Fatigue Damage Mechanisms in Duplex $\alpha-\gamma$ Steels

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ABSTRACT: *The evolution of the fatigue resistance of austenitic-ferritic duplex stainless steels modified by high nitrogen additions or by heat treatments (475°C) does not follow that of tensile properties, in particular at high applied strains or stresses. The cyclic damage mechanisms in such alloys are discussed from the point of view of interactions between short cracks and microstructural barriers. A generalised model of barriers taking into account the short crack nucleation site (which can be different in duplex steels according to the applied stress/strain amplitude), the physical properties of both phases and their respective responses to the cyclic loading is applied to interpret the experimental data of low cycle fatigue tests carried out on a medium nitrogen commercial SAF 2507 duplex steel. Compared with the first generation DSS (low nitrogen), the nitrogen addition of approximately 0.25% induces a quasi single phase fatigue behaviour of the material without a significant increase of the fatigue life at applied plastic strain amplitude. The radical reduction of the fatigue life which follows the structural hardening of the ferrite at 475°C is explained by the inversion of the fatigue damage pattern at high applied strains.*

INTRODUCTION

The search for higher mechanical resistance of austenitic-ferritic duplex stainless steels (DSS) has led to the development of new families of DSS in which the increase of the yield stress is obtained through nitrogen alloying and/or through structural hardening at 475°C [1]. While the principal effect of nitrogen in DSS is to stabilise and to strengthen austenite, the ageing at 475°C acts on the yield stress through the spinodal decomposition of the ferrite. Significant modification of the properties of phases can thus be obtained, often without incidence on the morphological features.

It is not surprising that both nitrogen alloying and ageing increase the fatigue limit and the fatigue lives at applied stress amplitudes compared with non modified DSS. However, in plastic strain controlled fatigue, the respective effects are more ambiguous. In which concerns low and medium nitrogen contents (N<0.30%), Akdut [2] has concluded that the variations of morphological parameters between different DSS mask the effect of nitrogen. At high nitrogen concentrations (N>0.50%), the fatigue lives decrease very sharply compared with low N steels, in particular at high plastic strain amplitudes $\Delta\varepsilon_p$ [3, 4]. Similar to the high nitrogen contents, structural hardening of the ferrite enhances the risk of failure at high applied $\Delta\varepsilon_p$ [5,6] but this negative effect decreases when $\Delta\varepsilon_p$ decreases [7].

In the present work, selected results of low cycle fatigue tests performed on a commercial SAF 2507 duplex steel containing 0.26 wt% N are discussed from the point of view of interactions between short fatigue cracks and α/γ interphase boundaries using a generalised approach to the problem of microstructural barriers first proposed by Stolarz and Foct [6].

MICROSTRUCTURAL BARRIERS IN TWO PHASE ALLOYS

It is well established that the propagation of short cracks in smooth fatigue samples is strongly affected through the presence of grain or phase boundaries and that the total arrest period of cracks in front of such "microstructural barriers" exceeds 50% of the fatigue lifetime N_F [8]. In most cases, the boundaries are simply considered as barriers. However, this basic approach does not allow to interpret correctly most experimental data concerning fatigue of two phase alloys.

The generalised approach to the problem of microstructural barriers is based on the idea that the short crack propagation across a boundary is a process which develops progressively through the plastic deformation of the adjacent grain, the nucleation of a new short crack and the coalescence of both cracks. Consequently, beside the properties of the interface, numerous other parameters can influence the resistance of a barrier to the short crack propagation:

★ the short crack length, directly related to the grain size of the material;
★ the physical properties of the adjacent grain or particle, in particular the local flow stress value in the vicinity of the barrier;
★ the deformation mode of the adjacent grain (planar or cross-slip);
★ the degree of plasticity developed in the adjacent grain (particle).

It is postulated that the resistance of a barrier (the number of cycles during which a short crack is arrested in front of it) increases when:

➢ the grain size decreases (for the same applied stress);
➢ the local flow stress in the adjacent grain increases;
➢ the adjacent grain deforms by planar slip rather than by cross-slip;
➢ the degree of plastic deformation in the adjacent grain is low.

It is noteworthy that, in the approach proposed, the same interface which separates an α-grain from a β-grain in a two phase α/β material can oppose radically different resistance to the propagation of a short crack depending of its nucleation site. If the crack nucleates in the grain of the "soft" phase, its propagation (into the grain with a higher yield stress) will be more difficult than in the opposite case (crack nucleated in the grain of the "hard" phase). Moreover, it is necessary to take into account the capacity of individual phases to accommodate plastic deformation which often decreases when the mechanical properties of a phase increase.

