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Fatigue strength of ODSC at elevated temperature

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Abstract

Rotating bending fatigue tests were carried out for an aluminum oxide dispersion strengthening copper alloy at room temperature and 350°C in order to investigate the fatigue strength of a notched member at elevated temperature. The results were discussed based on the influence of oxidation at elevated temperature on the crack initiation and propagation behavior. At the fatigue limit, which was defined as the limit for fracture at stress repetitions of 10^7, non-propagating cracks were observed at the notch roots of sharply notched specimens at both temperatures. The morphology of the crack at room temperature was ductile, while the ones at 350°C was brittle due to surface oxidation. The fatigue limit for crack initiation at 350°C decreased by brittleness of the surface oxide and softening of the matrix. On the other hand, the fatigue limit for crack propagation was higher at 350°C than at room temperature in spite of a decrease in static strength at 350°C. A thick oxide layer was observed around a non-propagating crack at 350°C. Therefore, the increase in fatigue limit for crack propagation at 350°C was caused by the suppression of crack propagation due to oxide induced crack closure.

1 Introduction

Pure copper and copper alloys have been used as materials for wiring harnesses, heat exchangers and so on because of their excellent properties of electrical and heat conductivities, corrosion and so on. However, their strength is not so high. Therefore, high strength copper alloys with the excellent properties of pure copper have been developed. For example, an aluminum oxide dispersion strengthening copper alloy not only has high electrical and heat conductivities, but also static

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but also static strength at room and elevated temperatures [1-3]. This alloy is expected to be used for the cooling tube of the heat exchanger for fusion reactor diverters in the ITER [4]. In the case where this alloy is used as a material for a heat exchanger, the thermal stress and vibration caused by fluid flow were applied cyclically at elevated temperatures. However, studies on the fatigue properties of this material, especially at elevated temperatures, were very limited [5-8].

In the present study, rotating bending fatigue tests were carried out for an aluminum oxide dispersion strengthening copper alloy at room temperature and 350°C in order to investigate the fatigue strength of a notched member at elevated temperature. The results were discussed based on the influence of oxidation at elevated temperatures on the crack initiation and propagation behavior.

2 Experimental procedures

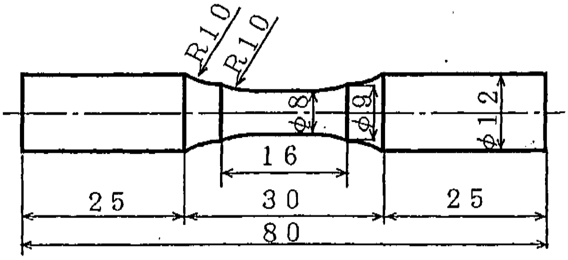
The material used was a round bar (19mm in diameter) of an aluminum oxide dispersion strengthening copper alloy, Grid Cop AL25 (Trademark of SCM Co. Ltd, USA, mentioned as ODSC hereinafter), produced by the powder metallurgy method and followed by the internal oxidation treatment. The chemical compositions (wt. %) were 0.26Al, 0.002Fe, 0.0006Pb, 0.016B and remainder Cu. The material was annealed at 1000°C for 1h considering that the temperature of diffusion-join between ODSC and SUS 316 planed in ITER is about 1000°C [4]. Figure 1 shows shapes and dimensions of specimens. In case of the observation of crack initiation and propagation behavior, a blunt and shallow notch was machined at the center of smooth specimen to localize the crack initiation site, Fig.1 (c). The strength reduction factor K_f was ~1.03 in the partially notched specimen. Therefore, the behavior of crack initiation and propagation in the partially notched specimen can be regarded as the one in a smooth specimen.

Prior to fatigue tests, specimens were electro-polished to remove the surface layer by ~20μm in smooth and partially notched specimens and ~10μm in notched specimens. Observations of fatigue damage and the measurements of crack length were carried out under an optical microscope directly or by using the plastic replication technique. The stress value referred to is the nominal stress amplitude, σ, at net area by ignoring the existence of partial notches. The fatigue tests were carried out at room temperature and 350°C in air (350°C was chosen considering the service condition of the cooling tube of a heat exchanger for the fusion reactor diverters in ITER).

