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Assessment of creep rupture life of heat resistant Mg–Al–Ca alloys

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ABSTRACT

Creep rupture tests were performed for three kinds of Mg–Al–Ca die-cast alloys at temperatures between 423 and 498 K, and the creep rupture lives were evaluated by using the Larson–Miller parameter (LMP). The value of LMP is uniquely described by the logarithm of the applied stress for the alloys, when the Larson–Miller constant is chosen as 20. The applied stress and the LMP value follow a linear relationship below the yield stress, which can be utilized to predict the long-term creep rupture life for the alloys under a given condition of temperature and applied stress.

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1. Introduction

Magnesium alloys are frequently used as lightweight structural materials within the automotive industry. Recently, there has been great interest in the potential applications of these alloys to achieve high fuel efficiency and reduce the emission of carbon dioxide [1]. The use of the alloys for automotive applications is currently restricted to relatively low-temperature components [2]. A substantial increase in the use of magnesium alloys is achieved by utilizing the alloys for elevated-temperature powertrain components [3]. The development of heat resistant magnesium alloys for automotive powertrain components is necessary to enable widespread use of the alloys and thereby enable manufactures to reduce the mass of vehicles [4,5].

Sufficient creep strength is a major requirement to enable magnesium alloys to replace the cast aluminum alloys or cast iron currently used in powertrain components [6,7]. Considerable efforts have been made to develop heat resistant magnesium alloys with superior creep strength, which are exposed to the temperatures above 423 K during service [8–10]. The main design concepts for attaining high creep strength include solid-solution strengthening [11] and grain-boundary strengthening by thermally stable intermetallic compounds to suppress the local deformation and/or sliding in the vicinity of grain boundaries [12–14]. Creep mechanisms [15] and crept substructures [16,17] of magnesium alloys have been extensively investigated and discussed over the last decade. However, the assessment of creep rupture life for these alloys is limited, despite their engineering importance [18].

An accurate assessment of long-term creep rupture life is critical to ensure the reliability and safety of high-temperature components [19]. A relationship to predict creep rupture life for heat resistant materials usually utilizes the Larson–Miller parameter (LMP) described by the following equation [20]:

$$\mathrm{LMP} = T[\log t_{\mathrm{rup}} + C_{\mathrm{LM}}], \tag{1}$$

where T is the creep testing temperature, t_{rup} the creep rupture life in hours, and C_{LM} is the Larson–Miller constant. The value of C_{LM} is phenomenologically determined, as the LMP is uniquely described by the logarithm of the applied stress. This technique has been used for creep rupture life prediction for heat resistant materials, and the C_{LM} value is generally suggested to be around 20 [21]. However, the assessment of creep rupture life by using the LMP has not been attempted for heat resistant magnesium alloys.

Die-casting is the preferred process for producing magnesium components, due to its excellent productivity of complex near net shape parts [22]. The creep strength of die-cast magnesium alloys has been improved by the addition of silicon, strontium, and calcium [23,24]. Among these elements, calcium is a promising elemental addition to rare-earth elements due to its low density and low cost. Cost-effective Mg–Al–Ca alloys with superior creep strength have been successfully developed owing to the recent efforts aimed at developing creep resistant magnesium alloys for the automotive powertrain applications [25–28]. The aim of the present study is to evaluate the creep rupture life for the die-cast Mg–Al–Ca alloys by using the LMP, and to establish the method for rupture life prediction for the alloys.

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Table 1
Chemical composition of the Mg–Al–Ca die-cast alloys used in this study (in mass%).

Alloy code	Al	Mn	Ca	Mg
AX50	4.90	0.28	0.47	Balance
AX51	5.20	0.22	0.95	Balance
AX52	4.98	0.29	1.72	Balance

2. Experimental

The three kinds of Mg–Al–Ca alloys (AX50, AX51, and AX52, where X represents calcium) were produced using a cold chamber die-cast machine. The chemical composition of these alloys is listed in Table 1. The melt temperature was controlled at 993 K, and the die-surface temperature was maintained constant at 473 K. The casting plates (150 mm × 70 mm) had a stair-like shape with three thickness gradations ranging from 1 to 3 mm. Specimens for the creep tests with a gage length of 28 mm and a rectangular cross-section of 6 mm × 3 mm were taken from the 3-mm thick sections of the plates. No heat treatment was applied to the specimens prior to creep testing. The microstructure of the alloys is characterized by the eutectic intermetallic phase covering the primary α-Mg grains with an average diameter of around 7 μm [29]. Our preliminary experiments by both X-ray diffraction and energy dispersive spectrometry indicate that the eutectic intermetallic phase is a C15-Al_2Ca phase in the equilibrium state [30].

