Microstructure and tensile creep behavior of Mg–4Al based magnesium alloys with alkaline-earth elements Sr and Ca additions

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Abstract

The microstructure, tensile property and creep behavior of three Mg–4Al–Sr (AJ) and two Mg–4Al–Sr–Ca (AJC) based alloys have been investigated. The as-cast microstructure of Mg–4Al–(1–3)Sr based alloys consists of the dendritic α-matrix and grain boundary second-phases. In the alloy with 1% of strontium added a lamellar eutectic Al4Sr compound is observed at grain boundaries. A ternary Mg–Al–Sr interphase exists at grain boundaries besides eutectic Al4Sr in the alloys containing 2–3% of strontium. Calcium addition to Mg–4Al–(1–2)Sr based alloys results in the formation of Mg2Ca and (Mg, Al)2Ca, which shows two morphologies, lamellar eutectic at grain boundaries and granular in the matrix grains. Creep properties of the Mg–Al–Sr based alloys at the temperatures between 150 and 200 °C and applied stresses between 50 and 80 MPa are significantly improved with the increase of strontium addition and higher creep resistance is obtained from the Mg–4Al–(1–2)Sr based alloys with 1% of calcium addition. The improvements on creep resistance for these alloys studied are mainly attributed to the formation of thermally stable interphases, Al4Sr and Mg–Al–Sr ternary phase as well as Mg2Ca and (Mg, Al)2Ca, which provide the pinning effect at the magnesium grain boundaries. Primarily assessments of creep mechanism based on stress dependence of secondary creep rate at 175 °C and temperature dependence of secondary creep rate at 70 MPa seem that both grain boundary sliding and dislocation climb contribute to the creep deformation.

Keywords: Magnesium alloys; Strontium; Calcium; Creep

1. Introduction

As the lightest applied structural alloys, magnesium alloys offer a good combination of castability and mechanical properties. For recent years, research and development of magnesium alloys have been greatly promoted by the lightweight requirement in the automotive industry. Aluminum as an alloying addition has found the most favor because it improves castability of the alloy by reducing the freezing range and provides strengthening by solid solution and precipitation of the intermetallic β phase (Mg17Al12) [1]. Some Mg–Al alloys, such as AZ91D and AM60B, have been extensive used in automotive products since these alloys exhibit superior die castability and a good balance of strength and ductility. However, these alloys are limited to some noncritical parts because of the restriction of strength and creep resistance at elevated temperatures [2,3].

More studies [4–6] have shown the poor elevated temperature creep properties of Mg–Al based alloys is due to discontinuous grain boundary precipitation of β phase (Mg17Al12) from the supersaturated α-Mg solid solution and coarsening of β in the interdendritic eutectic region at high temperatures. The service temperatures of automotive powertrain components are mostly above 150 °C, therefore, creep resistance is a major requirement for use of magnesium in critical automotive components that are currently made of aluminum or cast iron [3].

The alkaline-earth (Ca and Sr) containing Mg–Al alloys have been reported in latest investigations by General Motors Research & Development Center (GM R&D) and Noranda Inc. Technology Center [7–10]. The Mg–Al–Ca and Mg–Al–Sr alloys offer good creep resistance and low cost which can meet the materials requirements for automotive powertrain applications. The present paper reports the microstructure, tensile properties and creep behavior of five alloys based on Mg–Al–Sr ternary system Mg–Al–Sr–Ca quaternary system. The results show that the additions of strontium combined with calcium are very effective in improving creep resistance of Mg–Al based alloys at the temperatures between 150 and 200 °C.
Table 1
Chemical compositions of the alloys studied

<table>
<thead>
<tr>
<th>Alloy code</th>
<th>Designed compositions</th>
<th>Analyzed compositions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al Sr Ca Mn Mg</td>
<td>Al Sr Ca Mn Mg</td>
</tr>
<tr>
<td>AJ41</td>
<td>4.0 1.0 – 0.3 Bal.</td>
<td>4.05 0.96 – 0.24 Bal.</td>
</tr>
<tr>
<td>AJ42</td>
<td>4.0 2.0 – 0.3 Bal.</td>
<td>4.10 2.17 – 0.27 Bal.</td>
</tr>
<tr>
<td>AJ43</td>
<td>4.0 3.0 – 0.3 Bal.</td>
<td>4.05 3.1 – 0.26 Bal.</td>
</tr>
<tr>
<td>AJC411</td>
<td>4.0 1.0 1.0 0.3 Bal.</td>
<td>3.87 0.84 0.86 0.28 Bal.</td>
</tr>
<tr>
<td>AJC421</td>
<td>4.0 2.0 1.0 0.3 Bal.</td>
<td>3.79 2.22 1.01 0.31 Bal.</td>
</tr>
</tbody>
</table>

