The Effect of Trace Addition of Strontium and Zinc on the Creep Properties of Mg-6Sn-5Al-2Si Alloys

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Mg alloys containing Mg₂Si and Mg₂Sn phases are promising inexpensive heat-resistant magnesium alloys for automobile engine applications. This study examined the microstructure and creep properties of Mg-6Sn-5Al-2Si alloys. The microstructures of these alloys were characterized by the presence of thermally stable Mg₂Si and Mg₂Sn and thermally unstable Mg₁₇Al₁₂ precipitates. Creep tests were performed at 30, 50 and 70 MPa at 150, 180 and 200 °C. Trace amounts of Sr and Zn were added to these alloys to improve the mechanical properties by modifying the precipitates in the matrix. The influence of the combined addition of Sr and Zn on the microstructure and mechanical properties was also studied. Analyses of the mechanical properties indicated that Sr and Zn addition improved the tensile strength but decreased the creep resistance. [doi:10.2320/matertrans.MRA2008473]

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1. Introduction

Mg alloys are particularly attractive in the aerospace and automotive industry due to their low density. The typical alloys are Mg-Al based ones, such as AZ91 and AM60. Although they are used widely in the automotive industry, their applications are limited to the parts used at temperatures below 120 °C because they show poor creep resistance and a large decrease in strength at elevated temperatures due to the thermal instability of the microstructure. Therefore, improving the high-temperature properties is a major issue for possible applications of Mg alloys to power-train components. Many studies have attempted to develop creep-resistant magnesium alloys in an attempt to broaden the applications of magnesium. The common way of improving the heat-resistance is to form thermally stable precipitates to prevent grain boundary sliding during creep deformation. The most effective alloying elements for such purposes are rare earth metals that result in significant improvements in creep-resistance. However, these elements are expensive, which limits the widespread application of these alloys. Recent studies have indicated that the addition of Si to Mg-Al binary alloys can improve the creep resistance and Sn addition contributes to strengthening Mg alloys at elevated temperatures because Mg₂Sn has a high melting temperature of approximately 770 °C. Microstructural refinement is crucial if magnesium alloys containing Mg₂Sn particles are to be used for sand casting or permanent mould casting. Refinement of the microstructure is expected to improve the mechanical properties. Previous research has indicated that Sr is an effective refining element with other elements, such as P, Ca and Sb. It was reported that Zn addition improves the room temperature strength and corrosion resistance, but there has been less research on the effects of Sr and Zn addition on the creep properties. This study examined the microstructures and creep properties of Mg-6Sn-5Al-2Si alloy. Trace amounts of Sr and Zn were added to modify the shape of the precipitates in the matrix, and the influence of the combined addition of Sr and Zn on the microstructure and creep properties was studied.

2. Experimental Procedures

Table 1 shows the chemical compositions of Mg-6Sn-5Al-2Si based alloys with and without Sr and Zn modification. Melting was carried out in an electric resistance furnace with a steel crucible coated with boron nitride (BN) under the protection of CO₂ + 0.5%SF₆ mixed gases. The melt was held at 750 °C for 10 min and then poured into a permanent mould coated with BN and preheated to 350 °C. The microstructure was examined by optical microscopy (OM) and scanning electron microscopy (SEM) equipped with an energy dispersive X-ray spectrometer (EDS) after etching. A solution of 3 vol% nitric acid and ethyl alcohol was used to etch the samples. The volume fractions of the precipitates were measured using image analyzer. The gauge length of the tensile and creep test specimens was 3 mm × 6 mm × 30 mm. Tensile tests were carried out at an initial engineering strain rate of 2.0 · 10⁻⁴/min at room temperature. Creep tests were performed under pressures of 30, 50 and 70 MPa at 150, 180 and 200 °C.

3. Results and Discussion

3.1 Microstructure

Figure 1 shows the X-ray diffraction (XRD) patterns. The main phases in the TAS652 alloys (Mg-6Sn-5Al-2Si) were α-

