CHARACTERIZATION OF FATIGUE DAMAGE PROCESSES IN A FINE-GRAINED COPPER TESTED IN AIR AND IN VACUUM.

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The evolution of the surface fatigue damage in air and in vacuum with the number of fatigue cycles is characterized in both environments by the measurement of the density and the mean length of the surface microcracks.

From these data the effect of the air environment on the different stages of fatigue damage is discussed. The air environment fastens the fatigue damage during all the stages. Moreover, in high cycle fatigue conditions, the environment induces different microcrack nucleation mechanisms : crystallographic in air, intergranular in vacuum.

INTRODUCTION

The atmospheric environment generally reduces fatigue life of metals and alloys. When experiments are conducted in vacuum or in inert atmospheres, fatigue life is often longer than in air (1).

Although this behaviour is known since fifty years, the role of the environment on the different stages of the fatigue damage leading to failure is still discussed. In particular, its effect on the stage of crack initiation still remains a controversed subject (2). In the case of copper, oxygen is the primary damaging element, and its action is enhanced by water vapour (3). Two opposite points of view about the effect of environment on crack nucleation processes can be found in the litterature. Thompson et al. (4) have written that in air, persistent slip bands become regions of high oxygen concentration due to cyclic strain-induced vacancies generation. Then, this oxygen by diffusing in and near the bands could weaken the crystal, in a first time, leading to early microcracks formation near the surface. In a second time, oxygen prevents rewelding of nascent cracks and accelerates the nucleation process. On the contrary, Wadsworth and Hutchings (3) do not agree that gaseous environments affect crack nucleation. For these authors, the appearance of intrusions, extrusions and microcracks is similar in air and in vacuum for an equivalent number of cycles, and only further development of the fatigue cracks takes much more time in vacuum than in air.

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In fact, any definitive answer on the debated question of the environmental effects on crack nucleation processes cannot be deduced from the two mentioned papers. Firstly, because the two series of experimental results have been obtained for very different loading conditions ; Thompson et al. study has been conducted at low stress amplitudes, in the high cycle fatigue range, in which cracks nucleate in persistent slip bands ; on the contrary, Wadsworth et al. have realized their study at much higher stress amplitudes in the low cycle fatigue range in which cracks are initiated at grain boundaries. Secondly, because all the comparisons of the fatigue damage state have been made in a purely qualitative manner by comparing the aspect of the specimens surfaces.

Therefore, we have tried to bring out some light on this question, by conducting comparative experiments on a fine-grained OFHC copper tested in air and in vacuum, in the high cycle and low cycle fatigue domains. For each case we have realized quantitative measurements of some parameters characterizing the surface fatigue damage.

EXPERIMENTAL PROCEDURE

Fatigue smooth specimens were annealed in vacuum for 3 hours at 460 °C. The subsequent grain size obtained is 0.030 mm. All specimens were electropolished before annealing, and once more just before the fatigue tests. The tests were conducted on a servohydraulic machine, at room temperature, in the laboratory air and in vacuum (6.10^{-4} Pa). Low cycle fatigue tests were conducted with a total strain amplitude control mode at a frequency of 0.1 Hz. High cycle fatigue tests were conducted with a stress control mode (load ratio R = - 0.95), at a frequency of 37 Hz.

Specimens were cycled in both environments up to failure or with periodic interruptions to permit examination of the specimens surface in a Scanning Electron Microscope.

In each case the surface fatigue damage was characterized by the number of microcracks by unit area, the microcracks mean length, and the nature of their initiation sites.

When microcracks initiate an develop in an intergranular manner, their length has been estimated by the number of cracked boundaries (see schema in fig.3). For a given number of cycles the fatigue damage by unit area is characterized by two values : the number of microcracks δ, and the number of cracked boundaries η (the ratio η/δ giving the average length of microcracks $\bar{\ell}$) and by the histogram giving the number of microcracks as a function of their length.

RESULTS AND DISCUSSION

We should give here some examples which clearly emphasize, through the evolution of the parameters defined before, the important role of the atmospheric environment, on the fatigue damage processes.
We have listed in Table I the fatigue lives N obtained in air and in vacuum for three different loading conditions noted A, B and C.

