Phenomenological approach to precise creep life prediction by means of quantitative evaluation of strain rate acceleration in secondary creep

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Abstract. A method of creep life prediction by means of Strain-Acceleration-Parameter (SAP), $\alpha$, is presented. The authors show that the shape of creep curve can be characterized by SAP that reflects magnitude of strain-rate change in secondary creep. The SAP-values, $\alpha$, are evaluated on magnesium-aluminium solution hardened alloys. Reconstruction of creep curves by combinations of SAP and minimum-creep rates are successfully performed, and the curves reasonably agree with experiments. The advantage of the proposed method is that the required parameters evaluated from individual creep curves are directly connected with the minimum creep rate. The predicted times-to-failure agree well with that obtained by experiments, and possibility of precise life time prediction by SAP is pronounced.

1. Introduction

It is widely accepted that creep behaviors are mainly evaluated by minimum or steady state creep rate. The important parameters are its stress dependence, grain size dependence and temperature dependence, and are characterized by the stress exponent, $n$, the grain size exponent, $p$, and the activation energy of creep, $Q_c$. One of the general forms of equations that describe steady-state or minimum strain rates is the equation proposed by Mukherjee, et al. [1]:

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

(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 $\sigma$ are the absolute temperature and the applied stress which determine the creep conditions, and $d$ is the grain size.

The minimum creep rates are treated as the most important parameter describing creep behavior. The minimum creep rates, however, are evaluated from just a part of creep curve, and the same minimum creep rates would be observed from creep curves whose shapes are different to each other. For more precise determination and description of creep behavior, not only the minimum creep rates, but also the shape of creep curves should be considered.
Many methods of analysis of whole creep curves have been proposed. For example, the theta projection [2], the Omega projection [3], and the improved methods [4-5] are well known. In these methods, however, the minimum creep rates are expressed indirectly from the parameters estimated from a creep curve. Because the minimum creep rates are treated as the most important parameter that represents creep curve, authors believe the minimum creep rate should be explicitly expressed as an independent parameter, and proposed one parameter that reflects the shape of a creep curve, that is declared independently on the minimum creep rates [6-7].

In this paper, changes of creep rate in secondary creep in magnesium-aluminum solution strengthened alloys are quantitatively evaluated by means of the parameter, and reconstructed creep curves by means of the parameters are shown [7]. The reconstructed creep curves show three stages of creep, and estimated time-to-failure agrees well with that obtained by experiments. The possibility of precise life prediction by evaluating strain rate acceleration in secondary creep is shown.

2. Quantitative evaluation of creep curve

2.1. Evaluation of strain-rate acceleration in secondary creep

Authors propose a characteristic value, Strain-Acceleration-Parameter (SAP), $\alpha$, that reflects shape of creep curves and reflects acceleration of strain rate in secondary creep [6-7]:

$$\alpha = \frac{d^2}{d\varepsilon^2} \log_{10} \left( \dot{\varepsilon} / \text{s}^{-1} \right) \bigg|_{\varepsilon = \varepsilon_{\text{min}}}$$

(2)

$\alpha$ corresponds to the curvature of the common logarithm of strain rate as a function of strain. The value is defined at a strain of minimum creep rate, $\varepsilon_{\text{min}}$, and at a time of minimum creep rate, $t_{\text{min}}$. 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. To avoid this difficulty, authors applied least square spline interpolation for calculation of strain rate and related derivatives.

2.2. Reconstruction of creep curve with the Strain-Acceleration-Parameter, $\alpha$

As the Strain-Acceleration-Parameter, $\alpha$, is defined as a curvature of the common logarithm of strain-rate as a function of strain, the creep curve can be extrapolated and reconstructed with suitable initial conditions. As $\alpha$ is defined at minimum creep rate, and conditions at minimum creep rate, i.e., strain and strain-rate are known, the common logarithm of strain rate, $\log \dot{\varepsilon}$, as a function of strain, $\varepsilon$, can be described as equation (3).

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

(3)

Here, $\varepsilon_{\text{min}}$ and $\dot{\varepsilon}_{\text{min}}$ are evaluated experimentally from individual creep curves. Equation (3) can be solved numerically giving the creep curve, $\varepsilon(t)$. Required values to reconstruct the whole creep curve are the SAP $\alpha$, the minimum strain rate $\dot{\varepsilon}_{\text{min}}$, the strain at minimum creep rate $\varepsilon_{\text{min}}$, and the time at minimum creep rate $t_{\text{min}}$. Three of these required four parameters directly correlate with a condition at the minimum creep rate.

