The Influence of Grain - Boundary Migration on the Fatigue Life of O. F. H. C. Copper and a Copper Alloy at 490°C

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SUMMARY

High-strain low-cycle fatigue tests have been carried out at 490°C on a commercial copper dispersion alloy containing 1.7% Fe, 0.9% Co, 0.4% Sn and 0.1% P. The role of grain-boundary migration, grain-boundary sliding and crack linkage upon the fracture process have been studied. The presence of the dispersion retards grain-boundary migration which causes the boundaries to orientate preferentially at ∿45° to the stress axis in oxygen-free high-conductivity (o.f.h.c.) copper. Thus, the fatigue life is improved.

INTRODUCTION

During low-cycle fatigue at temperatures in the regime of half the absolute melting point, the processes leading to failure are similar to those in creep. Cavities are nucleated at stress concentrations generated by grain-boundary sliding (1) and grow by vacancy condensation (2), continued grain-boundary sliding (1) and plastic tearing (3). The cavities eventually link to produce an intergranular mode of fracture which is controlled by a void-sheet process or a Griffith-Orowan criterion (4). Grain-boundary migration often accompanies high-temperature fatigue and produces a "diamond" structure with grain boundaries aligned at 45° to the stress axis. This phenomenon is prevalent in pure metals (5,6,7) but its effect upon fatigue life is not well documented.

In the present work, a study has been made of the effect of plastic strain amplitude on the low-cycle fatigue life of a commercial copper dispersion alloy at 490°C. This alloy has been heat treated to produce a particle dispersion which might be expected to retard grain-boundary migration. The results are compared to the properties of o.f.h.c. copper tested under identical conditions, where grain-boundary migration is known to occur (7).

EXPERIMENTAL

The materials used in this investigation were o.f.h.c. copper and a commercial copper dispersion alloy containing 1.7% Fe, 0.9% Co, 0.4% Sn and 0.1% P. The copper specimens were annealed for 1 hr. at 600°C in vacuum to produce an equiaxed grain size of 80μm mean diameter. To achieve the same grain size in the alloy, specimens were annealed for 5 min. at 985°C to reprecipitate the particles dissolved at 985°C. Electron microscopy showed that the particles nucleated on grain boundaries and those which had not dissolved retarded grain-boundary migration during annealing.

Fatigue tests were performed in air using an Instron. Specimens were strained equally in tension and compression at a constant crosshead motion over a range of strain amplitudes from 0.09 to 0.013 giving frequencies between 0.5 and 3.8 cpm. After testing, the angular distributions of grain boundaries relative to the stress axis were plotted in 10° intervals by measuring at least 200 angles on optical photomicrographs of longitudinal sections.

RESULTS

Figure 1 shows the effect of plastic strain range on the fatigue lives of both materials at 490°C. The results are plotted according to the Coffin relationship (8) and the tensile ductility at 490°C is recorded at 0.25 cycles to failure. The tensile ductility of o.f.h.c. copper is higher than the ductility of the copper alloy but at plastic strain ranges below 0.08, o.f.h.c. copper exhibits lower fatigue lives. Grain-boundary migration occurred during the fatigue of o.f.h.c. copper, without a significant change in grain size (Fig. 2). On the other hand, the copper alloy showed no tendency to develop a "diamond" configuration (Fig. 3). Interrupted tests on o.f.h.c. copper showed that most migration occurred early in the fatigue life at low plastic strain amplitudes, e.g., after 5% of the expected fatigue life at a strain range of 0.02, considerable alignment of boundaries at 45° to the stress axis had occurred. However, a similar distribution was not observed until at least 50% of the expected fatigue life at a strain amplitude of 0.08. These observations imply that the initial rate of migration, measured as a function of fraction of fatigue life, decreases with increasing strain amplitude. Extensive cavitation was delayed until grain-boundary migration had ceased (6). The level of intergranular cracking in o.f.h.c. copper specimens was higher than in specimens of the copper alloy. Failure in both materials was intergranular at low strain

amplitudes and at a strain amplitude of 0.08, a small proportion of the fracture surface appeared to be transgranular.

