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Extrapolation of Creep Curve and Creep rate by Strain Acceleration Parameter in Al-Mg Solid Solution Alloys

Hiroyuki Sato[2*], Kosuke Omote[1], and Akira Sato[1]

[1]Graduate student, Graduate School of Science and Technology, Hirosaki University
3 Bunkyo, Hirosaki, 036-8561, JAPAN

[2]Department of Intelligent Machines and System Engineering,
Faculty of Science and Technology, Hirosaki University
3 Bunkyo, Hirosaki, 036-8561, JAPAN

e-mail: g4sato@cc.hirosaki-u.ac.jp (H. Sato)
3 Bunkyo, Hirosaki, 036-8561, JAPAN

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Abstract. It has been widely accepted that the creep characteristics at high temperatures are mainly evaluated by a minimum creep rate. Although, the shape of a creep curve may vary depending on deformation conditions, the apparent steady state or minimum creep rates can be the same. Thus, for detailed analysis and prediction of creep behavior, other values, which reflect the shape of each creep curve, should be considered. For this purpose, the authors have proposed Sato's strain-acceleration-parameter (Strain Acceleration and Transition Objective index, SATO-index) which reflects strain rate change during creep deformation. Based on the concept of the SATO-index, the entire creep curve can be represented by a small number of numerical parameters, and can be extrapolated from a part of the creep curve. In this paper, application of the SATO-index to creep curves of aluminum-magnesium solid solutions which show both the Alloy-type and Metal-type creep behavior is discussed. The creep curve can be extrapolated by the concept from the transient part of the creep curve, and the stress dependence of the extrapolated creep rates at the minimum creep rate agrees well with experiments. Efficiency of the concept of the SATO-index to creep experiments is presented.

Introduction

In creep curves obtained under a constant stress and temperature, it has been believed that the curve can be divided into three stages; transient, steady and acceleration creep. It is also widely accepted that creep behavior are mainly evaluated by minimum or steady-state creep rate. The important parameters are its stress dependence, grain size dependence and temperature dependence. Binary solid solution alloys such as aluminum-magnesium alloys are typical alloys for which the strain rate can be fitted by a power law. Well known general form of equations that describe steady-state creep rate is the equation proposed by Mukherjee, *et al.* [1]:

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

Here, A, D_0, G, b, k and R are; constant to be determined experimentally, frequency factor, 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, and d is the grain size. Creep behavior is represented by the stress exponent, n, the grain size exponent, p, and the activation energy of creep, Q_c.

When the grain size dependence is small and the activation energy of creep is not significantly different from the activation energy for diffusion, Eq. (1) is organized to Eq. (2).

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

Here, A', D, N and m are; a constant to be determined experimentally, the diffusion coefficient, the solute concentration and the concentration exponent, respectively. In this case, creep behavior is characterized by the concentration exponent, m, and the stress exponent, n. In power law creep of the solid solution alloys, it is well known that Alloy-type behavior of the stress exponent is about 3, and Metal-type behavior of the stress exponent is about 5, depending on deformation conditions and concentration [2-3]. This creep behavior is intended to be organized focusing on the steady-state or minimum creep rates, so the creep rate should be evaluated as accurate as possible. The minimum strain rate, however, could not be observed when the transient creep takes long time, or wrong creep rate could be evaluated by apparent steady-state. One should pay attention not only to the minimum creep rate but also to the shape of creep curve in transient stage, for detailed analysis of creep behavior. Authors have focused on strain rate change during creep as an evaluation index of creep behavior, and have proposed a way to extrapolate creep curve from a part of creep curve [4-5]. In this paper, we evaluate the transition creep curve of aluminum-magnesium solid solution alloy quantitatively, and extrapolate the entire creep curve based on the concept of SATO-index including imaginary minimum strain rate.

Experiments and measurements

1. Quantitative evaluations of creep curve. The minimum creep rates have been treated as the most important parameter to describe creep behavior. The minimum creep rates, however, are evaluated from just a part of the creep curve, and the same minimum creep rates would be observed from creep curves in which shapes are different. For more precise determination and description of creep behavior, one should consider not only the minimum or steady-state creep rate but also the shape of creep curve.