2. Experimental procedure

Five alloys were prepared and their designed compositions are listed in Table 1. All the alloys were prepared based on Mg–4Al with 1–3% of strontium addition and 1% of calcium was added in the last two alloys (alloys AJC411 and AJC421). Strontium and calcium additions were conducted by adding master alloys of Mg–27Sr (containing 27 wt% of Sr), and Mg–30Ca (containing 30 wt% of Ca), respectively. Melting of the alloys was conducted in a mild steel crucible under the protection of a mixed gas atmosphere of SF6 (1%, v/v) and CO2 (Bal.). After the alloying elements were dissolved, the melt was held at 680 °C for AJ alloys (alloys AJ41, AJ42 and AJ43) and 740 °C for AJC alloys (alloys AJC411 and AJC421) for 10 min then poured into a water-cooled mold made of cast copper. The chemical compositions of prepared alloys were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP) and the results are also listed in Table 1, which is in good agreement with the designed compositions.

3. Results

3.1. Microstructure

Optical micrographs taken from as-cast alloys AJ41, AJ42 and AJC421 are shown in Fig. 1, from which it can be seen that the as-cast microstructure of these three alloys consists of dendritic α-Mg matrix and interphases at grain boundaries. The volume fraction of interphase increases with the increase of strontium and calcium addition and a grain boundary interphase network can be observed in alloy AJC421, as shown in Fig. 1(c). SEM observations of AJ41 alloy reveal that the grain boundary second-phases show a kind of lamellar eutectic morphology with bright contrast (Fig. 2(a)). TEM micrograph as well as a selected area diffraction pattern (SADP) taken from the lamellar eutectic are shown in Fig. 2(c), which can be indexed as arising from Al4Sr with a body centered tetragonal structure (D13 with a = 4.46 Å and c = 11.07 Å). With increase of Sr addition, another bulky phase with intermediate contrast is observed, however, the electron diffraction patterns taken from the bulky grain boundary phase cannot be identified due to lack of the data concerning the crystal structure of Mg–Al–Sr ternary intermetallics. The chemical compositions of the phase determined by EDAX are approximately 12.4 wt%Al–9.6 wt%Sr–Mg. With increase of strontium addition, the volume fraction Al4Sr eutectic decreases, while the Mg–Al–Sr ternary intermetallic compound increases in the as-cast microstructure, as shown in Fig. 2(b), a SEM micrograph taken from the as-cast specimen of alloy AJ43.

With addition of calcium to the AJ alloys, a new interphase appears in as-cast microstructure. Fig. 3 shows SEM micrographs taken from as-cast specimens of alloys AJC411 and AJC421, respectively. Microanalysis performed on these

Fig. 1. Optical micrographs of as-cast AJ and AJC alloys sample: (a) AJ41, (b) AJ42 and (c) AJC421.
specimens reveals that the as-cast microstructure of both alloys consists of three phases, the α-Mg matrix, the Mg–Al–Sr ternary compound and a Ca containing compounds, which showing a lamellar morphology, and no Al4Sr phase has been observed. Fig. 3(c and e) shows the TEM bright field images of the lamellar phase in as-cast AJC421. Two SADPs taken from the eutectic lamellar compounds indicated by arrowheads in Fig. 3(c and e), respectively, are shown in Fig. 3(d and f), which can be indexed as arising from hexagonal structures C14 and C36 and are consistent with the structure of Mg2Ca and (Mg, Al)2Ca, respectively. The previous work carried out by Suzuki et al. [11,12] reported that both Mg2Ca (C14) and (Mg, Al)2Ca (C36) were observed in Mg–Al–Ca based alloys. The crystal structure of C14 and C36 are similar, both hexagonal, and the lattice parameter of C36 is twice of that of C14 along [0001] direction. However, no C15 structure (Al2Ca phase), which was found in some Mg–Al–Ca alloys [13,14], has been observed in the AJC alloys studied in the present investigation. Higher magnification SEM observation exhibits some tiny particles distributing in the matrix grains, as shown in Fig. 3(g). Microanalysis performed on these particles indicates that the composition of these tiny particles is close to that of lamellar (Mg, Al)2Ca. These two kinds of (Mg, Al)2Ca observed in the present investigation are labeled as A-type (lamellar) and B-type (granular), respectively. Microanalysis and electron diffraction performed on the as-cast specimens of AJC alloys indicates that the composition and crystal structure of the Mg–Al–Sr ternary compound in the AJC alloys are the same with that observed in AJ alloys without Ca addition.

