methodology; J.K., conceptualization, funding acquisition, writing—review and editing; F.P., conceptualization, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Joost, W.J.; Krajewski, P.E. Towards magnesium alloys for high-volume automotive applications. Scr. Mater. 2017, 128, 107–112, doi:10.1016/j.scriptamat.2016.07.035.
2. Yang, Q.; Guan, K.; Li, B.; Meng, F.; Lv, S.; Yu, Z.; Zhang, X.; Zhang, J.; Meng, J. Coexistence of 14H and 18R-type long-period stacking ordered (LPSO) phases following a novel orientation relationship in a cast Mg-Al-RE-Zn alloy. J. Alloy. Compd. 2018, 766, 902–907, doi:10.1016/j.jallcom.2018.07.053.
3. Zheng, X.; Du, W.; Liu, K.; Wang, Z.; Li, S. Effect of trace addition of Al on microstructure, texture and tensile ductility of Mg-Zn-0.5Er alloy. J. Magnes. Alloy. 2016, 4, 135–139, doi:10.1016/j.jma.2016.04.001.
4. Naghdi, F.; Mahmudi, R.; Kang, J.; Kim, H. Microstructure and high-temperature mechanical properties of the Mg-4Zn-0.5Ca alloy in the as-cast and aged conditions. Mater. Sci. Eng. A 2016, 649, 441–448, doi:10.1016/j.msea.2015.10.011.
5. Bettles, C.J.; Gibson, M.A.; Venkatesan, K. Enhanced age-hardening behaviour in Mg-4 wt.% Zn micro-alloyed with Ca. *Scr. Mater.* 2004, 51, 193–197.

6. Tong, T.; Zhang, F.; Liu, S.; Du, Y.; Li, K. Experimental investigation on the phase equilibria of the Mg-Sn-Ag system in the Mg-rich corner. *J. Magnes. Alloy.* 2017, 5, 41–47, doi:10.1016/j.jma.2017.02.003.

7. Liao, H.; Kim, J.; Liu, T.; Tang, A.; She, J.; Peng, F.; Pan, F. Effects of Mn addition on the microstructures, mechanical properties and work-hardening of Mg-1Sn alloy. *Mater. Sci. Eng. A* 2019, 754, 778–785, doi:10.1016/j.msea.2019.02.021.

8. Yu, Z.J.; Huang, Y.D.; Dieringa, H.; Mendis, C.L.; Guan, R.G.; Hort, N.; Meng, J. High temperature mechanical behaviour of an extruded Mg-11Gd-4.5Y-1Nd-1.5Zn-0.5Zr (wt%) alloy. *Mater. Sci. Eng. A* 2015, 645, 213–224.

9. Yang, Q.; Xiao, B.L.; Zhang, Q.; Zheng, M.Y.; Ma, Z.Y. Exceptional high-strain-rate superplasticity in Mg-Gd-Y-Zn-Zr alloy with long-period stacking ordered phase. *Scr. Mater.* 2013, 69, 801–804.

10. Yamasaki, M.; Sasaki, M.; Nishiijima, M.; Hiraga, K.; Kawamura, Y. Formation of 14H long period stacking ordered structure and profuse stacking faults in Mg-Zn-Gd alloys during isothermal aging at high temperature. *Acta Mater.* 2007, 55, 6798–6805, doi:10.1016/j.actamat.2007.08.033.

11. Zhang, J.; Liu, S.; Wu, R.; Hou, L.; Zhang, M. Recent developments in high-strength Mg-RE-based alloys: Focusing on Mg-Gd and Mg-Y systems. *J. Magnes. Alloy.* 2018, 6, 277–291, doi:10.1016/j.jma.2018.08.001.

12. Noda, M.; Matsumoto, R.; Kawamura, Y. Forging induces changes in the formability and microstructure of extruded Mg96Zn2Y2 alloy with a long-period stacking disorder phase. *Mater. Sci. Eng. A* 2013, 563, 21–27, doi:10.1016/j.msea.2012.11.072.

13. Kim, J.; Kawamura, Y. Influence of Rare Earth Elements on Microstructure and Mechanical Properties of Mg97Zn1Y1RE1 Alloys. *Mater. Sci. Eng. A* 2013, 573, 62–66, doi:10.1016/j.msea.2012.12.087.

14. Zhang, D.; Zhang, D.; Bu, F.; Li, X.; Li, B.; Yan, T.; Guan, R.; Yang, Q.; Liu, X.; Meng, J. Excellent ductility and strong work hardening effect of as-cast Mg-Zn-Zr-Yb alloy at room temperature. *J. Alloy. Compd.* 2017, 728, 404–412, doi:10.1016/j.jallcom.2017.09.016.

