# THERMAL AGEING AND ANISOTROPY EFFECTS ON THE FATIGUE CRACK GROWTH BEHAVIOUR OF DUPLEX STAINLESS STEELS

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The influence of thermal ageing and anisotropy on the fatigue crack propagation (FCP) behaviour of duplex stainless steels (DSS) has been investigated. In doing so, a detailed study of microstructural and mechanical characteristics of 5 mm thick rolled plates was conducted.

The results indicate that ageing increases strength, and also crack growth rates and threshold values $\Delta K_{th}$ are higher for aged material. Anisotropy effects on the tensile behaviour are clear. Nevertheless, these effects are only weak on FCP.

## INTRODUCTION

Over the last decades duplex stainless steels (DSS) have been succesfully used in many different fields, *e.g.* paper, oil and chemical industries. This is due to their excellent mechanical and corrosion-related properties (Charles *et al.* (1)). However, long-term service temperatures are usually limited to 250 °C because of their susceptibility to thermal ageing, specially within the intermediate temperature range, *i.e.* between 275 and 500 °C (*e.g.* Iturgoyen (2)). Thermal ageing promotes microstructural changes which induce an evolution of their mechanical properties. This phenomenon is quite important when industrial applications of these steels are considered. However, only a few studies on the influence of ageing on the fatigue properties of DSS have been published.

On the other hand, DSS can be produced by different processes, such as casting, forging, extrusion or rolling. Rolling DSS products exhibit an anisotropy on mechanical

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properties which is usually more pronounced than in other commercial steels. There is limited published work on this particular anisotropic behaviour of DSS (Hutchinson *et al* (3,4)) and this is particularly true when considering its influence on fatigue characteristics (Mayaki (5), Marrow (6), Boniardi *et al.*(7)).

The aim of this research is to investigate the influence of thermal ageing and anisotropy on the fatigue crack propagation (FCP) behaviour of DSS. In doing so, a detailed investigation of the microstructural and mechanical characteristics of a rolled sheet of alloy 2205 was conducted.

## EXPERIMENTAL PROCEDURE

The material used in this investigation was a commercially manufactured 5 mm thick hot rolled sheet of DSS corresponding to the standard UNS S31803 (or 2205). It has a typical chemical composition of 22.7% Cr, 5.0%Ni, 3.3%Mo, 0.12% N, 0.06%C. The microstructure is composed of almost identical volume fractions of ferrite and austenite, in the form of highly elongated lamellae following the rolling direction, as can be seen in **Fig. 2**.

Specimens for tensile testing were machined from the sheet at 0° (L), 45° (D) and 90° (T) to the rolling direction. Samples for FCP tests were obtained in three different crack plane orientations: L-T, T-L and D (at 45° to rolling direction). FCP testing was conducted under three point bending, in a load-controlled servo-hydraulic machine, at 20 Hz and R= 0.1. Crack lengths were measured with a QUESTAR long distance microscope, whose resolution is about 5 μm. The threshold value of the stress intensity factor amplitude $\Delta K_{th}$ was determined via decreasing the applied load until attaining a growth rate below $5x10^{-10}$ m/cycle. Both tensile and FCP tests were carried out for two sets of samples: one in the as-received condition (AR) and other aged at 475 °C for 200 hours (200h). From previous works it was known that this ageing condition produces a significant hardening and embrittlement.

## RESULTS

**Table 1** summarises the results obtained for the tensile tests. Aged materials exhibit higher strength and lower ductility than as-received ones. In both conditions, strength anisotropy is rather large, with the highest values of yield stress and ultimate tensile strength corresponding to T sample and the lowest ones occurring at 45°. Values for orientation L are closer to D than to T.

TABLE 1 - Tensile test data for as-received (AR) and aged (200h) steel.

| SAMPLE | $\sigma_y$ (MPa) | $\sigma_{max}$ (MPa) | Elongation (%) | SAMPLE | $\sigma_y$ (MPa) | $\sigma_{max}$ (MPa) | Elongation (%) |
|---|---|---|---|---|---|---|---|
| T - AR | 651 | 840 | 32 | T- 200h | 900 | 1181 | 24 |
| L - AR | 598 | 773 | 40 | L - 200h | 835 | 1076 | 30 |
| D - AR | 580 | 768 | 46 | D - 200h | 744 | 1048 | 33 |

From da/dN *versus* $\Delta K$ curves (**Fig.1**), parameters C and m in the Paris relationship ($da/dN = C.\Delta K^m$) have been calculated. **Table 2** shows the obtained parameters, together with the threshold values $\Delta K_{th}$. From them, it is found that: 1) ageing increases $\Delta K_{th}$ as well as the Paris exponent; 2) orientation effects, particularly between TL and LT, are more evident in stage I than in stage II, and these effects are less pronounced than those observed for ductility in tensile testing.

