Effect of Zn addition on the microstructures and mechanical behaviors of as-cast Mg-2.5Y-1Ce-0.5Mn alloy

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Keywords: Mg alloy, microstructure, ternary phases, nanoindentation, mechanical behavior

Abstract

The effect of Zn addition on the microstructures and mechanical behaviors of as-cast Mg-2.5Y-1Ce-0.5Mn alloy was investigated. Microstructure observation demonstrated that with the addition of 1wt%, 3wt% and 5wt% Zn, the ternary phases of LPSO phase, LPSO phase + W-phase and W-phase + T-phase (Mg-Zn-Ce) are precipitated orderly, and the volume fraction of eutectic phases increases. The results of tensile tests demonstrated that with increasing Zn addition, the yield strength (σYS) of as-cast alloys increases continuously while the ultimate tensile strength (σUTS) and elongation (Δ) increase nonlinearily. Based on the analysis of microstructure, nanoindentation results and deformation surfaces, it found that the σYS is increased by the increased volume fraction of hard ternary phases. The largest δ in 1wt% Zn alloy is contributed from the LPSO phase with an excellent plastic accommodation while the insufficient accommodated role of LPSO phase and the easily broken W-phase deteriorate the ductility of 3wt% Zn alloy. The hard and brittle T-phase also damages the ductility, while the fine grains contribute to the moderate elongation in 5wt% Zn alloy. The σUTS mainly arises from a sustainable increase of strain hardening ability after yielding that associated with both the high yielding point and excellent ductility.

1. Introduction

The Mg alloys are the environmentally-friendly structural materials in the 21st century due to their low density, high specific strength and stiffness, good workability and well recycling [1–4]. Accordingly, they are attractive in the application of automobile, aerospace, rail way and biomedicine [5–8]. However, their relatively low strengths and ductility of as-cast Mg alloys are still the serious problems which limit their applications. Alloying is generally the attractive method for improving both the strengths and ductility of Mg alloys. The properties improved by the alloying method is commonly attributed to the grain refinement, solid solution strengthening and the second phase strengthening. For the as-cast alloys, the eutectic second phases usually play an uncertain impact on mechanical properties due to their various type, volume fractions and distributions [9, 10].

It is acknowledged that Zn is one of the most effective elements to improve the properties of Mg-RE alloys (RE: rare earth) because Zn can combine with Mg and certain RE elements to form Mg-RE-Zn ternary phases and then further strengthen and/or toughen the Mg-RE-Zn alloys [11, 12]. Different types of ternary phases have been reported in the Mg-RE-Zn alloys in which the RE elements can be divided into the heavy and light ones. In the Mg-HRE (heavy RE) alloys, such as Mg-Y, Mg-Gd and Mg-Ho alloys, long period stacking ordered (LPSO) phase, I-phase and W-phase are usually induced via the addition of Zn [9, 12–15]. Among these ternary phases, LPSO phase is usually considered as a sufficient strengthening phase due to its well coherent interfaces with α-Mg matrix, which also contributes to the elongation significantly [14]. However, W-phase is regarded as an adverse phase to enhancing comprehensive mechanical properties in the as-cast alloys as a consequence of its weak bonding interface with Mg matrix [15, 16]. It is important and inevitable to note that in the Mg-LRE...
Simultaneously, the eutectic phases almost distribute at grain boundaries and become more abundant and cast alloys show a dendritic microstructure that mainly comprises of primary α-Mg grains and eutectic phases. It can be seen that the α-Mg grains become apparently finer after adding more Zn contents. The average grain size of four alloys measured by linearly intercepted method is around 72 μm, 59 μm, 48 μm and 40 μm, respectively. Simultaneously, the eutectic phases almost distribute at grain boundaries and become more abundant and

Table 1. The chemical compositions (wt%) of experimental alloys.

