Superplastic Behavior of Al-Mg-Cu Alloys*

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Synopsis

A new superplastic Al-Mg-Cu alloy is described. The effect of copper addition on superplastic properties of Al-Mg base alloy (AA5083) has been studied. By addition of 0.6 % Cu, a high elongation of about 700 % is obtained in deformation at a strain rate of $2.8 \times 10^{-3} \text{ s}^{-1}$ and 550°C. Typical mechanical properties of formed parts made from the new alloy are 340 MPa in tensile strength and 25 % in elongation. The present alloy sheet has a potential for general applications in building and construction because of its properties very similar to the conventional 5 000 system alloys and high productivity in the conventional casting and rolling process.

Key words: superplasticity; aluminum-magnesium alloy; alloying of copper; mechanical property; second phase.

I. Introduction

In recent years, superplastic aluminum alloys have been of considerable interest because they can be formed into complex parts by compressed air forming¹⁾ in the same manner as in the case of thermoplastic materials with particular intention to aerospace applications. So far various types of superplastic aluminum alloys were developed in laboratory scale.²⁻¹³⁾ However only a few alloys like Al-Cu-Zr^{14,15)} are in practical use. It is important for general applications to develop a superplastic aluminum alloy which has the chemical composition similar to the conventional wrought alloys and can be produced by the conventional mass production method.

In the present work the effect of copper addition on superplastic properties of an Al-Mg base alloy, AA5083,¹⁶⁾ was studied.

II. Experimental Procedure

The chemical compositions of four tested alloys are shown in Table 1. No. 1 is the standard Al-4.8%-Mg-0.7%Mn-0.13%Cr alloy equivalent to AA5083 alloy. Alloys Nos. 2 to 4 contain about 0.2, 0.4 and 0.6 % Cu, respectively. The alloys were cast into ingots with a size of 25×150×200 mm³ by using iron mold casting. The ingots were heated up to 500°C

at a rate of 80°C/h, homogenized for 4 h and scalped. They were hot-rolled to 8 mm thickness and finally cold-rolled 80 % to 1.6 mm thickness. The cold-rolled sheets were cut parallel to the rolling direction and machined into tensile specimens with a gauge-length of 15 mm and a width of 7 mm. Tensile tests were carried out in the temperature range 530~570°C in a hard testing machine. The specimens were heated up to the testing temperature at a rate of about 35°C/min, hold for 5 min prior to deformation. Total elongations were measured in testing at an initial strain rate of $2.8 \times 10^{-3} \text{ s}^{-1}$.

Microstructure observations were made by optical and electron microscopy. The latter were performed on a transmission microscope operated at 200 kV and equipped with a scanning unit and an energy dispersive system.

III. Results and Discussion

1. Optical Microstructures

The typical recrystallization structure of each alloy is shown in Fig. 1. In comparison with the copper free specimen No. 1, the remarkably fine recrystallization grains are obtained by addition of only 0.2 % Cu. The microstructures are uniformly refined with increasing copper content. The grain size determined by the average linear intercept method is less than 10 μm in the specimen No. 4 containing 0.6 % Cu.

2. High Temperature Mechanical Properties

Figure 2 shows the flow stress-strain curves of each alloy deformed at 550°C and an initial strain rate of $2.8 \times 10^{-3} \text{ s}^{-1}$. The maximum flow stress measured near about 20~30 % strain decreases with increasing copper content; it is a half smaller in the copper free specimen No. 1 than the specimen No. 4 containing 0.6 % Cu.

Figure 3 shows the effect of copper contents on total elongation tested between 530 and 570°C. Although the copper free specimen No. 1 exhibits only about 200 % elongation, addition of only 0.2 % Cu improves total elongation remarkably. Furthermore, the elongation increases with increasing copper content and a high value of about 700 % elongation was obtained in the specimen No. 4 containing 0.6 % Cu. The optimum deformation temperature of these alloys lowers with increase in copper content. This may be attributed to the drop of melting point with increasing

Table 1. Chemical compositions of specimens. (wt%)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
No. 1*	0.10	0.13	0.01	0.69	4.81	0.13	0.01	0.04
No. 2	0.08	0.12	0.20	0.70	4.86	0.13	0.01	0.03
No. 3	0.09	0.12	0.40	0.70	4.83	0.13	0.01	0.03
No. 4	0.09	0.12	0.61	0.71	4.87	0.13	0.01	0.04

* Alloy No. 1 equivalent to AA5083

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Fig. 1. Microstructure of rolled specimen after annealing at 530°C×30 min.

Fig. 2. Stress-strain curves for Nos. 1~4 alloys at 550°C.

Fig. 3. The effect of copper contents on total elongation.

copper content. Thus, alloy No. 4 containing 0.6 % Cu, having a nearly single-phase structure, is found to exhibit remarkable superplasticity when deformed at a suitable strain rate and temperature.