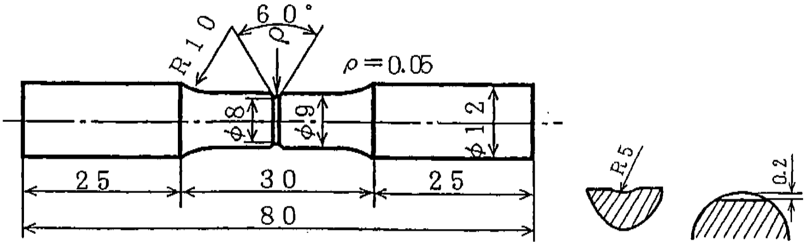
Fatigue tests were carried out using the Ono-type rotating bending fatigue testing machines with a capacity of 100N· m operating at about 55 Hz in air.

3 Experimental results and discussion

Figure 2 and Table 1 show stress strain curves and mechanical properties, respectively, at room temperature and 350°C. Both of static strength and ductility fairly decrease at 350°C.



(a) Smooth specimen



(b) Notched specimen (c) Detail of partial notch

Figure 1: Shapes and dimensions of specimens.

Figure 3 shows S-N curves for smooth and notched specimens at both temperatures. Figure 4 shows σ/σ_B –N curves considering softening at elevated temperature, where σ_B is the tensile stress at each temperature. In Figs. 3 and 4, the limiting stresses for crack initiation were also plotted by half solid marks at both temperatures, because non-propagating cracks were observed in notched specimens at the fatigue limit at both temperatures, as discussed later. Although the fatigue strength decreases at 350°C in a wide region, relative fatigue strength considered as the decrease of static strength due to softening is high at 350°C. In the case of notched specimens, in particular, fatigue strength around 10^7 is higher at 350°C than at room temperature. This means that there is a strengthening effect of the fatigue strength at elevated temperature, although the static strength decreased.

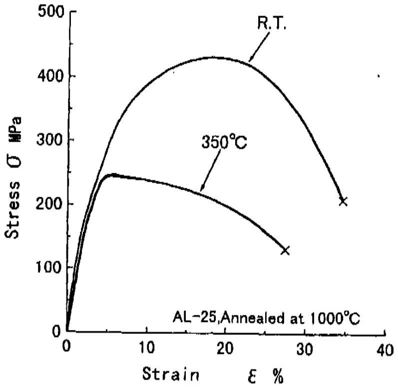


Figure 2: Stress strain curves.

Table 1: Mechanical properties.

	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	σ_T (MPa)	δ (%)	ψ (%)
R.T.	366	431	1220	31	83
350°C	195	247	392	25	66

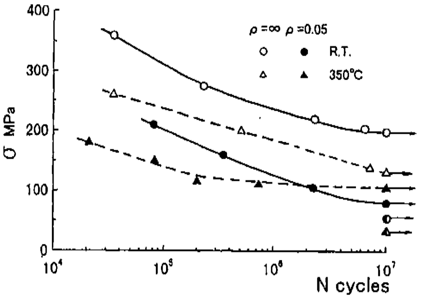


Figure 3: S-N curves.

