PERSISTENT SLIP BANDS INDUCED BY FATIGUE IN A NICKEL BASE SUPERALLOY

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A coarse grained cast nickel base superalloy, MARM 004, was studied in air at room temperature under push pull strain cycling conditions and using smooth cylindrical specimens. The cyclic stress-strain curve exhibits some flattening with decreasing plastic strain amplitude range and a breakpoint at very low strains. From metallographic observations this breakpoint was shown to correspond to persistent slip band formation. Cyclic plastic strain was mainly accommodated by these bands which carried out a constant strain. The significance of these results with respect to long life fatigue behaviour is briefly discussed.

INTRODUCTION

The life of plain fatigue specimens cycled under strain or stress control has long been recognized, at least near room temperature, to correspond mostly to the initiation and growth of stage I cracks (1,2). Stage I cracking especially in face centered cubic materials generally occurs along crystallographic slip planes and is intimately connected with persistent slip bands (PSBs). This was shown in particular by high voltage electron microscopy observations of Katagiri and coworkers on polycrystalline copper (3). Early surface cracks were actually found to propagate inside the PSBs.

Extensive work was carried out in strain cycled single crystals of copper from a physical metallurgy standpoint by Winter (4), Finney and Laird (5) and Mughrabi (6). These authors observed that the stress amplitude at saturation in crystals oriented for single slip exhibits a plateau as a function of plastic strain amplitude up to 0.7 to 1 pct shear strain (under plastic strain control). The plastic strain is almost only accommodated by shear in the PSBs whereas the remnant matrix is only slightly strained. This was demonstrated by the fact that coverage of specimen surface by PSBs increases almost linearly with applied plastic strain and supported by transmission electron microscopy work (7). Mughrabi was the first to demonstrate the existence of a critical plastic strain amplitude below which this plateau was suppressed and no PSBs were formed.

On the other hand Lukas, Klesnil and coworkers carried out long life strain controlled tests in polycrystals of Cu, Cu-Zn and steels (8,9). They concluded that the true stress fatigue limit corresponds to a critical plastic strain amplitude. From these two kinds of results, Laird concluded to the iden-

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tity of mechanisms in single and polycrystals (10). Thus he inferred that the fatigue limit in fcc materials does exist and corresponds to the critical strain amplitude to nucleate PSBs. Recent work in polycrystals of copper bears out the similarity between single and polycrystals. Winter, Pedersen and Rasmussen showed that PSBs actually form in the bulk of polycrystals using transmission electron microscopy (11). Some experiments suggest a near plateau behaviour in cyclic stress-strain in polycrystals (12,13) but this is still a controversial matter (14).

Therefore there has been a lot of activity in the area of PSBs in fatigue but mainly restricted to the case of pure copper. There is a definite need for investigating the PSBs behaviour in commercial compositions and in alloys of higher strength. The present article reports such a study in a commercial, medium strength, nickel base superalloy at room temperature. This alloy, MARM 004, is a cast precipitate strengthened alloy with a coarse grained structure. Therefore whereas only a few grains are tested in a smooth fatigue specimen, the orientation of individual crystals can be easily determined. The experimental procedure will be described first. The cyclic stress strain results will be reported with a metallographic study of PSBs on specimen surface. The significance of these results will be then discussed.

EXPERIMENTAL PROCEDURE

The alloy studied is a cast nickel based superalloy, MARM 004 which has the following composition in wt pct : 0.057C, 11.4Cr, 4.4Mo, 1.9Nb + Ta, 6.15Al, 1.5Hf, 0.05Fe, 0.05Co, 0.05Si, 0.05Mn, 0.011B, bal.Ni. Due to the casting conditions used, this alloy has a very large grain size which can reach one centimeter. The alloy is predominantly constituted by a matrix which is strengthened by a high volume fraction of cuboidal γ' precipitates (most of them have a size about 1 µm and some are about 0.1 µm wide). It contains in addition a low volume fraction of primary carbides and γ-γ' eutectics. Its room temperature yield and tensile strength are about 760MPa and 940 MPa respectively.

The plain fatigue specimens were cylindrical, 12 mm in gauge length and 8 mm in diameter. Only a few grains were so tested as shown by the optical macrograph of a polished and etched specimen (Fig. 1). Tests were carried out on an electrohydraulic machine under fully reverse saw tooth total strain cycling conditions. All the tests were made at room temperature in air. The total axial strain was adjusted during the test in order to keep a constant plastic strain amplitude as measured at zero load. The load was continuously recorded throughout the test and hysteresis stress-strain loops were recorded from time to time.

