Investigation on the Microstructures and Mechanical Properties of RE Containing Mg-5Zn-2Al Alloys

Xiaofeng Wan, Lulu Cao, Fubao Zhang and Zhiyang Li

ABSTRACT

As-cast microstructure Mg-5Zn-2Al-0.3Mn (ZA52) magnesium alloy consists of the α-Mg and eutectic phase Mg₅₁Zn₂₀. The eutectic Mg₅₁Zn₂₀ have been gradually replaced by Al₄RE phases when RE is added into the ZA52 alloy, further addition of RE leads to the increasing of grain boundary phases with Mg₅₁Zn₂₀ eutectic compounds reappearing and the grains size refining. Improved elevated temperature properties are obtained as compared to the ZA52 based alloy due to the thermal stability of Al-RE phases. At the temperature up to 175 °C, the creep resistance of RE containing alloys decrease with the refining grains size and Mg₅₁Zn₂₀ eutectic compounds increasing.

INTRODUCTION

Magnesium alloys are being increasingly used in the automobile industry in order to save weight thereby reducing fuel consumption and pollution. However, inferior high temperature mechanical properties of conventional Mg-Al system alloys, such as AZ91 and AM60, limit the potential utilization of these alloys in important parts due to the low melting point of the intermetallic phase β phase (Mg₁₇Al₁₂) in the microstructure, which is prone to soften at above 120°C[1].

Since Mg-Zn alloy system is solid solution and precipitation strengthening with noβphase, there is a great potential to develop the anti-creep property compared with Mg-Al alloys, in the meantime, conventional Zr elements can be substituted by Al in order to further increase the strengths[2]. It is reported that rare earth elements can improve the high temperature properties, especially the creep resistance according to the previous research. In this work, the microstructure and mechanical properties of several Mg-5Zn-2Al-RE alloys were investigated.

MATERIAL AND EXPERIMENTAL PROCEDURE

Five alloys of which the compositions are listed in Table 1 were prepared in a mild steel crucible under the protection of mixed gas atmosphere of SF₆ (1%) and CO₂ (Bal.). The base composition of the alloys studied was...
Mg-5Zn-2Al-0.3Mn (ZA52). Different amounts of RE were added in the other alloys in order to see the effect of RE addition and variation of RE concentration in the alloys on the microstructure and mechanical properties of the alloys. The melt was held at 740°C for several minutes then poured into metal moulds made of cast steel. The specimens selected were homogenized at 345°C by SX-2.5-10 furnace. Tensile specimens with a gauge section of 18 mm×3.2 mm×1.8 mm were cut by electric spark machining from the ingots. Creep specimens were machined according to National Standard GB2039-80 with dimensions of 10 mm in diameter and 100 mm in length and tested on the RD2-3 specified creep machine. The specimens were etched with a solution of 4 Vol.% nitric acid and ethyl alcohol for 5 s, then flushed with ethyl alcohol, the grain size was measured by using average linear intercept method. Micro-structural observation of the as-cast specimens as well as micro-compositional analysis of precipitates were conducted using optical microscopy (OM) and scanning electron microscopy (SEM) equipped with X-ray energy dispersive spectroscopy (XEDS). The phases of alloys were analyzed by X-ray diffraction (XRD).

| Table 1. Compositions of alloys prepared (mass fraction, %). |
|----------------|------|-----|-----|-----|-----|
| Alloy          | Mg   | Zn  | Al  | RE  | Mn  |
| ZA52           | Bal. | 5.0 | 2.0 | —   | 0.3 |
| ZAE5202        | Bal. | 5.0 | 2.0 | 0.2 | 0.3 |
| ZAE5205        | Bal. | 5.0 | 2.0 | 0.5 | 0.3 |
| ZAE5210        | Bal. | 5.0 | 2.0 | 1.0 | 0.3 |
| ZAE5220        | Bal. | 5.0 | 2.0 | 2.0 | 0.3 |

RESULTS

Microstructure

Figure 1. Optical micrographs of alloys ZA52 (a), ZAE5202 (b), ZAE5205 (c), ZAE5220 (d).

Figure 2. Micrographs of alloys ZA52 (a), ZAE5210 (b) after homogenizing treatment for 120h at 345°C.
Figure 1 shows the metallurgical microstructure of as-cast alloys. As can be seen from Figure 1, the semi-continuous inter-phases increase and form sharp and needle-like structure gradually, and the α-Mg dendrites are refined with the addition of RE. The amount of the dense lamellar eutectic phase decreases firstly and then increases with the increasing content of RE. Figure 2 shows the microstructure of homogenized alloys treated at 345 °C for 120 h. It can be seen that the grain size obviously decreases with the addition of RE, for instance, when the addition of 1.0% RE, the average grain size begins to decrease from 75 µm to 30 µm. Meanwhile, a small amount of insoluble Compounds are observed at grain boundary and intragranular in the ZAE5210 alloy, which indicates that the improved thermal stability of inter-phases or new stable phases are obtained by the addition of RE.