3. Application to creep of magnesium-aluminium solid solution alloys

3.1. Creep behaviour of magnesium-aluminium solid solution alloys at 600K

Magnesium-aluminium solid solution alloys are typical solid solutions whose creep characteristics are divided into two classes termed Alloy-type (Class-I) and Metal-type (Class-II). In case of coarse grained solid solution alloys, the effect of grain size is negligibly small, but solute concentration affects creep rates. As the activation energy of creep is similar to that for diffusion at 600K, one can have modified equation (4) of equation (1).
\[ \dot{\varepsilon} = A' \frac{DGb}{kT} N^{-m} \left( \frac{\sigma}{G} \right)^n \]  

At 600K, Mg-Al solid solutions show transition from Alloy-type to Metal-type at around 20MPa, depending on solute concentration [8].

3.2. Evaluation of the Strain-Acceleration-Parameter (SAP), \( \alpha \)

Figure 1 shows examples of evaluation of SAP \( \alpha \). The value defined by equation (2) is evaluated by least square spline fitting of the common logarithm of strain rate as a function of strain at the minimum strain rate. The short vertical lines indicate strain at the minimum creep rate, and the curvatures of the lines are evaluated as shown on Table 1. The \( \alpha \), increases with increasing solute concentration. In the alloys, \( \alpha \), are reasonably evaluated both in the stress range of Alloy-type and Metal-type.

![Figure 1. Examples of common logarithm of strain-rate as a function of strain. Curvature at the minimum creep rate is SAP \( \alpha \). [7].](image)

![Table 1. Examples of the estimated value of \( \alpha \), for the alloys at 600K, 20MPa.](image)

| Alloy   | \( \alpha \) | Creep behaviour |
|---------|-------------|----------------|
| Mg-0.6Al| 15          | Metal-type     |
| Mg-1Al  | 33          | Metal-type     |
| Mg-3Al  | 70          | Alloy-type     |

3.3. Extrapolation and Reconstruction of creep curves

Figure 2 shows an example of reconstruction of creep curves, obtained by numerical integration of equation (3). The curves agree well with the experimental creep curves at the same temperature and the applied stress. At the conditions shown in Figure 2, the times to failure are almost identical in experiment and reconstruction. It is therefore, suggested that the SAP defined at the minimum creep rate reasonably reflects the shape of the whole creep curve. This means that time-to-failure can be predicted by values evaluated quantitatively in secondary creep. The SAP and three values related directly to the minimum creep rate represent the whole creep curve at a given temperature and stress.

3.4. Estimated time-to-failure by SAP \( \alpha \), and experiments

Figure 3 shows a comparison of the time-to-failure estimated by the numerical integration, and experiments. Under the conditions analyzed in this paper, only a limited number of curves show failure in true strain below 0.4. The experimental times-to-failure agree well with that extrapolated from the four values evaluated at a minimum creep rate.

In Mg-1Al alloy, the transition from Alloy-type to Metal-type appears at around 18MPa at 600K. The predicted time-to-failure agrees well with that obtained by experiments in both Alloy-type regime and Metal-type regime. It seems that the quantitative evaluation of creep curve by means of SAP has potential of general application for precise life time evaluation.
4. Conclusions

1. We propose Strain-Acceleration-Parameter (SAP), $\alpha$, which reflects the shape of a creep curve at a minimum creep rate in secondary creep. The SAP corresponds to the curvature of common logarithm of strain rate as a function of strain.

2. A creep curve can be reconstructed from SAP and three values evaluated at condition of minimum creep rate. The reconstructed creep curve and that obtained by experiments agree well with each other in magnesium-aluminum solution strengthened alloys at 600K.

3. Time-to-failure, extrapolated based on the values evaluated in secondary creep, agree well with experiments. The possibility of precise life time prediction by means of SAP, $\alpha$, has been demonstrated. The advantage of this method is required values are essentially simple, and the three of four are directly related to a minimum creep rate.

4. In general, micro structural changes during creep deformation cause strain rate change in a complex manner. Applications of this method by means of SAP to a wide variety of alloys are expected to validate the possibility of life prediction from secondary creep.

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