Specimen surfaces were polished before testing down to 3 µm diamond paste. They were observed in a scanning electron microscope equipped with a eucentric goniometer stage. The orientation of individual crystals in the specimens was determined using the Laue back reflexion X-ray technique.

RESULTS AND DISCUSSION

Cyclic stress-Strain behaviour

The variation of the half maximum stress amplitude is reported in Fig. 2 as a function of the number of cycles for various plastic strain amplitudes. The stress amplitude weakly depends upon the number of cycles. The material slightly work hardens during a limited number of cycles (always less than 10 pct of fatigue life) before reaching saturation behaviour : the stress amplitude then remains stable or slowly decreases. Thus the behaviour of this alloy is similar to that of single phase alloy single or polycrystals and to that of alloys strengthened by unshearable particles (6,8,15). This was actually expected owing to the large size of nearly coherent γ' precipitates. This differs from the strong work hardening followed by a large softening in alloys which are strengthened by shearable particles, as observed in polycrystals of Al and Ni based alloys (15,16) and in single crystals of Al alloys (17).

The half maximum stress amplitude at mid-life is shown in Fig. 3 as a function of half plastic strain amplitude using a log-log plot. There is a large scatter in the results as expected from the few grains in specimen gauge lengths (as indeed in Young's modulus values which range from 127 GPa to 228 GPa). However though there is no definite plateau in the cyclic stress-strain curve, the curve flattens in the plastic strain range $5\ 10^{-5}$ - $2\ 10^{-4}$. For larger plastic strains it exhibits an increasing curvature as observed in polycrystalline copper (12-14). In the low strain range the cyclic stress drops off drastically for a plastic strain lower than about $4.5\ 10^{-5}$. Therefore there is a clear transition in cyclic stress-strain behaviour for stresses below 600 MPa and plastic strains smaller than $4.5\ 10^{-5}$ which should reflect differences in deformation mechanisms.

<u>Persistent Slip Band Observations</u>

After completion of fatigue cycling, the grains on specimen surface may exhibit PSBs along {111} slip planes or not. There are large variation in PSBs density from one grain to another, which reflects the large misorientations between individual grains. The plastic strain is thus highly inhomogeneous over the gauge length; therefore a real plateau which could exist in a single crystal is not expected to occur in the cyclic stress-strain behaviour of this multicrystal. In addition a single family of PSBs along one kind of slip plane was mostly observed in the plastically strained grains. This is in good agreement with observations on polycrystalline Cu (11,13,14). A typical situation is shown in Fig. 4 where one system of PSBs is activated with a fairly homogeneous slip distribution in the plastically strained region. A secondary stage I crack is observed to propagate inside PSBs with occasionnal kinks from one band to another one.

Winter proposed that in the plateau of the cyclic shear stress-strain curve of single crystals of Cu the plastic strain amplitude was essentially accommodated by shear in the PSBs and that the matrix outside PSBs could only accommodate a small strain. A simple rule of mixtures was used as :

$$\varepsilon_p = f\ \varepsilon_b + (1-f)\ \varepsilon_m$$

where ε_p is the applied plastic strain amplitude, ε_b is the strain in the band, ε_m the strain in the matrix and f the volume fraction of PSBs. Measurements by Winter and others (4-6) demonstrated that the average strain in the PSBs was constant. As emphasized earlier, a true plateau behaviour could not be expected in the multicrystal case studied here. However the flattening of the cyclic stress-strain curve in the range $5\ 10^{-5}$ - $2\ 10^{-4}$ suggests that a true plateau should exist for single crystals of the same material. Accordingly the two phase model of Winter may hold in the present alloy.

This was investigated using classical quantitative metallography to determine the volume fraction of PSBs, f. Strained grains with PSBs were mapped using scanning electron micrographs and the volume fraction in individual grains was averaged over the specimen gauge length. The average volume fraction of PSBs is reported as a function of the plastic strain amplitude ε_p in the log-log plot of Fig. 5. Mughrabi's results on copper single crystals oriented for single slip are also included for comparison (the shear strain was converted to a tensile strain using a Schmid factor of 0.5). Volume fractions of PSBs in MARM 004 are indicated with their 90 pct confidence interval. The two phase model as shown by the solid curve in Fig. 5 is consistent with the present results. Least square fit values $\varepsilon_b = 1.1\ 10^{-2}$ and $\varepsilon_m = 4.5\ 10^{-5}$ were derived for the nickel base superalloy when corresponding values were $3.75\ 10^{-3}$ and $3\ 10^{-5}$ for copper single crystals. Therefore the critical plastic strain for nucleating PSBs on specimen surface does correspond to the breakdown of the cyclic stress-strain curve. Accordingly PSBs are no longer formed for cyclic stresses below 600 MPa. This critical stress is obviously much higher than that in polycrystalline copper about 60 MPa (14), in spite of the comparable values of the critical plastic strain amplitude. On the other hand the plastic strain accommodated by the bands is about three times larger in the nickel base superalloy than in pure copper. These differences should be related to the presence of precipitates in this strong nickel base alloy but observations using transmission electron microscopy would be necessary to clarify this point.