Figure 3 shows the XRD patterns obtained for the as-cast ZA52 alloy with RE addition. It exhibits that the main phases of the ZA52 alloy are α-Mg and Mg₅₁Zn₂₀ precipitate, which shows the dense lamellar eutectic characteristics with a bct structure (space group *Immm* with lattice parameter \(a = 1.4083\) nm, \(b = 1.4486\) nm, \(c = 1.4025\) nm)[3], as is shown in Figure 1(a). The diffraction peaks of Al₄RE phases emerge as a result of the RE addition according to the current XRD analysis data. Figure 1(d) shows the microstructures of ZAE5220 alloy studied, among which the typical sharp and needle-like characteristics of intermetallic phases in the alloys are observed. The average elemental compositions of the phases are identified by the EDS spectra as A, B and C area in Figure 4, from which it can be indicated that the phase in area A and B may be the indexed Al-RE compound, and the phase in area C is the Mg₅₁Zn₂₀ precipitate. Figure 5 shows that the needle-like Al₄RE phase almost dose not dissolve during long period elevated temperature, which indicates the high thermal stability of the Al-RE phase.

![Figure 3. XRD results of as-cast alloys ZA52 (a), ZAE5220 (b).](image)

![Figure 4. SEM image of as-cast alloys ZAE5210.](image)
Tensile Properties

Table 2 shows the data of tensile tests of the alloys studied at different temperatures. It can be seen that additions of RE have different effects on the tensile properties at ambient temperature and 175℃. At ambient temperature RE addition does not results in increasing both strength and elongation obviously. Furthermore, the strength reduction of the alloy containing 2.0% RE reveals that with the increase of element content the strengthening effect of RE addition has weakened. While at 175℃ the tensile properties are improved with RE addition content not up to 1.0%, thus indicating the contribution of RE on the improvement of high temperature properties.

| Alloy     | Ambient temperature | 175℃          |
|-----------|---------------------|---------------|
|           | UTS(MPa) | YS(MPa) | ELO(%) | UTS(MPa) | YS(MPa) | ELO(%) |
| ZA52      | 228      | 101     | 10.2   | 118      | 73      | 20.1   |
| ZAX5202   | 231      | 107     | 10.5   | 122      | 88      | 17.4   |
| ZAX5205   | 233      | 105     | 10.7   | 127      | 90      | 9.0    |
| ZAX5210   | 237      | 111     | 11.4   | 131      | 97      | 6.0    |
| ZAX5220   | 221      | 92      | 9.3    | 125      | 79      | 6.2    |

Creep Properties

The tensile creep curves of the alloys tested at the applied stress 70 MPa and elevated temperatures of 175 ℃ are shown in Figure.6(a), and the results of the steady creep rate and 100 h creep strain of the alloys studied are listed in Figure.6(b). The creep data of as-cast AZ91 alloy is also shown together so that the creep properties of the Mg-Zn-Al alloys and the conventional Mg-Al alloy can be compared. At 175℃, it can be seen that the creep resistance of alloy AZ91 seems poor. The Mg-Zn-Al alloys studied, however, exhibit much lower steady creep rate and creep strain than AZ91 alloy. Compared to the Mg-Al alloy, the steady creep rate and 100 h creep strain of ZA52 alloy is decreased by 53% and 62%, respectively. Further improvement of creep resistance is achieved with RE addition. The steady creep rate of the alloy ZAE5210 containing 1.0% RE is reduced to $8.6 \times 10^{-9}$s⁻¹, almost one order of magnitude lower than that of the base alloy. Under the higher temperature 175 ℃, however, the 100 h creep strain of the alloy with high RE content seems a bit higher than that of the alloy containing less RE content, and the improving effect of RE on the creep properties decreases with the increase of addition amount.
DISCUSSION

The RE element is rich in solid-liquid interface during the solidification process due to the low solubility in α-Mg matrix[4]. The enrichment hinders the solute atoms diffusing to the matrix and results in the high Al, Zn atoms concentration near the grain boundary. Meanwhile, the enrichment of RE induces the constitutional supercooling at solidification interface front, thus accelerating nucleation of the matrix, and refining the grain. The degree of RE refining grain on pure magnesium can be described by growth restriction factor (GRF):

$$GRF = \sum m_i C_{0,i} (k_i - 1)$$

where $m_i$ is the liquids slope of binary phase diagram, $C_{0,i}$ is the initial concentration of solute, and $k_i$ is the equilibrium partition coefficient. The $GRF$ reflects the ability of forming a stable nucleus, the larger the $GRF$, the greater the ability of nucleation. Compared with other elements, RE has a higher $GRF$, thus exhibiting the great effect of grain-refining on the Mg-Zn-Al alloys. Moreover, the high solute concentration at grain boundary inhibits the Mg51Zn20 phase formed in ZA62 alloy by promoting the formation of Al4RE precipitates, which consume more solute atoms for the same mol fraction.