3.2. Tensile properties

Table 2 lists the tensile properties of the as-cast alloys at ambient and elevated temperatures of 175 °C. It can be seen that the AJ41 alloy has highest yield strength at both ambient and elevated temperatures. The changes of tensile properties with the variation of Sr and Ca concentrations in the alloys studied do not show an apparent regularity and as a whole, the tensile properties of the alloys studied at ambient temperature are lower than that

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Room temperature</th>
<th>175 °C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>σb (MPa)</td>
<td>σ0.2 (MPa)</td>
</tr>
<tr>
<td>AJ41</td>
<td>166.2</td>
<td>82.4</td>
</tr>
<tr>
<td>AJ42</td>
<td>161.7</td>
<td>114.3</td>
</tr>
<tr>
<td>AJ43</td>
<td>129.1</td>
<td>88.0</td>
</tr>
<tr>
<td>AJC41</td>
<td>143</td>
<td>97.6</td>
</tr>
<tr>
<td>AJC421</td>
<td>131.3</td>
<td>88.0</td>
</tr>
</tbody>
</table>
of commercial cast magnesium alloys, such as the alloys of AZ and AE series, and that of die-cast AJ series alloys reported in the previous investigations [3,5,15,16]. This may be accounted for by the coarse microstructure and the formation of grain boundary second-phases.

3.3. Creep properties

The creep tests in the present investigation have been carried out at the temperatures between 150 and 200 °C and applied stress between 50 and 80 MPa. The 100 h creep curves of as-cast alloys tested at 175 °C and 70 MPa are shown in Fig. 4. The creep curve of as-cast AE42 alloy (prepared by the same experimental procedure and tested under the same condition) is also shown in Fig. 4 so that the effects of alkaline-earth and rare-earth additions on creep properties of Mg–Al based alloys can be compared. From the gradient of the stage 2 in creep curves, the steady-state creep rate can be calculated and the results are shown in Table 3, in which 100 h creep elongation of the alloys are also listed. It can be seen that the creep resistance of alloy AJ41 and AE42 seems poor. The specimens of these two alloys ruptured after testing for 14 and 60 h, respectively. The other alloys studied, however, exhibit much lower steady creep rate and creep strain than these two alloys. With 2% of strontium added to Mg–4Al based alloy (AJ42), the creep rate of as-cast specimen reduced to $5.6 \times 10^{-9} \text{s}^{-1}$, one order of magnitude lower than that of AE42. Further improvement of creep resistance is achieved with the increase of strontium concentration and combined addition of strontium and calcium. The lowest creep rate obtained from alloy AJC421 containing 2% Sr and 1% Ca was $3.5 \times 10^{-10} \text{s}^{-1}$, beyond two orders of magnitude lower than that of the AE42 alloy. The data of secondary creep rate of AJ and AJC alloys at
Fig. 4. Creep curves of AJ, AJC and AE42 alloys at 175 °C/70 MPa during 100 h.

Table 3
The secondary creep rate and creep elongation of AJ, AJC and AE42 alloys at 175 °C and 70 MPa

<table>
<thead>
<tr>
<th>Alloys</th>
<th>175 °C, 70MPa, 100 h</th>
<th>175 °C total creep elongation εt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE42</td>
<td>5.6 x 10^{-9}</td>
<td>2.96a</td>
</tr>
<tr>
<td>AJ41</td>
<td>215.4 x 10^{-9}</td>
<td>2.35a</td>
</tr>
<tr>
<td>AJ42</td>
<td>5.6 x 10^{-9}</td>
<td>0.50</td>
</tr>
<tr>
<td>AJ43</td>
<td>3.3 x 10^{-9}</td>
<td>0.21</td>
</tr>
<tr>
<td>AJC411</td>
<td>0.96 x 10^{-9}</td>
<td>0.13</td>
</tr>
<tr>
<td>AJC421</td>
<td>0.35 x 10^{-9}</td>
<td>0.08</td>
</tr>
</tbody>
</table>

a Elongation to fracture.

