Transition of acceleration behavior and life time prediction of Mg-Al solution hardened alloys at around 0.6Tm

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Abstract. Creep characteristics and acceleration behavior in secondary creep of magnesium-aluminum binary solution hardened alloys are presented with numerical procedure proposed by authors. It is well known that the creep characteristics are mainly evaluated by minimum or steady state creep rate, which is evaluated from creep curves. Although, the shape of creep curves may vary depending on characteristics of materials and deformation conditions, the shape of creep curves are not always considered due to complexity of analysis. The minimum or steady-state creep rate reflects only a part of information of the creep curve, and the shape of the creep curve may differ, even the minimum or steady state creep rates show the same value. In this paper, authors propose simpler value that reflects shape of creep curves and acceleration of creep rates than that proposed previously. The application to magnesium-aluminum alloys, whose creep characteristics are reasonably understood, is represented. The stress dependence of the proposed parameter, changes at approximately the same transition stress of creep characteristics based on the stress and concentration dependence of the minimum creep rate. The proposed parameter and values, that are estimated at a strain near minimum creep rate appears, reconstruct a creep curve that agree well with that obtained experimentally. The possibility of precise life prediction by means of the proposed acceleration parameter is demonstrated, with comparison of the transition of Alloy-type to Metal-type creep behavior of solid solutions.

Introduction

It is well accepted that the creep characteristics of alloys are primarily determined by the minimum creep rate, $\dot{\varepsilon}_{\min}$ or the steady state creep rate, $\dot{\varepsilon}_s$. The Mukherjee-Bird-Dorn equation (1) is well known equation that links the creep rates as a function of the applied stress, temperature and grain size, and describes power law creep characteristics [1].

$$\dot{\varepsilon} = \frac{AD_0Gb}{kT}\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{G}\right)^n \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

Here, A, D_0, G, b, k and R are a constant, pre-exponential term of diffusion coefficient, shear modulus, the magnitude of Burgers vector, the Boltzmann's constant and the gas constant, respectively. The values T and σ are the absolute temperature and the applied stress which determine the creep conditions. The value, n, Q and p are the stress exponent, the apparent activation energy of creep and the grain size exponent, respectively, and characterize the creep behavior.

Typical solid solutions like Al-Mg(fcc) and Mg-Al(hcp) show reasonable agreement of the activation energy between that of creep and that for diffusion at 0.4-0.6T_m (T_m: the absolute melting temperature). When the activation energy of creep is similar to that for diffusion, the constant, A, includes concentration dependence of the creep rate, and can be written as a function of the solute concentration, as $A=A'N^{m}$. Here, A' is a constant, N is the solute concentration, and m is the concentration exponent. In coarse grained solid solutions, the grain size exponent, p, can be assumed to be zero. In that situation, the minimum creep rates or the steady-state creep rates can be described by the following equation (2).

$$\dot{\varepsilon} = A' \frac{DGb}{kT} N^{-m} \left(\frac{\sigma}{G} \right)^{n} \tag{2}$$

The stress exponent, n, and the concentration exponent, m, are the major characteristic value that describes creep characteristics of solid solution alloys.

It is well recognized that the power law creep behavior of solution strengthened alloys at high temperatures are divided into two classes, Alloy-type (Class-I) and Metal-type (Class-II) [2,3], based on the stress dependence and the concentration dependence of minimum or steady state creep rate[4-6]. Alloy-type behavior is appropriate to solid solutions, and Metal-type behavior is similar to the behavior of pure metals. Magnesium-aluminum solid solution alloys are one of the alloys that both the Alloy-type and Metal-type behaviors are observed. In this report, the analyses of acceleration behaviors are applied to the alloys. The creep characteristics of the alloys are presented in the next section.