Persistent slip bands and fatigue life behaviour

It is now widely accepted at least in pure copper that persistent slip bands are of primary importance in determining the fatigue life behaviour of single and polycrystals. However this has to be explored into more details. For the present nickel base superalloy the occurrence of PSBs and of the dominant crack giving rise to fatigue failure was investigated in the relevant grains. The orientation of these grains was determined from the Laue X-ray diffraction technique. It was found that the slip plane of PSBs was generally unique in a single grain, as recently observed in copper polycrystals. In most cases this plane was consistent with a maximum shear stress criterion (i.e. maximum Schmid factor) among the four possible slip planes. In addition in most cases the plane of the PSBs corresponded to that used for stage I crack initiation.

It was implicity assumed by Laird (10) and then by Mughrabi (6) that the fatigue limit should be associated with the critical strain and stress amplitude for PSBs nucleation. This was recently investigated by Hessler and coworkers in the case of polycrystalline copper with different grain sizes (18). These authors carried out high frequency cycling under total strain control in the life range 10^6 to 10^{10} cycles. Using the curve to 1 pct failure probability, they observed a true fatigue limit (which was equivalent to the endurance limit at 10^8 cycles). The critical stress for nucleating PSBs was found to increase with increasing strain amplitude in the limited endurance regime and to be constant above 10^8 cycles. However this critical stress was always definitely smaller than the true fatigue limit in contradiction with Laird's statements (10). Nevertheless the ratio of the PSBs nucleation stress to the fatigue limit decreases with increasing the grain size, which might support Laird's point of view for single crystals. A similar reasoning for the studied nickel base superalloy would suggest the existence of a fatigue limit for a plastic strain amplitude below $4.5\ 10^{-5}$ and a stress amplitude below about 600 MPa. Unfortunately plastic strain amplitude could not be measured with sufficient precision at such low values with the experimental conditions used. Tests were only conducted under total strain control down to stress levels around 150 MPa i.e. one quarter of the PSBs nucleation stress. The stress amplitude is reported schematically as a function of fatigue life in Fig. 6. This clearly shows that in the present alloy the fatigue limit if any is much lower than the stress for PSBs formation. The situation is thus the opposite of that in copper polycrystals. Thus in a commercial alloy of fairly high strength other initiation mechanisms can be activated besides slip band crystallographic cracking, such as cracking at second phase particles which are controlling the long life range (see e.g. 1, 19).

CONCLUSION

The fatigue behaviour of the coarse-grained cast nickel base superalloy MARM 004 was studied at room temperature under push pull axial strain control. The cyclic stress-strain behaviour of this precipitation-strenghtened alloy is in agreement with results on copper polycrystals. In a log-log plot the cyclic curve flattens with decreasing plastic strain amplitude; below a critical half amplitude about 4.5 10^{-5} the stress drops off rapidly.

The measurement of the volume fraction of persistent slip bands (PSBs) on fatigued specimens surfaces showed that this critical strain corresponds to the formation of PSBs. Measurements are consistent with a constant average shear deformation in the PSBs larger than in copper single crystals.

However the stress fatigue limit in this alloy is much lower than the stress for PSBs formation whereas the latter stress is a lower bound of the fatigue limit in copper polycrystals.

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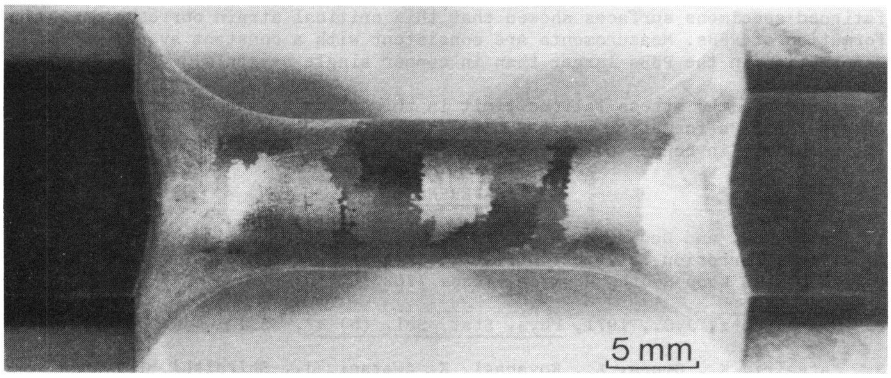

Figure 1 - Macrograph of a polished and etched specimen.