Creep rupture tests were conducted in air, using lever-arm creep machines at 423, 448, 473, and 498 K, under initial applied stresses that varied between 30 and 130 MPa. These temperatures were chosen because they are typical for the operation of automobile powertrain components [8]. Before loading, the specimens were held at test temperatures for at least 1 h in the creep furnace, to stabilize the temperatures of the specimens. The accuracy of the temperature and the temperature gradient along the gage length were controlled so that they remained within 2 K during the test. The elongation of the specimen was measured by an extensometer attached to ridges at both ends of the gage portion, where the displacement of the extensometer heads was continuously recorded by linear variable differential transformers (LVDTs).

3. Results and discussion

The long-term creep curves for the AX52 die-cast alloy tested at 498 K–40 MPa and 448 K–80 MPa are shown in Fig. 1, as typical examples. An instantaneous strain occurs at the stress application due to the elongation of the specimens, and then the normal transient creep follows at each condition. There is a gradual increase in the creep rate in the accelerating region, which leads to the final fracture of specimens. It has been demonstrated that the creep curves for the Mg–Al–Ca die-cast alloys exhibit three stages: a transient creep stage, a minimum creep rate stage, and, finally, an accelerating stage [31]. The minimum creep rate stage is revealed after approximately one-third of the time taken to rupture; this indicates that the creep of the alloy is predominantly occupied by the accelerating creep rather than the transient creep.

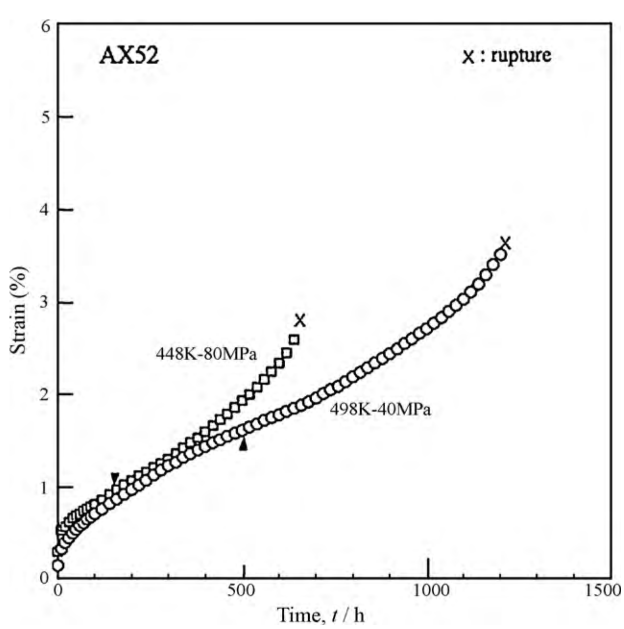

Fig. 1. Creep curves for the AX52 die-cast alloy at 498 K–40 MPa and 448 K–80 MPa. The times showing the minimum creep rates are indicated by arrowheads.

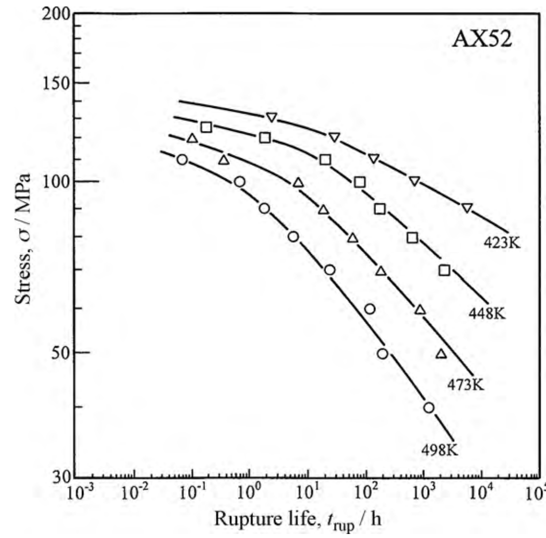

Fig. 2. Plots of creep rupture lives against stress for the AX52 die-cast alloy at temperatures between 423 and 498 K.

Fig. 2 shows the creep rupture lives for the AX52 die-cast alloy tested at the four temperatures summarized against stress. The plots are arranged according to an upward curvature at each temperature, and the gradient of the curves becomes prominent at higher temperatures. It appears that the rupture life decreases as the test temperature and applied stress increases. Such an upward curvature of the σ–t_{rup} relationship in the double logarithmic coordinates may be a general trend for heat resistant materials [32].