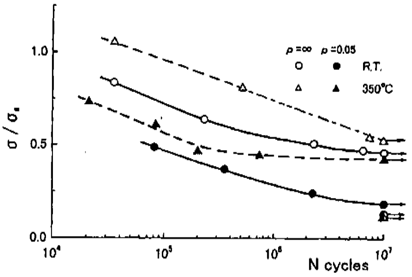
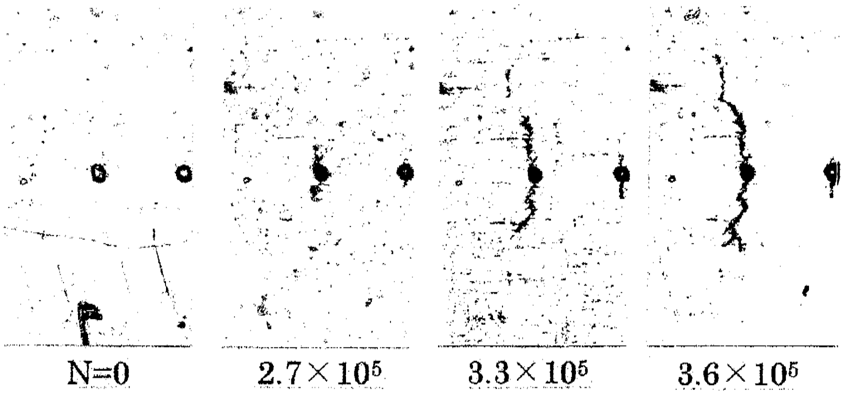
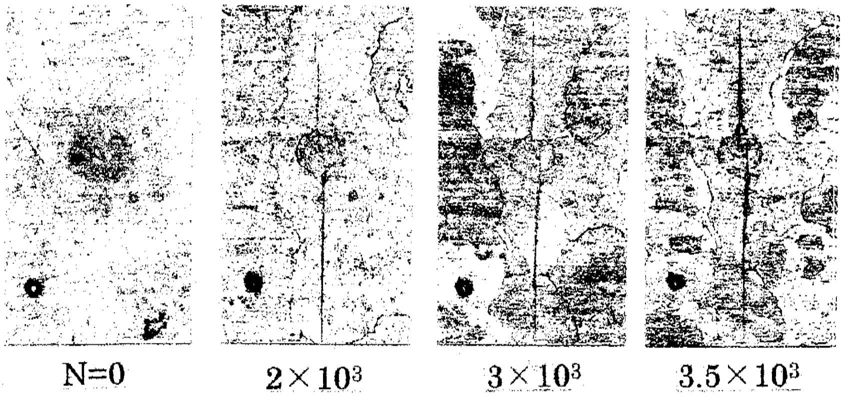


Figure 4: σ/σ_B curves.

Figure 5 shows the change in surface state of the specimens due to stress repetitions at both temperatures. Many cracks initiate at small voids and propagate in a zigzag manner at room temperature, while a fairly longer and brittle crack is observed suddenly at 350°C because of the covering of oxide films.



(a) R.T. (σ=220MPa, Nf=4.7×10^5cycles)



(b) 350℃ (σ=270MPa, Nf=7.7×10^3cycles)

Figure 5: Change in surface state of specimen due to stress repetitions.

Figure 6 shows crack growth curves at both temperatures. The initiation and propagation of cracks are delayed at 350°C in the case where they were compared considering the difference in static strength.

Figure 7 shows photographs of the surface state and the cross section of cracks at 350°C. The surface of the specimen is covered with oxide films of a few μm and the films are cracked in a brittle manner and many cracks have initiated. However, these cracks do not reach to the matrix at this stage. Therefore, it is considered that the cracking of oxide films is generated by the difference in ductility between the oxide films and the matrix. This means that the cracking of

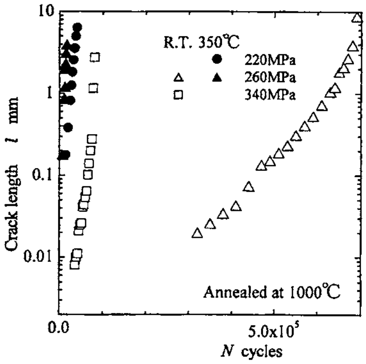
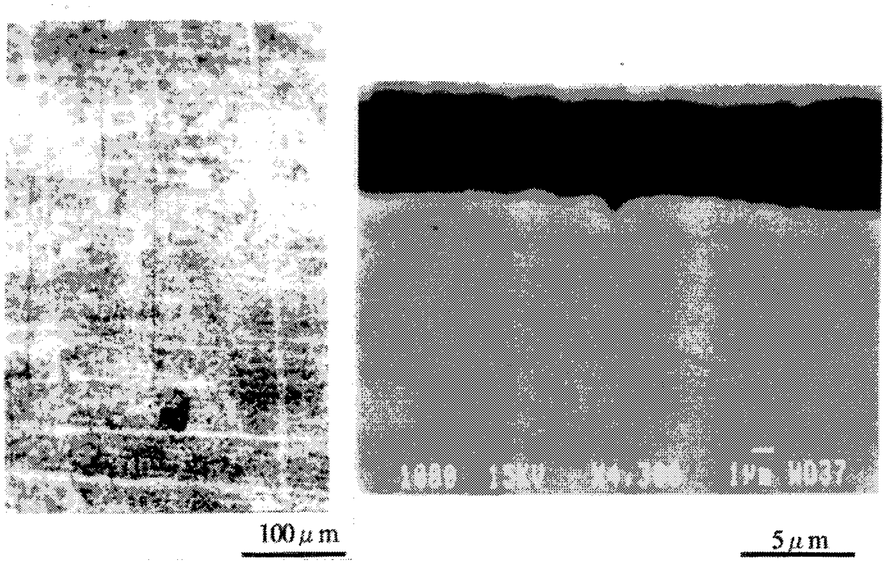