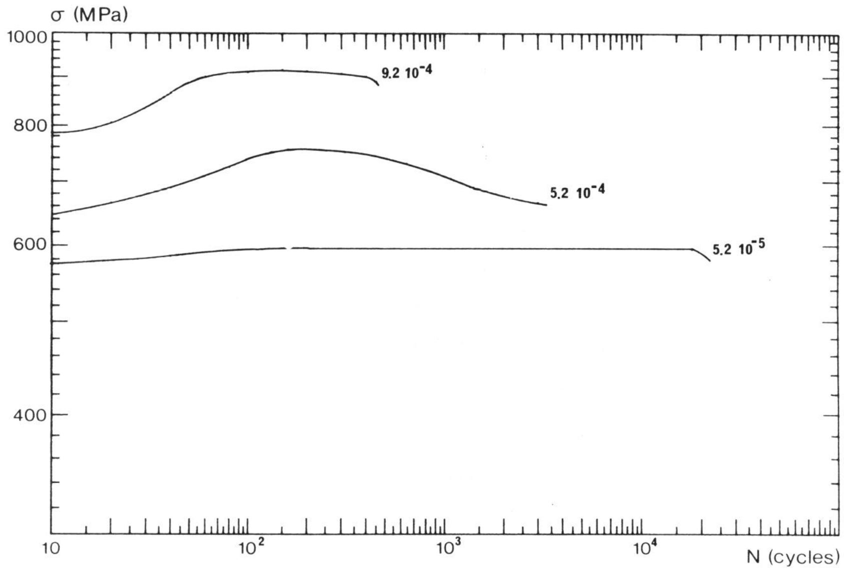

Figure 2 - Variation of half maximum stress amplitude (σ) with the number of cycles (N) for various plastic strains.

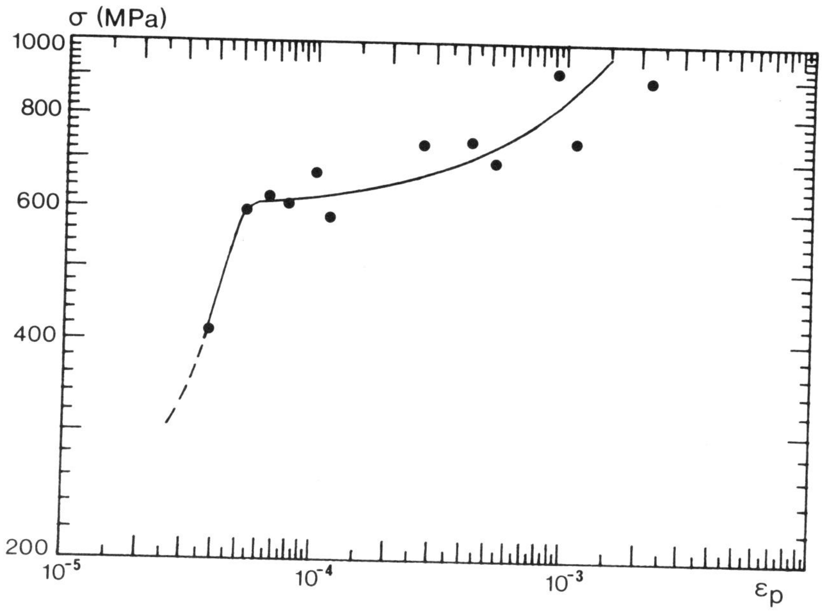

Figure 3 - Variation of the half maximum stress amplitude at mid-life (σ) as a function of half plastic strain amplitude (ε_p).

