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Fatigue behavior of nano-grained copper prepared by ECAP

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Abstract

In order to study the fatigue behavior of ultra-fine grained copper, rotating bending fatigue test has been carried out. After 4 passes of ECAP (equal channel angular pressing) with Bc route, grains with about 300 nm diameter were formed. Specimens were fatigued at three constant stress amplitudes; σ_a = 240, 120 and 80 MPa. Significant differences in morphological feature in fatigued surfaces between high and low cyclic deformation amplitudes were observed. To clarify the formation process of surface damage, morphological changes in surface damage caused by cyclic stresses were monitored successively by optical microscope and SEM.

Keywords: Nano-grain; Copper; ECAP; Fatigue; Fatigue damage

1. Introduction

To improve strength of copper, addition of other alloying elements and heat-treatments have been carried out. However, this way leads to considerable drop of electric conductivity and ductility. Another way to achieve high strength/ductility is refinement of grain size. The refinement of copper grain results from the combination of recrystallization and severe plastic deformation. The equal channel angular pressing (ECAP) is one of the most frequently used processes to obtain ultra-fine structured materials [1]. With regard to a copper, average grain size of 200–300 nm has been obtained by ECAP [2,3]. On the other hand, fatigue characteristics must be clarified to use the ultra-fine grained materials as the members of machines and structures, however, a few reports have studied the fatigue characteristics of ultra-fine grained materials [4].

In the present study, fatigue tests of an ECAP processed copper with grain size of about 300 nm were performed. Successive observations of the surface morphology were carried out to clarify the fatigue mechanism of ECAP processed copper. Putting the experimental results from the observation of each microstructure, fatigue damage of copper with ultra-fine grain was discussed.

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2. Experimental procedures

The material used was 99.99% pure oxygen-free copper. Before ECAP process, the material was normalized at 500 °C for 1 h. Repetitive ECAP was accomplished by Bc route. ECAP process was carried out at room temperature up to 4 passes. After ECAP, microstructure and mechanical properties were studied. The observations of fatigue damage on the specimen surface were carried out with an optical microscope and SEM.

3. Results and discussion

Table 1 shows the mechanical properties of the normalized and ECAP processed material.

Fig. 1 shows typical TEM micrographs and the matching SADP (selected area diffraction patterns of center area, 1 μm in diameter) for processed materials after: (a) one pass and (b) four passes. After one pass of ECAP, micro-deformation bands with an average thickness of about 300 nm are observed. The SADP forms a net, however the diffraction spots have a slight diffusion, indicating that there are small misorientations between deformation bands.

Fig. 2 shows the fatigue endurance curve (S–N curve) for normalized and ECAP processed (4 passes) copper. In general, the value of fatigue limit stress at 10^7 cycles, σ_w, for the metals with conventional grain size is roughly proportional to the static tensile strength. Additionally, σ_w increases with a decrease in grain size, e.g. σ_w for annealed steels with average grain sizes

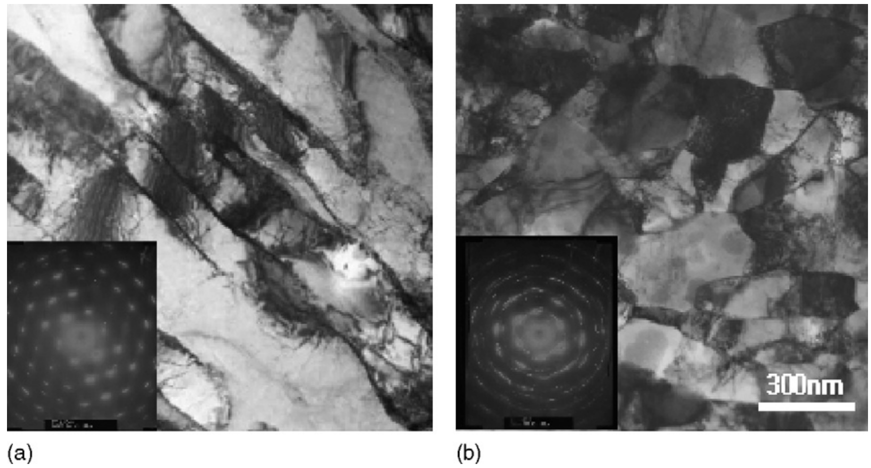

Fig. 1. TEM micrographs of ECAPed copper: (a) after one pass of ECAP and (b) after four passes of ECAP.

