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Effect of Cu on the Superplastic-like Behavior of Coarse-Grained Al-Mg Alloys

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In this study, the effect of Cu content on the superplastic-like behavior of Al-Mg alloys in coarse grain size condition has been studied. Five hot-rolled Al-Mg alloys with different Cu concentrations (0.5, 1.0, 1.5, and 2.0 wt.%) and without Cu were prepared. Tensile test specimens were machined parallel to the rolling direction. High-temperature elongation to failure tests were performed under a constant cross-head speed condition at different strain rates and temperatures. Grain size refinement is observed as Cu addition increases. Maximum tensile elongation of 373% could be achieved in the Al-4.5%Mg-1.5%Cu alloy with an average grain size of 28 μm at 500 °C and 1×10^{-2} s^{-1}. Grain size refinement after superplastic deformation was also observed.

Keywords aluminum alloys, grain refinement, superplasticity

1. Introduction

Currently, there is a considerable interest in superplastic-forming technology for the fabrication of automotive sheet parts from Al alloys to improve fuel efficiency and fulfill environmental requirements. In particular, Al-Mg alloys have attracted attention because of their good corrosion resistance, medium strength, and moderate degree of superplasticity (Ref 1, 2). For many years, it was believed that a material required a stable grain size of less than 10 μm to show superplasticity (i.e., usually elongations over about 200%). This fine grain size is a requirement of grain boundary sliding (GBS) mechanism associated with very high elongations due to the high strain-rate sensitivity, $m = 0.5$ (Ref 3). Because of this requirement, a special processing is necessary to create such a fine and stable grain size. As a result, superplastic materials are expensive (Ref 4). However, some studies have indicated the possibility of obtaining superplastic materials by taking advantage of enhanced ductility during solute drag creep (SDC) mechanism (Ref 5). As a consequence of the strain-rate sensitivity of $m = 0.33$ being related with this mechanism, tensile elongations over 300%, which are more than sufficient for many potential applications, have been accomplished (Ref 6). Since SDC is independent of grain size, expensive processing to create and retain a fine grain size may not be required, providing an immediate economic advantage over fine-grained superplastic materials (Ref 4). On the other hand, according to Watanabe et al. (Ref 7), the addition of 0.6% Cu in Al-Mg base alloys increased the ductility because of finely dispersed second-phase particles and grain size refinement. Therefore, it is interesting to investigate higher Cu additions. Hence, the purpose of this investigation is to study the effect of Cu concentrations on the superplastic behavior of Al-Mg alloys beyond the concentrations studied previously in coarse grain condition. Tensile ductility behaviors at temperatures from 300 to 500 °C and different strain rates are to be investigated with interest on the microstructural evolution during superplastic deformation.

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2. Experimental

One Al-4.5%Mg base alloy without Cu addition and four Al-4.5Mg-Cu alloys containing about 0.5, 1.0, 1.5, and 2.0 wt.% Cu, respectively (referred to as alloys without Cu, 0.5, 1.0, 1.5, and 2.0 Cu), were melted in an electrical furnace and then cast into an ingot. Argon gas was used as degassing agent. The chemical compositions of the alloys are shown in Table 1. The cast ingots with dimensions of 25 × 80 × 100 mm were homogenized at 430 °C for 72 h and then hot-rolled at 380 °C to a final thickness of 5 mm. Tensile test specimens with a gauge length of 15 mm, a width of 5 mm, and a thickness of 3.5 mm were machined parallel to the rolling direction. Elongation to failure tests were performed on a screw-driven testing machine. High-temperature elongation to failure tests were performed under a constant cross-head speed condition at strain rates from 5×10^{-4} to 5×10^{-2} s^{-1} and temperatures ranging from 300 to 500 °C. Specimens after rolling and elongation-to-failure tests were etched with Keller's reagent and then examined by optical microscopy. Grain size was measured by the linear intercept method.