Fig. 3 shows the logarithm of the applied stress as a function of LMP for the AX52 die-cast alloy. All 28 kinds of data shown in Fig. 2 fall on the single line independent of creep testing temperature and applied stress, in the rupture life range from a few minutes to 10,000 h. This indicates that the value of LMP is uniquely described by the logarithm of the applied stress for the alloy irrespective of the creep testing temperature, when the Larson–Miller constant is

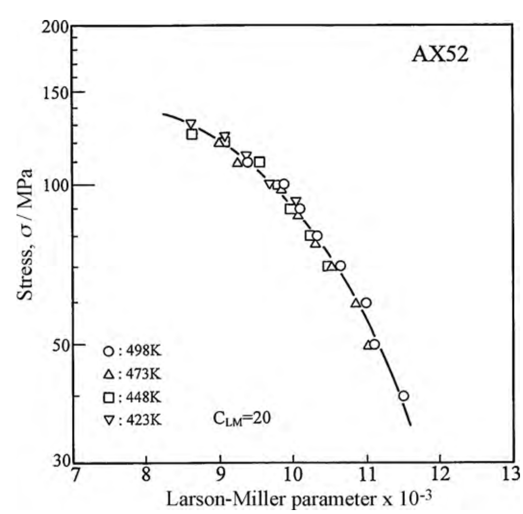

Fig. 3. Plots of Larson–Miller parameters against stress for the AX52 die-cast alloy, in which the Larson–Miller constant is chosen as 20.

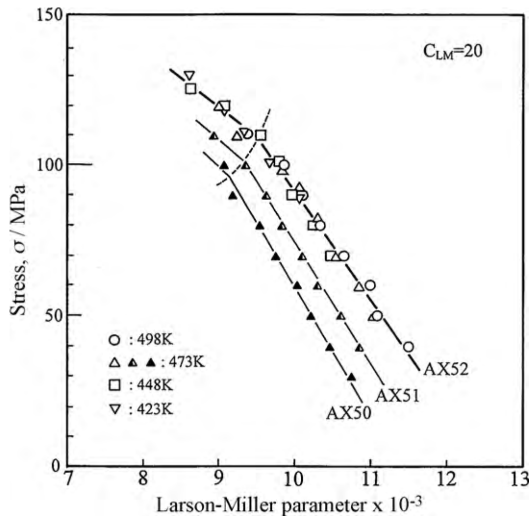

Fig. 4. Correlation between applied stress and Larson–Miller parameter for the Mg–Al–Ca die-cast alloys AX50, AX51, and AX52, in which the Larson-Miller constant is chosen as 20.

chosen as 20. Note that the plots are rather distributed, when the Larson–Miller constant is selected as 15 or 30.

It has been demonstrated that a plot of the applied stress and LMP value gives a linear relationship in the long-term creep for pure titanium with hcp crystal structure [33]. Fig. 4 shows the correlation between applied stress and LMP for the AX52 die-cast alloy obtained in this study, where both the parameters are presented in a linear scale. The creep rupture data are arranged by a two-stage linear relationship, and the critical stress of the low- and high-stress regimes is found to be around 110 MPa. Note that the critical stress is comparable to the 0.2% offset yield stress for the AX52 die-cast alloy at around 450 K [34]. The applied stress and the LMP value are correlated through the following equation in the low-stress regime:

$$\sigma \text{ (MPa)} = 461 - 0.037\,\text{LMP}, \quad (2)$$

which can be utilized to predict the long-term creep rupture life for the alloy under a given condition of temperature and applied stress.

The creep data for the AX50 and AX51 die-cast alloys at 473 K are summarized in Table 2, and the correlation between applied stress and LMP value for the alloys are plotted in Fig. 4. The value of LMP continuously increases with increasing calcium concentration at a given applied stress; this indicates that the creep rupture strength of the AX52 alloy is higher than that of the AX50 and AX51 alloys.

Table 2
Creep test conditions and results for the AX50 and AX51 die-cast alloys.