Table I shows that the higher are the fatigue lives the more important is the environmental effect. However, even for low cycle fatigue conditions the ratio $N_{F,vac}/N_{F,air}$ reaches a value of 6.

Test	Control Mode	Controlled parameter amplitude	$N_{F,air}$ cycles	$N_{F,vac}$ cycles	$\frac{N_{F,vac}}{N_{F,air}}$	Crack initiation sites AIR	Crack initiation sites VAC
A	Strain	$\frac{\Delta\varepsilon_t}{2} = 3.2\ 10^{-3}$	7200	43750	6	g.b.	g.b.
B	Load	$\frac{\Delta\sigma}{2} = 115$ MPa	$0.3\ 10^6$	$2.1\ 10^6$	7	g.b.	g.b.
C	Load	$\frac{\Delta\sigma}{2} = 86$ MPa	$5\ 10^6$	$> 53\ 10^6$	>10	p.s.b.	g.b.

TABLE I - Number of cycles to failure in air and in vacuum for three cyclic loading conditions and crack initiation sites ; grain boundaries (g.b.) or persistent slip bands (p.s.b.).

Test conditions A and B

For the test conditions noted A and B the crack initiation sites are the grain boundaries in both environments ; in B, some microcracks have also been observed in persistent slip bands, but in air as in vacuum they remain very superficial and do not play any role in the main cracks formation.

For A and B conditions the atmospheric environment does not modify the nature of the initiation sites ; moreover, apart from microcracks, all the other characteristic features of the cyclic deformation, the aspect of the slip bands or the steps formed at grain boundaries, present the same appearance in both environments for an equivalent number of cycles.

However, the evolution of δ and η given in Fig.1 and Fig.2 as a function of the number of cycles, clearly shows that microcracks nucleate and develop much earlier in air than in vacuum ; moreover, it also demonstrates that the characteristic features of the surface damage at specimens failure are very different in both environments.

The metal fatigue process is usualy divided into two stages ; a stage of crack initiation and a stage of crack propagation ($N_F = N_i + N_p$). If we consider that the begining of the stage of crack propagation can be defined by the number of cycles N_i at which the first microcrack starts propagating from its initiation site - i.e. when it involves more than 1 grain boundary - then, N_i can be deduced by comparing $\delta(N)$ and $\eta(N)$ results. N_i corresponds to the number of cycles from which the number of cracked boundaries becomes higher than the number of microcracks δ.

Fig.1 and 2 show that N_i is always higher than N_{mi}, the number of cycles at which the first cracks can be observed on the surface ($\delta > 0$), representing what we shall call here the micro-initiation stage.

The values of N_{mi} and N_i determined for both environments in tests A and B, are listed in Table II.

Test	Environment	N_{mi} cycles	N_i cycles	N_F cycles	N_i/N_F	δ_{max}	η_{max}
A	Air	500	800	7200	0.11	56	120
	Vacuum	2000	7000	43750	0.16	200	277
B	Air	$0.5\ 10^5$	$1\ 10^5$	$0.3\ 10^6$	0.30	32	46
	Vacuum	2.10^5	$4\ 10^5$	$2.1\ 10^6$	0.19	218	305

TABLE II - Fatigue damage characteristics for tests A and B. N_{mi} = number of cycles to micro-initiation. N_i = number of cycles to crack propagation; δ_{max} = number of surface intergranular cracks by mm^2 on broken specimens; η_{max} = number of surface craked boundaries by mm^2 on broken specimens.

Through the values of N_{mi} and N_i, it clearly appears that atmospheric environment modifies the different fatigue damage stages defined before ; the microcrack initiation as well as the crack initiation stages are lengthened by conducting the fatigue tests in vacuum. However, the ratio N_i/N_F increases more quickly with the fatigue life in air than in vacuum ; thus, the increasing of the environmental effect indicated by an increasing of the ratio $N_{F,vac}/N_{F,air}$ for the low stress amplitudes (see Table I) must be predominantly associated with crack propagation.