Many methods of analysis of the entire creep curve have been proposed. For example, the theta projection [6], the Omega projection [7], and the improved methods of the Omega [8-9] 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 the creep curve, the authors believe the minimum creep rate should be explicitly expressed as an independent parameter. Authors have proposed one parameter that reflects the shape of a creep curve, which is defined independently with the minimum creep rate [10-12]. The characteristic value, strain-acceleration-parameter (SATO-index), α, reflects the shape of a creep curve and reflects the magnitude of acceleration of the strain rate. It is defined as follows [4-5]:

$$\alpha = \frac{d^2}{d\varepsilon^2} \log\left(\dot{\varepsilon} / s^{-1}\right) \Big|_{\dot{\varepsilon}=\dot{\varepsilon}_{\min}} \tag{3}$$

The SATO-index, α, corresponds to the curvature of the common logarithm of strain rate as a function of strain. The value is defined at a strain of the minimum creep rate, $\dot{\varepsilon}_{\min}$, and the time at the minimum creep rate $t_{\min}$. Based on the definition of the value, the creep curve can be extrapolated and reconstructed with suitable initial conditions. The common logarithm of creep rate, $\log \dot{\varepsilon}$, as a function of strain, ε, can be described as Eq. (4).

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

Here, $\varepsilon_{\min}$ and $\dot{\varepsilon}_{\min}$ are evaluated experimentally from individual creep curves. Eq. (4) can be solved numerically and gives the creep curve, $\varepsilon(t)$. Required values to reconstruct the entire creep curve are; α, the minimum creep rate $\dot{\varepsilon}_{\min}$, the strain at the minimum creep rate $\varepsilon_{\min}$, and the time at the minimum creep rate $t_{\min}$. Three of these required four parameters directly correlate with values at the minimum creep rate. When the strain-rate can be represented by Eq. (4), the minimum creep rate $\dot{\varepsilon}_{\min}$ would be extrapolated from part of the creep curve, even when the minimum strain rate is not explicitly observed. Here, the extrapolated minimum creep rate is defined as "imaginary minimum strain rate (imaginary $\dot{\varepsilon}_{min}$)", and the definition is described in the following section.

2. Strain range for evaluation of SATO-index. **Fig.1** shows an example of a diagram in the strain range used in the evaluation of the strain-acceleration-parameter, *i.e.*, the SATO-index. The imaginary minimum strain rate represents the value at the vertices of the approximate curve fitted by Eq. (4).

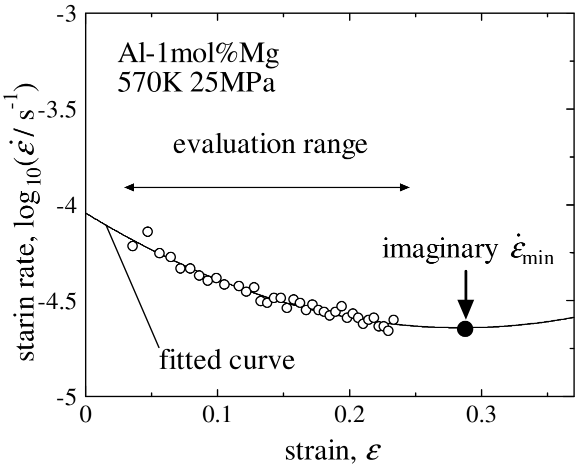

Fig.1. An example of diagram of the strain range used in the evaluation of strain-acceleration-parameter (Sato-index) and imaginary minimum strain rate.

3. Application to creep of an aluminum-magnesium solid solution alloy. Creep curves subjected to the current analysis are creep curves obtained by constant stress creep tests of Al-1mol%Mg solid solution alloy in air at 4~35MPa at 570K [10]. The grain size is about 0.2mm. The evaluation range used for the strain-acceleration-parameter (SATO-index), α, is in the strain and time range of transient creep. **Fig. 2** shows one of an example of a creep curve used for the analysis.

