EFFECTS OF SOLUTE CONCENTRATION ON CREEP CHARACTERISTICS OF SOLUTION HARDENED Al-Mg ALLOYS AT 600K

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Abstract

Creep characteristics of Al-Mg solid solution alloys whose concentration vary from a dilute range to near the solubility limit are shown. Stress exponent and concentration exponent vary depending on creep condition and creep characteristics are classified into four regions. Type-A behavior appears in a bounded range and disappears in low-concentration alloys. Concentration dependence in the type-A range is affected by the concentration and becomes smaller near the solubility limit. The change in the effect of solute concentration in type-A behavior is attributed to the change in concentration dependence of dislocation mobility.

Introduction

Creep behavior of solution hardened alloys have been investigated extensively and the power-law creep characteristics are traditionally classified into two classes, termed type-A (Alloy type, class I) and type-M (Metal type, class II). Aluminum-magnesium solid solutions are typical binary alloys which show both type-A and type-M behaviors. It has been experimentally shown that the types of creep behavior of Al-Mg alloys depend on the applied stress and that type-A creep behavior appears under a bounded stress range at temperatures about $0.6T$m (Tm: the melting temperature)[1,2].

In the power-law creep range, the steady-state or minimum creep rate is expressed experimentally by the following Dorn-type equation(1).

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

Here, A', G, b, k and R are the numerical constant, the shear modulus, the magnitude of Burgers vector, the Boltzmann's constant and the gas constant, respectively. The values, N, σ and T are the solute concentration, the applied stress and the temperature, respectively, that determine the creep condition. The values, m, n and Qc are constants that characterize creep behavior, and called the concentration exponent, the stress exponent and the apparent activation energy of creep, respectively. At a temperature, equation (1) can be simplified as $\dot{\varepsilon} = A'' \sigma^{n} N^{-m}$ and creep characteristics are represented by the stress exponent n and the

concentration exponent m.

In cubic solid solutions, such as Al-Mg solid solutions, the creep characteristics change with applied stress. The stress exponent changes from 5 to 3, and again to 5 with increasing the applied stress. In the stress range where the stress exponent is about 3, the apparent activation energy of creep is close to that for impurity diffusion and the creep behavior is termed type-A. In this stress range, the rate controlling process has been reasonably understood as a glide of dislocations which are surrounded by the solute atmosphere. In the lower and the higher stress ranges, the creep characteristics are similar to those of pure metals and termed type-M. The upper and the lower bound stresses of the region where the type-A behavior appears, had been determined experimentally[3]. The upper bound stress depends on the solute concentration so that the stress range where type-A behavior appears becomes narrower as decreasing the concentration. It has been suggested that the type-A behavior disappears as decreasing the solute concentration less than 0.3mol% on the bases of experimental results. It is, however, still not yet clear whether the type-A behavior disappear actually in low-concentration alloys or not.

In this report, the steady-state creep characteristics of Al-Mg solid solution alloys whose concentration ranges from a dilute concentration to the concentration near the solubility limit are presented. The effect of solute concentration on the lower bound concentration of Alloy-type behavior is shown and is discussed in terms of to the size-misfit-parameter. The concentration effect on creep rate at a higher concentration range is discussed in terms of the mobility of dislocations which are surrounded by the solute atmosphere[4].

Creep Behavior of Al-Mg Solid Solution Alloys

Figure 1 shows the steady-state creep rate of polycrystalline Al-Mg solid solution alloys as a function of applied stress. All data were obtained by tensile creep test performed at 600K in air.
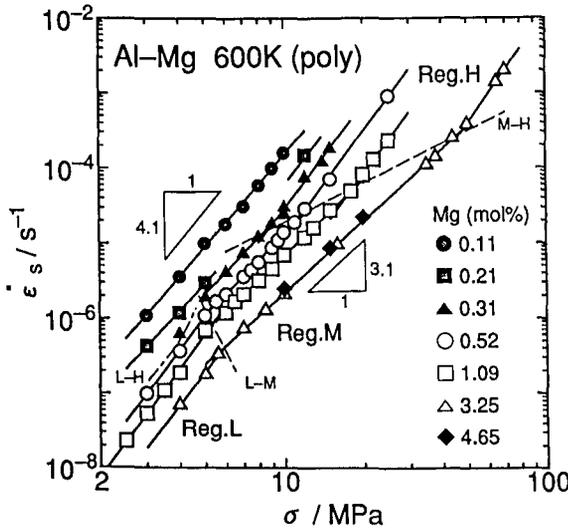

