CRACK INITIATION MECHANISMS DURING LOW CYCLE FATIGUE OF PURE FERRITIC ALLOYS

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ABSTRACT

During cyclic plastic deformation at room temperature, polycrystalline Fe, Fe-3 % Si and Fe-26 % Cr - 1 % Mo alloys may develop intergranular or transgranular surface cracks depending upon the applied strain rate and the strain amplitude. The fatigue behaviour of polycrystalline material is closely related to the cyclic stress-strain response of b.c.c. single crystals for which pronounced stress asymmetries and crystal shape changes are shown to occur at high (but not at low) strain rates. Moreover, the strain rate dependence of the crack initiation mode can be correlated with the relative values of the internal (σ_i) and effective stresses (σ^*). A simple criterion which correlates the values of the ratio $\frac{\sigma^*}{\sigma_i}$ to the low cycle fatigue crack initiation mode in ferritic polycrystals is proposed : when $\frac{\sigma^*}{\sigma_i} \geq 1{,}2$, crack initiation is intergranular; when $\frac{\sigma^*}{\sigma_i} \leq 0{,}8$, transgranular initiation is promoted. The validity of the criterion is examined through the influence of grain size and alloying elements on the behaviour of polycrystals.

KEYWORDS

Fatigue, low cycle, ferritic alloys, crack initiation mechanisms, strain rate effects, grain size, polycrystals, single crystals.

INTRODUCTION

Recent studies of the cyclic plastic deformation of b.c.c. single crystals (Mughrabi, Herz and Stark, 1976; Anglada and Guiu, 1979) have clearly demonstrated the importance of thermal activation processes in controlling the cyclic mechanical properties of these materials. In the low temperature regime of deformation, b.c.c. single cyrstals cycled in tension-compression may exhibit a pronounced stress asymmetry and / or a change in shape of the crystals. The consequences for polycrystalline materials of this single crystal behaviour have been previously investigated in the case of two ferritic alloys, Fe-3 % Si and Fe-26 % Cr-1 % Mo (Magnin and Driver, 1979). In particular, it was shown that the fatigue crack initiation mechanisms in polycrystals were sensitive to the cyclic strain rate $\dot{\varepsilon}_t$

and the relative values of the effective and internal stresses (respectively σ^* and σ_i). At high strain rates ($\sim 10^{-1}$ sec^{-1}), $\sigma^* > \sigma_i$ and intergranular crack initiation is promoted due to the shape changes of the grains; at low strain rates ($\sim 10^{-5}$ sec^{-1}), $\sigma_i > \sigma^*$ and transgranular cracking is observed.

The purpose of this paper is to examine the validity of using the relative values of σ_i and σ^* as a criterion for indicating the mode of fatigue crack initiation in high purity ferritic alloys. The parameters studied are the strain rate, grain size (which is expected to modify the values of σ_i) and the type of alloying element (which changes the slip character).

EXPERIMENTAL METHOD

The materials examined are three high purity ferritic alloys :

1) Fe - (2,5 to 3) % Si containing 30 ppm C and 10 ppm N.

2) Fe - (25,5 to 26,1) % Cr - (0,94 to 1,15) % Mo, containing about 15 ppm C and 25 ppm N.

3) Fe - 30 ppm C, obtained from a very pure iron (> 99,991 %).

Single crystals of the Fe-Si and Fe-Cr-Mo alloys were grown by controlled solidification in horizontal furnaces. The heat treatments and grain sizes of the three alloys are tabulated below (A = annealed, WQ = water-quench after a treatment under argon.)

TABLE 1 - HEAT TREATMENTS AND GRAIN SIZES OF THE ALLOYS

ALLOY	SINGLE CRYSTALS	POLYCRYSTALS	
	Heat Treatment		Grain size
Fe-3 % Si	A 1200°C, 10^{-5} Torr, 16 h	A 800°C, 10^{-5} Torr, 16 h	60 µm
Fe-26 % Cr-1 % Mo	A 1200°C, 10^{-5} Torr, 16 h + A 950°C 30 min + WQ	A 800°C, 10^{-5} Torr, 16 h + 950°C 30 min + WQ	60 µm
		A 1200°C, 10^{-5} Torr, 4 h + 950°C 30 min + WQ	400 µm
		A 1200°C, 10^{-5} Torr, 16 h + 950°C 30 min + WQ	1 mm
Fe-30 ppm C		A 500°C 1 h	80 µm

Symmetrical tests in tension-compression were carried out at constant strain rate (in the range 2.10^{-6} sec^{-1} to 2.10^{-1} sec^{-1}) on specimens of gauge length 10 mm under total strain control, using a servo-hydraulic machine. The detailed techniques of specimen testing and determination of the values of internal and effective stresses by cyclic strain rate changes have been reported elsewhere (Magnin and Driver, 1979). The methods of both Michalak (1965) and Li (1967) were used to evaluate σ^* and σ_i. The strain rate sensitivity factors, m^*, were determi--ned as 4, 15 and 35 for Fe, Fe-Cr and Fe-Si respectively.