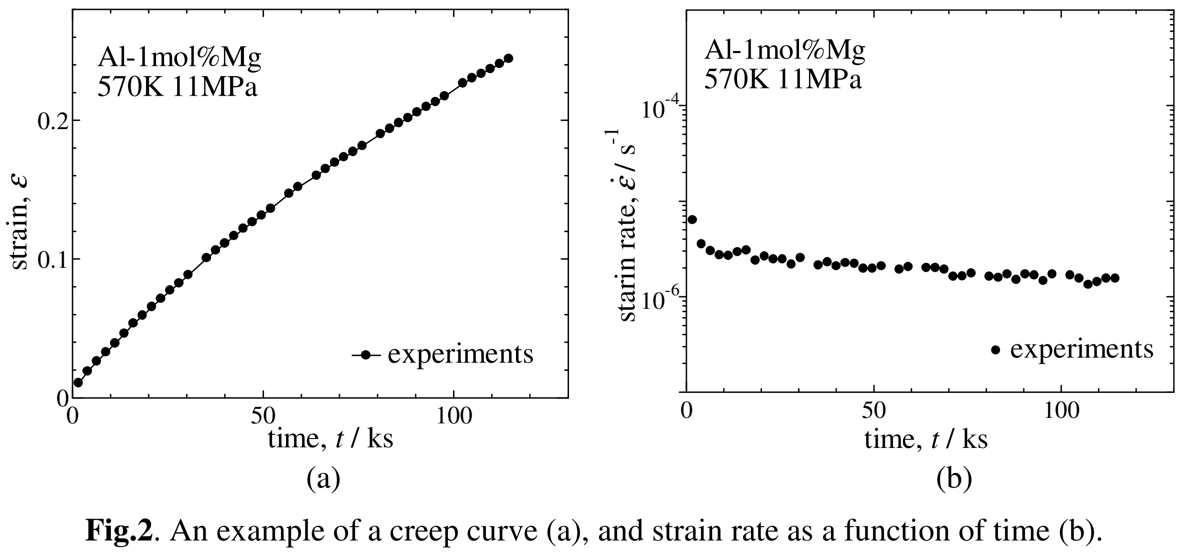

Fig.2. An example of a creep curve (a), and strain rate as a function of time (b).

Results

1. Stress dependence of the SATO-index. **Fig.3** shows the relationship between the strain rate and the strain obtained by experiments in Al-1mol%Mg solid solution alloy at 570K. Evaluated values of the strain-acceleration-parameter, SATO-index, α, are also shown on the figure. The stress dependence of the value is plotted as shown on **Fig.4**. The value, α, depends on the applied stress, and is larger at the lower and higher stresses. In addition, the value is almost the same at the stress range of 8~16MPa. **Fig.5** shows the stress dependence of the imaginary minimum creep rate as a function of the applied stress. The stress exponent changes from 3.2 to 6.2 at about 25MPa. The transition is similar to that of the deformation mechanism from Alloy-type to Metal-type [2-3].

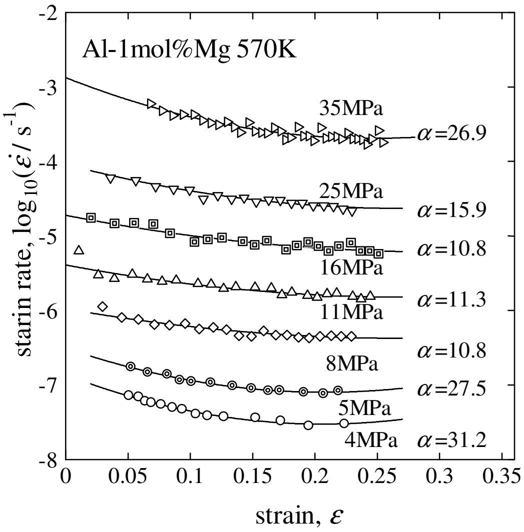

Fig.3. The relationship between strain rate and strain in Al-1mol%Mg solid solution alloys at 570 K and the value of the strain-acceleration-parameter, *i.e.*, the SATO-index, α.