| Alloys          | Nominal composition | Y   | Ce | Mn | Zn  | Mg |
|-----------------|---------------------|-----|----|----|-----|----|
| Alloy I         | Mg-2.5Y-1Ce-0.5Mn   | 2.64| 0.85| 0.50| —   | Bal.|
| Alloy II        | Mg-2.5Y-1Ce-0.5Mn-1Zn| 2.32| 1.08| 0.42| 1.08| Bal.|
| Alloy III       | Mg-2.5Y-1Ce-0.5Mn-3Zn| 2.38| 0.92| 0.46| 3.04| Bal.|
| Alloy IV        | Mg-2.5Y-1Ce-0.5Mn-5Zn| 2.13| 0.84| 0.56| 5.06| Bal.|

(light RE) alloys, i.e., Mg-Ce and Mg-Sm alloys, Zn addition can result in the formation of Mg-Zn-Ce (T-phase) and Mg-Zn-Sm ternary phases, respectively [7, 17, 18]. The T-phase can significantly increase the strengths of alloys but has an adverse effect on the ductility due to it coarsen presence [18]. However, the ternary phases in Mg-HRE-LRE-Zn alloys are less reported and the mechanical behavior dependence of ternary phases in as-cast Mg-HRE-LRE-Zn alloys is still unclear.

In this study, the Mg-2.5Y-1Ce-0.5Mn alloy is chosen as the base alloy in which Y and Ce are the typical HRE and LRE elements, increasing amounts of Zn are added in order to form different ternary phases of the sole LPSO phase, the combination of LPSO phase and W-phase, and the sole W-phase, based on the different ratios of Zn/RE. The effect of Zn addition on formation of ternary phases and the influence of microstructure (especially ternary phases) on the tensile mechanical behaviors are analyzed and discussed in details to elucidate the relationships between microstructure and mechanical behaviors in the as-cast of Mg-2.5Y-1Ce-xZn (x = 0, 1, 3, 5 wt%) alloys.

2. Material and experimental methods

The as-cast Mg-2.5Y-1Ce-0.5Mn-xZn (x = 0, 1, 3, 5 wt%) alloys in the present work were prepared by the pure Mg (99.95 wt%), pure Zn (99.95 wt%) and the master alloys of Mg-25Y (wt%) and Mg-20Ce (wt%) in an electric resistant furnace and then fabricated by the semi-continuous casting technology. The four types of as-cast ingots with diameter of 100 mm were machined into round bars with diameter of 95 mm. The as-cast Mg-2.5Y-1Ce-0.5Mn alloys with Zn addition of 0 wt%, 1 wt%, 3 wt% and 5 wt% were named as Alloy I, Alloy II, Alloy III and Alloy IV, respectively. The chemical compositions were determined by the method of inductively coupled plasma atomic emission spectrum (ICP-AES) and the results of chemical compositions were listed in table 1.

The phase analysis was determined by the X-ray diffraction (D/Max 2400 XRD) with Cu kα1 radiation (wavelength λ = 1.5406 Å(α)) at a scanning speed of 4° min⁻¹ under an accelerating voltage of 40 kV and a current of 30 mA. Microstructures were characterized by using optical microscopy (Olym-pusGX71 OM), scanning electron microscopy (S-4800 SEM) equipped with the energy dispersive spectroscopy (EDS) and transmission electron microscope (JEM-2100F TEM). The OM and SEM specimens were firstly polished and then etched in the acetic picric acid solution (5 g picric acid, 5 ml acetic acid, 10 ml water and 90 ml ethanol). Samples for the TEM observation were grinded to a thickness of around 20 μm, punched out 3 mm in diameter and then milled on an argon-ion-milling system (EMR101). The tensile tests were conducted on the material testing system (MTS810) at the initial strain rate of 1 × 10⁻³ s⁻¹. The tensile specimens were sampled at the same position in the four casting bars and prepared with a gauge size of 3 × 2.5 × 15 mm. The tensile tests for each alloy were repeated three times. The nanoindentation tests were performed at room temperature on a nano-indenter (Agilent-G200) by using Berkovich diamond indenter. The local regions of the specimens were indented with a loading rate of 20 μN s⁻¹ until reach the peak load of 10 mN. Then the indenter was directly withdrawn from the specimen surface to zero with an unloading rate of 20 μN s⁻¹. The thermal drift calibration was performed prior to testing and each indentation test was repeated more than ten times.