Poor creep resistance of alloy AE42 is accounted for by unstable microstructure at elevated temperatures above 150 °C [15,17]. In order to understand the mechanism responsible for the improvement of creep resistance caused by strontium and calcium addition, microstructure observations were performed on selected specimens after creep test. Fig. 7 shows the microstructure of the longitudinal section near the creep fractured surface of AJ41 specimen which rupture after 15 h creep test at 175 °C/70 MPa. Great amount of cracks can be observed along the grain boundaries. SEM observations on the same specimen reveal microcracks normal to the tensile stress axis as well as cavities around some interphases particle, as shown in Fig. 8(a and b). Cracks are also observed at the interphases near the grain boundaries in the specimens of alloys AJ42 and AJ43 after creep test.

3.4. Microstructure of specimens after tensile creep test

Table 4
The secondary creep rate of AJ and AJC alloys at 175 °C and 70 MPa

<table>
<thead>
<tr>
<th>Creep temperature (°C)</th>
<th>Creep stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 160</td>
<td>175 185 200</td>
</tr>
<tr>
<td>AJ42</td>
<td>0.86 2.6 5.6 8.2 50.6</td>
</tr>
<tr>
<td>AJ43</td>
<td>0.36 1.12 2.3 4.03 9.8</td>
</tr>
<tr>
<td>AJC411</td>
<td>0.33 0.47 0.96 – 3.87</td>
</tr>
<tr>
<td>AJC421</td>
<td>0.12 0.35 0.66 0.96</td>
</tr>
</tbody>
</table>
Fig. 7. Optical micrograph of cracks along the longitudinal section in AJ41 alloy after fracture at 175 °C/70 MPa creep.

Fig. 8. SEM micrographs of (a) microcracks on interphases and (b) cavity around the interphase particle of AJ41 alloy after creep rupture at 175 °C/70 MPa for 15 h; (c) the microcracks on interphases of AJ42 alloy after creep at 200 °C/70 MPa for 100 h; (d) the microstructure of AJC411 after creep at 200 °C/70 MPa for 100 h.

test at 200 °C/70 MPa for 100 h when both alloys are at the stage of the tertiary creep, and the micrograph taken from AJ42 is shown in Fig. 8(c). However, no cracks are observed in the specimen of AJ42 and AJ43 alloys after creep test at 175 °C/70 MPa for 100 h when they are in the stage of steady-state creep. For alloys AJC411 and AJC421 creep tests does not result in obvious changes in microstructure, as shown in Fig. 8(d), SEM micrographs taken from the specimen of alloys AJC411 after 100 h creep test at 200 °C/70 MPa. Neither cracks nor cavities have been observed and the grain size of the α-Mg matrix and the morphologies of the interphases are similar to that in as-cast microstructure.

4. Discussion

4.1. Microstructure

For commercial Mg–Al based alloys, such as AZ and AM series alloys, the β (Mg17Al12) phase commonly appears in as-cast microstructure and is considered as the main strengthening effect on the alloys at room temperature. However, the β phase has a low melting point (437 °C) and can readily soften and coarsen with increase of temperature due to accelerated diffusion [4, 5, 18], resulting in weakening of grain boundaries at elevated temperatures. In the alloys studied in the present investigation the β phase does not exist in the as-cast microstructure because of the additions of strontium and calcium. The absence of β might be the first factor accounting for the better creep properties of the alloys studied than other commercial Mg–Al based alloys.