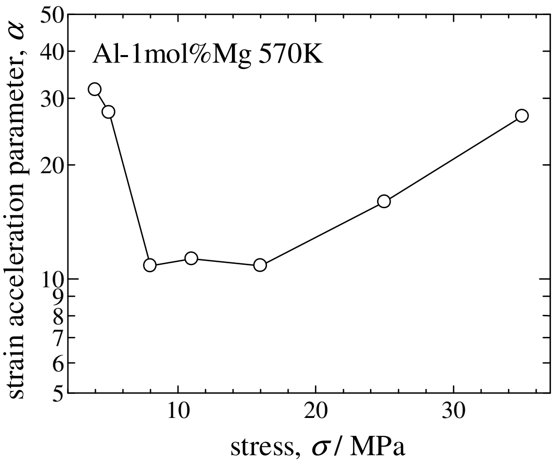

Fig.4. Stress dependence of the strain-acceleration-parameter, SATO-index, α.

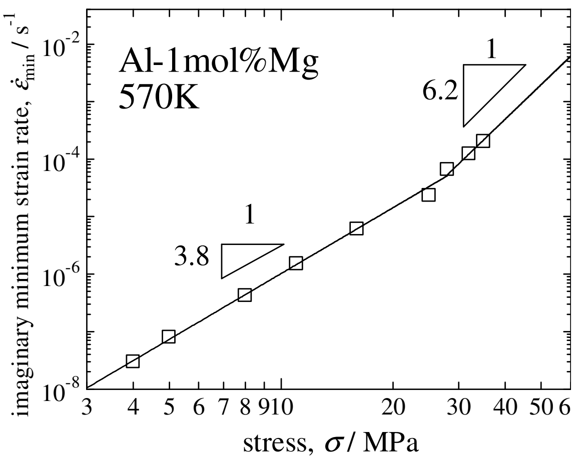

Fig.5. Stress dependence of the imaginary minimum strain rate.

2. Extrapolation of the creep curve. **Fig.6** shows an example of the extrapolation and reconstruction of the entire creep curve obtained by numerical integration of Eq. (4). The extrapolated creep curve agrees well with the experiment. Even when the minimum creep rate is not observed experimentally, the extrapolated creep curve agrees well with the experiment. This result suggests that creep behavior of solid solution alloys can be predicted to some extent from the short creep test. **Fig.7** shows the stress dependence of the predicted time to failure. Predicted time to failure has a power-law relationship when the time to failure is evaluated from transient creep by the SATO-index, and shows the transient in slope at 25MPa.

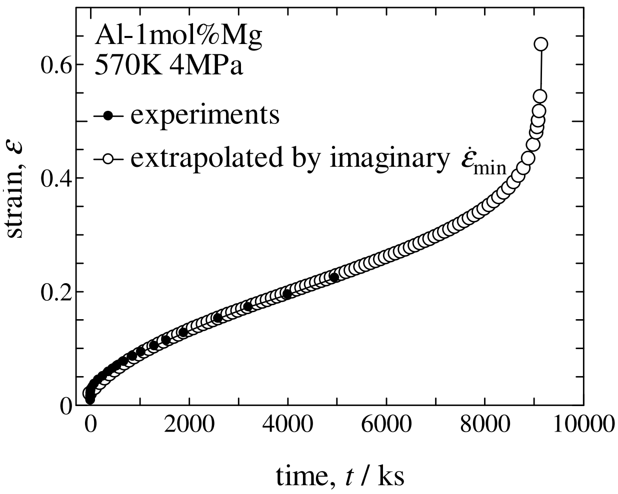

Fig.6. Extrapolated creep curve obtained by imaginary minimum creep rate.