3. Results

3.1. Microstructure of the as-cast alloys

Figure 1 shows the optical micrographs of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn (x = 0, 1, 3, 5 wt%) alloys. The as-cast alloys show a dendritic microstructure that mainly comprises of primary α-Mg grains and eutectic phases. It can be seen that the α-Mg grains become apparently finer after adding more Zn contents. The average grain size of four alloys measured by linearly intercepted method is around 72 μm, 59 μm, 48 μm and 40 μm, respectively. Simultaneously, the eutectic phases almost distribute at grain boundaries and become more abundant and
continuous with increasing Zn addition. The volume fractions of eutectic phases in the four alloys measured by the area calculation method are 4%, 10%, 11% and 14%, respectively.

Figure 2 shows the XRD patterns of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn (x = 0, 1, 3, 5 wt%) alloys. The XRD results indicate that the Alloy I without Zn has α-Mg, Mg24Y5 and Mg12Ce phases (named as Mg-RE phases), and the diffraction peaks of the Mg-RE phases are gradually weakened with increasing Zn addition. Meanwhile, the additional diffraction peaks of LPSO phase, LPSO phase and W-phase, and W-phase and T-phase are intensified, which indicates that the LPSO phase, W-phase and T-phase precipitate in order in Alloy II, Alloy III and Alloy IV, respectively.

Figure 3 shows the SEM images of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn alloys. It can be seen evidently from figures 3(a), (c), (e) and (g) that the eutectic phases are mostly distributed along the grain boundaries. Figures 3(b), (d), (f) and (h) are the corresponding magnification images of typical eutectic phases that marked by the white frames in figures 3(a), (c), (e) and (f). The typical eutectic phases that marked by the yellow solid
circles are clarified by the EDS method, and the chemical compositions of the observed eutectic phases are listed in table 2. As seen in table 2, the grey strip phase 1 observed in figure 3(b) consists of Mg and Ce elements while the white granular phase 2 adjacent to phase 1 composes of Mg and Y elements. Combined the results of EDS with XRD, it is inferred that the phase 1 is Mg12Ce and the phase 2 is Mg24Y5. In figure 3(d), it can be observed that the shallow-grey intermetallic phase 3 in Alloy II with irregular shape is mixed together with the grey block phase 5 while phase 4 with small size is neighbor to the mixed phases. Combined their chemical composition with XRD results, it is inferred that phase 3 and phase 4 are Mg12Ce and Mg24Y5, respectively, while the grey block phase 5 is mainly composed of Mg, Y and Zn elements. Moreover, the weight ratio of Zn/Y in phase 5 is approximate to 1:1, indicating the LPSO phase is formed in Alloy II. As is shown in figure 3(f), phase 6 in Alloy III with the network-like shape preferentially locate in the triple junctions of grain boundaries while some of them along the grain boundaries are separated by the block phase 7. EDS analysis indicates that the Zn/Y ratio at phase 6 and (Y, Ce)/Zn ratio at phase 7 are approximate to 1:1 and 2:3, which corresponds to the LPSO phase and W-phase, respectively. The intermetallic eutectic phase 8 with the network-like shape and phase 9 with irregular

Figure 3. SEM images of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn alloys: (a) and (b) Alloy I, (c) and (d) Alloy II, (e) and (f) Alloy III, (g) and (h) Alloy IV.
block-shape in Alloy IV are displayed in figure 3(h) and their chemical compositions listed in table 2 are 40.62Mg-16.40Y-6.20Ce-36.78Zn and 42.73Mg-39.72Zn-17.55Ce, which should be confirmed as W-phase and T-phase, respectively. These two typical eutectic phases are also in good agreement with the XRD result. The volume fraction of LPSO phase that measured by the area measurement in Alloy II and Alloy III is 8.5% and 4.5%, respectively, the volume fraction of W-phase that observed in the Alloy III and Alloy IV is measured to be 6.5% and 9.8%, respectively, and that of the T-phase in Alloy IV is 4.2%.