DISCUSSION

The results point to a determining influence of grain-boundary migration upon low-cycle fatigue lives under conditions where failure occurs by the nucleation, growth and linkage of intergranular cavities. Grain boundaries in o.f.h.c. copper tend to migrate to planes which experience the maximum alternating shear stress. Extensive grain-boundary sliding then initiates intergranular cracking which causes low fatigue lives. At 490°C, the presence of a particular dispersion of precipitate particles maintains a random distribution of boundaries by retarding grain-boundary migration. Only those boundaries already at 45° to the stress axis experience the highest shear stress. Thus, the incidence of intergranular cracking is low so that the fatigue life is improved.

The difference between the fatigue lives of the two alloys decreases with increasing plastic strain range until at a strain range of 0.08 they exhibit similar lives. As the strain range is increased, the fracture mode changes from one which is intergranular to one which is partly transgranular. This trend is in agreement with the observations of Coffin (8). The propagation path of a transgranular crack would not be expected to depend significantly upon the orientation of grain boundaries and this probably accounts for at least part of the similarity in fatigue lives at high strain ranges. The rate of migration is also of considerable importance in controlling fatigue lives. As the strain range is increased, the frequency is decreased and tensile or creep conditions are approached. Alignment of grain boundaries at 45° to the stress axis is not observed in o.f.h.c. copper tensile specimens tested to failure at 490°C and it is clear that a compressive component in the testing cycle is necessary to align the boundaries. Thus, low strain amplitudes might be expected to favour development of the "diamond" configuration of grain boundaries. At large strain amplitudes, migration continued to occur after 50% of the expected fatigue life; this would tend to isolate cavities within grains where they cannot contribute to intergranular failure. These considerations also account for the observed similarity in fatigue lives of the two materials at large strain amplitudes.

CONCLUSIONS

1. Migration of grain boundaries to planes at 45° to the stress axis occurs during low-cycle fatigue of o.f.h.c. copper at 490°C and is ultimately responsible for low fatigue lives at low strain amplitudes.

2. Grain-boundary migration can be prevented by the introduction of a suitable particle dispersion with a subsequent improvement in fatigue life. Most benefit is derived from the dispersion at relatively low strain amplitudes.

3. The rate of migration and mode of fracture both determine the influence of boundary migration upon fatigue lives.

ACKNOWLEDGEMENTS

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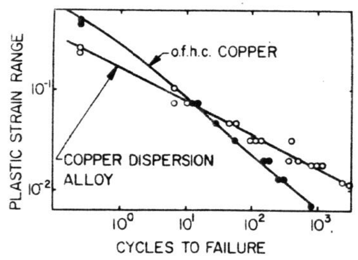


FIG. 1: The fatigue behaviour of o.f.h.c. copper and the copper dispersion alloy at 490°C.

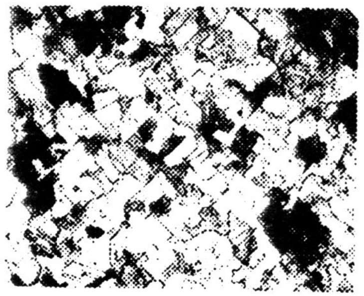
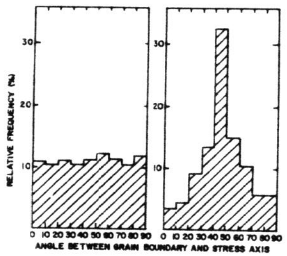


FIG. 2: Optical photomicrograph showing diamond configuration in o.f.h.c. copper (X60). Stress direction horizontal.



(a) (b)

FIG. 3: Distributions of grain boundaries in: (a) copper dispersion alloy; (b) o.f.h.c. copper. Strain amplitude= 0.027.