The minimum or the steady-state creep rates are evaluated from individual creep curves, and are obtained at a constant temperature and constant stress. As the rates reflect only a part of deformation behavior at a condition and a part of information of a creep curve, the same creep rates can be determined with different creep curves with different shape of the curve. For more precise determination and description of creep behavior, not only the minimum creep rates and the time to failure, but also the shape of creep curves should be considered. Some methods of analysis of whole creep curves have been proposed [7,8], and improvements of the methods are also proposed [9,10]. One way of evaluation that reflects the shape of creep curve is analysis of acceleration behavior of the strain rate as a function of time or strain. The Omega-method is one way to evaluate change in strain rate in tertiary creep [8,11]. These methods, however, the minimum creep rates are evaluated indirectly from the parameters estimated from a whole creep curve.

In this paper, we propose a simpler parameter that reflects shape of creep curves in secondary creep, and compare with the creep behavior of the alloys whose creep characteristics have been determined. The stress dependence of the parameter is compared with creep characteristics evaluated based on the stress and concentration dependence of the minimum creep rates. Change in strain rates (acceleration) near minimum creep rates are quantitatively evaluated, and reconstructed creep curves are compared with original creep curves.

Experiments and creep behavior

Creep curves used for this analysis are obtained from experimental results, which are reported previously [4,5]. Materials used were hot extruded rods, extruded at 550-620K. Most basal planes were nearly parallel to the extruded direction of the rods. Main impurities were Zn, Fe and Mn. Table 1 shows the designation and composition of the alloys.

Table 1. Alloy designation and compositions.

Alloy	Al (mol%)
Mg-0.6Al	0.59
Mg-1Al	1.04
Mg-3Al	2.97

Specimens for tensile creep tests of the gage length of 20mm were machined from the rods, and were annealed in argon atmosphere at 800K for 7.2ks to obtain grain size of about 0.2mm. Constant true stress creep tests are conducted in air at 600K ($\approx 0.65T_m$). The applied stresses were parallel to the extruded direction. Elongation of specimens was monitored and recorded continuously, and the applied load was controlled to maintain the constant true stress.

Figure 1 shows an example of creep curves (strain as a function of time, and strain-rate as a function of time) of Mg-3Al solid solution alloy at 600K. Shapes of the creep curves were the normal type. Steady state was not distinctly observed under the conditions, and strain rate increases after the minimum strain rate at the beginning of the creep curve.

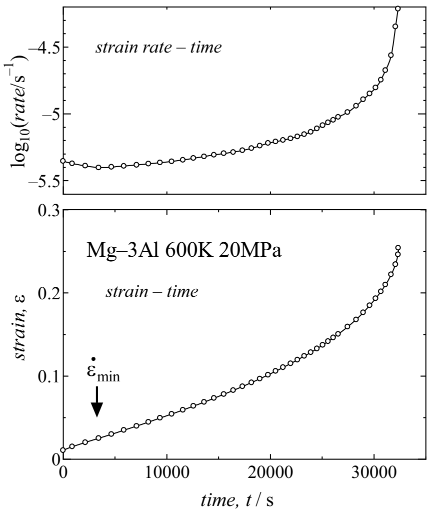

Figure 1. Example of creep curve (lower) and strain rate-time curve (upper) of Mg-Al alloy.

Figure 2 shows the stress dependence of the minimum creep rate of the alloys as a function of the applied stress at 600K. The stress exponent, *n*, increases with increasing the applied stress, and are 4 and 6 in lower and higher stress ranges, respectively. The change of the stress exponent is understood as the change of creep behavior from Alloy-type to Metal-type, similar to the transitions that were observed in many cubic solid solutions. The change in stress exponent occurs at the transient stress σ_t, that depends on the solute concentration. It is understood that change of creep characteristics from Alloy-type to Metal-type corresponds to the change of deformation mechanisms from viscous glide of dislocations to free-flight of dislocations [2]. The stress and concentration exponents of Mg-Al binary solid solutions are summarized in Table 2.

Table 2. Creep parameters of Mg-Al solid solution alloys at 600K.