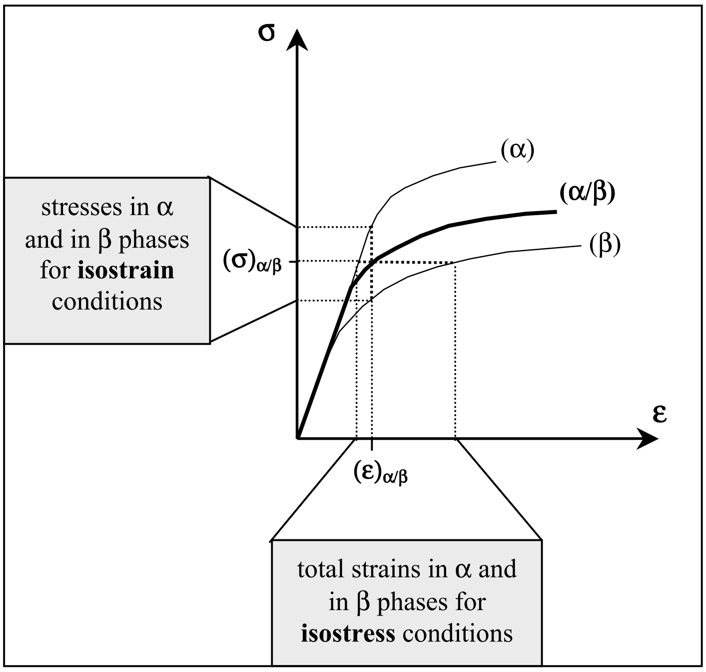

Figure 1: Individual responses of α and β grains in a two phase material under applied $\sigma_{\alpha/\beta}$ stress (cyclic hardening is not taken into account).

In the following, a pair of α and β grains is considered. Its response to the applied $\sigma_{\alpha/\beta}$ stress is represented by the respective σ–ε curves of individual phases and of the two phase α/β composite (Figure 1). The distribution of charge in individual grains depends on the microstructure morphology, the extreme cases being the isostrain and the isostress ones. Whatever the situation, for the example schematised in Figure 1, the "soft" β phase deforms plastically while the possibility of plastic flow in "hard" α grains depends on the charge distribution. The isostrain conditions promote a more equilibrated distribution of plastic deformation between the grains of both phases. On the other hand, under isostress loading, plastic deformation tends to be localised within the grains of the soft phase but the corresponding deformation is higher than in the previous case. The distribution of plastic deformation has direct consequences on the nucleation of short cracks which are most often formed at the intersections of slip bands with the metal surface.

The propagation of a short fatigue crack requires in most cases previous plastic deformation in the adjacent grain. According to the model, for low strain/stress amplitudes, no plastic flow takes place in the grains of the hard phase during cyclic loading. In such cases, the presence of a short crack in the vicinity of the interface is necessary to enhance locally the stress σ_a acting on dislocation sources in the adjacent grain through the interactions of the plastic zone at the crack tip with the interface. If σ_a exceeds the local flow stress value in the adjacent grain, dislocation sources can be activated and consecutive crack nucleation becomes possible. The number of cycles during which the short crack is arrested in front of a barrier for a given applied stress depends on the physical properties of the second grain (yield stress, ductility, deformation mode, …). According to Figure 1, the isostress conditions will make easier the crack nucleation in the grains of the soft phase but the propagation of such cracks in the hard β grains is much more difficult than for the isostrain conditions.

LOW CYCLE FATIGUE IN SAF 2507 DUPLEX STEEL

Material and testing conditions

Low cycle fatigue tests at room temperature in air under plastic strain control have been carried out on smooth specimens (6mm diameter, 10mm gauge length) of the commercial SAF 2507 DSS (25.0%Cr, 7.0%Ni, 0.26%N) produced by AB Sandvik Steels, containing approximately 50 volume percent of each phase. The samples have been tested in the solution treated state and after ageing at 475°C during 200 hours followed by water quenching, which is the optimised treatment for the α-phase hardening in duplex steels. The fatigue short cracks have been observed *post mortem* by optical and scanning electron microscopy on the sample surface.

The effect of ageing on the fatigue life

A section of the Coffin-Manson plot for low and medium nitrogen (N<0.30%) duplex stainless steels is schematically represented in Figure 2 by the scatter band situated between the straight segments corresponding to the LCF behaviour of single phase α and γ steels.