Table 2. EDS results of the typical eutectic phases and the matrix.  

| Alloy | Phases | Mg | Y | Ce | Zn |
|-------|--------|----|---|----|----|
| 1     |       |    |   |    |    |
| 2     |       |    |   |    |    |
| Matrix|       | 98.54 | 0.75 | 0.51 |    |
| 3     |       | 84.63 |    | 15.37 |    |
| 4     |       | 74.79 | 25.21 |    |    |
| 5     |       | 84.38 | 7.90 |    | 7.62 |
| Matrix|       | 96.89 | 1.19 | 0.54 | 0.38 |
| 6     |       | 85.03 | 7.38 |    | 7.39 |
| 7     |       | 48.60 | 11.93 | 9.67 | 29.80 |
| 8     |       | 96.40 | 0.85 | 0.82 | 1.33 |
| 9     |       | 42.73 |    |    | 17.55 39.72 |
| Matrix|       | 96.35 | 1.05 | 0.88 | 1.72 |

The true stress (YS) of Alloy II, Alloy III and Alloy IV are obviously increased to 179.8 MPa, 176.1 MPa and 198.3 MPa, respectively, compared with the Zn free alloy, with YS/UTS and ε values are 179.8 MPa, 176.1 MPa and 198.3 MPa, while the ε values are 12.5%, 9.7% and 10.8% respectively. It should be emphasized that along with increasing Zn content, the YS value is gradually increased with increasing Zn addition. At higher strain range (the ε smaller than 0.03), the YS value is gradually increased with increasing Zn addition. At higher strain range (the ε larger than 0.03), the YS values are nonlinearly varied owing to the special performance of Alloy III. The true stress (YS) increases continuously, however, the ε values are nonlinearly varied owing to the special performance of Alloy III. The true stress (YS) in figure 5(c) is sustainably increased with increasing the true strains (εT). The variations of strain hardening rate shown in figure 5(d) can be expressed as:

\[ \Theta = \frac{\partial \sigma_T}{\partial \varepsilon_T} \]  

where \( \sigma_T \) and \( \varepsilon_T \) are obtained from the true stress-strain curves in figure 5(c). The values of \( \Theta \) drop rapidly at the initial strain range and then decrease slowly with increasing the true strains. At lower strain range (the \( \varepsilon_T \) smaller than 0.03), the \( \Theta \) value is gradually increased with increasing Zn addition. At higher strain range (the \( \varepsilon_T \) larger than 0.03), the \( \Theta \) versus \( \varepsilon_T \) curves overlap together and show comparable strain hardening abilities until the
points of plastic instability. In the point of plastic instability, the Alloy IV shows the largest strain hardening ability while the Alloy I exhibits the lowest strain hardening ability.

Figure 6 compares the ultimate tensile strength \( \sigma_{UTS} \) and elongation \( \delta \) of present as-cast Mg-2.5Y-1Ce-0.5Mn-xZn \((x = 0, 1, 3, 5 \text{ wt%})\) alloys with the published results of tensile tests in other as-cast Mg-RE or Mg-RE-Zn alloys \[10, 16, 19-30\]. It is notable that the other as-cast alloys exhibit various \( \sigma_{UTS} \) values in a wide range while most of their \( \delta \) values are lower than 8%. In contrast, the present as-cast Mg-2.5Y-1Ce-0.5Mn-xZn \((x = 1, 3, 5 \text{ wt%})\) alloys own higher \( \delta \) values and medium \( \sigma_{UTS} \) values as compared with other reported as-cast alloys.

Figure 7 shows the morphologies of lateral fracture surfaces of the four as-cast alloys after tensile tests. On the lateral surfaces, microcracks and shear lines are prone to extend across the eutectic phases, especially in the alloys containing more Zn element. Microcracks in the eutectic phase reveal the flow stress is easily concentrated around the eutectic phases in as-cast state of present alloys. It should be noted that shear lines change their extending directions after shearing the mixed phases \((\text{Mg}_{12}\text{Ce} \text{ phase and LPSO phase})\) (figure 7(b)), while shear lines easily pass across the LPSO phase without changing their extending directions when the W-phase and LPSO phase arrange in interval (figure 7(c)). Furthermore, as seen in figure 7(d), the microcracks are easily and widely performed inside of W-phase and T-phase.