Stress Region	Lower	Higher
Type of Behavior	Alloy	Metal
Stress exponent, *n*	4	6
Concentration exponent, *m*	1	2

In this report, the stress range where Alloy-type appears, *i.e.*, below σ_t, is designated as the lower stress region, and the stress range where Metal-type appears, *i.e.*, above σ_t, is designated as the higher stress range.

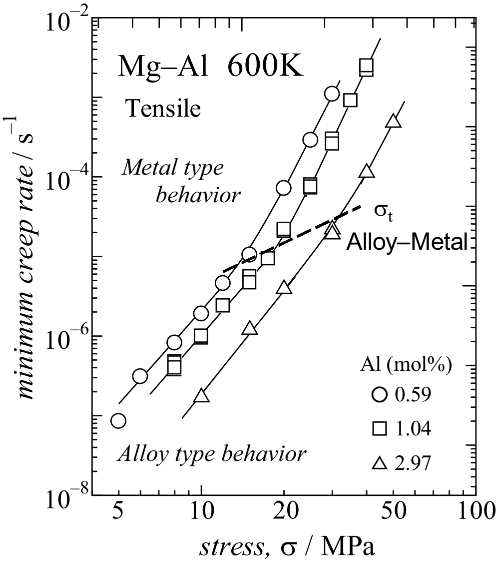

Figure 2. Stress dependence of minimum creep rate of Mg-3Al alloy.

Quantitative evaluation of acceleration behavior

Proposal of the characteristic value, α

We propose a simpler characteristic value, α, that reflects shape of creep curves and acceleration of strain rate in secondary creep, as it is defined by the following equation (3) [6].

$$\alpha = \frac{d^2}{d\varepsilon^2}\log_{10}\left(\dot{\varepsilon}/\mathrm{s}^{-1}\right)\Bigg|_{\varepsilon=\dot{\varepsilon}_{\min}} \qquad (3)$$

The α corresponds to the curvature of the common logarithm of strain rate as a function of strain. It is defined at a strain of minimum creep rate, $\varepsilon_{\min}$, at a time, $t_{\min}$. Because, it is the second order differential of strain, the values evaluated by means of simple finite differential vary and spread depending on the precision of calculation. We believe the major difficulties are caused by numerical difficulties of data analysis. To avoid the difficulty in evaluation of the differentiation, we applied the least square spline interpolation for calculation of strain rate, and related derivatives.

Figure 3 shows an example of strain-rate as a function of strain evaluated by means of simple finite differential (upper) and of least square spline fitting (lower).

Figure 4 shows the diagram of interpolation and evaluation of the second order derivative of the common logarithm of strain-rate as a function of strain, ε. First, strain-time creep curve is fitted to least square cubic spline, and strain rate as a derivative of creep curve is evaluated. Then, the common logarithm of the strain rate as a function of strain is fitted again to least square cubic spline.

Finally, the first and the second order derivatives of strain rate-strain function are evaluated, then the characteristic value, α, is defined at the condition corresponds to the minimum creep rate.

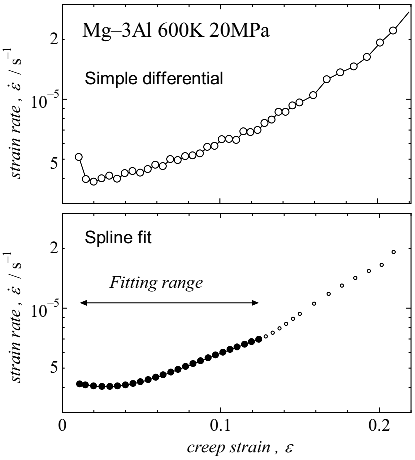

Figure 3. Example of difference of variation of derivatives between by simple finite differential (upper) and by least square fitting (lower).

