The Mechanical Property and Strengthening Mechanism of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

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Abstract. Tensile properties at $T_R$ with different stretch velocity, and tensile properties at $T_{150\,^\circ C}$ were investigated in this study, and the strengthening mechanism was discussed preliminarily. Firstly, tensile properties of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy at $T_R$ with the stretch velocity increases from 1 to 6 mm•min$^{-1}$, and results suggest that the studied alloy exhibits low strength sensitivity as both of $R_m$ and $R_{p0.2}$ maintaining at 240 MPa and 190 MPa, which is attributed to the not enough time for the dynamic recrystallization at the higher deformation velocity. Meanwhile, as the stretch velocity increases, although $A$ increases first and then decreases because of the more stress concentration near grain boundaries, $A$ maintains above 20%, suggesting the good plastic sensitivity. Secondly, when stretched at $T_{150\,^\circ C}$, both of $R_m$ and $R_{p0.2}$ of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy decrease compared to that at $T_R$, which is attributed to the increased dislocation movement at the higher temperature, while $A$ increases at $T_{150\,^\circ C}$ than at $T_R$ because of the decreased critical shear stress at the higher temperature. Even though, because the Mg$_{12}$La phases impede the dislocation movement and the Sm atoms result in the solution strengthening, the mechanical properties of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy are still higher than that of the Mg-0.5Zn-0.2Mn alloy at the higher temperature.

1. Introduction

As the resource decreases and environmental pollution intensifies, lightweight and environmentally friendly materials are needed in the aerospace and transportation industries. As the industries develop rapidly, the requirement to the lightweight alloy is increased. The wrought magnesium alloy is noticed as the lightweight material, due to its low density, abundant reserves and easy recycling [1]. However, the wrought magnesium alloy has low absolute strength and poor formability at room temperature [2], limiting its applications as the structural materials in many fields.

Adding rare earth (RE) could improve the mechanical properties of the wrought magnesium alloy, and the high strength magnesium alloy is generally prepared by adding heavy RE substantially, such as Gd and Y[3-7], increasing the material cost significantly and limiting its applications in the civil field. Nd stand out as the light RE has the similar effect of the heavy RE, while it is also expensive [8-11]. Sm and La belong to the light RE, and they could also refine grains and enhance the mechanical properties. Significantly, Sm and La are much cheaper than Nd, and the price of Sm is nearly a tenth of Nd, therefore, adding Sm and La could greatly reduce the costs of magnesium alloys compared with the same amount of Nd. However, Sm and La are not researched adequately compared with that of Nd, especially their
combination addition, besides, the strengthening mechanism of the combination addition needs more study. Our previous study has shown that micro-adding Sm and La could influence the microstructure and property of the magnesium alloy [12-15], and the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy performed well at room temperature ($T_R$) than the Mg-0.5Zn-0.2Mn alloy [16], while, the mechanical properties under other conditions were not researched, such as the higher temperature. Therefore, tensile properties at $T_R$ with different stretch velocity, and tensile properties at $T_{150}^\circC$ were investigated in this study, and the strengthening mechanism was discussed preliminarily. The present work is somewhat useful for further development of new magnesium alloys with low cost and high ductility.

2. Experimental procedure

The studied Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy (mass fraction, %, analyzed by ICP spectrometer) was prepared with commercially pure Mg, Zn, anhydrous MnCl$_2$, and Mg-30Sm and Mg-25La master alloys under the CO$_2$ atmosphere for protection. Firstly, the pure Mg was put in a stainless steel crucible and the temperature was raised to 700±5 $^\circC$. After the pure Mg was melted, the pure Zn was put in the melt and raised the temperature to 730±5 $^\circC$. Then, the Mg-30Sm and Mg-25La master alloys were put in the melt, 10 min later, the anhydrous MnCl$_2$ was put in the melt, simultaneously the flux RJ-5 was put under stirring to refine the melt. 10 min later, the temperature was lowered to 700±5 $^\circC$ for 5 min, and cast the melt into the mold which was preheated at 150$^\circC$. The as-cast alloys were held at 420$^\circC$ for 10h, and extruded into rod bars at 350$^\circC$. The extrusion ratio was 17.4:1 and the exit velocity was 1.4~1.6 m•min$^{-1}$.

Microstructures were examined by X-ray diffraction (XRD), optical microscope (OM), and scanning electron microscope coupled with an energy-dispersive X-ray analyzer (SEM-EDS). The texture measurement was characterized by electron backscatter diffraction (EBSD). Tensile tests were carried out with the universal electronic tensile testing machine at $T_R$ and $T_{150}^\circC$, respectively, and the stretch velocity was 1.0 mm•min$^{-1}$, 2.0 mm•min$^{-1}$, 3.0 mm•min$^{-1}$, respectively. The specific dimension was processed according to GB-T 228-2202, and three specimens were tested under the same condition for diminishing error.

3. Results and discussion

It is well known that the mechanical property relies on the microstructure strongly, so that the mechanical property and microstructure of the studied Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy were both investigated and discussed, in order to better understand the effect of combined additions of Sm and La.

3.1. Microstructures of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

The SEM image of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy is shown in Fig. 1(a), indicating white new phases with lamellar structure precipitating near the grain boundaries. According to the EDS analysis result of the corresponding precipitates in Fig. 1(b) and (c), most new phases were Mg$_{12}$La, and Sm was solid solute in the matrix and Mg$_{12}$La phases. No peaks of Mg-Sm phases observed in the XRD patterns in Fig. 2 also suggested the above appearance. Besides, all new phases were crashed and distributed into streamline along the extrusion direction (ED), as shown in Fig. 3.