Figure 1. The steady-state creep rate of Al-Mg solid solution alloys at 600K as a function of applied stress.

Main impurities in the materials were silicon and copper, but the concentrations of these impurities are negligibly small (<0.008mass%) comparing with that of alloying element. The grain sizes of the specimens were about 0.3~0.6mm in all samples. The data shown by open marks are those reported previously[3]. Creep characteristics are classified into regions characterized on the basis of the stress exponent.

Regions in Al-Mg Solid solutions

Alloys can be grouped into two categories based on the stress-dependence of stress exponent. One is a low-concentration alloy (Al-0.1mol%Mg) that show no obvious change in the stress exponent under the examined stress range. The others are high-concentration alloys (Al-(0.3-3)mol%Mg) which show changes in stress exponent with the applied stress and the stress region of those alloys can be divided into three regions (Regions L, M and H). The stress exponents are almost the same in all alloys in each stress range. The region M, where the stress exponent is about 3, is not observed in the low-concentration alloy.

The concentration exponent has been reported as almost unity in region L and M, while it is lager than unity in region H[3]. The concentration exponent depends not only on the applied stress but also on the solute concentration itself. Figure 2(a) shows the concentration dependence of the steady-state creep rate as a function of the solute concentration at 10MPa. The concentration exponent changes at 0.4mol%Mg from 1.7 to unity as increasing solute concentration. The concentration dependence of the creep rate becomes smaller above 3mol%. The stress exponent of Al-3mol%Mg is almost the same as that of Al-5mol%Mg, and the steady-state creep rate is also almost the same in both alloys (see Figure 1). The concentration range, where the concentration dependence becomes very small, is termed region M' in this report. The concentration ranges are classified into region H, M and M' at 10MPa with accounting the stress dependence on the creep rate. Similar change in the concentration exponent is observed at 4MPa as shown in Figure 2(b). The regions are classified into regions H and L at 4MPa.

The creep characteristics of Al-Mg solid solution alloys depend intricately on the applied stress and on the solute concentration, and are classified into four regions. The stress exponent and the concentration exponent in each region obtained in alloys investigated are summarized in Table 1. The transition stress and the transition concentration between regions obtained in Al-Mg alloys are shown in Figure 3. The upper transition stress
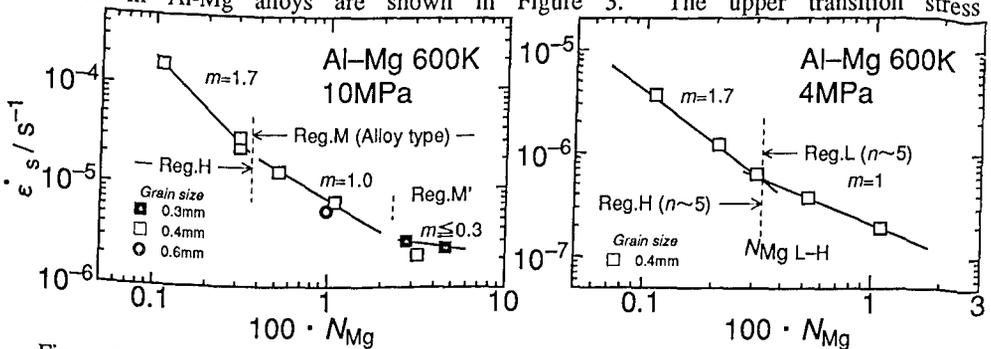

Figure 2. The concentration dependence of the steady-state creep rate of Al-Mg alloys at 10MPa(a) and 4MPa(b). The slope indicates the concentration exponent m, and decreases with increasing concentration.

