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Analysis of Yield Strength for Isothermal Aged Al-Mg-Si Alloys

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Two Al-Mg-Si alloys with different content of Si were isothermally aged at 373 K for 120 h (Al-0.62Mg-0.32Si) and 600 h (Al-0.62Mg-0.81Si) and for intentional formation of Mg-Si clusters with different Mg/Si ratio. The formations of Mg-Si clusters were confirmed, and their volume fractions as well as average radius were measured by three-dimensional atom probe (3DAP). The yield strength was increased with the aging period due to the interaction between Mg-Si clusters and moving dislocations during the tensile test, which could be explained by the yield strength model developed for Al-Mg-Si alloy with β" precipitate. Two kind of parameters which were classified as strong obstracle and weak obstacle were applied in the analysis. The breaking angle of dislocations pinned by the clusters was calculated as 73-170º for both alloys, which suggests that the maximum interaction force of Mg-Si clusters acting on the moving dislocation is small, that the clusters was shared with dislocations.

Keywords: *Al-Mg-Si alloy, yield strength, Mg-Si cluster,3DAP*,

1. Introduction

There is currently strong interest in using Al-Mg-Si alloys with high strength and high elongation for automotive panel application to reduce weight and to save energy. As the mechanical properties of age-hardenable aluminum alloys are dependent on their microstructures and composition of precipitates, characterization of microstructural evolution during the aging is essential for optimizing process and properties in aluminum alloys. Edwards et al. observed the formation of Mg-Si clusters at temperatures lower than 343 K and found Mg-Si precipitates with unknown structure at the temperature ranging from 343 to 453 K in Al-Mg-Si alloys [1]. Serizawa et al. reported the formation of Mg-Si clusters during the aging at 373 K [2]. Maruyama et al. studied the composition and structure of precipitates from excess Si containing Al-Mg-Si alloys aged at 448 K for 9 hours by TEM, and determined the structure of β" as monoclinic a=0.714±0.017, b=0.658±0.013, c=0.405(nm), γ=75º ± 1, with the orientation relationship between β" and Al matrix, $[100]_{\beta"}//[3\text{-}10]_{Al,}$ $[010]_{\beta"}//[230]_{Al}$ [3].

Although microstructural evolutions of precipitation in Al-Mg-Si alloys have been characterized in detail, strengthen mechanism of them has not fully been understood. According to the study about the interaction between dislocation and precipitates, Delmas et al. reported the sharing or by-passing of β" by dislocation without the consideration of interaction between the dislocation and the Mg-Si cluster [4]. Esmaeili et al. developed the yield strength model for Al-Mg-Si-Cu alloy during aging at 453 K, in which precipitates acted as either strong or weak obstacles [5].

In this study, Al-Mg-Si alloy was aged at 373 K with different content of Si, and Mg-Si clusters were characterized using three-dimensional atom probe (3DAP). The interaction between dislocation and Mg-Si clusters was then proposed using the yield strength model, originally developed for precipitation hardening mechanisms.

2. Experiment

2.1 Sample

Two Al-Mg-Si alloys with different Mg/Si ratio were prepared by Furukawa-Sky Aluminum Co. for the experiment. Their impurity contents are listed in Table.1; one is a balanced alloy (Mg/Si ≈ 2) and another one with excess amount of Si (Mg/Si ≈ 0.8). Both alloys were cast, homogenized at 803 K for 6 hours, hot-rolled at 803 K, cold-rolled in 1mm thickness, and heated in an electric furnace at 823 K for 30 minutes in air. They were quenched into the iced water and stored in the liquid nitrogen. Both alloys were intentionally annealed isothermally at 373 K for the formation of Mg-Si clusters.