### 3.3. Nanoindentation results

Figure 8 shows the load-depth curves and the corresponding modulus and microhardness of matrix and ternary phases in the as-cast alloys. As is seen in figures 8(a) and (b), when the maximum force is fixed at 10 mN, the loading depths in different targets are different after unloading. A shallow indentation depth corresponds to a high microhardness. The values of modulus and microhardness of the matrix and the various ternary phases in four alloys are displayed in figures 8(c) and (d), respectively. Figure 8(c) shows that the modulus of matrix gradually increases from 42.3 GPa to 50.1 GPa and the microhardness is raised from 0.56 GPa to 0.82 GPa with
increasing Zn addition. Figure 8(d) shows that the modulus and microhardness of the T-phase (61.2 GPa and 2.32 GPa), the W-phase (57.8 GPa and 2.16 GPa), the LPSO phase plus Mg12Ce (56.1 GPa and 1.95 GPa) and the LPSO phase (53.5 GPa and 1.63 GPa) are decreased in order.

4. Discussions

4.1. Effect of Zn addition on the ternary phase formation
One of the experimental results by microstructure observation is that with increasing Zn addition, the ternary phases appear in order of LPSO phase, LPSO phase + W-phase and W-phase + T-phase in Alloy II, Alloy III

Figure 5. The tensile properties of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn alloys: (a) conventional stress-strain curves; (b) variation of the σy, σUTS and δ corresponding to the conventional stress-strain curves; (c) the true stress-strain curves and (d) the strain hardening rate versus the true strain curves.

Figure 6. Comparisons of ultimate tensile strength and elongation of as-cast Mg-2.5Y-1Ce-0.5Mn-xZn alloys with the published results in other as-cast Mg-RE or Mg-RE-Zn alloys.
Figure 7. Morphologies of the lateral fracture surfaces after tensile test. (a) Alloy I, (b) Alloy II, (c) Alloy III and (d) Alloy IV.

Figure 8. Load-depth curves and the microhardness and modulus of the matrix and the second phases in as-cast alloys: (a) and (c) the matrix, (b) and (d) the ternary phases.
and Alloy IV, respectively. Such precipitation order is mainly resulted from the solidification process where the eutectic reaction takes place and the Zn content required for forming the precipitated phases in the as-cast Mg-2.5Y-1Ce alloy.

During solidification process, when the temperature falls to the eutectic temperature, the eutectic reaction can be performed until the requirement of chemical composition for the reaction in the redundant liquid is achieved by the accumulated solute atoms. Then the eutectic phases corresponding to the products of eutectic reactions precipitate along the α-Mg dendritic boundaries. The eutectic temperatures reported for LPSO phase, W-phase and T-phase that observed in the previous work are 535 °C, 510 °C and 500 °C, respectively and their eutectic reactions can be expressed as follows: L \xrightarrow{535 \degree C} \alpha_{Mg} + LPSO; L \xrightarrow{510 \degree C} \alpha_{Mg} + W; L \xrightarrow{500 \degree C} \alpha_{Mg} + T \[12, 31\]. Besides of the eutectic temperature, the chemical composition in residual liquid that dependent on the Zn content should also be achieved in order to precipitate these ternary phases. The requirement of chemical composition for precipitating the ternary phases is mainly determined by the Zn/Y atom ratio for the Mg-Y-Zn alloys. The LPSO phase, LPSO phase + W-phase and W-phase can be formed in order with increasing the Zn/Y ratio under their certain ratio conditions \[12, 13, 32\]. It is found that the Zn/Y weight ratio that required in precipitating the LPSO phase, the LPSO phase + W-phase and the W-phase is in the range of less than 0.6, 0.65 ~ 0.85 and 0.85 ~ 2.05, respectively \[12, 13\]. However, in the recent, Lizi Liu et al report that the Zn/Y ratios in the range of 0.44 ~ 0.53, 0.9 ~ 1.0 and 2.32 ~ 3.22 correspond to the formation of LPSO phase, W-phase + LPSO phase and W-phase + I-phase, respectively \[33\]. In the present work, based on the actual composition as shown in table 1, the actual Zn/Y weight ratio increasing with more Zn addition, which is 0.47, 1.28 and 2.38 respectively in the Alloy II, Alloy III and Alloy IV, can meet the requirements of chemical composition for forming LPSO phase, LPSO phase + W-phase and W-phase. However, it is seen that the Zn/Y weight ratios in the Alloy III and Alloy IV are not well consistent with that reported in the previous references.