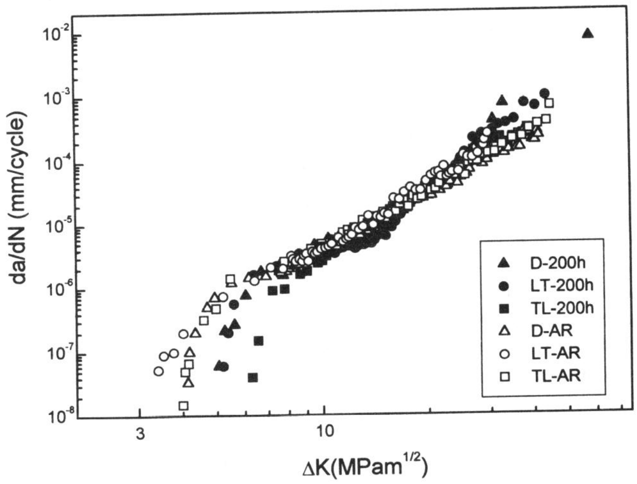


FIGURE 1.- Fatigue crack growth curves for as-received (AR) and aged (200h) steel.

TABLE 2 - Fatigue crack growth parameters and threshold values for as-received (AR) and aged (200h) steel.

| SAMPLE | $\Delta K_{th}$ ($MPa.m^{1/2}$) | m | C | SAMPLE | $\Delta K_{th}$ ($MPa.m^{1/2}$) | m | C |
|---|---|---|---|---|---|---|---|
| **TL- AR** | 3.98 | 2.89 | $5.62\ 10^{-9}$ | **TL- 200h** | 6.29 | 3.50 | $9.33\ 10^{-10}$ |
| **LT - AR** | 3.40 | 3.23 | $2.57\ 10^{-9}$ | **LT - 200h** | 5.21 | 3.67 | $4.89\ 10^{-10}$ |
| **D - AR** | 4.11 | 2.90 | $5.01\ 10^{-9}$ | **D - 200h** | 5.05 | 3.01 | $4.16\ 10^{-10}$ |

## DISCUSSION

The changes in properties induced by ageing, in both tensile behaviour and fatigue crack growth characteristics, confirm the susceptibility of DSS to "475°C embrittlement". On the other hand, the anisotropy induced by rolling was clearer on the monotonic response, particularly in ductility. The dependence of tensile parameters with orientation indicate that the possibility of a mechanical fibring effect is not feasible. This effect would increase strength along the rolling direction L. However, the observed behaviour is the opposite, *i.e.* maximum strength is obtained for direction T.

Anisotropy on the tensile behaviour of DSS has been analysed by several authors (3,4, Ul Haq *et al.* (8)) in the basis of crystallographic texture. These studies have shown that DSS have unusually sharp preferred crystallographic orientations, and it becomes more pronounced with decreasing plate thickness. Hence, the directionality of strength should rather be a result of texture hardening. Taylor factors have a minimum at 45° to the rolling direction and local maxima at 0° and 90°. This agrees quite well with our experimental results on tensile testing.

From the point of view of FCP, ΔK may be related to the crack tip opening displacement, CTOD, by means of the following expression (Broek (9)):

$$CTOD = \frac{A(\Delta K)^2}{E\sigma_y} \qquad [1]$$

where A is a constant, E is the Young modulus and $\sigma_y$ is the yield stress. It can be deduced that for high values of ΔK, high plastic strains will develop in the front of the crack tip. Therefore, higher crack propagation rates should be expected in the aged material because it has a lower fatigue resistance at high plastic strains (Iturgoyen and Anglada (10)). At small values of ΔK, the opposite is true since at small plastic strains the fatigue resistance is higher for the aged steel (10). This is consistent with the higher values of the Paris exponents and the thresholds measured for the 200h condition.

No remarkable variations in the m parameter were measured as a function of specimen orientation. However, there was a trend to higher m values for LT as compared to the others. The hypothesis of a growth rate decreasing with the number of interfaces in the crack path (5,6) must be rejected, because it would imply a slower rate for LT orientation. However, for LT specimens crack deflection was not observed (**Fig. 2a**), as it was for TL (**Fig. 2b**) and especially for D orientations (**Fig. 2c**). These changes on the crack path are suggested to be the source of the slower crack propagation rates measured.

