CREEP STRENGTH AROUND 600K OF TWO TERMINAL PHASES IN Al-Mg BINARY SYSTEM

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ABSTRACT Creep strength of two terminal phases of aluminum-magnesium binary system, *i.e.*, Al-Mg and Mg-Al, around 600K are discussed. Stress and concentration exponents vary depending on the creep conditions, so that creep characteristics are classified into regions in both alloys. Although both terminal phases show changes of creep characteristics from Alloy-type to Metal-type, and the deformation mechanisms are considered as the same in the alloys, observed creep rates are obviously different at the same applied stress. In this report, normalized creep strengths in regions of both terminal alloys are compared with each other, and relative fundamental strengths of the terminal alloys in aluminum-magnesium system are presented.

Keywords *solution hardening, normalized strength, high temperature characteristics, diffusion controlled creep, cubic and hexagonal alloys*

1.INTRODUCTION

Aluminum-magnesium binary system composes two terminal phases of solid solution. The size misfit parameters of aluminum and magnesium in each phase are about 0.1 and the phases are strengthened mainly by the size effect. In both terminal phases, maximum solubility of solute and the melting points are not so much different between phases and are about 5~7mol% and 920~930K, respectively. At 600K, the homologous temperatures are about $0.6T_m$ (T_m: the melting temperature), so that high temperature creep proceeds in both terminal phases.

It is well recognized that the creep behavior of cubic solid solutions can be divided basically into two classes, type-M(Metal-type) and type-A(Alloy-type), and the deformation mechanisms in both classes are reasonably understood[1]. Cubic aluminum-magnesium solid solution is one of the typical solid solutions which show both types of creep behavior and hcp magnesium-aluminum solid solutions also show the similar behavior[2-5]. In these solid solutions, steady-state or minimum-creep rate, $\dot{\varepsilon}$, is described by the power low as following Dorn-type equation (1).

$$\dot{\varepsilon} = A' \frac{Gb}{kT} N^{-m} \left(\frac{\sigma}{G} \right)^n \exp\left(-\frac{Q_c}{RT} \right) \qquad (1)$$

Here, A', G, b, k and R are a numerical constant, the shear modulus, the magnitude of Burgers-vector, the Boltzmann's constant and the gas constant, respectively. The values T, N and σ are the absolute temperature, the solute concentration and the applied stress which determine the creep conditions. The value m, n and Q_c characterize the creep behavior and are the concentration exponent, the stress exponent and the apparent activation energy of creep, respectively. These values are determined experimentally. In both behavior, Alloy-type and Metal-type, the apparent activation energy of creep Q_c is close to that for inter-diffusion or self-diffusion. Under conditions where the Alloy-type appears, creep rate is controlled by dragging of solute cloud formed around a moving dislocation, while the nonconservative motion of dislocations control strain rates under

conditions where Metal-type appears.

In aluminum-magnesium solid solutions, creep characteristics depend on deformation conditions in complex manners, but it has been found that Al-(0.3~3)mol%Mg solid solutions show the Alloy-type behavior under bounded stress range at 600K. The bounding conditions depend on temperature and solute concentration [1-2]. Theoretical prediction of the behavior has also been performed[6].