Table 1 Chemical composition of aluminum alloys (in wt.%)

Alloy	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti
B	0.05	0.32	0.13	0.05	0.62	0.01	0.04	0.01
ES	0.06	0.81	0.16	0.05	0.65	0.01	0.04	0.01

2.2 Methods

The tensile tests were conducted at room temperature by Autograph AG-10TA (Shimazu, Japan). Vickers hardness measurement was carried out by using a 1kg load by MVK-G3, Akashi, Japan. 3DAP measurement was conducted by Three-dimensional atom probe, Oxford nanoScience Ltd, UK to observe the size and the density of Mg-Si clusters. Two parameters, d and Nm, were used for defining Mg-Si clusters for the particle analysis of 3DAP. Here, d (=0.8nm) is the distance between a solute atom and another one, and Nm (=20) is the minimum number of solute atoms found with d from a solute atom [6].

2.3 Analysis

A precipitation hardening component of yield strength, σ_p, is given as:

$$\sigma_p = \frac{MF}{bL} \quad , \tag{1}$$

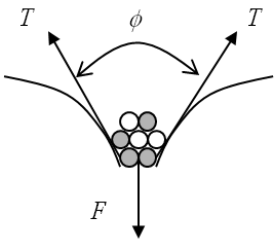

Fig.1 Dislocation-precipitate interaction

where M, F, b and L are the Taylor factor, the maximum interaction force between a precipitation and a dislocation, magnitude of Burgers vector, and the average spacing between the precipitates which are acting as obstacles to the dislocation motion, respectively. When a moving dislocation encounters a precipitate, it bows out to some angle until it reaches the breaking angle, ϕ, as shown in Fig.1 can be estimated;

$$\phi = 2\cos^{-1}\left(\frac{F}{Gb^2}\right) \tag{2}$$

Precipitates can be classified as strong or weak obstacle to dislocation motion. $\phi \approx 0$ for strong obstacle, and $\phi \cong \pi$ for weak obstacle L is given as [7]:

$$\left(\frac{2\pi}{3f}\right)^{1/2} r \le L \le \frac{4r}{3f}, \tag{3}$$

where f and r is the average volume fraction and the average radius of precipitate.

Assuming a linear addition of yield strength, the yield strength obtained in tensile test, σ, is given as [2]:

$$\sigma=\sigma_0+\sigma_s+\sigma_p\ , \tag{4}$$

where σ_0 is the yield strength component from the pure matrix and σ_s is the one from solute atoms. σ_0 is already known[5] and σ_s is given as [8,9];

$$\sigma_s = \mathrm{K}C_0^{2/3}\ , \tag{5}$$

where K and C_0 is the constant and the concentration of solute atoms, respectively.

3. Results and discussions

It was found from Vickers hardness test that the maximum hardness reached 120 Hv for the case of ES alloy and 100 Hv for that of B alloy, as shown in Fig.2. The hardness started increasing from 46 Hv for ES alloy after 4 hours and from 36 Hv for B alloy after 24 hours. The initial hardness of alloys and initiation period of hardening were different due to the solid-solution hardening of excess amount of Si.

Fig.3 shows the stress-strain curves obtained in B alloy aged for 120 hours and ES alloy aged for 600 hours. A total elongation in ES alloy was greater than one in B alloy. The yield strengths were found as 145 MPa for B alloy and 299 MPa for ES alloy, due to the differences in the size and the density of Mg-Si clusters. It is therefore necessary to measure the density of Mg-Si clusters to find the contribution of them on yield strength, since the amount of solute atoms was known.

The presences of Mg-Si clusters were confirmed by 3DAP for both alloys as shown in Fig. 4. For the case of B alloy, the number density of clusters were found 7.7×10^{23} m^{-3} and the average radius as 0.82 nm. For the case of ES alloy, the number density of clusters were found 3.2×10^{24} m^{-3} and the average radius as 0.78 nm. Although the number density of clusters in ES alloy was 4 times larger than that in B alloy, the average radius of clusters were almost the same. The effect of the number density is far more significant on mechanical properties of Al-Mg-Si alloy as in the case of precipitation hardening with comparison to the size of clusters.