σ_{M-H}, *i.e.*, the upper bound stress of region M, is proportional to the solute concentration as seen in the figure. The Alloy-type creep behavior appears in the bounded stress range and in the bounded concentration range (region M). Region L can be observed also in the bounded condition and disappears under the concentration range less than or equal to 0.1mol%.

Disappearance of Alloy-type Creep in a Low-Concentration Alloy

When the Alloy-type behavior appears, the rate-controlling mechanism is reasonably understood as the viscous motion of a dislocation which are dragging a solute atmosphere. The rate-controlling mechanism in the Metal-type behavior is considered as the nonconservative

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

Mg Concentration(mol%)	≤0.3	0.3~3			3~5
Region	H	L	M	H	M'
Type of Behavior	Metal	(Metal)*	Alloy	Metal	Alloy
Stress exponent, n	5	5	3	5	3
Concentration exponent, m	2	1	1	2	≈0

* 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 in this report.
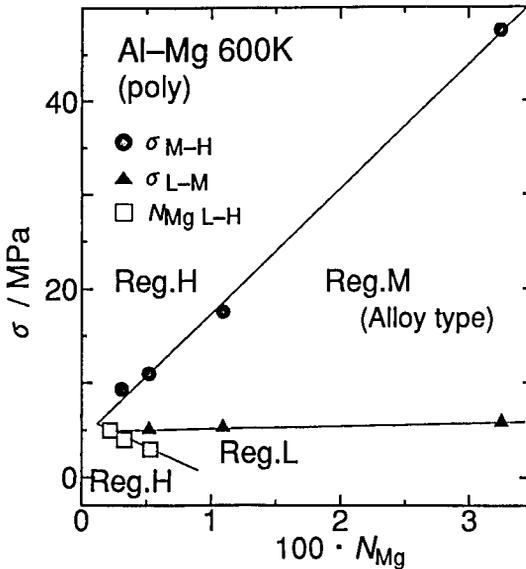

Figure 3. Regions classified and the transition conditions between regions. Type-A behavior is observed in bounded conditions and are not observed in Al-0.1mol%Mg.

motion of dislocations. When the mean velocity of dislocation becomes very high, the glide of dislocation cannot be the rate-controlling process so that the creep behavior changes to type-M in the high stress range[1].

The velocity of a moving dislocation depends on the solute concentration, because dragging stress caused by a solute atmosphere depends on the number of solute atoms interacting with the dislocation. In Al-Mg solid solutions, the dominant interaction between a dislocation and solute atoms is expected to be the size effect[5]. According to Cottrell[6], the average velocity of edge dislocations can be estimated by the following equation(2) in low-concentration solid solutions[5-7].

$$\bar{\upsilon} = B \cdot \bar{\tau}^* = \left(\frac{DkT}{68 n_0 G^2 e^2 r^6 b} \right) \cdot \bar{\tau}^* . \qquad (2)$$