3.2. Tensile properties of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

Our previous study has reported that the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy performed well than as-extruded Mg-0.5Zn-0.2Mn alloy at $T_R$ [16]. Given that the stretch velocity affects the tensile properties significantly, and the more complex the chemical composition of the alloy, the more sensitive the relationship between strain rate and plasticity [17], the tensile properties of the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy with the stretch velocity of 1, 3 and 6 mm•min$^{-1}$ were carried out at $T_R$ in this study. The results are showing in Fig. 4. It could be seen that the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy exhibited $R_m$ of 239 MPa, $R_{90,2}$ of 190 MPa and $A$ of 23.9 % at 1 mm•min$^{-1}$, both of $R_m$ and $R_{90,2}$ had low stretch velocity dependence, which respectively maintaining at 240 MPa and 190
MPa. Although $A$ of the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy increased first and then decreased, it still maintained above 20% with the stretch velocity of 3 and 6 mm$\cdot$min$^{-1}$. The above results suggested that the studied Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy exhibited low sensitivity with the stretch velocity.

Figure 1. SEM image (a) of the as-cast Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy and EDS analysis results of precipitate A (a) and B (c)

Figure 2. XRD patterns of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

Figure 3. SEM image of the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

Fig. 5 shows the tensile stress vs strain curves of the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy at $T_{150^\circ}$. It could be seen that the strength of the as-extruded Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy decreased at $T_{150^\circ}$, while the plasticity increased. The specific tensile properties at $T_{150^\circ}$ were $R_m$ of 119 MPa, $R_p0.2$ of 97 MPa and $A$ of 68.85 %, which were much higher than that of the as-extruded Mg-0.5Zn-0.2Mn alloy at $T_{150^\circ}$.
3.3. Strengthening mechanism of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy

Generally, the strengthening mechanism at $T_R$ is related to the weakened recrystallization texture, which is caused by the particle stimulated nucleation (PSN), shear band induced nucleation (SBIN), and deformation twin induced nucleation (DTIN)the second phases enhancement[18-20]. Therefore, the dynamic recrystallization distribution, {0001} pole figures, twin distribution and misorientation distribution of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy were investigated in the present study, shown in Fig. 6. It could be seen that the dynamic recrystallization ratio was about 30% of the overall regions, which was not enough as reported in other researches [18, 21, 22], and a few higher distributions of large angle grain boundaries of 82-85° just revealed the dynamic recrystallization. Besides, the substructures reaching 30% of the overall regions were observed in the microstructure, and a few higher distributions of small angle grain boundaries of 1-3° just indicated the above appearance [17]. These results suggested the relatively weak texture of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy, and some fine broken new phases observed in the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy after the extrusion suggested the PSN mechanism was the main reason.

![Figure 6. Dynamic resrystallization distribution(a), {0001} pole figures (b), texture twin distribution maps (c) and misorientation distribution maps (d) of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy](image)

Researches have shown that the $R_m$, $R_{p0.2}$ and $A$ have great dependence on the stretch velocity at $T_R$, representing that $R_m$ and $R_{p0.2}$ increase while $A$ decreases as stretch velocity increases. The reason was related to the more nucleation, more refined dynamic recrystallization and more stress concentration near grain boundaries. However, the $R_m$ and $R_{p0.2}$ maintained as the stretch velocity increased, indicating that there was not enough time for the dynamic recrystallization because of the higher deformation velocity [23].

Our previous research showed that the excellent balance of strength and ductility in the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy was caused by the weakened recrystallization texture and large numbers of substructured grains[16]. However, during the deformation process at high temperature in this study, the decrease of the strength of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy was attributed to the increased dislocation movement, while the increase of the plasticity was attributed to the decreased critical shear stress. Because the Mg-La phases in the microstructure could impede the dislocation movement, and the solid solution Sm atoms could lead to the solution strengthening, the mechanical properties of the Mg-0.5Zn-0.2Mn-0.2Sm-0.3La alloy were higher than that of the Mg-0.5Zn-0.2Mn alloy, which was the same with the results in other researches[24].
4. Conclusion

Tensile properties of the Mg-0.5Zn-0.2Mn-0.3La alloy at \( T_R \) with different stretch velocity were studied, and tensile properties of both Mg-0.5Zn-0.2Mn-0.3La and Mg-0.5Zn-0.2Mn alloys at \( T_{150^\circ C} \) were investigated in this study. The strengthening mechanism was discussed preliminarily and the major results were summarized as below:

1. The studied alloy exhibited low strength sensitivity with the stretch velocity increasing from 1 to 6 mm•min\(^{-1}\), and both of \( R_m \) and \( R_{p0.2} \) maintained at 240 MPa and 190 MPa due to the not enough time for the dynamic recrystallization at the higher deformation velocity;

2. With the stretch velocity increasing from 1 to 6 mm•min\(^{-1}\), \( A \) increased first and then decreased because of the more stress concentration near grain boundaries, while \( A \) maintained above 20%;

3. Both of \( R_m \) and \( R_{p0.2} \) of the Mg-0.5Zn-0.2Mn-0.3La alloy decreased at \( T_{150^\circ C} \) than at \( T_R \) due to the increased dislocation movement at \( T_{150^\circ C} \), while the \( A \) increased at \( T_{150^\circ C} \) than at \( T_R \) due to the decreased critical shear stress at \( T_{150^\circ C} \);

4. The mechanical properties of the Mg-0.5Zn-0.2Mn-0.3La alloy were higher than that of the Mg-0.5Zn-0.2Mn alloy at \( T_{150^\circ C} \) due to the Mg\(_{12}\)La phases with impeding the dislocation movement and the Sm atoms with solution strengthening.

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