Effect of Prior Deformation on Creep Behavior of a Die-Cast Mg-Al-Ca Alloy

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The creep of die-cast Mg-Al-Ca alloys is characterized by the pronounced decrease in creep rate during the transient region. Higher creep rates immediately after the stress application for the alloys can result in the degradation of bolt-load retention in the automotive powertrain applications. In this study, the effect of prior deformation on creep behavior was investigated for the Mg-Al-Ca AX51 (X representing calcium) die-cast alloy, where the prior deformation was introduced by using the creep machine at temperatures of 423 and 473 K. The creep curves of the specimens with the prior deformation were compared with that of the as die-cast specimen at the creep testing condition of 423 K and 80 MPa. It was found that the prior deformation introduced by the creep machine is not effective to decrease the creep rates for the alloy. The obtained results of creep behavior are discussed on the basis of dislocation movements during creep. [doi:10.2320/matertrans.MAW200901]

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1. Introduction

Magnesium alloys, as lightweight structural materials, have recently received great interests in their real and potential applications in the automotive industry to achieve high fuel efficiency.1-3) The cost effective Mg-Al-Ca alloys with superior creep strength have been successfully developed owing to the recent efforts to develop creep resistant magnesium alloys for the automotive powertrain applications.4-7) The creep curve of the Mg-Al-Ca alloys produced by die-casting is usually characterized by the pronounced decrease in creep rate during transient region, and the reduction of creep rate is emphasized at the creep condition with lower temperatures and lower stresses.8) The higher creep rates immediately after the stress application for the alloys can result in the degradation of bolt-load retention in the automotive powertrain applications.9)

Strain hardening is the phenomenon whereby a metallic material becomes harder and stronger as it is plastically deformed.10) The aim of the present study is to reduce the creep rate immediately after the stress application by introducing the prior plastic deformation, to avoid the degradation of bolt-load retention for the Mg-Al-Ca die-cast alloys. In this study, the effect of prior deformation on creep behavior is investigated for the AX51 (X representing calcium) die-cast alloy, where the prior deformation is introduced at higher temperatures by using the creep machine. It is mentioned that cold working is not available for the alloy due to the lower ductility of the eutectic intermetallic phases.11)

2. Experimental

The AX51 alloy with the chemical composition listed in Table 1 was produced by a cold chamber die-casting machine. The melt temperature was controlled at 993 K, and the die-surface temperature was maintained constant at 473 K. The casting plates with 150 × 70 mm² had a stairlike shape with three thickness gradations from 1 to 3 mm. All the specimens used in this study were taken from the 3 mm thickness sections of the casting plates.

Prior deformation was introduced to the specimens with no ridges in the gage portion shown in Fig. 1(a), by using lever arm creep machines at 423 and 473 K under applied stresses that varied between 60 and 80 MPa. The prior deformation was interrupted at the time corresponding to the end of transient region for each creep condition,12,13) by using compressed air under load followed by water quenching. The creep specimens with a gage length of 28 mm and a rectangular cross section of 6 × 3 mm² shown in Fig. 1(b) were machined from the interrupted specimens.

The tensile creep tests were carried out in air at 423 K under 80 MPa. Tensile displacement was measured using extensometers attached to ridges at both ends of the gage portion, and the displacement of the extensometer heads was continuously recorded as a function of time by the linear

Table 1 Chemical composition of the AX51 die-cast alloy used in this study (in mass pct).

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Al</th>
<th>Ca</th>
<th>Mn</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX51</td>
<td>5.20</td>
<td>0.95</td>
<td>0.22</td>
<td>bal.</td>
</tr>
</tbody>
</table>

Fig. 1 Specimens used in this study without ridges (a) and with ridges (b) in the gage portion (in mm).

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variable differential transformers. Before loading, the specimens were held at the test temperature for at least 1 h in the creep furnace, to stabilize the temperature of the specimens.

3. Results and Discussion

The creep rate vs. time curve at 423 K and 80 MPa for the as die-cast AX51 alloy without prior deformation is shown in Fig. 2. The curve shows a downward curvature in the whole of creep. After a transient creep region, the curve shows a minimum in the creep rate followed by a region with increasing creep rate; a distinct steady-state region with constant creep rate is not identified. It is found that the creep rate after $10^{4} \text{h}$ (36 s) is $1.7 \times 10^{-2} \text{h}^{-1}$ and the minimum creep rate is $3.8 \times 10^{-5} \text{h}^{-1}$. The creep rate is reduced to about 1/450 during the transient stage at this creep condition.

The plots of creep rates against time at 423 K and 80 MPa for the alloys with the prior deformation at 473 K/80 MPa/1 h, 473 K/60 MPa/10 h and 423 K/80 MPa/160 h, respectively, are shown in Fig. 3, together with the curve for the as die-cast specimen. It is noted that the prior deformation was interrupted at the time corresponding to the end of the transient region and the plastic strain introduced during the prior deformation is around 1 pct at every condition. All the plots of creep rate for the alloys with the prior deformation fall well on the curve for the as die-cast specimen, irrespective of temperature and stress in the prior deformation. It is obvious that the prior deformation introduced by the creep machine is not effective to decrease the creep rates for the alloy.

The microstructure of the Mg-Al-Ca die-cast alloys is characterized by the eutectic intermetallic phase covering the primary $\alpha$-Mg grains. The eutectic structure consists of the $\alpha$ phase and a ternary (Mg,Al)2Ca intermetallic compound with a C36 dihexagonal structure and the ternary compound would transform to C15-Al2Ca equilibrium phase during high temperature exposure. It has been demonstrated that the eutectic intermetallic phase covering the primary $\alpha$-Mg grains detected in the alloys is stable in morphology below 473 K. Dislocations are introduced within the primary $\alpha$-Mg grains for the Mg-Al-Ca alloys in the die-casting process, which may be due to the fast cooling under geometric constraint that was experienced by the die-cast specimen. The dislocation density in the $\alpha$-Mg grains for the as die-cast Mg-Al-Ca alloy specimens tends to be rather high in the order of $10^{13} \text{m}^{-2}$.