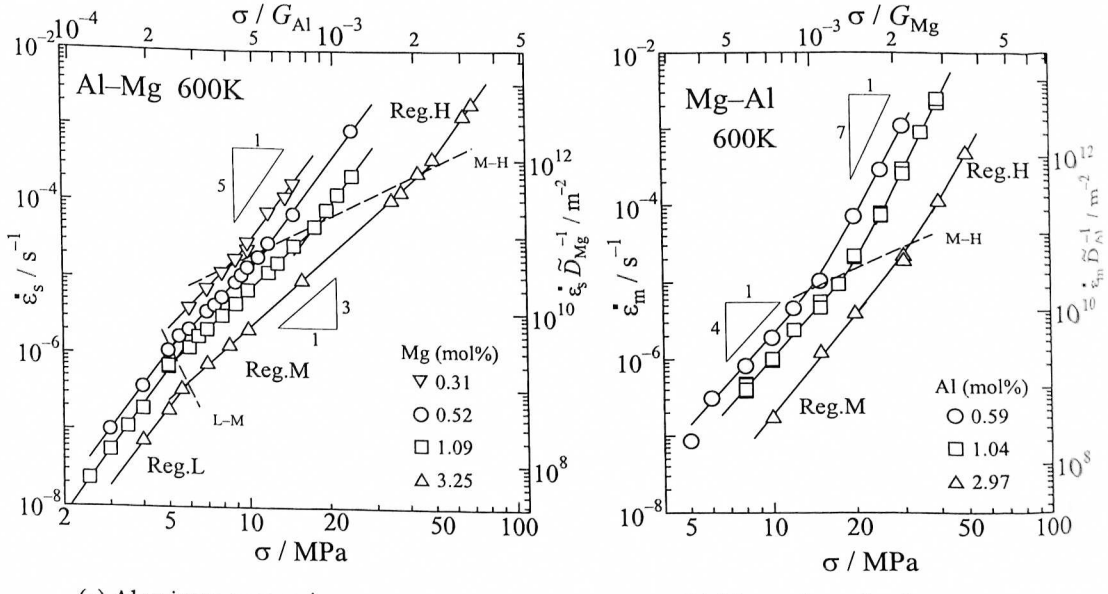
In magnesium based solid solutions, limited number of studies have been reported and the creep characteristics have not been widely investigated. Magnesium-aluminum solid solution alloy is one of hcp solution hardened alloys which creep behavior has been investigated.

Present report supplies information of creep characteristics of the two terminal phases which show the Alloy-type creep behavior, and relative creep strength between the phases are discussed by means of normalized creep rate and normalized stress.

2.CREEP BEHAVIOR OF TWO TERMINAL PHASES

2.1 Aluminum-magnesium solid solution

Creep parameters appear in equation (1) are summarized in Table 1. Figure 1(a) shows the steady-state creep rates of aluminum-magnesium solid solutions as a function of the applied stress σ. Data points are taken from references[2,7]. Grain sizes of the alloys were 0.3~0.4mm. Around 600K, the apparent activation energy of creep Q_c of the alloys depends on the applied stress and is obviously larger than that for diffusion in region L, while it is similar to that for diffusion in region M and H. In region M, the rate controlling mechanism of the alloys is considered to be the dragging of solute atoms, so that the normalized creep rate by the inter-diffusion coefficient of magnesium in aluminum $\tilde{D}_{Mg}$ is also shown in figure 1(a), together with the normalized applied stress by shear modulus G_{Al} at the temperature. Here, the diffusion coefficient and the average shear modulus used are evaluated as $3.7\times10^{-16}m^2s^{-1}$ and 21.34GPa, respectively, based on references[8-10]. It can be clearly seen that the stress range where the Alloy-type behavior appears



(a) Aluminum-magnesium (b) Magnesium-aluminum

Figure 1. Strain rate as a function of the applied stress. Normalized strain rate by diffusion coefficient and normalized stress are also shown.

become wider with increasing the magnesium concentration. The upper bounding stress where creep behavior changes from Alloy-type to Metal-type, strongly depends on the solute concentration N_{Mg}, while the lower bound stress is less affected. Typical concentration dependence of the creep rate is shown in figure 2. The concentration exponent m becomes larger in Region H.

Table 1. Creep parameters of Al-Mg solid solution alloys at 600K

Region	L	M	H
Type of Behavior	(Metal)*	Alloy	Metal
Stress exponent, n	5	3	5
Concentration exponent, m	1	1	2
Activation energy, Q_c	$Q_c > Q_D$	$Q_c \approx Q_{\tilde{D}}$	$Q_c \approx Q_{Dself}$

* Creep behavior in this stress range is not the same as in ordinal Metal-type behavior. The rate-controlling mechanism in this region is not yet clear so that the behavior is classified as Metal-type tentatively.