3. Results and Discussion

Optical micrographs of the as-rolled alloys without Cu, 0.5 and 2.0 Cu are shown in Fig. 1. They consist of recrystallized

Table 1 Compositions in weight percent (remainder Al) and grain size after rolling

Alloy	Mg	Cu	Fe	Si	Grain size, μm
Without Cu	4.50	0.00	0.05	0.04	69.73 ± 3.43
0.5 Cu	4.45	0.47	0.05	0.04	58.40 ± 6.40
1.0 Cu	4.48	1.02	0.05	0.04	47.05 ± 3.56
1.5 Cu	4.47	1.62	0.05	0.04	28.73 ± 1.62
2.0 Cu	4.50	2.02	0.05	0.03	25.39 ± 0.88

grains. Although particles cannot be observed in the micrographs, we might suppose that most of the present holes were occupied by particles. Hence, it is clearly seen how the particles in 2.0 Cu alloy, Fig. 1(c), increase considerably in number and size regarding 0.5 Cu alloy, Fig. 1(b). The presence of large particles is not preferable because they can become nucleation sites for cavitation (Ref 8). As Cu concentration increases, the grain size refines from 69 to 25 μm as shown in Table 1.

Elongation to failure as a function of the strain rate at 500 °C is shown in Fig. 2(a). The best elongations were obtained at this temperature. It is clear how the Cu concentration affects ductility. Maximum elongation of 373% was achieved in the specimen containing 1.5% Cu at 10^{-2} s^{-1}. The lowest Cu concentration shows the best ductility at low strain rates. However, the rest of specimens with higher Cu content do not behave superplastically at low strain rates. Instead, higher Cu concentrations reach the maximum ductility at higher strain rates. It can be explained by the grain size refinement, since the largest elongations move from low-to-high strain rates as Cu concentration increases (Ref 9). Besides, it has been observed that the dominant deformation mechanism changes from GBS to SDC as strain rate increases, cavitation being the main failure mechanism when GBS is the dominant mechanism (Ref 10). Considering that coarse grain size produces a negative effect to the grain rotation process under GBS in addition to the increase in the amount of particles as Cu increases, the eventual failure by cavitation is expected at low strain rates. In contrast, superplastic elongations in specimens with higher Cu concentration are obtained when SDC is the dominant mechanism at high strain rates.

True stress-true strain curves at two initial strain rates and 500 °C for the alloy without Cu and 1.5 Cu are shown in Fig. 2(b). With increasing strain rate, the flow stress increases. It is observed that the curves are characterized by a high initial yield point with a progressive decrease in stress with strain which is more prominent in 1.5 Cu than without Cu alloy. This behavior is the well-known creep transient effect of solute-drag creep which in the case of 1.5 Cu is more notorious, while the subsequent drop in stress is proven because of flow localization being more tenuous in 1.5 Cu alloy. Such a behavior is similar to the typical stress-strain curve of 5083 alloys where a peak stress is observed, followed by a decrease in stress with the increase in strain (Ref 11, 12), and contrary to other 5083 Al alloys processed by severe plastic deformation with an initial fine grain (Ref 13). In the first case, SDC mechanism with dynamic recrystallization takes place, while GBS is the dominant mechanism with associated grain growth in the other (Ref 10). This is another indication that SDC could be the primary deformation mechanism at high temperature in Al-Mg-Cu alloys.

Figure 3 shows micrographs of three different points of a superplastically deformed specimen, alloy with 1.5% Cu tested