The alloys studied in the present investigation are based on Mg–Al–Sr ternary and Mg–Al–Sr–Ca quaternary systems. The microstructure of Mg–Al–Sr based alloys was studied in previous investigations [9, 10] and two types of intermetallic compounds identified as Al3Sr and a ternary compound designated as Al12Mg13Sr were observed. The authors of the previous work [10, 16] proposed that the type of interphase in Mg–Al–Sr based alloys depends on the ratio of Sr/Al concentrations. If the Sr/Al ration in the alloy is lower than 0.3, the interphase existing in the microstructure is Al3Sr. When the concentration of Sr
is increased and Sr/Al ratio is higher than 0.3, the Mg–Al–Sr ternary compound will appear besides Al4Sr. Microstructure observations in the present investigation also reveal Al4Sr in the alloy AJ41, in which the Sr/Al ratio is 0.25, and the Mg–Al–Sr ternary compound in the alloys AJ42 and AJ43, in which the Sr/Al ratio is 0.50 and 0.75, respectively. All these results are consistent with the previous investigation.

There is not much information related with the Mg–Al–Sr–Ca quaternary system. In the present investigation, new interphases have been observed at grain boundaries as well as in the matrix grains (see Fig. 3) when 1% of calcium is added to Mg–Al–(1–3)%Sr based alloys, and the binary Al4Sr interphase, which exists in the alloys without calcium addition, disappeared. Microanalysis and electron diffraction have identified that the new phases are Mg2Ca and (Mg, Al)2Ca with some Al entering the Mg2Ca structure. According to the Mg–Ca and Mg–Al–Ca phase diagrams a little amount of calcium can be dissolved in the α-Mg matrix, thus, it can be believed that the lamellar eutectic (Mg, Al)2Ca forms during solidification of the melt and the tiny granular (Mg, Al)2Ca particles are precipitates formed after solidification. The replacement of Al4Sr by Mg2Ca and (Mg, Al)2Ca in the alloy with calcium addition indicates that the free energy of formation of Mg2Ca is lower than that of Al4Sr in Mg–Al–Sr–Ca quaternary system.

The previous work reported the microstructural changes of AZ91 [4,18] and AE42 [15,17] during elevated temperature creep. Extensive coarse discontinuous precipitation of α-Mg17Al12 occurred during creep test of AZ91 alloy and for AE42, the Al11RE3 phase is unstable and decomposes to Mg3Al2 above 150 °C. In the present investigation, no obvious morphological changes related with interphases and α-Mg matrix are observed after creep tests, indicating the microstructure of the alloys with Ca and Sr additions has relatively high thermal stability. The formation of cracks on interphases distributing along grain boundaries perpendicular to the stress axis during creep may be attributed to the pile-up of dislocation at the interface between the α-Mg and intermetallic compounds. With the increase of strontium and calcium addition, the volume fraction of interphases increases and an interphase network forms at grain boundaries, thus, the capability of inhibiting grain boundary sliding and crack initiation during creep test increases, consequently, the creep property improves.

4.2 Creep behavior

The steady-state secondary creep rate (ε) of magnesium alloys is generally described by a power-law equation in the stress (σ) and temperature (T) ranges of interest to applications (σ = 20–100 MPa; T = 100–250 °C) [7,19–22].

\[ \dot{\varepsilon} = A\sigma^n \exp \left( -\frac{Q}{RT} \right) \]  

where A is a materials-related constant, R the gas constant, Q the apparent activation energy for creep and n is the stress exponent. The stress exponent (n) can be calculated from the slope of ln ε versus ln σ plot at a given temperature from Eq. (1), and an Arrhenius plot (ln ε versus 1/T) at a specific stress level will yield the apparent activation energy (Q) value. The n and Q parameters are used to infer the dominant creep deformation mechanisms for a material in specific ranges of stress and temperature. Therefore, a preliminary assessment of the likely creep deformation mechanisms for the alloys studied can be proposed by determining the stress exponent (n) and the apparent activation energy (Q), as shown in Figs. 5 and 6.

As shown in Fig. 5, the creep rates of alloys AJ42 and AJ43 at 175 °C exhibit two-stage behavior with n = 5 at low stresses (in the range 50–60 MPa for AJ42 and 50–65 MPa for AJ43 alloy), and much higher value of n, which is 12.39 in AJ42 and 17.41 in AJ43, at higher stresses. For most of Mg–Al based alloys, the previous investigation proposed that dislocation climb was the controlling mechanism responsible for creep deformation at the temperatures between 120 and 175 °C if the n-value is in the range of 4–6, hence, the creep of alloys AJ42 and AJ43 at lower stress level seems to be dislocation controlled. Whereas an abrupt increase of stress exponents of 12–17 in these two alloys indicates a power-law breakdown. Similar stress exponents have been reported in Mg–rare-earth alloys [1,6]. While the stress exponents in the investigated range of stress indicate dislocation creep leading to power-law breakdown, the contributions to creep by grain boundary sliding or related mechanism cannot be ignored in these alloys. Alloys AJC411 and AJC421, on the other hand, do not show two-stage creep behavior and the stress exponents in these two alloys are relatively low, which is 3.75 in alloy AJC411 and 3.35 in alloy AJC421, and close to 4, associating with dislocation controlled creep, but nevertheless, grain boundary migration or sliding can still make strong contributions to the overall strain.