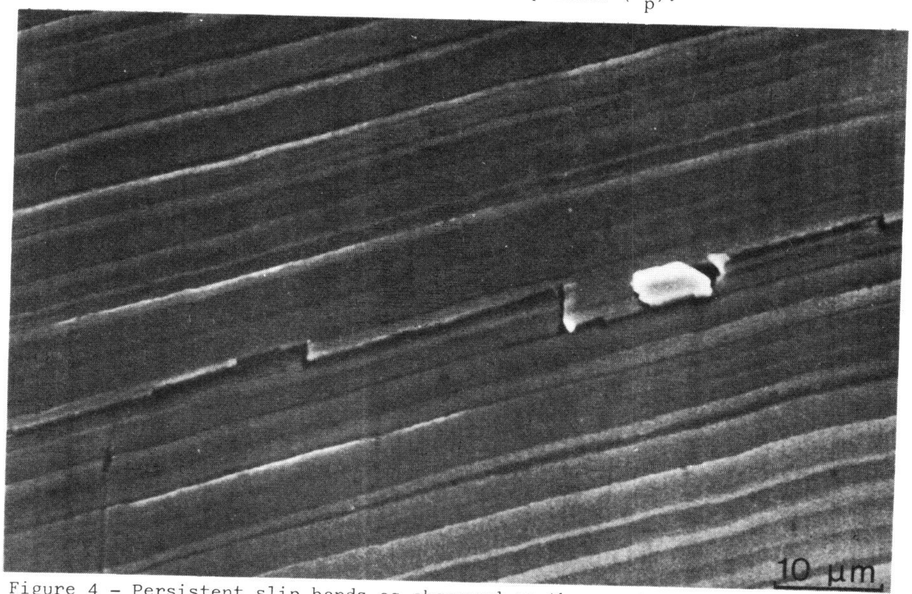

Figure 4 - Persistent slip bands as observed on the specimen surface (ε_p = 1.12 10^{-3}).

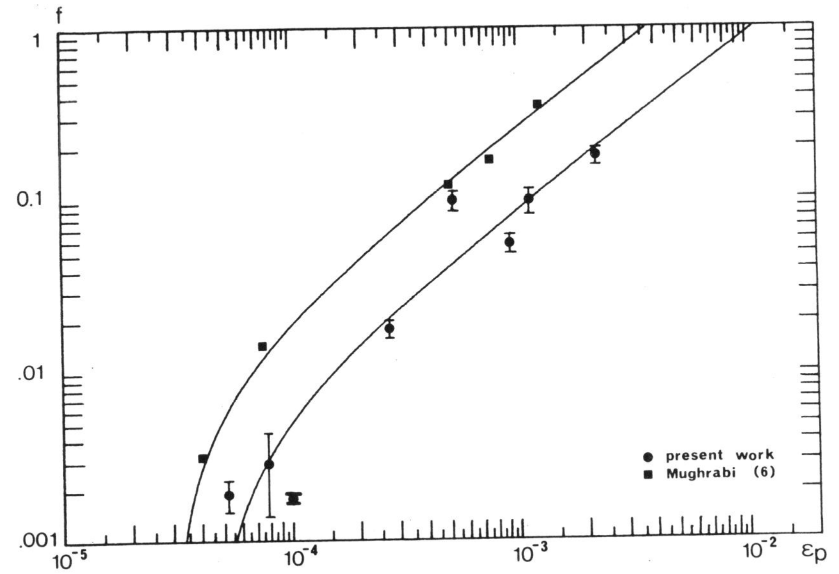

Figure 5 – Variation of the average volume fraction of PSBs (f) as a function of plastic strain amplitude (ε_p).

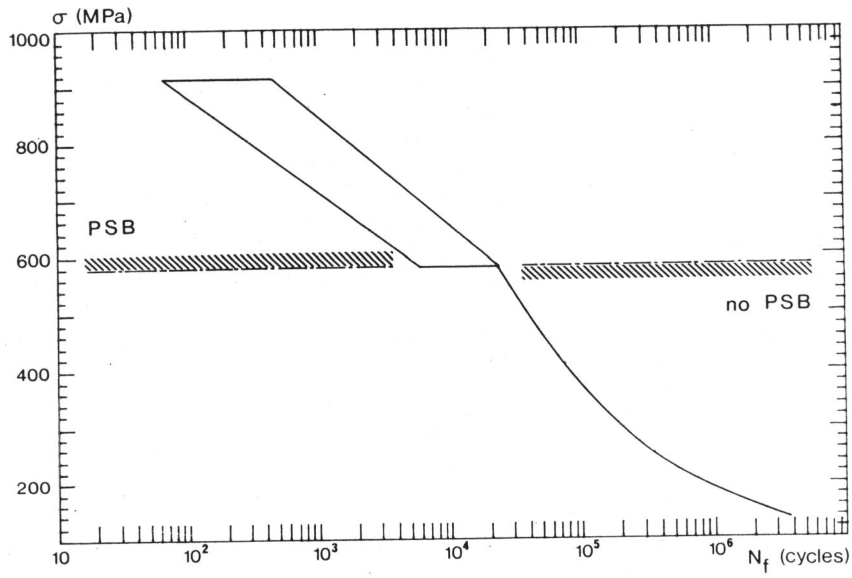

Figure 6 – Variation of the cyclic stress amplitude (σ) as a function of the number of cycles to failure (N_f).