Fig.5 shows a linear relationship between $C_0^{2/3}$ and σ_0 in alloys B and alloy ES as quench. Substituting the experimental values of σ, r, N and K, and the parameters of aluminum alloy, M, b, σ_0 and G in Eqs. (1) - (5) [4], ϕ can then be calculated. The Mg-Si cluster is shared by the dislocation because ϕ is not zero. ϕ do not depend on the Mg/Si ratio of alloy composition.

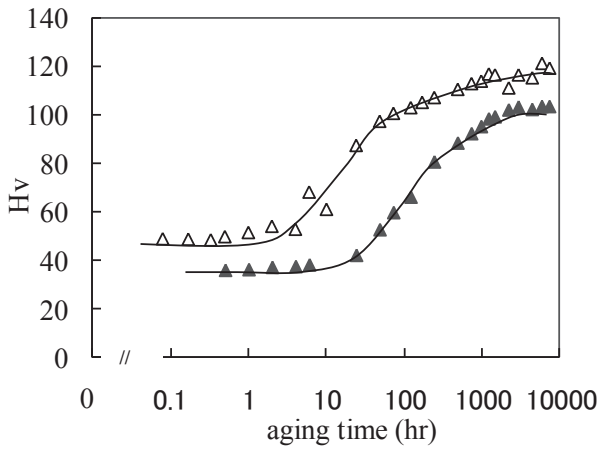

Fig.2 The aging curve of Vickers hardness;
▲:alloy B aged at 373 K
△:alloy ES aged at 373 K

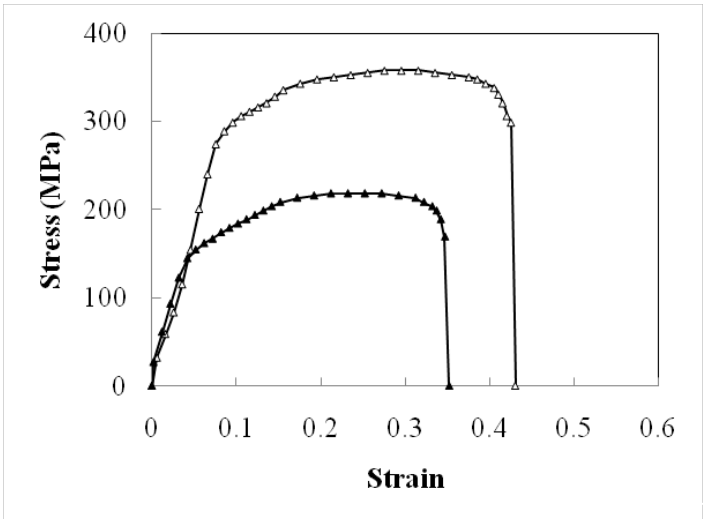

Fig.3 Stress-strain curves in two alloys.
▲ alloy B aged at 373 K for 120 h
△ alloy ES aged at 373 K for 600 h