RESULTS AND DISCUSSION

Single crystal behaviour

Shape changes. When the slip systems in tension and compression are different, the mass displacements between tension and compression are not the same. Single crystals specimens which exhibit such slip asymmetry will therefore change shape when cyclically deformed with a net axial strain per cycle equal to zero. We have studied in detail the case of [011] Fe-Cr single crystals for which the slip planes in tension are about 8° from those in compression when $\dot{\varepsilon}_t = 2.10^{-3}$ sec^{-1} (Magnin and Driver, 1979). Specimens were oriented such that the initially square cross section became diamond-shaped during cycling (Fig. 1). The shape change is then defined by the ratio d_{max}/d_o where d_{max} and d_o are the maximum and initial diagonal lengths respectively.

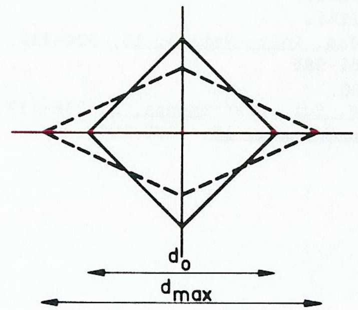


Fig. 1. Typical shape change of a cyclically deformed crystal

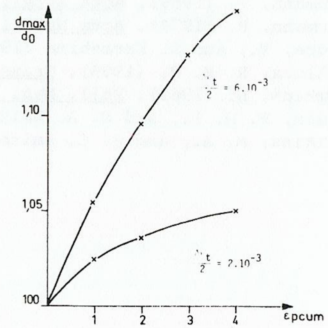


Fig. 2. Influence of strain amplitude $\Delta\varepsilon_T/2$ on the shape change of [011] Fe-26Cr crystals, $\dot{\varepsilon}_T = 2.10^{-3}$ sec^{-1}

Figure 2 shows the influence of the strain amplitude on the shape changes of [011] Fe-Cr crystals cycled at $\dot{\varepsilon}_t = 2.10^{-3}$ sec^{-1}. It is clear that the shape changes are both substantial (attaining d_{max}/d_o values of the order of 1,05 and 1,1 at cumulative plastic strains $\varepsilon_{pcum} = 2$) and continuous, even after saturation which occurs at $\varepsilon_{pcum} \simeq 0,25$. In addition, shape changes are more pronounced at high than at low strain amplitudes for a given cumulative plastic strain. The influence of strain rate on the shape changes of these crystals has been described previously (Magnin and Driver, 1979) : at lower strain rates ($\dot{\varepsilon}_t \simeq 2.10^{-5}sec^{-1}$) d_{max}/d_o is only 1,015 compared with a value of 1,055 at $\dot{\varepsilon}_t = 2.10^{-3}$ sec^{-1}, for $\varepsilon_{pcum} = 1$ and $\frac{\Delta\varepsilon_t}{2} = 6.10^{-3}$. Both the strain rate and strain amplitude dependences of these shape changes are in good qualitative agreement with these determined by Mughrabi and Wüthrich (1976) on Fe single crystals oriented for single slip.

The influence of strain rate on the cyclic stresses. The variation of the effective (σ^*) and internal (σ_i) components of the flow stress ($\sigma = \sigma^* + \sigma_i$) was studied as a function of strain rate for [011] crystals of both Fe-Cr and Fe-Si alloys, cycled to saturation at a total strain aplitude $\frac{\Delta\varepsilon_t}{2} = 6.10^{-3}$ (Fig. 3).

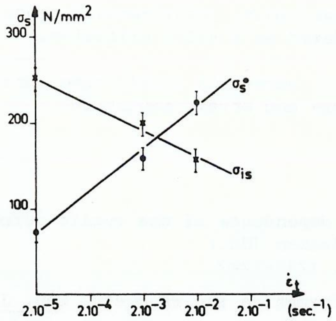


Fig. 3a. Influence of strain rate on σ^* and σ_i : [011] Fe-26 Cr crystals.