Table 1
Mechanical properties of copper in different states

Number of passes	Y.S. (MPa)	U.T.S. (MPa)	Elon. (%)	Vickers hardness
0	63	232	51	63
1	319	339	25	128
4	358	413	21	138

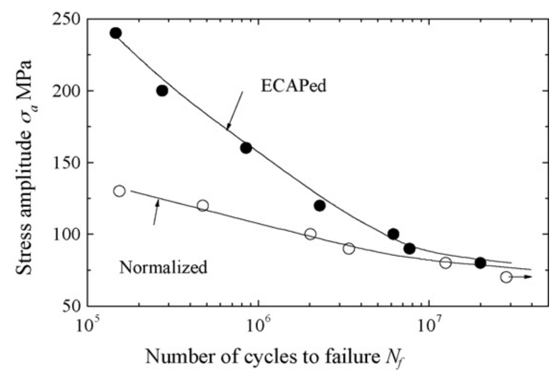

Fig. 2. Fatigue endurance curve for normalized and ECAP processed (4 passes) copper.

$d = 25$, 40 and 70 μm was $\sigma_w = 245$, 225 and 205 MPa, respectively. However, there is no difference in σ_w between normalized and ECAP processed copper, nevertheless the tensile strength of ECAP processed copper is about 1.8 times larger than normalized one. For the stress beyond fatigue limit stress, fatigue life of ECAP processed specimens is larger than normalized one, and the difference in fatigue life increases with an increase in stress amplitude. Generally, fatigue limit is dependent on the yield strength of metal, however nano-grained copper in this study showed strange value of fatigue strength.

Fig. 3(a) shows the OM micrograph of normalized specimen fractured by cycling at $\sigma_a = 120$ MPa ($N_f = 4.739 \times 10^5$). As observed other ordinary grained materials, few specific grains are partially damaged and slip bands are developed along the limited slip planes within such grains. Fig. 3(b and c) shows the

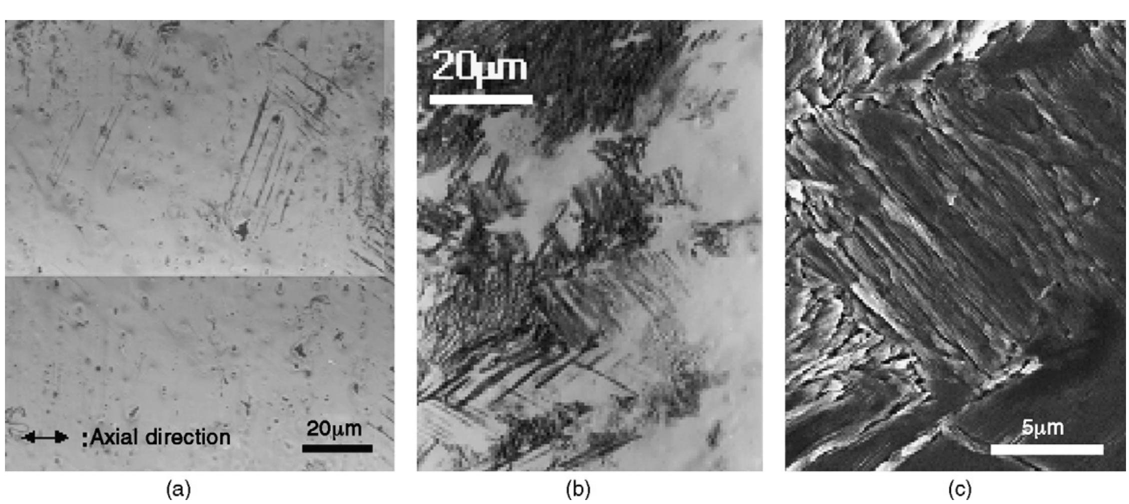

Fig. 3. Surface morphology of normalized and ECAPed specimen after the fracture, $\sigma_a = 120$ MPa. (a) Normalized OFC, $N_f = 4.739 \times 10^5$; (b) ECAPed OFC, $N_f = 3.75 \times 10^6$; (c) SEM magnification of the (b).

OM and SEM micrograph of ECAPed specimen. Fatigue damage is observed within entire surface region. And, also observed that damaged regions gradually become dark with cycling. The surface morphology of ECAP processed copper after the repetitions of stress is quite different from that of normalized copper.

4. Conclusions

Experimental results suggest that the fatigue behavior of ultra-fine grained copper processed by ECAP is quite different from conventional grained coppers. Although the static tensile strength is 1.8 times higher than conventional grained copper, no increase in fatigue limit stress is obtained. Therefore, ultra-fine grained structure contribute to the increase in resistance to the macroscopic deformation, conversely an increase of the resistance to the repetitions of microscopic deformation are negligible. This means that small grain cluster could easily move and accumulation of damage were considerably accelerated in grain boundary regions which was stressed. The value of stresses used in the present study is relatively small, never produces the macroscopic plastic deformation.

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