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

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Abstract: The microstructures and mechanical properties of the $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-X}\text{RE}_X$ (RE = Yb and Ce, X = 0, 1.5, 3.0, and 4.5) (wt.%) alloys were investigated in the present study. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$. The alloys containing the LPSO phases possessed a stratified microstructure and exhibited excellent mechanical properties. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ at room temperature was 358 MPa. The ultimate tensile strength of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ 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

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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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ (wt.%) at 293–773 K. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ 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 $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$. 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 $\text{Mg-8Gd-1.2Zn-0.5Zr}$ 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 $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-X}\text{RE}_X$ (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 $0.1 \mu\text{m}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-x}\text{RE}_x$ alloys. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ comprised α -Mg, Mg_{12}ZnY (LPSO phase), and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ (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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$. The primary second phases in $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{3.5}\text{Yb}_{3.0}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$ were Mg_2Yb and $\text{Mg}_3\text{Zn}_3\text{Y}_2$. The intensity of the peak of Mg_2Yb increased with the increase in the Yb content. The substitution of Y with Ce induced the disappearance of the peaks of $\text{Mg}_3\text{Zn}_3\text{Y}_2$ and the appearance of the peaks of Mg_{12}Ce . The intensity of the peaks of Mg_{12}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.

Figures 2 and 3 show the SEM micrographs of the as-cast $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-x}\text{RE}_x$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$, and this result was consistent with the XRD analysis. The XRD data indicated that the $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases constituted the compounds in $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$. The Mg_2Yb phases were the primary constituents of the compounds in the Mg-Zn-Y-Yb alloys, while the $\text{Mg}_3\text{Zn}_3\text{Y}_2$ and Mg_{12}Ce phases were the primarily constituents of the compounds in the Mg-Zn-Y-Ce alloys.

Figure 2. SEM microstructure of the as-cast alloys: (a) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$; (b) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Yb}_{1.5}$; (c) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{3.5}\text{Yb}_{3.0}$; (d) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$.

Figure 3. SEM microstructure of the as-cast alloys: (a) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$; (b) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$; (c) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{3.5}\text{Ce}_{3.0}$; (d) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Ce}_{4.5}$.

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 extru-

sion. Furthermore, only the particles of Mg_2Yb were detected in $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$. These observations were consistent for the XRD and SEM analyses of the as-cast alloys.

Figure 4. SEM microstructure of the extruded alloys: (a) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$; (b) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Yb}_{1.5}$; (c) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{3.5}\text{Yb}_{3.0}$; (d) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$.

Figure 5. SEM microstructure of the extruded alloys: (a) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$; (b) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$; (c) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{3.5}\text{Ce}_{3.0}$; (d) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Ce}_{4.5}$.

The mechanical properties of the extruded alloys at room temperature and 200 °C are presented in Figures 6 and 7, respectively. $\text{Mg}_3\text{Zn}_3\text{Y}_2$ 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. $Mg_{88.5}Zn_5Y_{5.0}Ce_{1.5}$ exhibited the highest strength, while $Mg_{88.5}Zn_5Y_{2.0}Yb_{4.5}$ 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. $Mg_{88.5}Zn_5Y_{5.0}Ce_{1.5}$ exhibited the maximum strength at 200 °C with a TYS and UTS of 330 MPa and 360 MPa, respectively. It was observed that $Mg_{88.5}Zn_5Y_{5.0}Ce_{1.5}$ 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.

Figure 7. Mechanical properties of the extruded alloys at 200 °C: (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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Yb}_{1.5}$ were higher than the creep resistance of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$. 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ were superior to those of the other alloys. EBSD analyses were performed to compare the crystallographic features of the extruded $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$, 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ exhibited an increase in the grain size after heat treatment at 400 °C for 1 h. Furthermore, the heat treatment induced static recrystallization in $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$, 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ were finer than those in $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$, for both the as-extruded and heat-treated states [22].

Figure 9. Inverse pole figure (IPF) maps of extruded (a) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and (b) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$; heat-treated (c) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and (d) $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$.

Figure 10 shows the TEM micrographs of the extruded $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$: (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. $\text{MgZn}_5\text{Y}_{6.5}$ 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 $\text{MgZn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$. 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{2.0}\text{Yb}_{4.5}$. The XRD analysis indicated that Zn and Y formed a compound, $\text{Mg}_3\text{Zn}_3\text{Y}_2$, 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ alloys is 1.5 μm . In fact, the average grain size of all the alloys is almost 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. $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Yb}_{1.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Yb}_{1.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ were higher than the mechanical strength of $\text{MgZn}_5\text{Y}_{6.5}$ 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.

Figure 12. Variation in the tensile yield strength with the volume fraction of the LPSO phases.

As shown in Figure 9, the worked Mg grains that existed in the $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_5\text{Ce}_{1.5}$ and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_5\text{Ce}_{1.5}$ alloy with low LPSO phases have much more strain energy to induce recrystallization than the $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ alloy, and leads to a finer grain size after heat treatment. The thermal stability of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ was higher than that of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$ at high temperature, and $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{5.0}\text{Ce}_{1.5}$ exhibited a high strength and creep resistance at 200 °C. The creep resistance of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_5\text{Yb}_{1.5}$ was higher than that of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5}$. There was a decrease in the creep resistance with the increase in the content of Yb that substituted Y. The creep resistance of $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_2\text{Yb}_{4.5}$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-x}\text{Ce}_x$ 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 $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-x}\text{Yb}_x$ alloys was the same as that for the $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_{6.5-x}\text{Ce}_x$ alloys; however, the LPSO phases disappeared at a Yb content of 4.5 wt.% (Type B). $\text{Mg}_{88.5}\text{Zn}_5\text{Y}_2\text{Yb}_{4.5}$ did not contain the LPSO phases; therefore, it exhibited a low strength, low creep resistance, and high elongation.

Figure 13. Schematic diagram of the microstructures of the Mg-Zn-Y-RE alloys.

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}Zn₅Y_{2.0}Ce_{4.5} was also low. Furthermore, the LPSO phases did not exist in Mg_{88.5}Zn₅Y_{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}Zn₅Y_{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}Zn₅Y_{5.0}Ce_{1.5}.

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