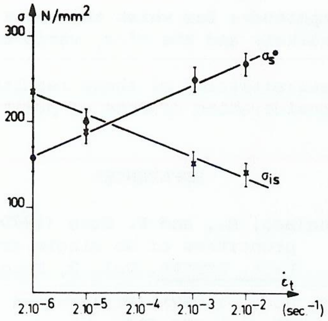


Fig. 3b. Influence of strain rate on σ^* and σ_i : [011] Fe-3 Si crystals.

It is clear that σ^* represents the major part of the flow stress at high strain rates but that σ_i becomes predominant at low strain rates. Tests on other crystal orientations show that this behaviour is general and independent of orientation. Finally, it should be noted that the values of $\dot{\varepsilon}_t$ for which $\sigma^* \sim \sigma_i$ are higher for Fe-Cr ($\sim 2.10^{-3}$ sec^{-1}) than for Fe-Si crystals ($\sim 10^{-4}$ sec^{-1}).

The relation between the values of $\frac{\sigma^*}{\sigma_i}$ and the deformation regime - Direct observations of the dislocation arrangements in fatigued Fe-Cr crystals by T.E.M. (Magnin, 1980) have confirmed the importance of the cyclic strain rate : at high strain rates, plastic deformation is controlled by straight screw dislocations (low temperature regime) and at low strain rates by mixed dislocations (high temperature regime). There is thus a good correlation between the microstructural observations and the relative values of σ^* and σ_i obtained as above using thermal activation theory. It is concluded that the cyclic mechanical properties of the Fe-Cr crystals are characteristic of the low temperature regime (i.e., slip asymetry and large shape changes) when $\frac{\sigma^*}{\sigma_i} \geq 1,2$ and characteristic of the high temperature regime (very small shape changes) when $\frac{\sigma^*}{\sigma_i} \lesssim 0,8$.

Polycrystal behaviour

Strain rate effects. The values of the saturation internal and effective stresses of the three alloys (grain size 60-80 µm) are given in Fig. 4 as a function of the applied strain rate for a total strain amplitude of 6.10^{-3}. It should be noted that at saturation, σ_i of Fe-Cr and Fe-Si alloys is well defined and constant during cycling; this is not the case for pure Fe which always exhibits a slight hardening during cycling. We have taken σ_i for Fe at 100 cycles.

Clearly substitutional elements increase both σ_i and σ^* , but for our purposes their most interesting effect is on the ratio σ^*/σ_i. This ratio is equal to unity at different strain rates for the different alloys : Fe-C $\sim 2.10^{-4}$ sec^{-1}, Fe-Si $\sim 2.10^{-5}$ sec^{-1}, and Fe-Cr $\sim 2.10^{-3}$ sec^{-1}. This effect indicates the in-

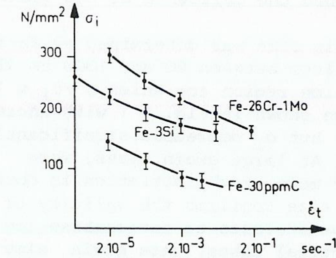


Fig. 4a. Strain rate dependence of the internal stress σ_i

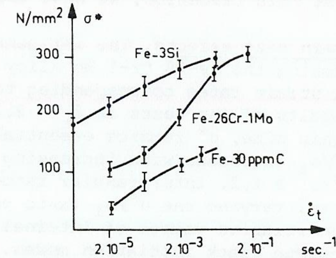
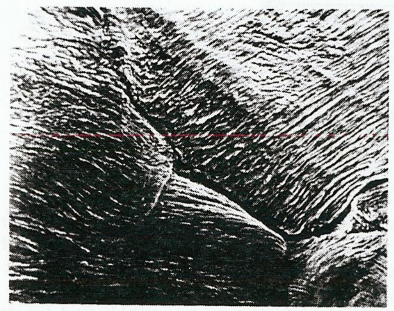


Fig. 4b. Strain rate dependence of the effective stress σ^*

fluence of these alloying elements on the deformation regime since, according to the single crystal results σ^*/σ_i may be taken as a reasonable indication of the regime.

The ratio σ^*/σ_i may also be correlated with the crack initiation mechanisms. For all three steels, crack initiation is predominantly intergranular when $\sigma^*/\sigma_i \geq 1,2$ (Fig. 5a) and transgranular when $\sigma^*/\sigma_i \leq 0,8$ (Fig. 5b). It should be emphasized that these results apply to the range of strain amplitudes used in this study (10^{-3} to 10^{-2}) and grain sizes $\sim$ 60 µm.