An other significant information given by the $\delta(N)$ and $\eta(N)$ curves is that the characteristic features of surface damage are never identical in air and in vacuum : for the same value of the surface cracks density δ, the mean crack length $\bar{\ell}$ is much lower in vacuum than in air ; and for the same value of $\bar{\ell}$, δ is much higher in vacuum than in air. Thus, the specimens failure is reached with a surface damage state very different, depending on the environment. This point is illustrated by the values δ_{max} and η_{max} measured on broken specimens surfaces (see Table II), which are always much higher in vacuum than in air. In the same way, the distribution of surface cracks as a function of their length, given in fig.3 for test B, shows that in vacuum crack density is higher for every class of length.

Test Conditions C

For high cycle fatigue tests corresponding to the loading conditions noted C in Table I, the effect of environment leads to a modification of crack initiation mechanisms in reference to vacuum.

For a stress amplitude level leading to fatigue lives in air of several millions of cycles, our results in air agree with those of other authors as Thompson et al.(4) or Thompson and Backofen (5) : in air, microcracks were found to be nucleated in persistent slip bands (the classical Stage I crack initiation mechanism on crystallographic planes inclined about 45 deg. to the applied stress direction).

On the other hand, the observation of the surface of the specimens cycled in vacuum at the same stress level, reveals a much more original result : in vacuum, fatigue cracks nucleate at grain boundaries as at higher levels of stress amplitude.

Moreover, in air, there is a little number of cracks on the specimen surface which increases very slowly with the number of cycles (cracks density $\approx 2/mm^2$) and only a few isolated cracks grow independently somewhat before failure ; whereas, in vacuum, the characteristic features of the distributed surface damage evolve in a similar manner as for high stress levels : the test conducted in vacuum was stopped before failure after $N = 53\ 10^6$ cycles, and the surface examination has revealed that the density of the intergranular cracks and the number of cracked grain boundaries were already as high as $\delta = 273$ and $\eta = 551$ respectively (see in Table II the values of δ_{max} and η_{max} reached in vacuum for tests A and B).

So, the change in crack nucleation mechanism known to be existing in air between low cycle and high cycle fatigue ranges (intergranular $\rightarrow$ intragranular) does not appear in vacuum.

In polycrystalline copper cycled in air, the nucleation of fatigue cracks of Stage I type is therefore associated with the environmental reactions which take place at the intersection of the persistent slip band and the surface. This effect seems to be enhanced by the great degree of plastic strain localization which occurs into the grains at low cyclic stress amplitudes. An oxydation mechanism of Thompson's type (4), by oxygen diffusion into the bands, can be evoked to explain crack nucleation characteristics in air. Damage features found in vacuum seem to prove that, in copper, the degree of strain reversibility is much lower in grain boundaries than in persistent slip bands.

CONCLUSION

This work has permitted to point out several important informations about the differences in fatigue damage characteristics induced by the air environment in polycrystalline copper.

1°/ In low cycle as in high cycle fatigue conditions, all the stages characterizing the fatigue damage processes are shortened in air with regard to vacuum ; however the maximum of the environmental effect must be associated with the propagation stage, in particular in high cycle fatigue conditions.

2°/ It has been found that in vacuum no change in nucleation mechanisms occurs between high stress and low stress cyclic amplitudes and microcracks always nucleate at grain boundaries.

The classical differences in cracks initiation mechanisms - intergranular at high stress levels and Stage I crack initiation in persistent slip bands at low stress levels - has been observed in air.

Therefore, the Stage I crack initiation process must be associated with an environmental effect.

SYMBOLS

$\delta(N)$; δ_{max} : microcrack density (number by mm^2) after N cycles of fatigue ; at the specimen failure.

$\eta(N)$; η_{max} : number of cracked boundaries by mm^2 after N cycles of fatigue ; at the specimen failure.

$\bar{\ell} = \eta/\delta$: average crack length.

$\Delta\varepsilon_t/2$: cyclic total strain amplitude in strain-controlled tests.

$\Delta\sigma/2$: cyclic stress amplitude in load-controlled tests.

$N_{F,air}$;$N_{F,vac}$: number of cycles to failure in air ; in vacuum.

N_{mi} : number of cycles at which the first cracks can be observed on the specimens surface (micro-initiation stage).

N_i : number of cycles at which the first crack start propagating from its initiation site (crack initiation stage).

$N_p = N_F - N_i$: number of cycles for crack propagation.