Here, $\bar{\tau}^*$ is the effective stress for dislocation moving with the velocity $\bar{\upsilon}$, D is the inter-diffusion coefficient, n_0 is the average number of solute atoms per unit volume, e is the size misfit parameter, r is a radius of solvent atoms. The mobility of dislocation, B, is inversely proportional to the average solute concentration and to the second power of the size misfit parameter as described in the equation (2). The size misfit parameter can be determined from principal strains estimated from the change in the lattice parameter of solid solution alloy[8] as $e = 1/a_{(0)} \cdot da / dN \cong 1/a_{(0)} \cdot (a_{(N)} - a_{(0)}) / N$. Where a is the lattice parameter as a function of solute concentration N. Figure 4 shows the size misfit parameter as a function of solute concentration estimated from the lattice parameter measured by X-ray diffraction cited in reference[9]. The misfit parameter depends on the solute concentration at the low concentration range and becomes small significantly with decreasing the concentration. The misfit parameter at 0.3mol%Mg is less than a half of the value of Al-2mol%Mg. Thus, the dislocation velocity in low-concentration alloys becomes greatly higher than that on high concentration alloys under a given effective stress. The dislocation velocity is not proportional
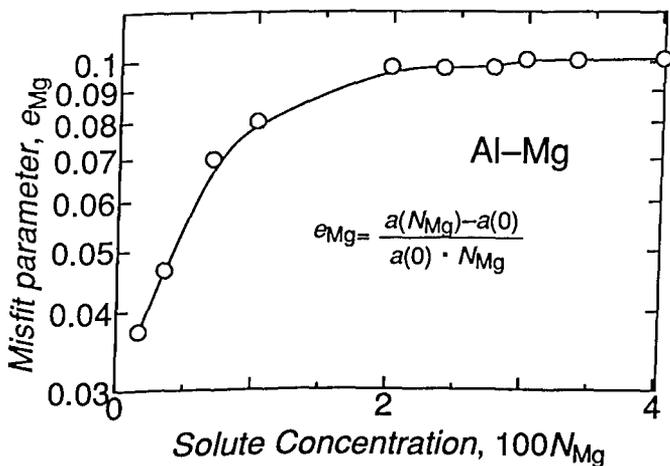

Figure 4. The size misfit parameter estimated from the concentration dependence of the lattice parameter which are quoted from reference[9]. Lattice parameters used for calculations are those reported by Poole and Axion(1952).

to the inverse of solute concentration, so that the mobility becomes drastically large in a very low concentration range. In this very low concentration range, the glide of dislocations cannot be the rate-controlling mechanism and the type-A behavior cannot be observed. The concentration dependence of the misfit parameter causes the disappearance of the type-A behavior in the low concentration alloy.

Saturation of Concentration Effect in Alloy-Type Creep

Figure 5 shows the dependence of the steady-state creep rate on the solute concentration N in a high concentration range near the solubility limit. The effect of the concentration on creep rate is different from intermediate concentration range (Figure 2). In the intermediate concentration range up to about 3mol% solute, the concentration exponent m is roughly unity in region M as reported previously. At the high concentration range, however, m is smaller than unity. These data are obtained in samples having similar grain size. Therefor, the changes in the solute concentration dependence are not caused by the difference of the grain size[10].
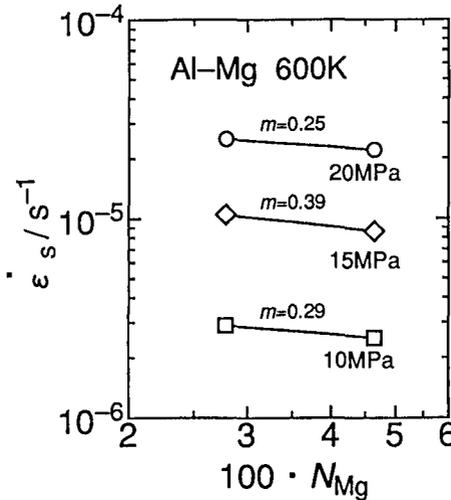

Figure 5. The steady-state creep rate of Al-Mg solid solutions in a high concentration range (near the solubility limit) as a function of concentration. The concentration exponent is obviously smaller than that in low concentration alloys. All samples have similar grain size, ~0.3mm.

When dislocations move viscously, the strain-rate can be represented by the Orowan's equation, $\dot{\varepsilon} = \phi \rho_m b \bar{\upsilon}$, where ϕ is the geometrical factor and ρ_m is the mobile dislocation density. The value, $\bar{\upsilon}$ is the mean dislocation velocity expressed as $\bar{\upsilon} = B\bar{\tau}^*$. Thus, the effect of solute concentration on creep rate at a given effective stress is essentially attributed to the product $\rho_m B$.