This inconsistent result should be associated with the Ce element. Based on the EDS results (seen in table 2), it reveals that the Ce acts as one of rare earth element could combine with Y to form the W-phase in Alloy III and Alloy IV, and the chemical composition of W-phase can be written as Mg\(_3\)(Y, Ce)\(_2\)Zn\(_8\). Then the formation of W-phase should dependent on the Zn/(Y, Ce) ratio which is calculated to be 0.92 and 1.72 in the Alloy III and Alloy IV, respectively. Such results are consistent with that reported by Lizi Liu et al \[33\]. Additionally, in case of T-phase, due to its lower eutectic reaction temperature and larger amounts of Zn element requirement, it only appears in Alloy IV. As is seen that when the Zn/Y ratio is larger than 2.32, the I-phase should precipitate in Alloy IV. However, based on our observation, few I-phase are found in the Alloy IV, while are replaced by the T-phase. It should be attributed to the higher temperature for the eutectic reaction of T-phase (500 °C) than that of I-phase (438 °C) and the limit Zn amounts cannot meet the requirement of chemical composition for the precipitation of I-phase. In another aspect, it is hard to observe T-phase in Alloy II and Alloy III whose Zn amounts are consumed to form other ternary phases with higher reaction temperatures than those for precipitation of T-phase in Alloy IV. As a result, increasing Zn addition leads to the ternary phases precipitate following the order of LPSO phase, LPSO phase + W-phase and W-phase + T-phase in Alloy II, Alloy III and Alloy IV, respectively.

### 4.2. The effect of Zn addition on the tensile mechanical behavior

The tensile test results show that the addition of Zn element improves the \(\sigma_{YS}\), \(\sigma_{UTS}\) and \(\delta\) values of the as-cast Mg-2.5Y-1Ce-0.5Mn alloy, in which the \(\sigma_{YS}\) value increases sustainably while the \(\sigma_{UTS}\) and \(\delta\) show nonlinear increments with increasing Zn from 1 to 5wt%.

It is well known that the plastic flow strength of crystalline solids is generally increased by restricting dislocation motion. The most common employed obstacles are internal boundaries such as grain boundaries, solute atoms and second phases that can be present in a crystalline material to produce such an effect. The yield strength \(\sigma_{YS}\) thus can be linearly expressed by using the following equation \[4\],

\[
\sigma_{YS} = \sigma_{Mg} + \sigma_{gb} + \sigma_{n} + \sigma_{p} \tag{2}
\]

where \(\sigma_{Mg}\) is the intrinsic stress to resist basal slip for pure Mg (21 MPa), \(\sigma_{gb}\) is the grain boundary contribution through the Hall-Petch relation, \(\sigma_{n}\) is the solid solution strengthening and \(\sigma_{p}\) is the second phase strengthening.

According to equation (2), the increment of \(\sigma_{YS}\) \((\Delta\sigma_{YS})\) from the employed obstacles after Zn addition can be written as

\[
\Delta\sigma_{YS} = \Delta\sigma_{gb} + \Delta\sigma_{n} + \Delta\sigma_{p} \tag{3}
\]

Firstly, the \(\Delta\sigma_{YS}\) values in equation (3) can be calculated by the difference of \(\sigma_{YS}\) values which are obtained directly from the results of tensile test (in figure 5(b)). Then the \(\Delta\sigma_{YS}\) values after calculations are 10 MPa, 22 MPa and 29 MPa for Alloy II, Alloy III and Alloy IV, respectively.
Based on the empirical Hall-Petch equation [34], the $\Delta \sigma_{gb}$ in equation (3) can be deduced as

$$\Delta \sigma_{gb} = k\left(d_{Mg-Zn-Ce}^{-\frac{1}{2}} - d_{Mg-Zn-Ce}^{-\frac{1}{2}}ight)$$

(4)

where $d$ is the measured grain size and $k$ is the experimental constant (173 MPa $\mu$m$^{-1/2}$) [34]. It indicates that the grain boundary strengthening effect can be enhanced by smaller grain size. The $\Delta \sigma_{gb}$ contributed from grain refinement in the present work is calculated to be 2.1 MPa, 4.5 MPa and 6.9 MPa for Alloy II, Alloy III and Alloy IV, respectively.