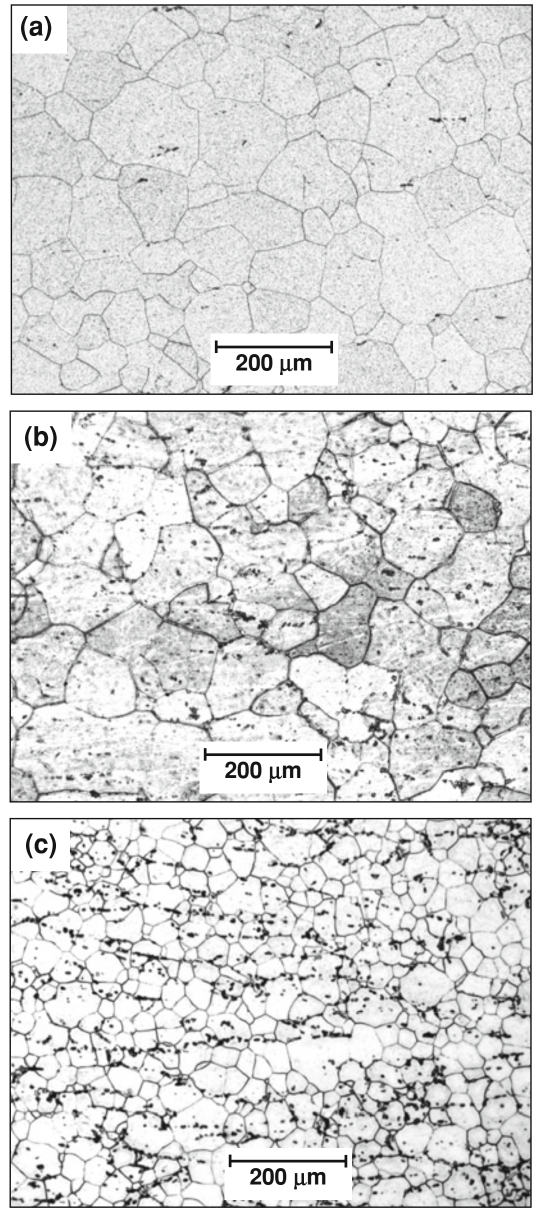

Fig. 1 Optical micrographs of the as-rolled alloys (a) without Cu, (b) 0.5 Cu, and (c) 2.0 Cu. Grain sizes were 69, 58, and 25 μm, respectively

at 500 °C and 1×10^{-2} s^{-1}. The measured grain size of the deformed region near the fracture was much finer than that of the grip region. The region between grip and fracture shows an intermediate grain size. Such behavior is not usually reported but has been observed in this study as well as in a previous study on coarse-grained Al-Mg-Zn alloys (Ref 11). The grain refinement observed in these coarse-grained Al-Mg-Zn alloys is explained in terms of dynamic recrystallization as a consequence of a dislocation-controlled-creep mechanism, with SDC being the dominant mechanism. Because one or more dislocation-controlled-creep processes can be acting in Al-Mg-Cu alloys as the dominant deformation mechanisms at high strain rates, further investigation is needed.

Figure 4 shows the intermediate grain size of the undeformed and deformed specimen observed in Fig. 3. Figure 4(b) shows the presence of subgrains after superplastic deformation,

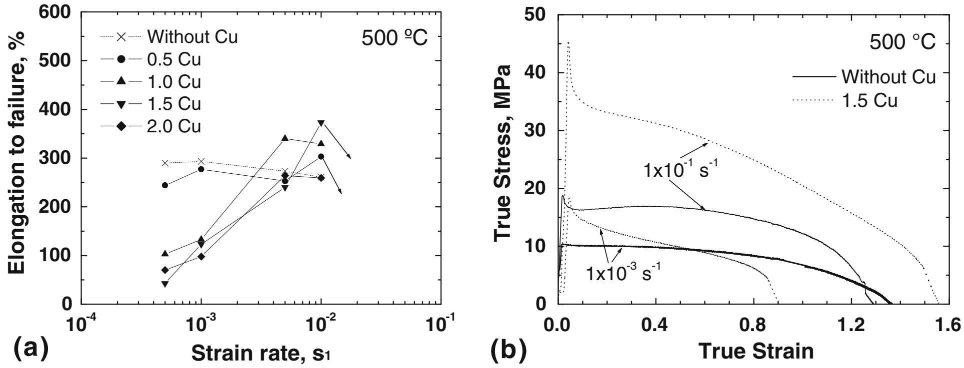

Fig. 2 (a) Elongation to failure as a function of strain rate at 500 °C for all alloys. (b) True stress-true strain plots for the alloys without Cu and with 1.5 Cu

