THE EFFECT OF A PRIOR CYCLIC STRENGTHENING ON THE SUBSEQUENT FATIGUE BEHAVIOUR OF POLYCRYSTALLINE COPPER

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The influence of a prior cyclic strengthening on the subsequent fatigue properties of polycrystalline copper was investigated at room temperature. To this end specimens were firstly precycled in vacuum under different cyclic plastic amplitudes and then electropolished to eliminate surface damage. The fatigue behaviour and the surface damage characteristics of these precycled specimens were established in air under a constant plastic strain amplitude of $6x10^{-4}$; the results were compared to that observed on annealed copper directly cycled at this amplitude.

INTRODUCTION

The study of fatigue damage accumulation in low-high or high-low step tests is frequently approached by phenomenological and global methods without separating the role of the different mechanical and physical factors determining cyclic damage.

In particular, very few work has been devoted to understand the role of the internal dislocation substructures previously formed by cyclic deformation on the subsequent fatigue behaviour of the material especially when submitted to a lower cyclic plastic strain amplitude. Indeed it can be expected that in this case, strain history effects or changes in cyclic plastic strain distribution in the bulk could significantly modify fatigue damage characteristics which are known to control the fatigue resistance such as the microcrack density, the secondary microcracks length or the major crack length evolution, with regard to that established from constant amplitude fatigue tests. A better knowledge of

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these strain history induced modifications in fatigue damage would permit to improve life predictions models for multi level testing conditions.

With this aim fatigue experiments have been conducted on polycrystalline copper at room temperature using a high vacuum environment for precycling the specimens ; by this way they can be cycled up to large cumulative plastic strain levels with a limited surface microcracking damage. We report in this paper results obtained on smooth precycled specimens from which all surface damage such as microcracks or surface irregularities has been removed to only conserve the dislocation substructure formed in the bulk by precycling and which have been then submitted to a constant cyclic strain amplitude in air.

EXPERIMENTAL METHODS

Annealed cylindrical smooth specimens of an OFHC copper of commercial purity (99,99 %) with a mean grain size of 30 µm were cycled in tension-compression at room temperature in air or in a high vacuum ($6x10^{-4}$ Pa) under plastic strain control. Three plastic strain amplitudes were selected : $\Delta\varepsilon_p/2 = 6x10^{-4}, 2x10^{-3}, 5x10^{-3}$.

The vacuum environment was used to precycle the specimens under different cyclic plastic amplitudes and to different accumulated plastic strains. Indeed, tests in vacuum permit to reach large cumulative plastic strains associated with a low surface damage at the opposite of what is obtained in air (1). An electropolishing of these vacuum cycled specimens is then sufficient to remove all the surface damage and to prepare smooth specimens with different internal dislocation substructures.

These predeformed specimens were then cycled in air under a constant plastic strain amplitude of $\Delta\varepsilon_p/2 = 6x10^{-4}$ and their behaviour related to the stress-strain response, the fatigue life or the surface microcracking features were compared to that observed on the annealed specimens.

RESULTS

Fig. 1 shows the cyclic hardening curves ($\Delta\sigma/2$-N), stress amplitude vs the number of cycles for annealed specimens cycled in vacuum under constant plastic strain amplitudes. Letters A to F in Fig. 1 indicate the different states of precycling reached for the six precycled specimens investigated in this work. It must be noted that specimens A, D and F have been cycled up to a number of cycles equivalent to the fatigue life obtained in air on the annealed material for each of the three cyclic plastic strain amplitudes considered here : $6x10^{-4}$, $2x10^{-3}$ and $5x10^{-3}$ respectively.

Data related to specimens A and F concerning either the precycling conditions or the subsequent fatigue life and stress response when cycled under $\Delta\varepsilon_p/2 = 6x10^{-4}$ in air are reported in Table 1.

Specimen	Saturation stress $\Delta\sigma/2$ (MPa)	Fatigue life N_F, cycles
Reference	115	117 000–125 000
A - precycled at $6x10^{-4}$ (ε_{pcum}=288)	119	150 000
B - precycled at $2x10^{-3}$ (ε_{pcum}=12)	117	125 000
C - precycled at $2x10^{-3}$ (ε_{pcum}=24)	120	110 000
D - precycled at $2x10^{-3}$ (ε_{pcum}=40)	124	144 000
E - precycled at $5x10^{-3}$ (ε_{pcum}=16)	125	130 000
F - precycled at $5x10^{-3}$ (ε_{pcum}=40)	137	127 000

Table 1 – Cyclic stress amplitude at saturation and fatigue life for annealed and precycled copper specimens cycled at $\Delta\varepsilon_p/2 = 6x10^{-4}$ in air.

In the case of specimen A, which has been precycled at $6x10^{-4}$, cyclic hardening continuous to follow the same curve as in vacuum during 150 000 cycles that is for a number of cycles very close to the fatigue life of the reference annealed material.

Fig. 2 illustrates the cyclic behaviour of specimens B, C and D previously precycled under $\Delta\varepsilon_p/2 = 2x10^{-3}$ to different accumulated plastic strain levels. For these specimens the cyclic behaviour under $\Delta\varepsilon_p/2 = 6x10^{-4}$ is characterized by a progressive softening which starts after about 50 cycles to lead to a quasi-saturation state after 3000 cycles. However a strain memory effect is observed on the precycled specimens since the stress-strain relationship corresponding to the annealed material is never exactly recovered. As it can be noted in Fig. 2 for specimens B, C and D, this increase in the flow stress depends on the accumulated plastic strain level ; nevertheless, for all the three specimens precycled at $2x10^{-3}$ the memory effect remains minor.