2.2 Magnesium-aluminum solid solution

Figure 1(b) shows the minimum creep rate as a function of the applied stress. Data are taken from previous reports[4,5]. Materials used were machined from hot-extruded rods and had the grain size of about 0.2mm. The inter-diffusion coefficient and the shear modulus used are the same with that used by Vagarali[3], and are $4.3 \times 10^{-16} m^2 s^{-1}$ and 14.04GPa, respectively. It is evident that two power-law stress regions can be recognized in each alloy. Table 2 summarizes the creep parameters obtained under conditions examined, and one can find that the creep characteristics are basically similar to that of aluminum-magnesium solid solutions, although the stress exponent is slightly larger. The effects of concentration on creep rates are shown in figure 2. Around 600K, the apparent activation energy of creep reported previously[5] is slightly larger than that for inter- or self-diffusion but the value reasonably agrees with the value reported earlier for Mg-0.8%Al solid solution[3].

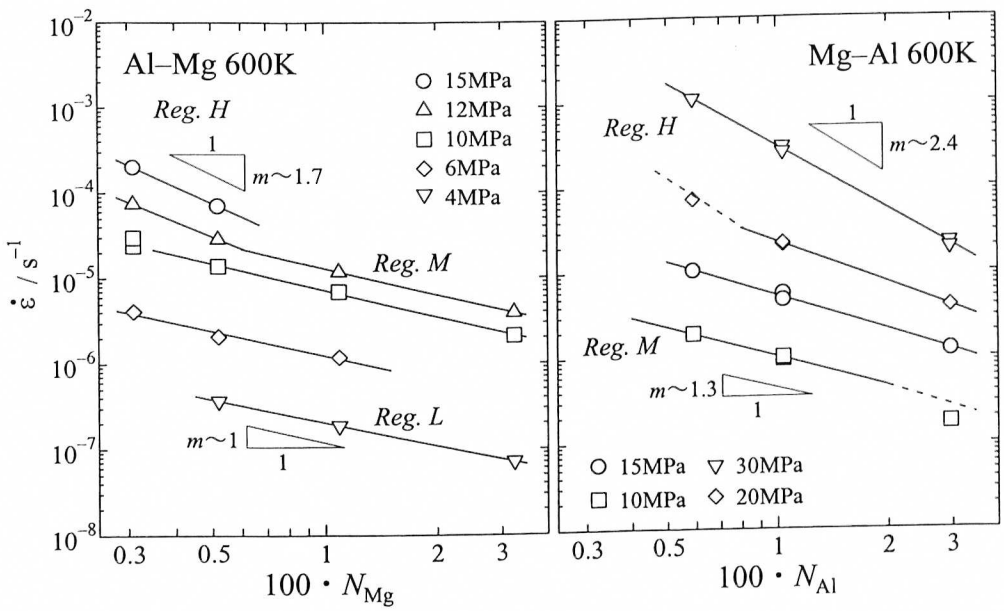


Figure 2. Example of the concentration dependence of the strain rate in both terminal solid solutions.

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

Region	M	H
Type of Behavior	Alloy	Metal
Stress exponent, n	4	6~7
Concentration exponent, m	1	2
Activation energy, Q_c	$Q_{\tilde{D}}, Q_D$	

2.3 Transition behavior from Alloy-type to Metal-type

Under the stress range described above, Alloy-type behavior is observed in both terminal alloys at the region M. The region M is bounded by the transition stress, $\sigma_{L\text{-}M}$ and $\sigma_{M\text{-}H}$, but no obvious lower-bound stress $\sigma_{L\text{-}M}$ has been observed in magnesium-aluminum alloys. The transition stresses between regions are illustrated in figure 3, as a function of the concentration in both terminal alloys. Solid lines show the lower and the upper bound stress where Alloy-type appears in aluminum-magnesium alloys, and dash-and-doted lines show the upper bound stress in magnesium-aluminum solid solutions. The upper-transition stress $\sigma_{M\text{-}H}$ increases linearly with increasing solute concentration in both alloys and the slope is almost the same. In magnesium-aluminum solid solutions, the transition from region M to H proceeds gradually with increasing stress[4,5], so that the transition stress is defined as the intercept stress of rate equations in region M and region H obtained experimentally. This transition from region M to H is understood as the breakaway of dislocation from solute atmosphere.