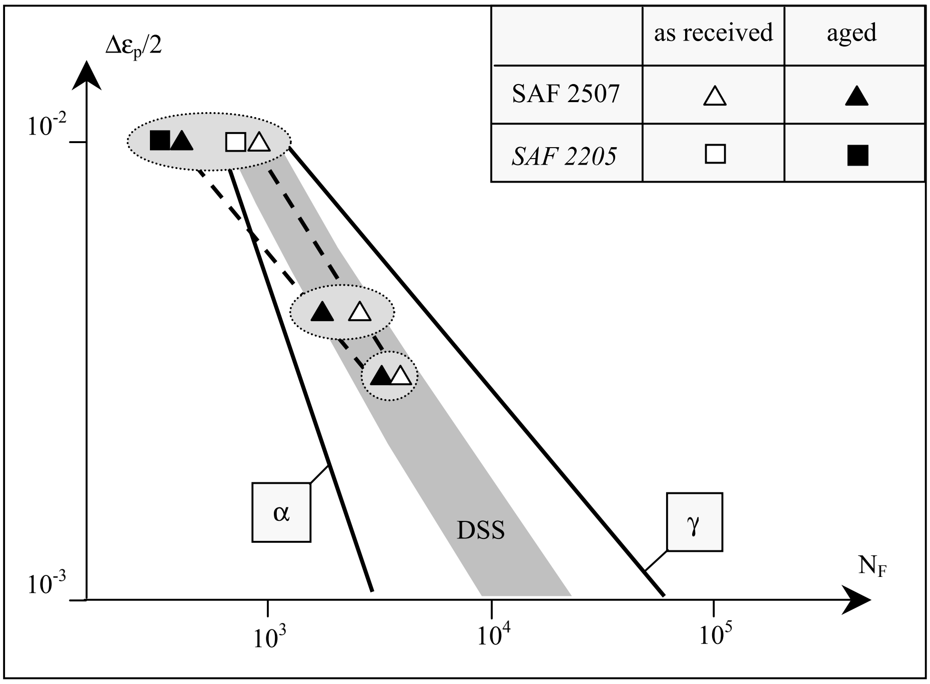

Figure 2: The effect of ageing on the low cycle fatigue resistance of SAF 2507 medium nitrogen and of SAF 2205 low nitrogen duplex steels.

White triangles represent the LCF results for the as received (solution treated) SAF 2507. The ageing at 475°C (black triangles) induces a decrease of the fatigue resistance similar to that observed by Vogt et al. [7] in a similar duplex steel (UR52N+ produced by Usinor Industeel). At $\Delta\varepsilon_p/2=\pm 0.4\%$, the respective fatigue lives are close one to another and the difference becomes significant at the plastic deformation amplitude of ±0.6% and particularly at ±1.0%.

The data collected on SAF 2507 are compared with those obtained previously [5] on SAF 2205 with a similar microstructure size scale as that of SAF 2507 but with a nitrogen content of 0.13wt%. The relative effect of ageing at $\Delta\varepsilon_p/2=\pm 1.0\%$ is the same in both steels but the respective fatigue lives are about 20% shorter in SAF 2205.

Cyclic hardening of α and γ phases in SAF 2507

In order to analyse the effects of cyclic straining on the behaviour of individual phase in SAF 2507 duplex steels, microhardness measurements have been carried out separately on austenite and ferrite grains prior to fatigue tests and after failure ($\Delta\varepsilon_p/2=\pm 0.4\%$ and ±0.6%).

TABLE 1: Microhardness (H_V25) of ferritic and of austenitic grains in non deformed solution treated and aged SAF 2507

N=0	$H_V25(\alpha)$	$H_V25(\gamma)$
solution treated	244 ± 12	257 ± 17
aged	390 ± 40	274 ± 42

The hardness of both phases in the solution treated state is nearly identical (Table 1), due to the solution hardening through nitrogen in the f.c.c. lattice. Consequently, simultaneous plastic deformation of both phases under cyclic loading can be expected.

TABLE 2: Microhardness (H_V25) of ferritic and of austenitic grains in solution treated and aged SAF 2507 after fatigue test at $\Delta\varepsilon_p/2=\pm0.4\%$ and $\pm0.6\%$

$N=N_F$, $\Delta\varepsilon_p/2=\pm0.4\%$	$H_V25(\alpha)$	$H_V25(\gamma)$
solution treated	268 ± 25	277 ± 20
aged	392 ± 18	297 ± 15
$N=N_F$, $\Delta\varepsilon_p/2=\pm0.6\%$		
solution treated	283 ± 11	284 ± 16
aged	402 ± 45	317 ± 22

Fatigue at $\Delta\varepsilon_p/2=\pm0.4\%$ of the solution treated sample leads to the hardening of both phases (Table 2), while in the aged state only austenitic grains harden. The tendency described above remains valid after fatigue at $\Delta\varepsilon_p/2=\pm0.6\%$ (Table 2), the corresponding effects in ferrite and austenite in the solution treated state and in austenite after ageing being more pronounced than in the previous case.