For the solid solution strengthening, it is generally calculated by the equation [4]

$$\Delta \sigma_{ss} \simeq \kappa_c c^{2/3}$$

(5)

where $\kappa_c$ is a constant and $c$ is the atom concentration. It reveals that the higher solid solution strengthening effect can be achieved by more solute atoms dissolved into the Mg matrix. The value of $\kappa_c$ for Zn is selected as 905 MPa (at%) [4]. The increment of solid solution strengthening resulted from the solute Zn atoms in Alloy II, Alloy III and Alloy IV is 1.8 MPa, 3.1 MPa and 3.6 MPa, respectively. The increasing strengthening effect from solute Zn atoms can also be supported by the increased microhardness of the matrix (figures 8(a) and (c)).

Combine the equations of (3), (4) and (5), the strengthening increment from the ternary phases can be deduced as follows

$$\Delta \sigma_p = \Delta \sigma_{YS} - \Delta \sigma_{gb} - \Delta \sigma_{ss}$$

(6)

then the increment of $\sigma_p$ resulted from the ternary phases in Alloy II, Alloy III and Alloy IV can be deduced to 6.2 MPa, 16.1 MPa and 18.7 MPa, respectively. As is seen, with increasing Zn addition, the increment of $\sigma_{YS}$ from these ternary phases is much more than twice that from refined grains and solute atoms. The strengthening effect of ternary phases is mainly due to their increased volume fractions which can provide more obstacles to inhibit the dislocation movement, and the interactions between the hard phase with the dislocation is much more strongly and intensively. In the present work, the largest volume fraction of hard W-phase and T-phase gives the Alloy IV with the highest yield strength. Due to the complex morphologies and composite distribution of the ternary phases in Alloy II, Alloy III and Alloy IV, the plastic accommodation ability and/or the strain hardening behavior in these alloys should also be different and directly impact their $\sigma_{UTS}$ and $\delta$ values. [35, 36].

Regarding to Alloy II, LPSO phase is the main ternary phase. It has been reported that the LPSO phase possesses of the bending or kinking ability under high loading stress, and the LPSO phase can store the local strains and high density of dislocations and providing a sufficient plastic accommodation ability [37]. Such ability of LPSO phase can accommodate the deformation between two grains with different orientations, which can be confirmed by the bending shear lines in figure 7(c). The well accommodated ability from LPSO phase delays the plastic instability and provides the alloy with the largest $\delta$. When the Mg$_{12}$Ce phase is mixed with the LPSO phase, the enhancement of strain hardening ability from them should be much more effective than that from LPSO phase itself, which can be confirmed by the higher microhardness of the combined Mg$_{12}$Ce with LPSO phases than that of LPSO phase (figure 8(d)). The excellent elongation allows a continuous increase of strain hardening ability and contributes to the comparable $\sigma_{UTS}$ value in Alloy II with that in Alloy III.

With respect to Alloy III, an additional ternary phase (W-phase) that usually precipitated in the Mg-HRE-Zn alloys is arranged in the interval space of LPSO phase and/or distributed in the region of triangle boundaries. Even though the W-phase shows higher modulus and microhardness than the LPSO phase (figures 8(b) and (d)), the W-phase is easily cracked during tensile process due to the incoherent interfaces between W-phase and Mg matrix, it is indicated that the W-phase is a hard and brittle phase; so microcracks can be easily observed on its lamellar surfaces (figure 7(c)). Besides this, when the W-phase and LPSO phase are arranged in interval and the (00018)$_{Mg}$(00018)$_{Mg}$ stacking plane of LPSO phase are perpendicular to the grain boundary, the slip lines can easily move across the LPSO phase (figure 7(c)). It is indicated that the limited accommodation role of LPSO phase and the concentration stress would not aggregate or accumulate on the LPSO phase, so the LPSO phase could not provide its sufficient roles to accommodate the plastic deformation and strengthen the alloy. As the easily cracked W-phase and insufficient accommodation role of LPSO phase, the plastic instability should perform easily and the elongation in Alloy III is smaller than that in Alloy II. The earlier plastic instability inhibits the flow stress from increasing sustainably and results in the $\sigma_{UTS}$ of Alloy III being less of 3.7 MPa than that of Alloy II.