Figure 6: Crack growth curves.



(a) Surface

(b) Cross section

Figure 7: Cracking of oxide film.

oxide films promotes the early propagation of cracks owing to the notch effect, although surface slip is suppressed by the formation of oxide films.

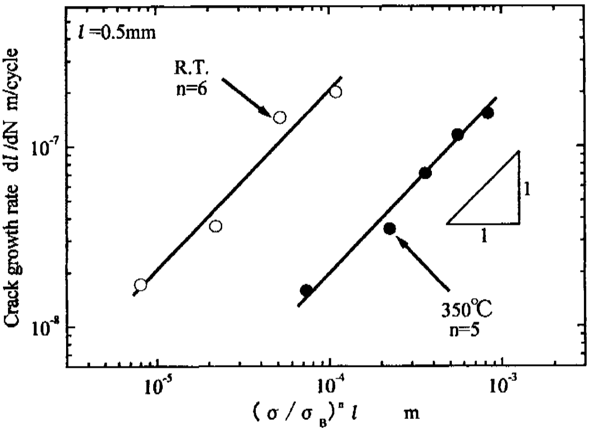


Figure 8: $d\ell/dN$-$(\sigma/\sigma_B)^n\ell$.

Figure 8 shows the comparison of the resistance of crack growth at both temperatures. This comparison was evaluated by the following equations [9,10] based on the relation of $d\ell/dN \propto \ell$ as shown in Fig.6.

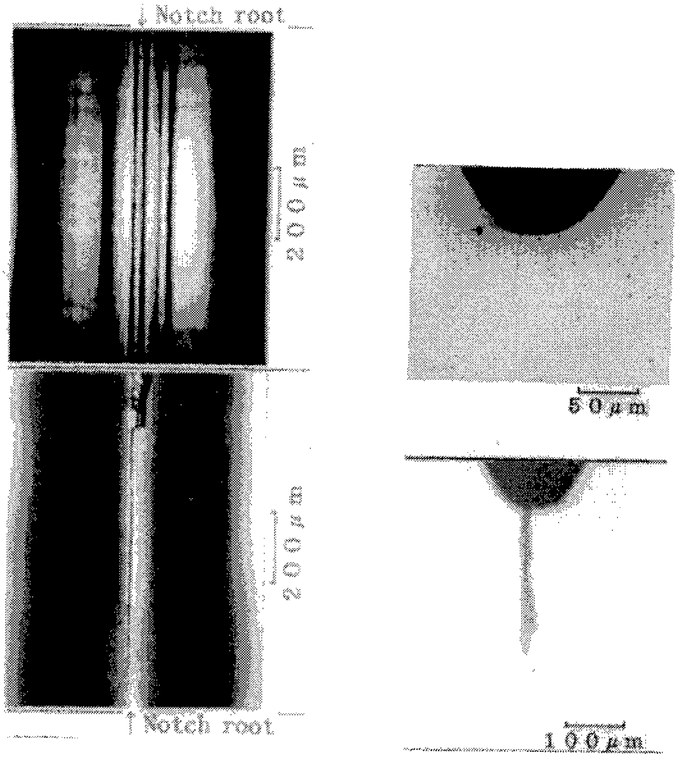
$$d\ell/dN = C\sigma^n \ell \qquad (1)$$

$$d\ell/dN = C'(\sigma/\sigma_B)^n \ell \qquad (2)$$

The second equation is derived by considering the change in the static strength due to the difference of tested temperature. That is, the physical meaning of the reciprocal of constant, 1/C', is considered as the resistance of crack growth. As seen from the figure, the resistance of crack growth is higher at 350°C than at room temperature.