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Table 1 Chemical compositions of the TAS 652 alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sn  (mass%)</th>
<th>Al  (mass%)</th>
<th>Si  (mass%)</th>
<th>Sr  (mass%)</th>
<th>Zn  (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS652</td>
<td>5.98</td>
<td>4.97</td>
<td>1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAS652-Sr</td>
<td>6.02</td>
<td>5.04</td>
<td>1.98</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>TAS652-Zn</td>
<td>6.04</td>
<td>5.05</td>
<td>2.02</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>TAS652-Sr-Zn</td>
<td>6.10</td>
<td>5.02</td>
<td>2.01</td>
<td>0.20</td>
<td>1.04</td>
</tr>
</tbody>
</table>
Mg, Mg$_{17}$Al$_{12}$, Mg$_2$Si and Mg$_2$Sn. Figure 2 shows optical micrographs of the as-cast TAS652 alloys. The microstructures were changed slightly by the addition of Sr or Zn. With the addition of Sr, the ‘Chinese script’ morphology of Mg$_2$Si changed to a polygonal shape with a refined microstructure. When Zn was added, the volume fraction of Mg$_{17}$Al$_{12}$ increased slightly. In the TAS652 alloy containing both Zn and Sr, all the Chinese script Mg$_2$Si had changed to a polygonal shape and the amount of Mg$_{17}$Al$_{12}$ was also slightly increased. Figure 3 presents SEM images of the precipitates in these alloys. Mg$_{17}$Al$_{12}$ and Mg$_2$Sn were formed mainly along the grain boundaries while Mg$_2$Si was formed randomly along the grain boundaries and within the matrix. Figure 4 shows the microstructures of the TAS652 and the TAS + Sr alloys after heat-treatment at 420°C for 4 h. The average grain size decreased from 105 to 78 μm. The reduced grain size by Sr addition might be due to the finely distributed polygonal type Mg$_2$Si particles in the interface of liquid-solid phase during solidification, which restrains further grain growth. Figure 5 and Table 2 show that the area fraction Mg$_{17}$Al$_{12}$ phases increased from 1.7 to 2.6% after the addition of Zn.

### 3.2 Tensile properties

Figure 6 shows the tensile properties of the alloys tested at room temperature. The trace addition of Sr to the alloy had an effect on the mechanical properties of the TAS652. Both the fracture strength and elongation increased as a result of the morphological change from Chinese script Mg$_2$Si to a polygonal shape. In case of Zn addition, the amount of Mg$_{17}$Al$_{12}$ was increased from 1.7 to 2.6%. It appears that as Zn was added, the Al dissolved in the Mg matrix was extracted and formed Mg$_{17}$Al$_{12}$. This phenomenon improved the fracture strength slightly. The optimum mechanical property combination was obtained when both Sr and Zn were added to the TAS652 alloy. Both the fracture strength and elongation were increased approximately 50% compared with the TAS652 alloy because most of the Chinese script Mg$_2$Si had changed to a polygonal shape after Sr addition and the volume fraction of Mg$_{17}$Al$_{12}$ was increased by Zn addition.

### 3.3 Creep behavior

Figures 7 and 8 show the creep strains vs. time curves of the TAS652 alloys. Table 3 lists the minimum creep rates of the alloys. Under identical test conditions, the minimum creep...
Fig. 3 SEM micrograph and EDS patterns of the TAS652-Sr alloy.

Fig. 4 Optical micrographs showing the effect of Sr addition on the TAS652 alloy (a) T4 heat-treated TAS652, (b) T4 heat-treated TAS652 + Sr.

Fig. 5 Optical micrographs showing the distribution of $\text{Mg}_{17}\text{Al}_{12}$ precipitates (a) as-cast TAS652 (b) as-cast TAS652 + Zn.
rate had the following sequence: TAS652 + 0.2Sr + 1Zn > TAS652 + 1Zn > TAS652 + 0.2Sr > TAS652. When tested at 200°C with an applied stress of 70 MPa, the TAS652 alloy showed a lower minimum creep rate than the other alloys. It appears that Sr modification decreased the creep rupture strength and increased minimum creep rate of TAS652 alloy slightly due to the refined microstructure. Zn addition decreased the creep resistance due to the increased amount of the Mg_17Al_12 phases that were unstable at temperatures > 120°C. Although both Sr and Zn addition increased the fracture strength and elongation dramatically, they decreased the creep resistance. It is possible that the creep resistance decreased as a result of the combined effect of the increased concentration of Mg_17Al_12 phases by Zn addition and the refined microstructure by Sr addition. The stress dependence of the secondary creep rate at a given temperature and the temperature dependence at a specific applied stress was plotted to obtain the stress exponent, n, and apparent activation energy, Q, which are indicative of the creep mechanisms in the stress and temperature conditions. Figure 9 presents the stress dependence of the secondary creep rate of the TAS652 alloys tested at 150°C. The calculated exponent, n, was close to 2. The creep mechanism was grain boundary sliding when the stress exponent, n, was approximately 2. Therefore, the dominant creep mechanism for the TAS652 alloys was grain boundary sliding. Figure 10 gives an Arrhenius plot of the temperature dependence of the secondary creep rate of TAS652 alloys under an applied stress of 50 MPa. The calculated Q values were approximately 49 kJ/mol over the temperature range, 150°C to 180°C. The Q value of 49 kJ/mol is in agreement with other researchers, who reported 36 to 44 kJ/mol for the creep of AZ91D and AS21 and related it to the grain-boundary sliding mechanism promoted by the discontinuous precipitation of Mg_17Al_12 for which the activation energy was 30 kJ/mol. Therefore, the n and Q
values indicate grain boundary sliding to be the dominant creep mechanism of TAS652 alloys.