Figure 4 shows the dependence of flow stress σ and strain rate sensitivity index $m^{17,21)} = \partial \log \sigma / \partial \log \dot{\epsilon}$ on strain rate $\dot{\epsilon}$ for the commercially rolled sheet having a chemical composition similar to the specimen No. 4. The stress and strain relationships determined by the strain-rate change method for various temperatures show a characteristic sigmoidal curve. The slope m of the stress-strain rate curve is higher than $m=0.3$, the value considered as the criterion of superplasticity, at a considerably wide range of strain rates and deformation temperatures above 500°C. A very high value of the maximum m of about 0.7 was obtained in deformation at a strain rate of about 10^{-3} s^{-1} and 545°C, though the maximum m obtained for each temperature lowers and shifts toward lower strain rates with temperature drop. Furthermore, the m value is over 0.4 even in deformation at a high strain rate of about 10^{-2} s^{-1} ; about 500 % at a strain rate of $1.1 \times 10^{-2} \text{ s}^{-1}$ and 520°C.

3. Metallography

As described above, superplastic properties of AA-5083 base alloy are significantly improved by a small addition of copper. This can be discussed in terms of the dispersion of second phases.

Figure 5 shows the electron micrographs of recrystallized specimens Nos. 1 and 4. As obvious from these photographs, the specimen No. 4 has more of finely dispersed particles than the copper free specimen No. 1.

Figure 6 shows the results of energy dispersive spectrometric (EDS) analysis of the dispersed phases. In copper free alloy (a), EDS spectra show the presence of aluminum, manganese, iron and chromium, so that these particles seem to be $\text{Al}_6(\text{Mn, Fe, Cr})$ com-

Fig. 4. Dependence of flow stress σ and strain rate sensitivity index m on strain rate $\dot{\epsilon}$ for Al-5%Mg-0.6%Cu alloy.

pounds. While two types of particles are found in copper containing alloy (b): Cu-Mn-Al base compound and Cu-Mg-Al base precipitate which is fine than 0.1 μm in diameter.

Figure 7 shows the variation in Vickers hardness with heating temperatures for the as cold-rolled sheets of Nos. 1~4 alloys. In comparison with the copper free specimen, the recrystallization temperatures of copper containing specimens evidently elevate by about 20°C.

From these results, it seems that in the copper containing alloys a lot of finely dispersed particles inhibit the growth of subgrains in continuous recrystallization and result in very finely recrystallized grain structures. Further, these particles suppress the grain growth during superplastic deformation, so that superplasticity significantly improves.

4. Properties after Superplastic Forming

Typical mechanical properties at room tempera-

ture after superplastic forming of a new superplastic aluminum alloy sheet, having the composition similar to the alloy No. 4, are shown in Table 2, in comparison with the other commercial superplastic aluminum alloys and AA5083. The present alloy shows about 340 MPa tensile strength and 25 % elongation superior to AA5083 alloy, which is a typical of medium-strength alloys usually used for construction.

Table 3 compares the corrosion resistance of the new alloy, AA5083, and 6061 alloys measured by the salt spray test for periods up to 1 000 h. The present alloy possesses good corrosion resistance as comparable to these of 5 000 system alloys. Moreover, it can be anodized or painted with normal architectural finishes.

Table 2. Mechanical properties of products as-formed.

Type of alloy	Tensile strength (MPa)	0.2% proof strength (MPa)	Elongation (%)
Al-5% Mg-0.6% Cu*	334	172	25
Al-5% Cu-0.5% Zr**	181	123	7
Al-5% Zn-5% Ca**	179	159	19
AA5083-0	289	147	22

* The newly developed alloy
** Figures obtained from publication data

Fig. 5. Transmission electron micrographs of Nos. 1 and 4 alloys.

Fig. 7. Variation in Vickers hardness with heating temperatures for Nos. 1~4 alloys.

Fig. 6. Energy dispersive X-ray analyses of second phases in alloys No. 1 (Cu free) and No. 4 (0.6 % Cu).

Table 3. Corrosion resistance. (By salt spray test for periods up to 1 000 h).

Type of alloy	Corrosion weight reduction (mg/dm ²)
Al-5%Mg-0.6%Cu	50
AA5083-0	37
AA6061	67

IV. Conclusion

The effect of copper addition on superplastic properties of Al-Mg base alloy was investigated.

The following conclusion may be drawn:

- (1) By addition of copper in Al-Mg base alloy (AA5083), the recrystallized grains are remarkably refined. The grain size gets finer and more uniform with increasing copper contents to be less than 10 μm in the specimen containing 0.6 % Cu.
- (2) Superplastic elongation is remarkably improved by addition of copper. A high elongation of about 700 % is obtained in the specimen containing 0.6 % Cu. An optimum deformation temperature of Al-Mg-Cu alloys is determined in connection with strain rate.
- (3) The strain rate sensitivity index *m* is higher than *m*=0.3 in copper containing specimen and the maximum *m* value of about 0.7 is obtained in deformation at a strain rate of about 10⁻³ s⁻¹ and 545°C. Furthermore, the *m* value is over 0.4 even in deformation at a high strain rate of about 10⁻² s⁻¹.
- (4) In copper contained specimen, more of finely dispersed particles are observed than in the copper free specimen. The recrystallization temperature is elevated by copper addition.
- (5) A new superplastic aluminum alloy having the composition of Al-5%Mg-0.6%Cu has a good mechanical properties compared with AA5083 alloy: about 340 MPa tensile strength and 25 % elongation. It shows a good corrosion resistance as comparable to

these of 5 000 system alloys.

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