However as it appears in Fig. 3, the strain history effects cannot be ignored for specimens prestrained at $5x10^{-3}$ particularly for those cycled up to a high number of cycles ; indeed, for specimen F the flow stress at the imposed cyclic plastic strain amplitude of $6x10^{-4}$ is increased by a factor 1.3 with respect to the annealed material.

This behaviour is associated with the dislocation substructures formed during precycling in the specimen F, which are composed of equiaxed cells in the proportion of 80 per cent. This structure, which is observed to remain unchanged during cycling in air at $6x10^{-4}$, is therefore significantly different from the substructures directly formed at $6x10^{-4}$ in the annealed material and which are composed of veins, walls and channels and in a short majority of elongated cells (2).

On the other hand, whatever the stress amplitude reached at saturation, all the precycled specimens exhibit the same fatigue resistance as the reference annealed one (see Table 1).

Interrupted tests conducted on precycled specimens show that no significant differences appear on the cyclic prestrained samples concerning the major crack length evolution (2). However an increase in the surface microcrak density can be observed at failure on the precycled specimens. This is illustrated in Fig. 4 by histograms giving the distribution in number and surface length for the population of microcracks observed at failure on the annealed specimen and on the specimen C previously cycled under $\Delta\varepsilon_p/2 = 2x10^{-3}$.

Although the number of cycles to failure of these specimens are very similar, 117 000 cycles and 110 000 cycles respectively, the microcrack density for the specimen C is twice higher (67 microcracks/mm^2 instead of 31 microcracks/mm^2). It can be noted that this increase in the number of surface microcracks concerns especially the very small cracks with a length lower than 100 μm.

CONCLUSIONS

It has been shown using electropolished specimens previously precycled in vacuum that strain history effects on the flow stress levels can be observed in copper for high-low fatigue step tests which are associated with the dislocation substructures formed under high strain amplitudes. These effects are accompanied by an increase in the number of microcracks initiated during the second part of the step test. However modifications induced in the internal microstructures have no influence on the fatigue life of the predeformed specimens when they are cycled at a lower strain amplitude after repolishing. These results suggest that the internal dislocation substructure and the associated flow stress level have a weak influence on the rate of initiation and growth of the main crack which appears to be controled in copper by the cyclic plastic strain amplitude (3).

REFERENCES

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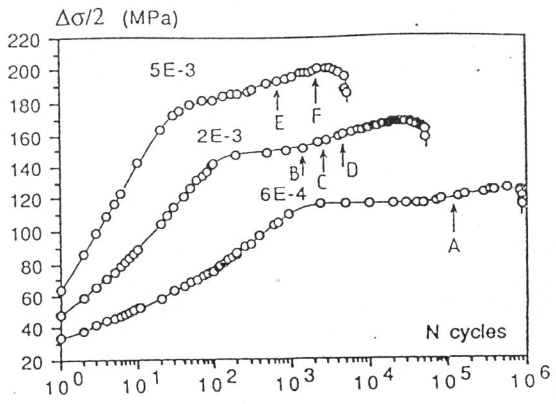


Figure 1 : Cyclic behaviour in vacuum of annealed copper and conditions of precycling.

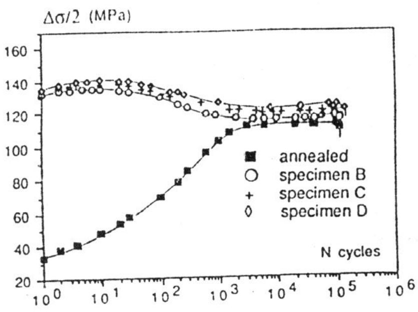


Figure 2 : Cyclic behaviour at 6×10^{-4} in air of specimens B, C and D precycled at 2×10^{-3}.

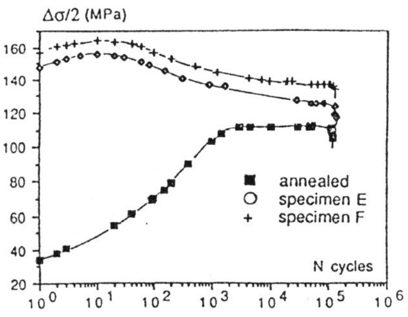
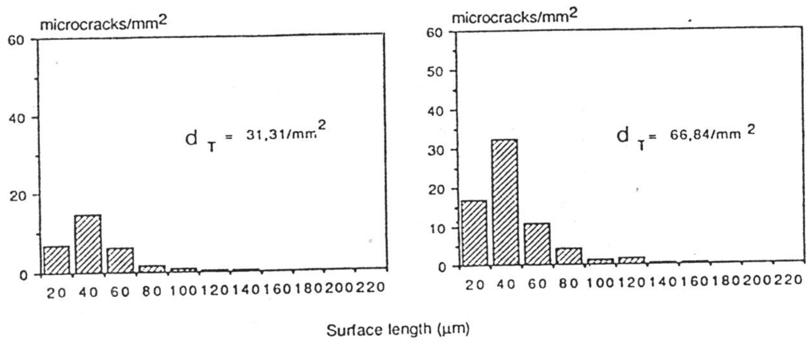


Figure 3 : Cyclic behaviour at 6×10^{-4} in air of specimens E and F precycled at 5×10^{-3}.



(a) (b)

Figure 4 : Number of the surface microcracks per mm^2 at failure vs. their surface length. (a) annealed specimen, (b) specimen B precycled at 2×10^{-3}.