3.4 Fractography

Figure 11 shows the microstructures of the longitudinal section of the specimen after the creep test. The thermally unstable Mg$_{17}$Al$_{12}$ precipitates became coarse at high temperatures and cracks propagated along the grain boundary. It appears that the Mg$_2$Sn and Mg$_2$Si precipitates at the grain boundary prevent the grain boundary sliding caused by the Mg$_{17}$Al$_{12}$ degradation. Figure 12 shows the gauge length and head region of the specimens after the creep test. At the gauge length where the stress was concentrated, the size of Mg$_{17}$Al$_{12}$ phases became coarser than those at the head region, while Mg$_2$Si and Mg$_2$Sn phases remained relatively

Fig. 10 Temperature dependence of minimum creep rate for TAS652 alloys at 150°C, 180°C with 50 MPa.

Fig. 11 The OM images of the TAS652 alloy after the creep tests.

Fig. 12 Comparison of the microstructure between the gauge length and head region after the creep test.
unchanged during the creep test. From these images, it can be assumed that Mg$_2$Si and Mg$_2$Sn phases were more stable during the creep test than the Mg$_{17}$Al$_{12}$ phase. Figure 13 shows the microstructures of the TAS652 alloys after the creep tests. The microstructure of TAS652-Sr was finer than that of the TAS652 alloy. It appears that Sr addition refined the microstructure of the TAS652 alloy and decreased the creep resistance by promoting grain boundary sliding. In the TAS652 alloy containing Zn, the amount of the Mg$_{17}$Al$_{12}$ phases in TAS652 that were unstable at temperatures > 120°C increased, which decreased the creep resistance. In the TAS652 alloy containing Sr and Zn, the creep resistance decreased as a result of the combined effects of the higher concentration of Mg$_{17}$Al$_{12}$ phases through Zn addition and the refined microstructure by Sr addition. Figure 14 shows void initiation and crack propagation during the creep test. The crack initiated mainly at Mg$_{17}$Al$_{12}$. The Mg$_2$Sn and Mg$_2$Si phases prevented crack propagation. These images suggest that Sr modification was less effective on the creep properties than on the tensile properties. This is because in the tensile test, the cracks initiated at the tip of Mg$_2$Si and the fracture strength was increased by the modification of Mg$_2$Si. However, in the creep tests, the cracks initiated mainly at the thermally unstable Mg$_{17}$Al$_{12}$ hence, Mg$_2$Si modification did not improve the creep properties.

The deformation behavior suggests that the grain boundaries are the weakest link in these alloys because grain boundary cracking was evident with no apparent cracking within the grains. Therefore, grain boundary sliding might be accommodated by grain boundary cracking.
4. Conclusions

This study examined the tensile and creep properties of the Mg-6Sn-5Al-2Si alloys containing Zn and Sr and the following conclusions were drawn:
1. Sr addition decreased the creep rupture strength of the TAS652 alloy due to the increased grain boundary area, which is the weakest link, but increased the tensile strength by changing the Chinese script $\text{Mg}_2\text{Si}$ to a polygonal shape.
2. Zn addition decreased the creep resistance of the TAS652 alloy due to the increased volume fraction of $\text{Mg}_{17}\text{Al}_{12}$ where cracks initiated. The creep resistance of the TAS652 alloy was decreased by the addition of both Sr and Zn.
3. The calculated $n$ and $Q$ values indicated grain boundary sliding to be the dominant creep mechanism for the TAS652 alloys.
4. The deformation behavior suggests that the grain boundaries are the weakest link in the TAS652 alloys because most cracks initiated and propagated along the grain boundaries with no apparent cracks occurring within the grains.

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REFERENCES