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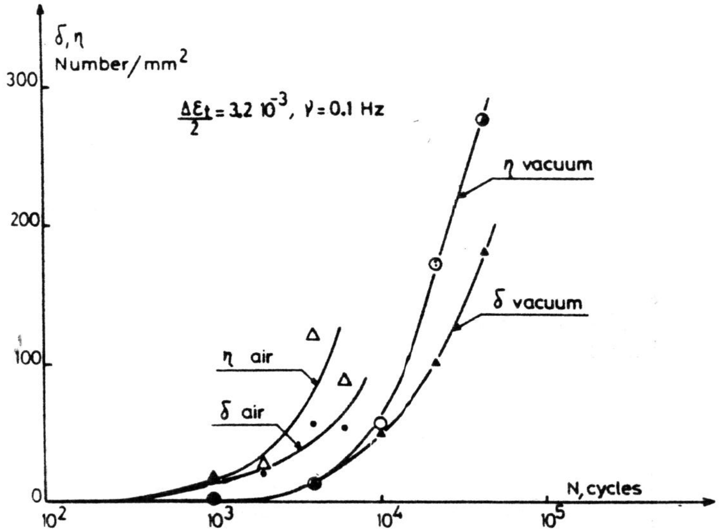

FIG.1 - Number/mm^2 of intergranular microcracks (δ) and cracked boundaries (η) versus the number of cycles (Test A).

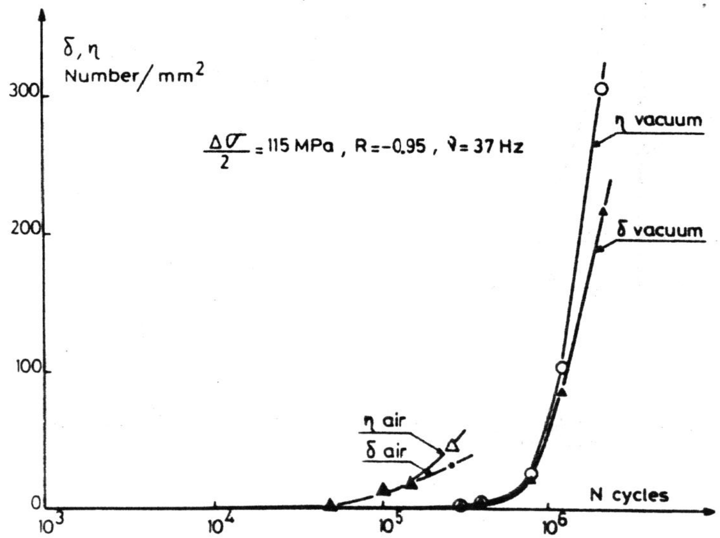

FIG.2 - Number/mm^2 of intergranular microcracks (δ) and cracked boundaries (η) versus the number of cycles (Test B).

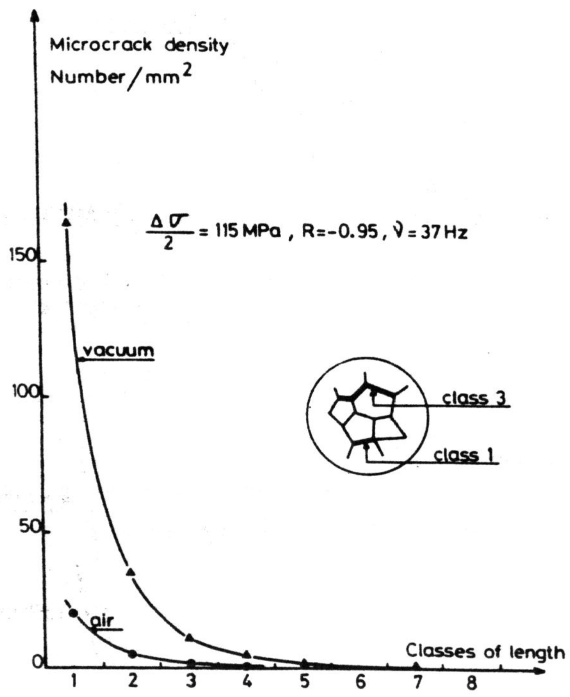

FIG.3 - Crack length distribution after specimen failure (Test B).