LETTERS TO THE EDITOR

The Strain Rate Dependence of the Ductility Minimum of a Copper and a Cu-Zn Alloy at Intermediate Temperatures

The ductility minimum termed the intermediate temperature embrittlement is known to occur in copper, titanium, nickel, Cu alloys and Al alloys. Many investigations have been carried out on the ductility minimum of copper and Cu alloys^{(1)~(6)}. It is reported that the ductility minimum of copper disappears in the deformation at a high strain rate (10^2 s^{-1}) and the ductility minimum is not observed in a Cu-Zn alloy containing a small amount of zinc (1%Zn), and also that the strain rate dependence of the ductility minimum temperature (designated hereafter by DMT) of copper is very small at low strain rates ($2 \times 10^{-3} \sim 2 \times 10^{-1} \text{ s}^{-1}$)⁽⁴⁾. However, the strain rate dependence of ductility minimum of dilute zinc-copper alloys at low strain rates has not been investigated in detail. The strain rate dependence of the ductility minimum behaviors of a copper and a Cu-Zn alloy containing a small amount of zinc (0.25%Zn) at low strain rates is presented in this study.

An OFHC copper, supplied by Mitsubishi Metals Co. Ltd., and the Cu-Zn alloy prepared by melting the OFHC copper and zinc (99.8% Zn) in vacuum were used. Sheet tensile specimens with a gage section 4.0 mm wide and 30 mm long were machined from cold rolled strips with 1.0 mm thickness. These specimens were annealed at 700°C for 30 min in a vacuum of about $5 \times 10^{-3} \text{ Pa}$. Zinc content of the alloy was analyzed chemically after annealing. The average grain sizes of the copper and the Cu-Zn alloy are 50 and $70 \mu\text{m}$, respectively. Tensile tests were performed in vacuum at room temperature to 700°C and at the strain rates of $4 \times 10^{-4} \sim 4 \times 10^{-2} \text{ s}^{-1}$.

Figure 1 shows the variation in total elongation of the copper with temperature. The DMT increases with strain rate.

Fig. 1 Total elongation of copper as a function of testing temperature.

The total elongation of the Cu-Zn alloy is shown in Fig. 2 as a function of temperature. DMT of the alloy increases more rapidly with strain rate compared with that of the copper.

Two models have been proposed for the occurrence of the ductility minimum. One is a vacancy diffusion model⁽⁷⁾ and the other is a grain boundary sliding model⁽⁸⁾. With a scanning electron microscope, microcracks formed along grain boundaries were observed in both copper and Cu-Zn alloy specimens stretched at 250 to 700°C up to the ultimate tensile strength. Therefore, the ductility minimum cannot be explained solely from the existence of the grain boundary microcracks.

Figures 3 and 4 show the nominal stress-

Fig. 2 Total elongation of Cu-0.25%Zn alloy as a function of testing temperature.

Fig. 3 Stress-strain curves of copper.

strain curves of the copper and the Cu-Zn alloy tested at the strain rate of $4 \times 10^{-3} \text{ s}^{-1}$, respectively. From these illustrations, it is found that there should be two types of deformation mode, *i.e.*, a low temperature deformation mode and a high temperature deformation one. The low temperature deformation is characterized by an abrupt fracture with a small elongation beyond necking in the specimen. In the high temperature deformation, a large elongation is observed even after necking. Figures 3 and 4 indicate that the ductility minimum occurs at a transition temperature at which the deformation mode is changed. The above finding was also true in

Fig. 4 Stress-strain curves of Cu-0.25%Zn alloy.

all tests stretched at strain rates other than $4 \times 10^{-3} \text{ s}^{-1}$. These two deformation modes are considered to be determined by work hardening exponent and strain rate hardening exponent⁽⁹⁾. Therefore, the occurrence of the ductility minimum can be explained in terms of the variation of both hardening exponents with temperature. Namely, at temperatures lower than DMT, total elongations decrease with decreasing the work hardening exponent^{(10)†}, which becomes smaller with temperature. On the other hand, at higher temperatures, as discussed by Yamagata *et al.*⁽²⁾ and Igata *et al.*,⁽⁶⁾ total elongations increase with an increase of the strain rate hardening exponent, which becomes larger with temperature. The ductility minimum is thus caused at intermediate temperatures. Since the grain boundary microcracks will decrease the ductility of specimens but will have little effect on the deformation modes, the ductility minimums will be related mainly to the intrinsic properties such as the work hardening exponent and the strain rate hardening exponent as discussed above.

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† At the lower temperatures, the total elongation is considered to be nearly equal to a uniform strain which is determined by the work hardening exponent, because of a small local elongation.

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Naohiro Igata, Kazuya Miyahara and
Kaoru Tanaka

Department of Metallurgy and Materials Science,
Faculty of Engineering, The University of Tokyo,
Hongo, Bunkyo-ku, Tokyo 113, Japan.

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