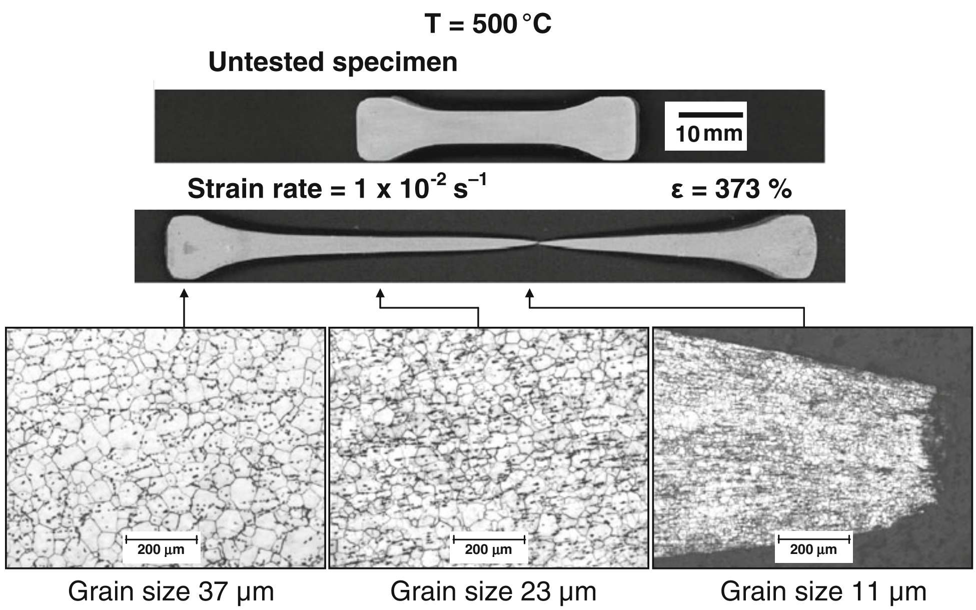

Fig. 3 Optical micrographs of 1.5 Cu alloy after deformation at 500 °C and 1×10^{-2} s^{-1} illustrating the grain structures of three different regions in the tensile specimen

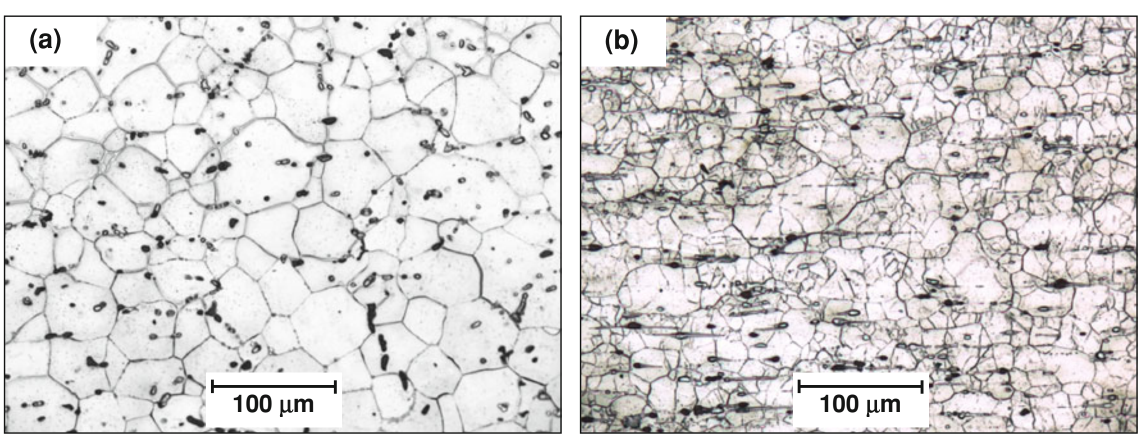

Fig. 4 Optical micrographs of 1.5 Cu alloy (a) before and (b) after deformation at 500 °C and 1×10^{-2} s^{-1} illustrating the presence of subgrains in the deformed microstructure

which supports the possibility that a dislocation-controlled-creep mechanism is responsible for the continuous dynamic recrystallization during high-temperature deformation, since subgrain structure requires a high density of dislocations.

4. Conclusions

Superplastic-like behavior was observed in coarse-grained aluminum-magnesium alloys containing a small amount of copper addition. Grain size refinement is observed as the added amounts of Cu increases. Maximum elongation of 373% was observed in the alloy containing 1.5% Cu tested at 500 °C and 1×10^{-2} s^{-1}. Grain size refinement after superplastic deformation was also observed. It was explained in terms of dynamic recrystallization as a consequence of a dislocation-controlled-creep mechanism.

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