The mean effective stress can be represented by $\bar{\tau}^* = M^{-1}(\sigma - \bar{\sigma}_i)$, where M is a Taylor factor ($M=1/\phi$), σ is the applied stress and $\bar{\sigma}_i$ is the mean internal stress. The mean internal

stress has a square-root proportionality with dislocation density ρ, i.e., $\overline{\sigma}_i = \alpha MGb\sqrt{\rho}$. The TEM observations show that the dislocation density depends only on the applied stress and that no systematic dependence on temperature or solute concentration[11,12]. Assuming that the dislocation density ρ observed by TEM as the mobile dislocation density ρ_m, the strain rate can be represented by the following equation (3),

$$\dot{\varepsilon} = C \cdot B \cdot \sigma^q \left(\sigma - k' \cdot \sigma^{q/2} \right).$$
(3)

Here, the relation $\rho = k \cdot \sigma^q$ is used[11], where k and q are the constants determined experimentally. Values C and k' are expressed by $C = 2M^{-2}bk$ and $k' = \alpha MGb\sqrt{k}$. Under a given applied stress σ, it is expected that the strain-rate is directly proportional to the mobility B. As a consequence, the dependence of creep rate on the concentration is equal to the dependence of the mobility.

It has been reported[13] that the dragging force, the inverse of the mobility B, of a moving dislocation surrounded by a solute atmosphere is not proportional to the solute concentration when a wide range of concentration is concerned, while linear proportionality is expected according to Cottrell. Figure 6 shows the concentration dependence of the mobility B of Al-Mg alloys estimated numerically by a modified Yoshinaga-Morozumi's method based on the flux analysis of solute atom around a moving dislocation[14]. It is seen that the effect of the solute concentration on the mobility becomes smaller with increasing concentration. In the high concentration range, the concentration exponent m, obtained from creep experiments is almost equal to the apparent concentration exponent of B estimated from the numerical calculations. Although, in medium concentration range (0.5-3mol%Mg), the concentration exponent observed in creep experiments is higher than that of numerical calculations, the effects of concentration on the creep rate and on the mobility show essentially the same trend. The effect of concentration both on creep rate and on mobility decreases as increasing the solute concentration. Thus, the decrease in the effect of the concentration on the creep rate can be
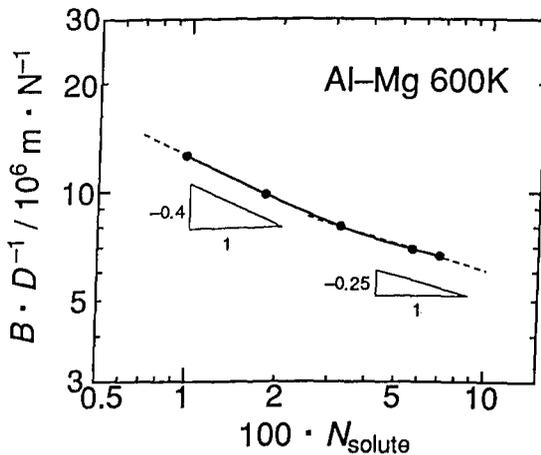

Figure 6. The mobility of dislocations B compensated by diffusion coefficient D as a function of solute concentration. The concentration effect on the mobility decreases as increasing solute concentration.

essentially attributed to the decrease in the effect on the mobility of dislocations which have solute atmospheres.

Conclusions

1. Creep characteristics of Al-Mg solid solutions depend on the applied stress and the solute concentration and are classified into four regions. Alloy-type behavior appears in the bounded concentration and the bounded stress range. Alloy-type behavior is not observed in Al-0.1mol%Mg, because the misfit parameter becomes small and the glide process of a dislocation cannot be the rate-controlling mechanism in the low-concentration alloy.
2. The effect of solute concentration on the creep rate of Al-Mg solid solution alloys decreases approaching the solute concentration to near the solubility limit. The decrease of the effect of the solute concentration on creep rate is caused by the decrease of the effect on the mobility of a dislocation which are dragging a solute atmosphere.

Acknowledgments

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