Alloy code	T/K	σ/MPa	$\dot{\varepsilon}_{min}$/h^{-1}	t_{rup}/h	LMP (C_{LM} = 20)
AX50	473	100	4.6×10^{-1}	0.16	9084
		90	1.1×10^{-1}	0.26	9183
		80	3.8×10^{-2}	1.5	9543
		70	9.3×10^{-3}	4.0	9745
		60	3.1×10^{-3}	15.4	10,022
		50	1.4×10^{-3}	37.3	10,203
		40	2.3×10^{-4}	125	10,452
		30	5.6×10^{-5}	533	10,750
AX51	473	110	5.6×10^{-1}	0.08	8941
		100	6.2×10^{-2}	0.73	9395
		90	2.2×10^{-2}	2.3	9631
		80	5.7×10^{-3}	6.0	9828
		70	1.6×10^{-3}	22.5	10,100
		60	5.5×10^{-4}	59.8	10,300
		50	1.5×10^{-4}	275	10,614
		40	3.3×10^{-5}	825	10,839

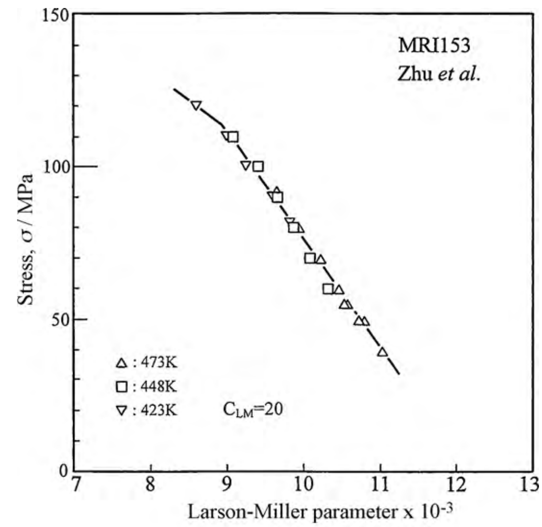

Fig. 5. Correlation between applied stress and Larson–Miller parameter for the squeeze cast MRI153 (Mg–9Al–1Ca–0.7Zr–0.1Sr, in mass%) alloy, in which the Larson–Miller constant is chosen as 20. The creep rupture data for the alloy were reported by Zhu et al. [35].

It is found that the gradient of the line in the low-stress regime becomes less prominent at higher calcium concentration. The coefficients of LMP for the AX50 and AX51 die-cast alloys are evaluated as 0.044 and 0.041, respectively.

The creep rupture life data for the Mg–Al–Ca alloy have been reported for the squeeze cast MRI153 (Mg–9Al–1Ca–0.7Zr–0.1Sr, in mass%) alloy at temperatures between 423 and 473 K by Zhu et al. [35]. The microstructure of the alloy exhibits a coarse dendritic α-Mg phase with the dendrite cell size of around 20 μm and the eutectic intermetallic phases in the interdendritic region, where the dendritic α-Mg phase is not fully covered by the eutectic intermetallic phases. Fig. 5 shows the correlation between the applied stress and the LMP value for the squeeze cast MRI153 alloy, in which the Larson–Miller constant is chosen as 20. All the creep rupture data are arranged by a two-stage linear relationship, as in the case for the AX52 die-cast alloy. The critical stress is detected at approximately 112 MPa, and the following equation is obtained in the low-stress regime for the alloy:

$$\sigma \text{ (MPa)} = 436 - 0.036\,\text{LMP}. \quad (3)$$

The LMP with C_{LM} = 20 is an efficient design parameter to evaluate the creep rupture life. Therefore, the stress–LMP plot can be utilized to predict the long-term creep rupture life for the heat resistant Mg–Al–Ca alloys irrespective of the method used for alloy production. Figs. 4 and 5 show that the creep rupture strength of the squeeze cast MRI153 alloy is comparable to that of the AX51 die-cast alloy, where the content of calcium for both alloys are similar to each other. A higher content of Al and the microaddition of Zr and Sr can improve the creep rupture strength; on the other hand, a lower coverage of the dendritic α-Mg phase by the eutectic intermetallic phases reduces the creep strength for the Mg–Al–Ca alloys [29].

4. Conclusions

Creep rupture tests were performed for three kinds of Mg–Al–Ca die-cast alloys at temperatures between 423 and 498 K, and the creep rupture lives were evaluated by using the Larson–Miller parameter (LMP). The value of LMP is uniquely described by the logarithm of the applied stress for the alloys, when the Larson–Miller constant is chosen as 20. It was found that the applied stress and the LMP value follow a linear relationship below the yield stress, which is utilized to predict the long-term creep rupture life for the alloys under a given condition of temperature and applied stress. The stress–LMP plot can be effective to predict the creep rupture life for the heat resistant Mg–Al–Ca alloys, irrespective of the method used for alloy production.

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