Effect of ageing on short crack nucleation and propagation

The behaviour of fatigue short cracks in solution treated SAF 2507 reflects the respective properties of both phases which are, at least in what concerns the plasticity limit, nearly the same. The plastic deformation is equally shared between the grains of ferrite and of austenite and numerous short cracks nucleate in α and in γ. The surface crack density increases when the applied plastic strain increase, as observed in single phase stainless steels. In fact, the fatigue behaviour of the solution treated SAF 2507 can be qualified as quasi single phase one, at least with respect to the damage mode at the scale of grains.

Observations of short cracks in aged samples after fatigue reveal a radical modification of damage mechanisms, in particular at high $\Delta\varepsilon_p$. Concerning multiple cracking, the tendency observed in the previous case is inverted: the surface density of short cracks decreases when $\Delta\varepsilon_p$ increases. At $\Delta\varepsilon_p/2=\pm0.4\%$, short cracks appear in both phases but those which nucleate in the ferrite result from microcleavage rather than from the intersection of slip bands with the surface as in the solution treated state. Moreover, γ/α interphase boundaries clearly appear as preferred nucleation site of short cracks in ferrite (Figure 3).

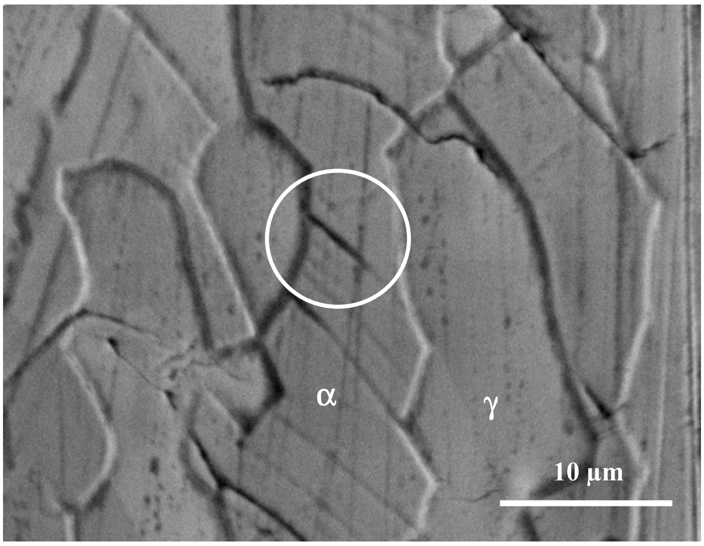

Figure 3: Surface damage in SAF 2507 ($\Delta\varepsilon_p/2=\pm0.4\%$, N_F). Nucleation of cleavage cracks in the ferrite at γ/α interphase boundaries.

When the plastic strain amplitude increases, the crack density decreases and the fraction of short cracks in ferrite increases. At $\Delta\varepsilon_p/2=\pm1.0\%$, the damage tends towards single cracking. The nucleation of short cracks in ferrite at γ/α interphase boundaries can be identified as resulting from the interactions of slip bands in the austenite with the γ/α boundaries. In fact, plastic deformation in aged SAF 2507 is entirely localised in the austenite, conforming with results reported by Gironès et al. [5] and which are indirectly confirmed through the evolution of microhardness after fatigue.

DISCUSSION

The behaviour of fatigue short cracks in the solution treated SAF 2507 duplex steel corresponds to the habitual pattern observed in ductile alloys.

The particularity of the short crack behaviour in the aged SAF 2507 consists in the fact that short fatigue cracks nucleate in hardened ferritic grains, even if this phase does not take part in the initial stages of cyclic plastic deformation. The most negative consequences of this process appear at high plastic strain amplitudes at which microcleavage in α takes place before any ductile crack nucleation can take place in the austenite.

From the point of view of microstructural barriers, this situation is particularly dangerous because a short crack resulting from cleavage of an α grain has to propagate across a strongly deformed γ grain characterised by lower yield stress than α. The resistance of such a barrier is very low.

The loss of fatigue resistance at high $\Delta\varepsilon_p/2$ results mainly from the embrittlement of α grains. It can be imagined that a hardening of the ferrite without any loss of ductility would generate higher resistance of barriers. In fact, short cracks would nucleate in soft γ grains with hard and non deformed α grains as barriers. The situation would be analoguous, except the higher maximal stress values, to that of "old" low nitrogen duplex steels.

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