Figure 9 shows the surface state of a notch root and its cross section of a notched specimen after 10^7 repetitions under the stress of fatigue limits at each temperature. Non-propagating cracks are observed at both temperatures. The feature of cracks is brittle at 350°C, although it is ductile at room temperature, similar to the results for the smooth specimen. On the other hand, an oxide film is observed between the crack face at 350°C. Moreover, oxides are formed around the crack of the notched specimen.

Figure 10 shows the hardness around a non-propagating crack of the notched specimen at 350°C. Marked hardening around the crack is confirmed.



(a) Surface

(b) Cross section

Figure 9: Surface and cross section of non-propagating crack.

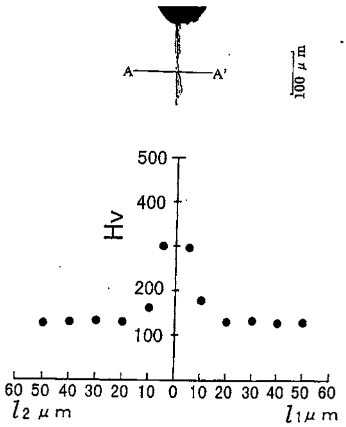


Figure 10: Hardness around crack.

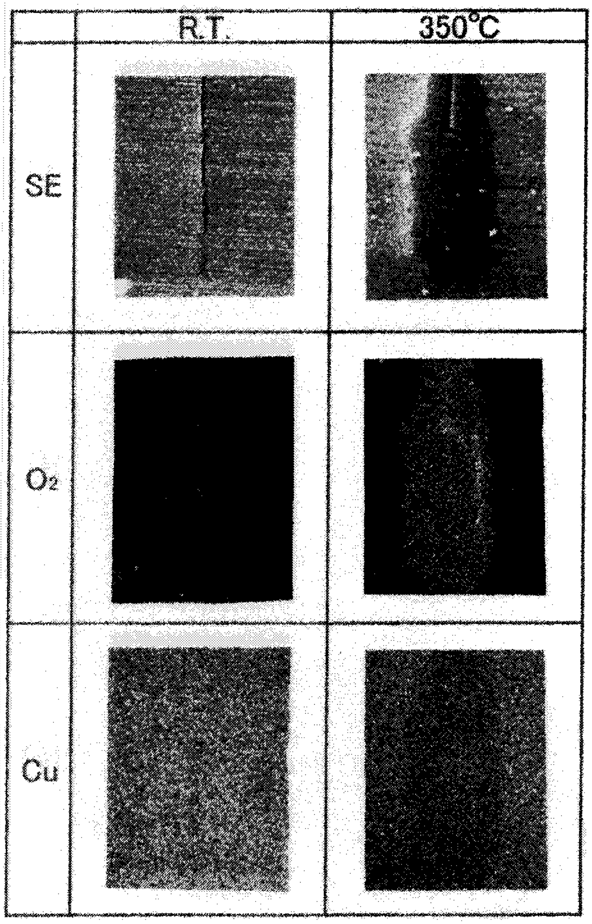


Figure 11: EPMA analysis around crack.

Figure 11 shows EPMA analysis around the crack. A thick oxide layer is observed. From these results, the suppression of crack growth due to oxide induced crack closure is the main reason why the fatigue strength at the same relative stress σ/σ_B is higher at 350°C than at room temperature.

4 Conclusions

Rotating bending fatigue tests were carried out using smooth and notched specimens of an aluminum oxide dispersion strengthening copper alloy at room temperature and 350°C in order to investigate the notch effect in fatigue at elevated temperature. Softening at 350°C decreased both static and fatigue strengths. However, fatigue life at the same relative stress σ/σ_B was longer at

350°C than at room temperature, especially in the notched specimen. This was caused by the suppressions of crack initiation due to surface oxidation and its propagation due to oxide induced crack closure. The latter suppression effect was marked in the notched specimen, so that the fatigue limit was higher at 350°C than at room temperature. The morphology of the initial crack was straight and brittle at 350°C, whereas it was ductile and zigzag manner at room temperature.

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