15. Yu, W.; Liu, Z.; He, H.; Cheng, N.; Li, X. Microstructure and mechanical properties of ZK60-Yb magnesium alloys. *Mater. Sci. Eng. A* 2008, 478, 101–107, doi:10.1016/j.msea.2007.09.027.

16. Li, B.; Guan, K.; Yang, Q.; Niu, X.; Zhang, D.; Yu, Z.; Zhang, X.; Tang, Z.; Meng, J. Effects of 0.5 wt.% Ce addition on microstructures and mechanical properties of a wrought Mg-8Gd-1.2Zn-0.5Zr alloy. *J. Alloy. Compd.* 2018, 763, 120–133, doi:10.1016/j.jallcom.2018.05.308.

17. Li, B.S.; Guan, K.; Yang, Q.; Niu, X.D.; Zhang, D.D.; Lv, S.H.; Meng, F.Z.; Huang, Y.D.; Hort, N.; Meng, J. Microstructures and mechanical properties of a hot-extruded Mg8Gd3Yb1.2Zn0.5Zr (wt%) alloy. *J. Alloys Compd.* 2019, 776, 666–678.

18. Yu, H.; Kim, Y.M.; You, B.S.; Yu, H.S.; Park, S.H. Effects of cerium addition on the microstructure, mechanical properties and hot workability of ZK60 alloy. *Mater. Sci. Eng. A* 2013, 559, 798–807, doi:10.1016/j.msea.2012.09.026.

19. Liu, L.; Chen, X.; Pan, F.; Tang, A.; Wang, X.; Liu, J.; Gao, S. Microstructure, texture, mechanical properties and electromagnetic shielding effectiveness of Mg-Zn-Zr-Ce alloys. *Mater. Sci. Eng. A* 2016, 669, 259–268, doi:10.1016/j.msea.2016.05.098.

20. Zhua, S.M.; Abbotta, T.B.; Gibsona, M.A.; Nie, J.F.; Easton, M.A. The influence of minor Mn additions on creep resistance of die-cast Mg-Al-RE alloys. *Mater. Sci. Eng. A* 2017, 682, 535–541.

21. Zhang, D.; Tan, Z.; Hao, Q.; Xiao, Z.; Fang, Z.; Yang, X. Dynamic recrystallization behaviors of Mg-Gd-Y-Zn-Zr alloy with different morphologies and distributions of LPSO phases. *Mater. Sci. Eng. A* 2018, 715, 389–403, doi:10.1016/j.msea.2017.12.103.

22. Robson, J.D.; Henry, D.T.; Davis, B. Particle effects on recrystallization in magnesium-manganese alloys: Particle-stimulated nucleation. *Acta Mater.* 2009, 57, 2739–2747, doi:10.1016/j.actamat.2009.02.032.

23. Kawamura, Y.; Hayashi, K.; Inoue, A.; Masumoto, T. Rapidly Solidified Powder Metallurgy Mg97Zn1Y2Alloys with Excellent Tensile Yield Strength above 600 MPa. *Mater. Trans.* 2001, 42, 1172–1176, doi:10.2320/matertrans.42.1172.

24. Gao, H.; Ikeda, K.-I.; Morikawa, T.; Higashida, K.; Nakashima, H. Analysis of kink boundaries in deformed synchronized long-period stacking ordered magnesium alloys. *Mater. Lett.* 2015, 146, 30–33, doi:10.1016/j.matlet.2015.01.136.

25. Homma, T.; Kunito, N.; Kamado, S. Fabrication of extraordinary high-strength magnesium alloy by hot extrusion. *Scr. Mater.* 2009, 61, 644–647, doi:10.1016/j.scriptamat.2009.06.003.

26. Yu, Z.; Huang, Y.; Qu, X.; Wang, G.; Meng, F.; Hort, N.; Meng, J. Fabrication of a high strength Mg-11Gd-4.5Y-1Nd-1.5Zn-0.5Zr (wt%) alloy by thermomechanical treatments. *Mater. Sci. Eng. A* 2015, 622, 121–130, doi:10.1016/j.msea.2014.10.077.

27. Heng, X.; Zhang, R.; Wong, W.; Wu, Y.; Peng, L. A super high-strength Mg-Gd-Y-Zn-Mn alloy fabricated by hot extrusion and strain aging. *Mater. Des.* 2019, 169, 107666, doi:10.1016/j.matdes.2019.107666.

28. Pérez, F.; Medina, J.C.; Garces, G.; Adeva, P. Influence of Y/ CeMM ratio on the microstructure and mechanical properties of Mg95Zn2(Y, CeMM)3 alloys. *Intermetallics* 2012, 31, 196–201, doi:10.1016/j.intermet.2012.07.005.