The strength of alloys varies with grain size, and the relationship usually follows the Hall-Petch equation:

$$\sigma_y = \sigma_0 + Kd^{-1/2}$$

where $\sigma_y$ is the 0.2% yield strength, $d$ is a measure of grain size, and $\sigma_0$ and $K$ are parameters determined for the polycrystalline material. Comparing with the grain size of the RE containing alloys, it decreases with the increasing RE (seen from Figure 2). According to the Hall-Petch equation, the yield strength should increase with the refining grain, however, the result is not completely consistent with the experimental results (Table 2). Generally, the intermediate phase can also greatly influence the mechanical properties. The interdentritic compounds increase and become more continuous needle-like structures with RE addition. Such continuous networks are known to deteriorate the mechanical properties of magnesium alloys, due to their morphology of needle and their distribution on the grain boundaries, thus easily disserving the matrix during deformation process. Additionally, the solution hardening effect of solute atoms should also be considered. Experimental results suggest that the Al, Zn solute atoms content decreases in the α-Mg matrix with increasing RE, which consumed by the new formed interphases. Thus, solution hardening effect of solute atoms can be expected to decrease and that is another reason for the decreased strength with RE addition. Therefore, compared with the
negative factors of weakening performance, grain-refining strengthening effect might play a minor role in the strength of the RE containing alloys.

Improved elevated temperature properties, especially anti-creep performance are obtained in the RE containing alloys. Such improvements are attributable to the formation of new thermal stability compounds, such as Al4RE precipitates, which is very similar to that of Al2Ca in the Mg-Al based alloys with calcium addition[18]. With high stability at elevated temperatures, the interphases observed in the as-cast microstructure of RE containing alloys are effective on straddling and pinning the grain boundaries during creep deformation, leading to remarkable improvement of creep properties. However, at the higher temperature it seems that the decrease of creep resistance with the RE addition content up to 2.0% is probably accounted for the refinement of microstructure, which is also caused by the increase of RE addition. Moreover, with the increasing RE content the low melting point Mg51Zn20 phase reappearing is also considered to be the important factor responsible for the poor creep resistance of RE containing alloys.

Since the creep resistance is affected by the grain size, and the results are consistent with the creep mechanisms based on the diffusional creep and grain boundary sliding, finer grain structures are expected to exhibit higher creep rates[5], which also indicates grain boundary sliding is easy to occur in the alloy with smaller grain size. Apparently, compared with the effect of grain refinement, the contribution of those Al-RE inter-phases on pinning and strengthening the grain boundaries is limited during high temperature creep process.

ACKNOWLEDGMENTS

The authors are grateful for the project supported by Natural Science Found of Jiangsu province (No. BK20130391) and the Project (BK2014037) supported by the Nantong Science and Technology Commission of China.

REFERENCES

[1] K.C. Park, B.H. Kim and S.M. Jo, S.H. Kim, Y.H. Park and I.M. Park, Mechanical and Creep Properties of the Cast Magnesium Alloy. Applied Mechanics and Materials. 152 - 154 (2012) 1207-1210.

[2] D.H. Kim, J.Y. Lee, H.K. Lim, W.T. Kim, D.H. Kim, Effect of Al addition on the elevated temperature deformation behavior of Mg-Zn-Y alloy. Materials Science and Engineering: A. 487 (2008) 481-487.

[3] I. Higashi, N. Shiotani, M. Uda, T. Mizoguchi, H. Katoh, The crystal structure of Mg51Zn20. Journal of Solid State Chemistry. 36 (1981) 225.

[4] C.M. Liu, X.R. Zhu, H.T. Zhou, Magnesium Phase Diagram. Changsha: Central South University of Technology Press, 2006.

[5] X.F. Wan, Y.S. Sun, F. Xue, J. Bai, W.J. Tao, Microstructure and mechanical properties of ZA62 based magnesium alloys with calcium addition. Trans. Nonferrous Met. Soc. China. 20(2010) 757-762.