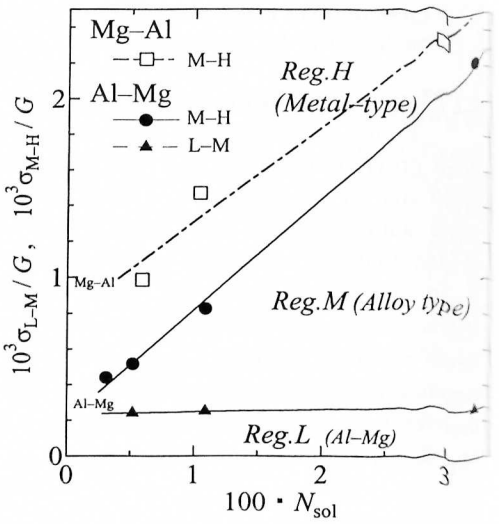


Figure 3. Transition conditions between regions in both terminal solid solutions.

3.DISCUSSION

3.1 Normalized rate equation

As described previous sections, the strain rate is described by the power-law formed as equation (1). Around at 600K, the apparent activation energies of creep take similar value with that for diffusion in both terminal phase alloys. Thus, the equation (1) is formed as equation (2).

$$\frac{\dot{\varepsilon}kT}{DGb} = AN^{-m}\left(\frac{\sigma}{G}\right)^n \qquad (2)$$

Here, D is the diffusion coefficient including the exponential term. The value, D, is the inter-diffusion coefficient, $\tilde{D}$, of the solute when the rate-controlling process is dragging of solute atoms around a moving dislocation, while is the self-diffusion coefficient, D_{self}, when nonconservative motion of dislocations control the creep rate. The values, G, D and b, depend on alloys and temperature, so that the left-hand nondimensional term $\dot{\varepsilon}kT/DGb$ is defined as the normalized creep rate. This equation has the similar form with that proposed by Mukherjee[11], but the term of solute concentration is included instead of the term of grain size.

3.2 Relative strength in both terminal phases

Figure 4 shows the nondimensional normalized strain rates as a function of the normalized applied stress in both terminal phases. For the inter- and self-diffusion coefficient in the alloys are close to each other in the alloys, inter-diffusion coefficients are used here. Strain rates of aluminum-magnesium solid solutions are about two orders higher than that of magnesium-aluminum solid solutions at region M where the Alloy-type appears. As shown in figure 4, the transition from region M to H (Alloy-type to Metal-type) occurs at the normalized strain rate around 10^{-10}, independent of phases. Phenomenological points of view, the normalized stress could be shifted with each other to get unified master curve.

Typical examples of concentration dependence of the normalized creep rate are shown in figure 5. Curves are drawn based on the experimental results and on inter or extrapolated values at the same normalized stresses. Marks show the points obtained experimentally. At the same normalized strain rate, the normalized stresses in aluminum-magnesium alloys are less than the half of that of magnesium-aluminum.

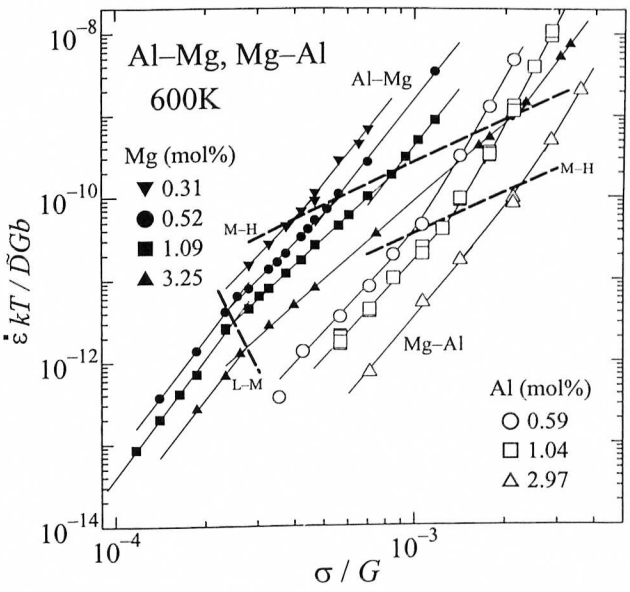


Figure 4. Normalized strain rate as a function of the normalized applied stress in both terminal solid solutions.