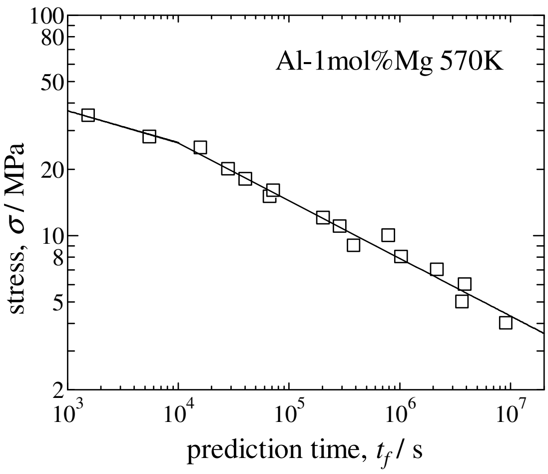

Fig.7. Prediction time to failure of extrapolated creep curves.

Discussion

In the present investigation, it is confirmed that it is possible to extrapolate and reconstruct a creep curve from the transient creep in an aluminum-magnesium solid solution alloy without explicit appearance of the minimum creep rate. The imaginary minimum creep rate can be extrapolated by evaluating the SATO-index.

The value of the SATO-index, α, is lower in the stress range from 9 to 15MPa. The stress range corresponds to the range where the Alloy-type behavior appears at the temperature [12]. The value increases both in the high stress and low stress regions, where the Metal-type behavior appears. The SATO-index reflects stability of the strain rate during creep and shows that transient creep appears significantly in Metal-type creep conditions. The stress exponent increases from 3.8 to 6.2 at about 25MPa and the stress roughly agrees with that of the transient stress from Alloy-type to Metal-type creep. It is considered that the shape of the creep curve depends on deformation mechanisms. Not only the steady state or minimum creep rate, creep behavior in transition creep changes depending on deformation mechanisms.

As for the prediction of creep life by an extrapolated creep curve, power-law relations between time to failure and the applied stress are obtained in wide stress ranges. This relationship appears in the magnesium-aluminum solid solution alloy as well, and time to failure is predictable [3]. It can be said that time to failure can be predicted from a part of the creep curve in some solid solutions.

Conclusion

1. The minimum creep rate and the time to failure are extrapolated by the concept of strain-acceleration-parameter, the SATO-index in the Al-Mg solid solution alloy. With introducing an imaginary minimum creep rate, prediction and extrapolation of the creep curve become possible from the creep curve in transient stage.
2. The creep curve can be extrapolated from a part of the creep curve, and time to failure can also be predicted from the extrapolated creep curve.
3. The strain-acceleration-parameter, the SATO-index shows different stress dependence depending on the stress range. The transition corresponds to change of deformation mechanisms and of deformation behavior. The strain-rate change during deformation is stable in the stress range where Alloy-type appears, and the rate controlling mechanism is considered to be viscous glide of dislocations.

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References

[1] A.K. Mukherjee, *et al.*: *The Interaction between Dislocations and Point Defects*, Vol. II, Part III, ed. by B.L. Eyre, Atomic Energy Authority, Harwell, UK, (1968), 422-495.

[2] H. Oikawa, H. Sato and K. Maruyama, Materials Science and Engineering, 75(1985), 21-28.

[3] H. Sato and H. Oikawa, Scripta Metall., 22(1988), 87-92.

[4] H. Sato, K. Fujita: JILM60 (2010), 353-5.

[5] H. Sato, T. Miyano: ICSMA-15 Journal of Physics: Conference Series 240 (2010) 012089

[6] R.W. Evans, *et. al.*:, *Recent Advances in Creep and Fracture of Engineering Materials and Structures*, Ed. by B. Wilshire and D.R.J. Owen, Pineridge Press, U.K., (1982), p135

[7] M. Prager: *Strength of Materials*, Eds. by H. Oikawa, *et. al*., JIM, (1984), 571-574.

[8] K. Maruyama and H. Oikawa: J. Pressure Vessel Tech., 109, (1987), 142-146

[9] K. Maruyama, *et. al.*: ISIJ International, 37 (1997), 419-423.

[10] H. Sato: Suppl.Proc, Vol.3, 137th Annual Meeting & Exhibition, TMS2008, (2008), 199-204.

[11] H. Sato: Multiple Approach to Fracture of Materials, Composite and Structures, 17th European

[12] Hiroyuki Sato et al., Key Engineering Materials, 592-593(2013), 606, DOI 10.4028/ www.scientific.net/ KEM.592-593.606