Studies on dislocation analysis for the die-cast Mg-Al-Ca alloy indicate that the introduced dislocations in the die-casting process, which are mostly $\alpha$-type, consist of both the basal and non-basal segments. In the course of creep deformation, the basal segments of dislocations introduced in the die-casting process are able to bow out and glide on the basal planes under the influence of a stress and the non-basal segments follow the basal segments with the help of climb as illustrated in Fig. 4. The distribution of dislocations in the $\alpha$-Mg grains turns from homogeneous to inhomogeneous during creep, which would be ascribe to the lower rate of dislocation annihilation at the grain boundaries covered by the eutectic intermetallic phase. It is supposed that the basal segments of dislocations introduced in the die-casting process bow out and glide on the basal planes during the prior deformation, however, the bow-shaped segments revert back to their stable configuration during high temperature exposure at 423 K before the application of stress in the creep test. The higher creep rates immediately after the stress application for the alloy would result from the bowing out of the basal segments of dislocations introduced in the die-casting process.

Fig. 2 Creep rate vs. time curve of the AX51 die-cast alloy at 423 K and 80 MPa.

Fig. 3 Plots of creep rates against time at 423 K and 80 MPa for the AX51 die-cast alloys with the prior deformation at 473 K/80 MPa/1 h, 473 K/60 MPa/10 h and 423 K/80 MPa/160 h, respectively. Creep rate vs. time curve for the as die-cast specimen is included.

Fig. 4 Schematic illustration showing the dislocation configuration during creep deformation for a die-cast Mg-Al-Ca alloy. The movements of each dislocation during creep take place by the combination of the easy glide of basal segments and the climb of non-basal segments. The non-basal planes are dotted in the figure.
How long does it take for the bow-shaped segments to revert back during high temperature exposure at 423 K? To evaluate the taking time, the following experiments were carried out by using the creep specimens with ridges in the gage portion shown in Fig. 1(b). First of all, to advance the basal segments of dislocations the prior deformation was introduced by using the creep machine at 423 K and 80 MPa. Secondly, all the stress of 80 MPa is relieved at the time of 160 h followed by the aging at 423 K with no stress in the creep furnace for 0.01–10 h, to revert back the bow-shaped segments. It is noted that the negative strain continues during the aging at 423 K up to 10 h. And lastly, the stress of 80 MPa is applied again followed by the evaluation of the creep behavior.

The plots of creep rates against time at 423 K and 80 MPa for the alloys with the prior deformation at 423 K/80 MPa/160 h followed by the aging at 423 K for 0.01 and 10 h, respectively, are shown in Fig. 5. The creep rate vs. time curve for the as die-cast specimen shown in Fig. 2 is included in the figure. It is found that the creep rates during transient region for the alloy aged for 0.01 h are one order of magnitude smaller than those for the as die-cast specimen. The creep rates during transient region increases, when the aging time at 423 K is prolonged to 10 h. On the contrary, the minimum creep rates of the specimens with the prior deformation followed by the aging treatment are almost same as that for the as die-cast specimen.

The creep rates at $10^{-2}$ h for the specimens with the prior deformation at 423 K/80 MPa/160 h followed by the aging at 423 K are plotted against aging time in Fig. 6. The creep rate at $10^{-2}$ h is higher than the minimum creep rate by a factor of $\sim 50$, when the aging time at 423 K is 0.01 h. The creep rate slightly increases with aging time in the range from 0.01 to 10 h. It is supposed that the basal segments of dislocations, which bow out and glide on the basal planes during the prior deformation at 423 K/80 MPa/160 h, revert back to a large extent within 0.01 h (36 s) during the aging at 423 K. The eutectic intermetallic phase covering the primary $\alpha$-Mg grains is stable in morphology below 473 K, then, the increase in creep rate at $10^{-2}$ h with the aging time at 423 K shown in Fig. 6 would be ascribed to the reversion of the basal segments of dislocations rather than the collapse of the eutectic intermetallic phase. It is expected that the negative strain during the aging at 423 K is pronounced and the creep rate immediately after the stress application is smaller, when the bowing out of the basal segments of dislocations introduced in the die-casting process is remarkable in the prior deformation.

The glide of the basal segments of dislocations introduced in the die-casting process is controlling the creep rates immediately after the stress application of creep tests for the alloy. The introduced dislocations can be reduced by decreasing the geometric constraint of the products in the die-casting process, and this could be enabled by increasing the melt temperature and/or mold temperature. Such a modification in manufacturing process to lower the dislocation density of the die-cast materials would be necessary for the heat resistant Mg-Al-Ca alloys, in order to decrease the creep rates immediately after the stress application and to avoid the degradation of bolt-load retention in the automotive powertrain applications.

4. Conclusions

The effect of prior deformation on creep behavior was investigated for the Mg-Al-Ca AX51 die-cast alloy, where the prior deformation was introduced by using the creep machine at temperatures of 423 and 473 K. The creep curves of the specimens with the prior deformation were compared with that of the as die-cast specimen at the creep condition of 423 K and 80 MPa. It is presented that the prior deformation introduced by the creep machine is not effective to decrease the creep rates for the alloy. The basal segments of dislocations introduced in the die-casting process bow out and glide on the basal planes during the prior deformation, however, the bow-shaped segments revert back to a large extent during high temperature exposure at 423 K within 36 s.
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REFERENCES