In case of Alloy IV, T-phase instead of the LPSO phase precipitates as another additional ternary phase which is not observed in Alloy II and Alloy III. T-phase is the common ternary phase in the Mg-Zn-Ce alloys [17, 18], however, the effect of T-phase on the mechanical properties is less reported. Based on the results of nanoindentation and the observation of lateral surface in our study, it found that the T-phase is also a hard and brittle phase because its higher microhardness and modulus when compared with W-phase and LPSO phase (figure 8(d)), and the microcracks are easily found on its surface (figure 7(d)). It is known that the hard particles that introducing into Mg alloys can significantly enhance the tensile strengths through inhibiting the movement of dislocations intensively, so the hard W-phase and T-phase distributed around GBs can strengthen the present...
Mg alloy. Unfortunately, both the W-phase and T-phase are the brittle phases which would initiate the earlier performance of microcracks. It implies their lower plastic accommodation abilities, which are not beneficial to improving the ductility. However, amounts of these W-phase and T-phase that precipitate around grain boundaries can inhibit the growth of initial α-Mg grains and refine the Mg grains. The refined grains can disperse the concentration strains and be subjected to larger plastic deformation. Thus, the Alloy IV shows a more excellent ductility than Alloy III. The strain hardening ability from W-phase and T-phase can sustain to increase until the fracture of tensile sample performs. By this way, the Alloy IV exhibits the largest $\sigma_{UTS}$ value among the three alloys with Zn addition.

5. Conclusion

The effect of Zn addition on the microstructures and mechanical behaviors of as-cast Mg-2.5Y-1Ce-0.5Mn alloy were investigated in the present work.

(1) Microstructure analysis indicated that besides of α-Mg dendritic refinement, the Mg$_{12}$YZn phase (LPSO phase), Mg$_5$(Y, Ce)$_2$Zn$_3$ phase (W-phase) and Mg-Zn-Ce phase (T-phase) were precipitated as a new ternary phase in the alloys with 1 wt%, 3 wt% and 5 wt% Zn addition, respectively.

(2) The result of tensile tests revealed that with increasing Zn addition, the yield strength ($\sigma_{YS}$) of as-cast Mg-2.5Y-1Ce-0.5Mn alloy was sustainably increased from 87.9 MPa to 117.1 MPa, while the ultimate tensile strength and elongation exhibited nonlinear change trends. The values of $\sigma_{UTS}$ and $\delta$ were 138.5 MPa and 8.1%, 179.8 MPa and 12.5%, 176.1 MPa and 9.7%, and 198.3 MPa and 10.8% for Alloy I, Alloy II, Alloy III and Alloy IV, respectively.

(3) The increase of $\sigma_{YS}$ was mainly attributed to the increased volume fraction of ternary phases compared with the grain refinement and solute Zn atoms. Among the three as-cast alloys with Zn addition, the largest $\delta$ in Alloy II mainly arose from the LPSO phase who provided a well plastic accommodation, while the easily broken W-phase and the insufficient accommodation of LPSO phase in Alloy III decreased the $\delta$. Both the easily broken W-phase and T-phase deteriorate the ductility, while the grain refinement provided the Alloy IV with a moderate $\delta$. The large $\sigma_{UTS}$ was associated with the sustainable strain hardening ability after yielding and it is directly determined by the values of $\sigma_{YS}$ and $\delta$.

Acknowledgments

This work was financially supported by the project of National Key R&D Program of China [grant number 2018YFA0703300 and 2018YFC1507900], National Natural Science Foundation of China [grant numbers 51371089, 51201068, 51271152 and 51601067] and the Science and Technology Development Program of Jilin Province [grant number 20160520007H].

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