When dislocations move viscously in region M, strain-rates can be represented by the Orowan's equation $\dot{\varepsilon} = \phi\rho_m b\bar{\upsilon}$. Here ϕ is the geometrical factor, ρ_m is the mobile dislocation density and $\bar{\upsilon}$ is the mean dislocation velocity which is proportional to the mean effective stress, $\bar{\tau}^*$. The mean effective stress is connected with mean internal stress, $\bar{\sigma}_i$, as $\bar{\tau}^* = \phi(\sigma - \bar{\sigma}_i)$, thus the strain rate is described by the equation (3).

$$\dot{\varepsilon} = \phi^2\rho_m bB(\sigma - \bar{\sigma}_i) \qquad (3)$$

Here, B is the mobility of dislocations and the mean internal stress $\bar{\sigma}_i$ has a square-root proportionality with a dislocation density ρ, *i.e.*, $\bar{\sigma}_i = \alpha\phi^{-1}Gb\sqrt{\rho}$. The alpha is a numerical constant. Thus, the normalized strain rate is described as a function of dislocation density as

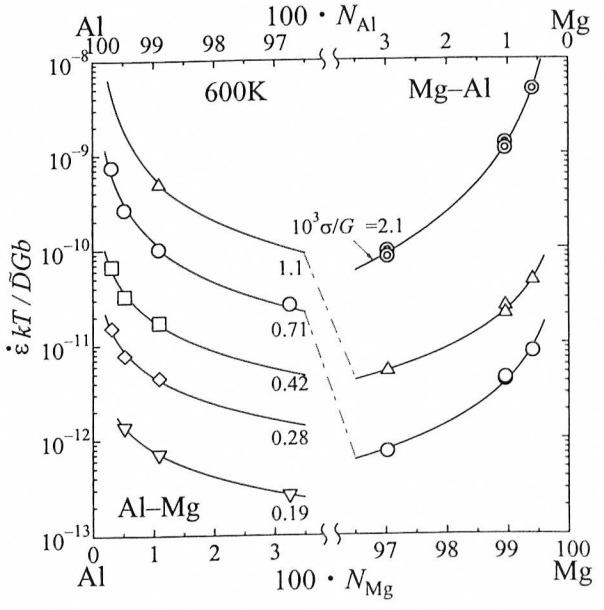


Figure 5. Effect of the solute concentration on the normalized strain rate in both terminal phases.

following equation (4).

$$\frac{\dot{\varepsilon}kT}{Gb} = \phi^2 kT\rho_m B\left(\frac{\sigma}{G} - \frac{\alpha b}{\phi}\sqrt{\rho}\right) \qquad (4)$$

The equation (4) suggests that under constant normalized stress, the normalized strain rate depends on both dislocation density and the mobility. TEM observations in aluminum-magnesium solid solutions show that the dislocation density depends only on the applied stress and that no systematic dependence on temperature nor solute concentration[9,12]. Thus, the concentration dependence of the normalized strain rate under constant normalized stress is attributed to the change in the mobility. Huge difference between two terminal phases in the normalized strain rate at the same normalized stress may be attributed to the difference in dislocation density and related mean internal stress. Although quantitative information is still lacking, it seems reasonable that the average internal stress is higher in magnesium-aluminum solid solutions than aluminum-magnesium solid solutions, because hcp system has limited number of primary slip systems and large hardening rate is expected.

SUMMARY

(1) Creep strengths at 600K in both terminal phases are different at the same normalized stress, and the creep rate is about two-orders higher in aluminum-magnesium than that of magnesium-aluminum solid solution.

(2) Transition from Alloy-type to Metal-type occurs at the normalized strain-rate of about 10^{-10}, independent on phases. It is considered that the difference of creep strength between two phases is coursed by difference of the mean internal stress in both phases.

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