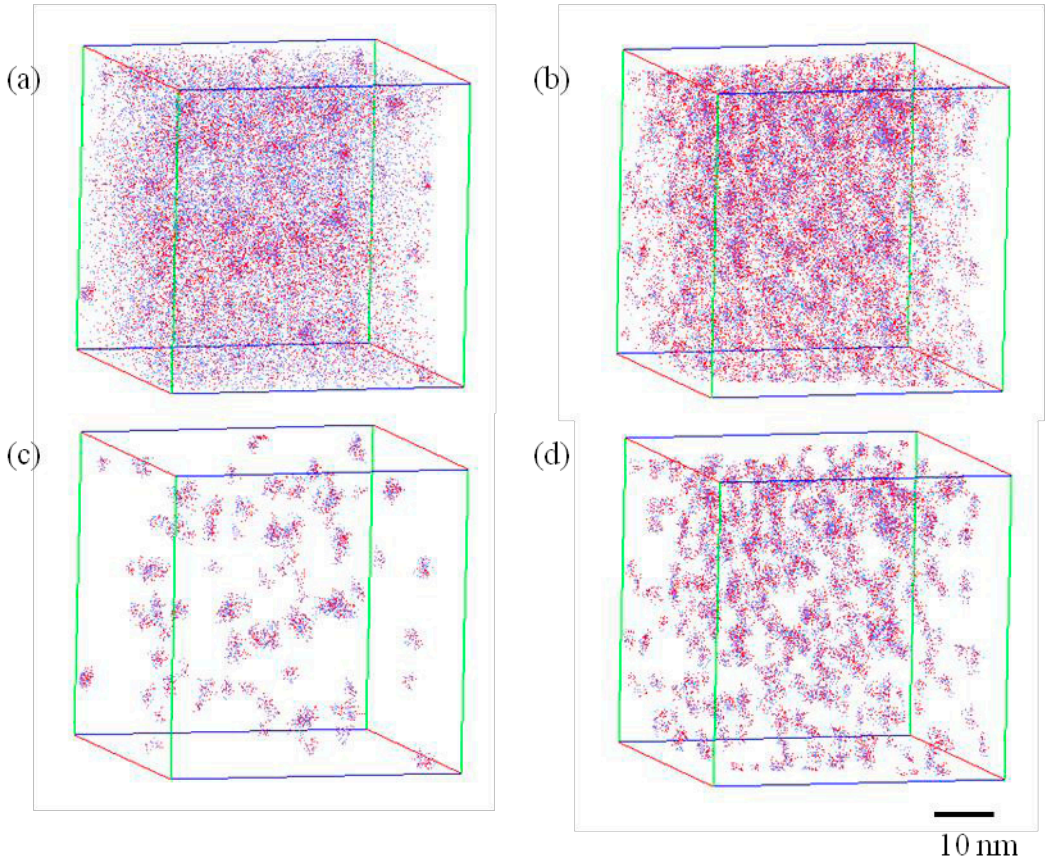

Fig.4 Mg and Si atom map in B alloy aged at 373 K for 120 h (a) and the one in ES alloy aged at 373 K for 600 h (b) obtained in 3DAP measurement and Mg and Si map after particle analysis in B alloy (c) and the one in ES alloy (d); in (a) and (b) the dense regions in both alloys indicate the Mg-Si clusters, while the other regions indicate the Mg and Si atoms as solid solution. The Mg and Si atoms are depicted by blue and red, respectively.

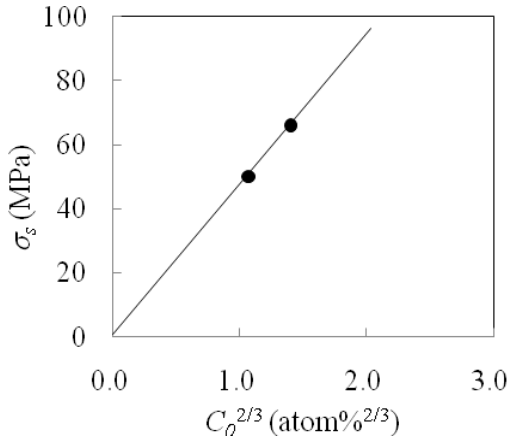

Table 2 Calculated values

Alloy	Aging condition	ϕ (°) strong obstacle	weak obstacle
B	373 K - 120 h	170	73
ES	373 K - 600 h	167	113

Fig.5 Relationship between the concentration of Mg and Si atoms, c_0 and the yield strength induced by these atoms, σ_s. Both values is obtained in the tensile tests in alloy B and alloy ES as quench. An inclination is estimated at 38.98.

4. Conclusion

The density and the size of Mg-Si clusters in Al-Mg-Si alloys with different content of Si were obtained using 3DAP measurement. The breaking angle of dislocation pinned by the cluster, ϕ, was calculated using the yield strength model as 73-170º. These provide the following findings; (1) Mg-Si clusters are shared by the moving dislocation and (2) maximum interaction force between cluster and dislocation was small.

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