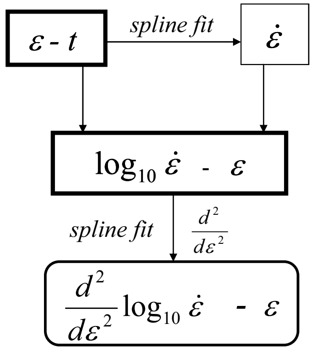

Figure 4. Schematic diagram of flow of numerical evaluation of derivatives.

Figure 5 shows an example of evaluation of α for alloys at the same applied stress. The characteristic value corresponds to the curvature of the figure are summarized in Table 3. It is evident that the shapes of the creep curves can be numerically evaluated by the characteristic value, α, and vary with alloys and deformation conditions.

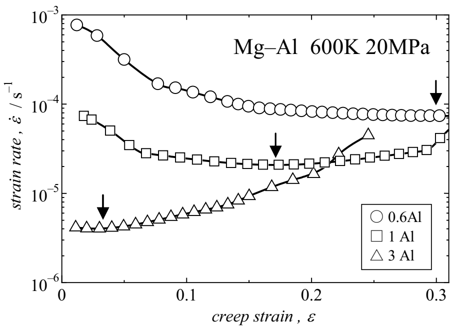

Figure 5 Example of common logarithm of strain-rate as a function of strain. Curvature of the plot at minimum creep rate corresponds to the characteristic value (Table 3).

Table 3. Evaluated parameter α for the alloys at 600K, 20MPa.

Alloy	α
Mg-0.6Al	15
Mg-1Al	33
Mg-3Al	70

Stress dependence of the characteristic value, α

Figure 6 shows the stress dependence of the characteristic value, α, as a function of the applied stress at 600K. The value, α, tend to increase with increasing solute concentration. At the stress corresponds to lower stress range, *i.e.* attributed to the Alloy-type with stress dependence and the concentration dependence of the minimum creep rate, show positive stress dependence. By contrast, at the higher stress range attributed to the Metal-type behavior, stress dependence looks different and has no or negative stress dependence. At around the transition stress of creep behavior from Alloy-type to Metal-type, the characteristic value, α, takes approximately maximum and the stress dependence changes. It shows that the shape of the creep curve depends on the applied stress. Moreover, it suggests that at the critical condition that corresponds to the change of rate controlling mechanism, the strain rate is more sensitive with deformation [6].

It is evident that the shape of creep curve depends on alloys and deformation condition and can be characterized by the proposed parameter, α, at minimum creep rate.

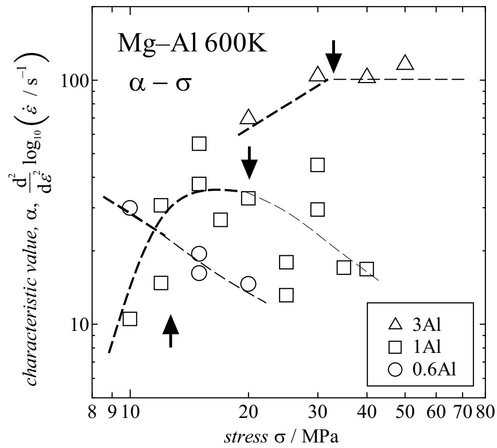

Figure 6 Stress dependence of the characteristic value, α. Arrows show the transition stress of the minimum creep rate from Alloy-type to Metal-type.

Reconstruction of creep curve with the characteristic value, α.