10µm

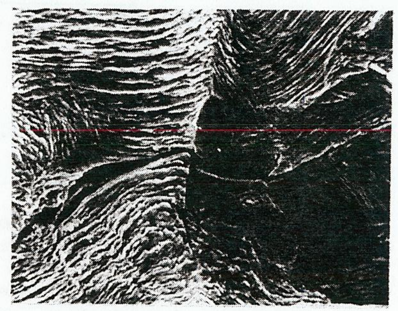


Fig. 5a. Intergranular crack initiation in Fe-30 ppmC. $\Delta\varepsilon_T/2 = 6.10^{-3}$ $\dot{\varepsilon}_T = 10^{-2}$ sec^{-1}

Fig. 5b. Transgranular crack initiation in Fe-30 ppmC. $\Delta\varepsilon_T/2 = 6.10^{-3}$ $\dot{\varepsilon}_T = 2.10^{-5}$sec^{-1}

Given that $\sigma^*/\sigma_i > 1,2$ indicates a low temperature deformation regime characterised by significant asymmetric slip and large crystal shape changes, one would expect the shape change effect to promote intergranular cracking. On the other hand, when $\sigma^*/\sigma_i < 0,8$ (characteristic of a high temperature regime), the shape change effects are markedly reduced and the large internal stresses promote transgranular cracking (Magnin, 1980).

It would appear therefore that the ratio σ^*/σ_i may be proposed as a criterion for the fatigue crack initiation mechanism in high purity b.c.c. polycrystals. To test this criterion, we have therefore examined the influence of the grain size.

Grain size effects. The influence of the grain size was determined by fatigue testing the Fe-26 Cr-1 Mo alloy with grain sizes between 60 and 1000 µm (Table 1) at strain rates corresponding to the transition region for which $\sigma^*/\sigma_i \sim 1$. The results of the tests at $\dot{\varepsilon}_t = 2.10^{-3}$ sec^{-1} are shown in Fig. 6 : with increasing grain size, σ^* remains essentially constant, but σ_i decreases significantly, i.e. σ^*/σ_i increases with increasing grain sizes. At large grain sizes, when $\sigma^*/\sigma_i \geq 1,2$, intergranular rather than mixed mode crack initiation is observed. Thus, varying the σ^*/σ_i ratio via the grain size confirms the validity of using the relative values of internal and effective stresses to rationalise low cycle fatigue crack initiation modes. In most practical cases, this grain size effect is, however, expected to be of relatively secondary importance compared with the strain rate effect.

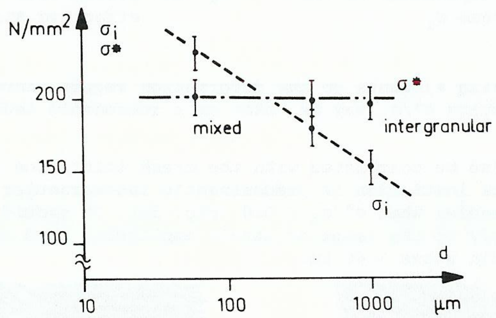


Fig. 6. Influence of the grain size, d, on the values of σ_i and σ^* : Fe-26 Cr-1 Mo , $\dot{\varepsilon}_T = 2.10^{-3}$ sec^{-1} , $\Delta\varepsilon_T/2 = 6.10^{-3}$

CONCLUSION

From the single crystal experiments, we conclude that the influence of strain rate on the cyclic deformation regime of ferritic alloys can be adequately characterised by the values of the internal and effective stresses, as measured by the strain rate change technique. Similarly for polycrystals, the dependence of the fatigue crack initiation modes on the strain rate can be explained by the cyclic deformation regime which is correlated simply with the σ^*/σ_i ratio. For the three high purity ferritic alloys examined, at strain rates such that $\sigma^*/\sigma_i \leq 0,8$ transgranular crack initiation predominates and, conversely at strain rates such that $\sigma^*/\sigma_i \geq 1,2$ intergranular initiation occurs. Since the influence of temperature on the deformation behaviour of b.c.c. materials is inversely related to the strain rate dependence, it seems logical to suggest that intergranular crack initiation would be a pronouced feature of high strain fatigue of b.c.c. materials at low temperatures.

It should be noted however that the strain amplitude can also influence the crack initiation mechanisms. At low strain amplitudes, the shape changes of the single crystals are relatively small (at constant ε_{pcum}). Thus, at very low strain

amplitudes for which the shape changes are negligible, intergranular cracking is unlikely and the σ^*/σ_i ratio cannot be considered as a valid criterion.

Generalization of these results to other b.c.c. materials should take into consideration effects of purity, microstructure and strain amplitude.

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