The temperature dependence of the creep rate for the alloys studied at an applied stress of 70 MPa is shown in the Arrhenius plots of Fig. 6. The slope of these straight line relationships multiplied by −R (gas constant) gives the apparent activation energy for creep, Q. Values for Q have been estimated from lines of best fit to the data in Fig. 6. For alloys AJ42 and AJ43, Q is equal to 123.3 and 91.8 kJ/mol, respectively, and falls in the range of 92–135 kJ/mol reported for the activation energy for dislocation glide in basal planes of pure magnesium [1.7,16]. Lower Q values, 83.2 and 69.9 kJ/mol, have been obtained for alloys AJC411 and AJC421, respectively, which is close to 80 kJ/mol. Thus, the mechanism responsible for these two alloys seems to be grain boundary diffusion according to the previous investigation [16] and different from that assessed on the value of stress exponents of the alloys shown in Fig. 5.

Creep properties of Mg–Al–Sr based alloys have been studied in several previous investigations but there is not much information concerning the mechanism responsible for creep behavior of the alloys based on Mg–Al–Sr and Mg–Al–Sr–Ca systems. It is obvious that the thermal stability of as-cast microstructure is the key factor contributing to the improvement of creep property. In the alloys studied in the present investigation microstructure stability is improved due to strontium and calcium additions. In alloy AJ41 only 1% of strontium is added and the volume fraction of the interphase Al4Sr is not high enough to form a grain boundary network (see Fig. 1(a)), hence, the alloy shows poor creep properties at elevated temperatures. With increase of stron-
tium and calcium concentration the volume fraction of grain boundary interphase increases and continuous grain boundary network forms, which is effective on inhibiting grain boundary migration and sliding so that the creep resistance of the alloy is significantly improved. Higher creep resistance achieved from the alloy with 1% of calcium addition to Mg–Al–Sr–Ca based alloys may be attributed to the formation of fine granular (Mg, Al)2Ca particles, which strengthen the α-matrix and pin dislocation during creep deformation. Based on above discussion, it can be proposed that the possible mechanism responsible for creep in the alloys studied is a mixed mold of grain boundary migration and dislocation climb.

5. Conclusions
(1) The as-cast microstructure of Mg–Al–Sr based alloys consisting of the dendritic α-matrix and grain boundary second-phases. In the alloy with 1% of strontium added a lamellar eutectic Al4Sr compound is observed at grain boundaries. A ternary Mg–Al–Sr interphase exists at grain boundaries besides eutectic Al4Sr in the alloys containing 2–3% of strontium. Calcium addition to Mg–Al–Sr–Ca based alloys results in the formation of Mg2Ca and (Mg, Al)2Ca, which shows two morphologies, lamellar eutectic at grain boundaries and granular in the matrix grains.

(2) Creep properties of the Mg–Al–Sr based alloys at the temperatures between 150 and 200 °C and applied stresses between 50 and 80 MPa are significantly improved with the increase of strontium addition and higher creep resistance is obtained from the Mg–Al–Sr–Ca based alloys with 1% of calcium addition.

(3) The improvements on creep resistance for these alloys studied in the present investigation are mainly attributed to the formation of thermally stable interphases, Al4Sr and Mg2Ca and (Mg, Al)2Ca, which provide the pinning effect at the magnesium grain boundaries.

(4) For the Mg–Al–Sr and Mg–Al–Sr–Ca based alloys primarily assessments of creep mechanism based on stress dependence of secondary creep rate at 70 MPa seem to both grain boundary sliding and dislocation climb contribute to the creep deformation at the temperatures between 150 and 200 °C and applied stress between 50 and 80 MPa.

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References