As the characteristic value, α, is defined as a curvature of the common logarithm of strain-rate as a function of strain, creep curve can be extrapolated and reconstructed with suitable initial conditions. The characteristic value, α, is defined at the minimum creep rate, and equation (3) gives common logarithm of strain rate, $\log \dot{\varepsilon}_{\min}$, as a function of strain, ε, as shown in equation (4).

$$\log \dot{\varepsilon}(\varepsilon) = \frac{\alpha}{2}(\varepsilon - \varepsilon_{\min})^2 + \log \dot{\varepsilon}_{\min} \quad (4)$$

Here, $\varepsilon_{\min}$ and $\dot{\varepsilon}_{\min}$ are the strain and strain rate at the minimum creep rate, evaluated experimentally from individual creep curves. Equation (4) can be solved numerically and gives strain at a given time, with suitable initial conditions at the minimum creep rate. Figure 7 shows examples of reconstruction of creep curves, obtained by numerical integration from equation (4) and values evaluated only near the minimum creep rate. The reconstructed creep curves agree well with the observed creep curve at the temperature and the applied stress. In figure 7(a), the minimum creep rate is observed at the beginning of the creep curve, and difference between original and reconstructed curves are small and almost agree with each other. At the conditions shown in figure 7, the time to failure are almost identical between that obtained experimentally and obtained by reconstruction.

The characteristic value defined at the minimum creep rates reflects shape of the whole creep curve and suggests possibility of application to precise life time evaluation of creep deformation.

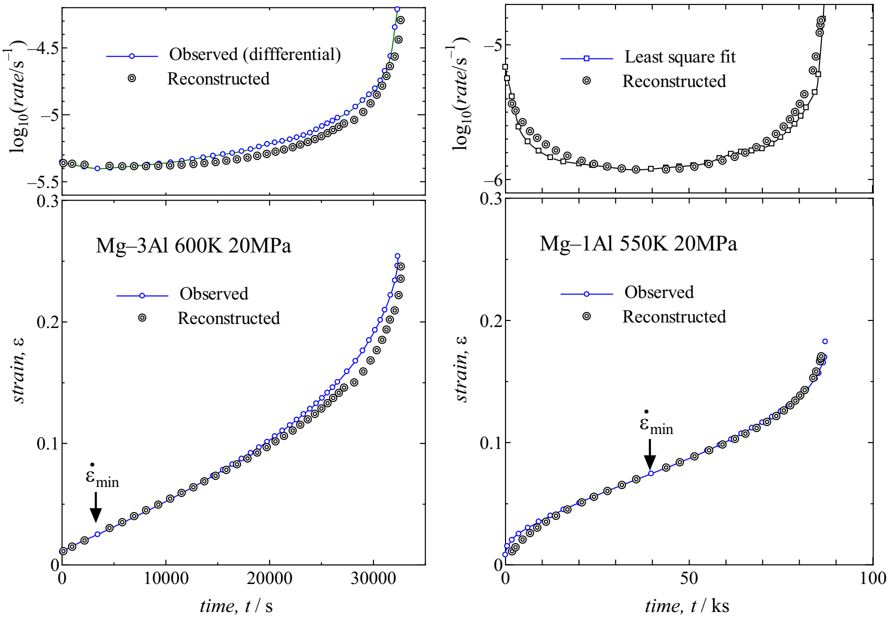

Figure 7. Examples of creep curves obtained experimentally and that reconstracted from acceleration parameter, α. (a: left) Mg-3Al, 600K 20MPa, (b: right) Mg-1Al, 550K 20MPa.

Conclusions

1. We propose characteristic value that reflects shape of a creep curve around minimum creep rate in secondary creep.
2. The proposed characteristic value corresponds to the curvature of common logarithm of strain rate as a function of strain. Least square spline technique improves accuracy of second and third order derivatives of strain and numerically illuminates change of strain rate and shape of creep curves.
3. The stress dependence of the proposed characteristic value, α, is different in Alloy-type creep regime and Metal-type creep regime in magnesium-aluminum solid solutions. The maximum value of the characteristic value, α, appear approximately at the transition stress from Alloy-type to Metal-type.
4. Creep curve can be reconstructed from the acceleration parameter, α, and values evaluated only near condition of minimum creep rates. The original creep curve and the reconstructed curves agree well with each other. The possibility of precise life time prediction by acceleration parameter, α, has been demonstrated.

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