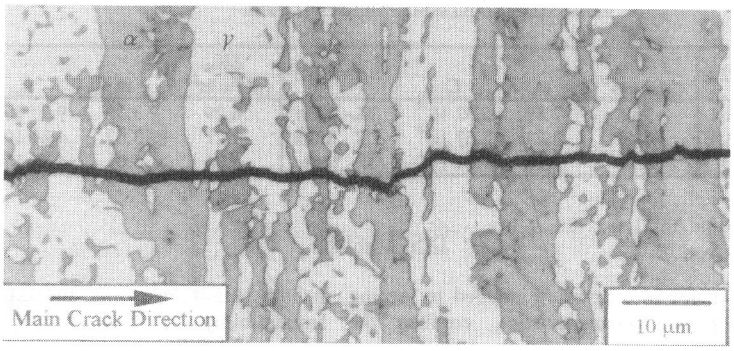


FIGURE 2.- Crack path in aged (200h) steel: **a)** LT orientation.

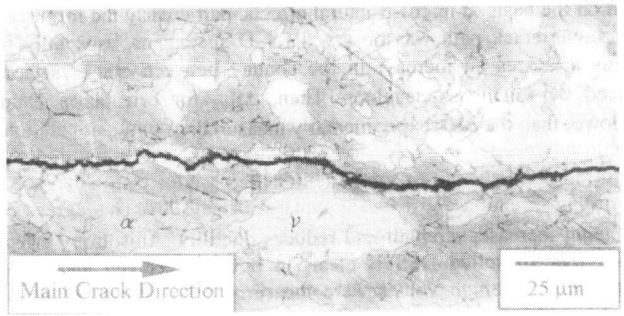


FIGURE 2.- Crack path unaged (AR) steel: **b)** TL orientation.

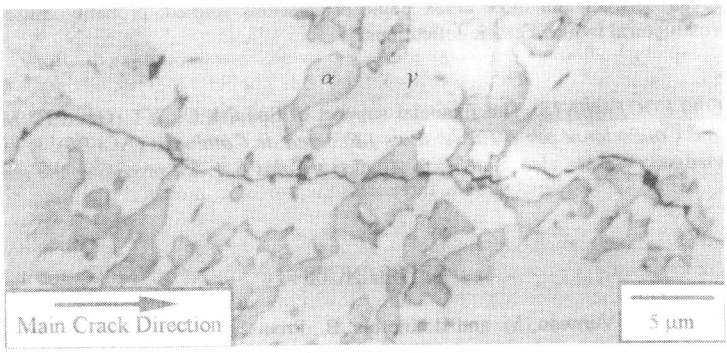


FIGURE 2.- Crack path in aged (200h) steel: **c)** D orientation.

From equation [1] and the notion that the threshold for the onset of crack growth occurs when the crack tip opening displacement (CTOD) attains a value comparable to a critical microstructural dimension, the following relationship may be deduced (Suresh, 11):

$$\Delta K_{th} \propto \sqrt{\sigma_y E l} \qquad [2]$$

where $l$ is the microstructural size scale, such as grain size. The highest yield stresses correspond to the T orientation; whereas different grain sizes should be considered for each orientation. Thus, for TL orientation the characteristic size is the length of the grains and for LT is the width, which is smaller because the measured shape factor (length/width) was 1.6. From these conditions, threshold values should be higher for TL orientation as compared to LT, relation which is satisfied for both as-received and aged materials. Concerning propagation at 45° to the rolling direction, yield stresses are the lowest ones and grain size is close to the width, so $\Delta K_{th}$(D) should be similar to $\Delta K_{th}$(L-T). This is true for the aged material, but not for the as-received condition, which exhibits a threshold even higher than $\Delta K_{th}$(T-L). An additional consideration may be established on the basis of microstructural effects, particularly the influence of crack closure. A tortuous crack path was observed for D specimens, especially in the AR condition. This produces an increase in the contact between crack surfaces so that closure induced by roughness develops. Then, $\Delta K_{eff}$ for orientation D should be significantly lower than the $\Delta K_{th}$ experimentally measured.

## CONCLUSIONS

- Thermal ageing increases strength and reduces ductility. Anisotropy effects on the tensile behaviour of rolled DSS is clear, in both as-received and thermal aged conditions. Higher strength values were measured for T direction as a result of texture hardening.
- Threshold values $\Delta K_{th}$ and crack growth rates are higher for the aged material. Anisotropy effects on FCP behaviour are relatively weak. Some differences are observed between the three crack plane orientations studied, probably caused by microstructural induced crack deflections.

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