Influence of Temperature and Strain Rate on the Low Cycle Fatigue of Duplex Stainless Steels

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ABSTRACT

Low cycle fatigue tests on a duplex stainless steel have been performed at two temperatures (598 and 748 K). These temperatures have been selected to analyse the effects of dynamic strain ageing and thermal ageing. Also, in order to evaluate the influence of strain rate on both phenomena, tests were conducted at two different strain rates. The experimental findings are discussed in terms of the substructural evolution observed.

INTRODUCTION

It is well known that during elevated temperature low cycle fatigue (LCF) of austenitic stainless steels, dynamic strain ageing (DSA) occurs /1-3/, and this has also been reported on ferritic stainless steels /4,5/. Due to the austeno-ferritic nature of duplex stainless steels (DSSs), it might be expected that they would manifest DSA too, and indeed recent publications have confirmed this fact /6/.

DSA is a complex phenomenon that depends on many parameters, especially those that affect dislocation glide as well as solute diffusivity /7/. As a consequence, DSA is a characteristic deformation feature during a specific regime of temperature, strain and strain rate ($\dot{\varepsilon}$).

On the other hand, the ferritic phase of DSSs experiences spinodal decomposition at temperatures around 748 K, which is accompanied by a severe drop in toughness, a phenomenon known as "475°C embrittlement" /8,9/.

The present investigation is focused on assessing the influence of strain rate on the LCF behaviour of a DSS at temperatures where both DSA and thermal ageing can affect their mechanical response. In doing so, comparisons of the cyclic hardening-softening responses and the substructures developed in both constituent phases, i.e. austenite and ferrite, for each testing condition have been conducted.

EXPERIMENTAL DETAILS

An EN 1.4410 DSS with chemical composition (in mass %) given by 25 Cr – 7 Ni – 3.8 Mo – 0.24 N – 0.011 C was employed. Its microstructure consisted of 54% in volume of a discontinuous austenitic phase within a ferritic matrix. Grains were elongated in the rolling direction, which corresponded to the loading axis in all tested specimens.

Specimens with a gauge length of 5 mm in diameter were used. Tests were carried out under an imposed

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total strain amplitude ($\Delta\varepsilon/2 = 9x10^{-3}$, at a stress ratio R = -1, in an electromechanical machine with a coupled environmental chamber. The experimental procedure consisted on heating from room temperature to the testing one and then holding for 30 minutes before starting the cyclic loading test. Two strain rates, with an order of magnitude of difference ($\dot{\varepsilon}$ = 10^{-2} and 10^{-3} s-1) were considered. Also, two temperatures were chosen for testing: 598 and 748 K. The first one was selected because it corresponds to maxima DSA effects for this steel under tensile testing /10/, while 748 K was chosen because around this temperature thermal embrittlement processes due to spinodal decomposition of ferrite is fastest /8,9/. Dislocation structures developed within each of the constitutive phases after cyclic loading were examined in a transmission electron microscope (TEM) operating at 120 kV.

RESULTS AND DISCUSSION

Cyclic responses for the four different testing conditions are shown in Figure 1. Plastic strain amplitudes obtained were around 5 × 10^{-3} for all the cases.

Tests at 598 K

Regarding the cyclic responses, a strong cyclic hardening ($\Delta\sigma_H$), defined as the difference between the maximum stress amplitude value reached during the test and that measured for the first cycle, is observed for both strain rates. Maximum stress values are reached after around 15 cycles (Fig. 1). For the slowest strain rate test $\Delta\sigma_H$ is 150 MPa, whereas for the fastest one it is only about 100 MPa. This is a consequence of the inverse strain rate sensitivity, a clear evidence for DSA processes, i.e. the lower the strain rate, the higher the effectiveness of the solute atmospheres for blocking the mobile dislocations, and therefore higher stresses are needed to unlock dislocations and to accommodate the imposed strain /7/.

TEM micrographs corresponding to dislocation arrangements in austenitic and ferritic grains after cycling at $\dot{\varepsilon}$ = 10^{-3} s^{-1} are shown in Figure 2. Concerning ferrite, dense tangles tending to form veins or poorly defined walls constitute the main feature (Fig. 2a). This type of arrangement is very different from the cells, walls and channels observed for tests at the same plastic strain but at room temperature /11/. The

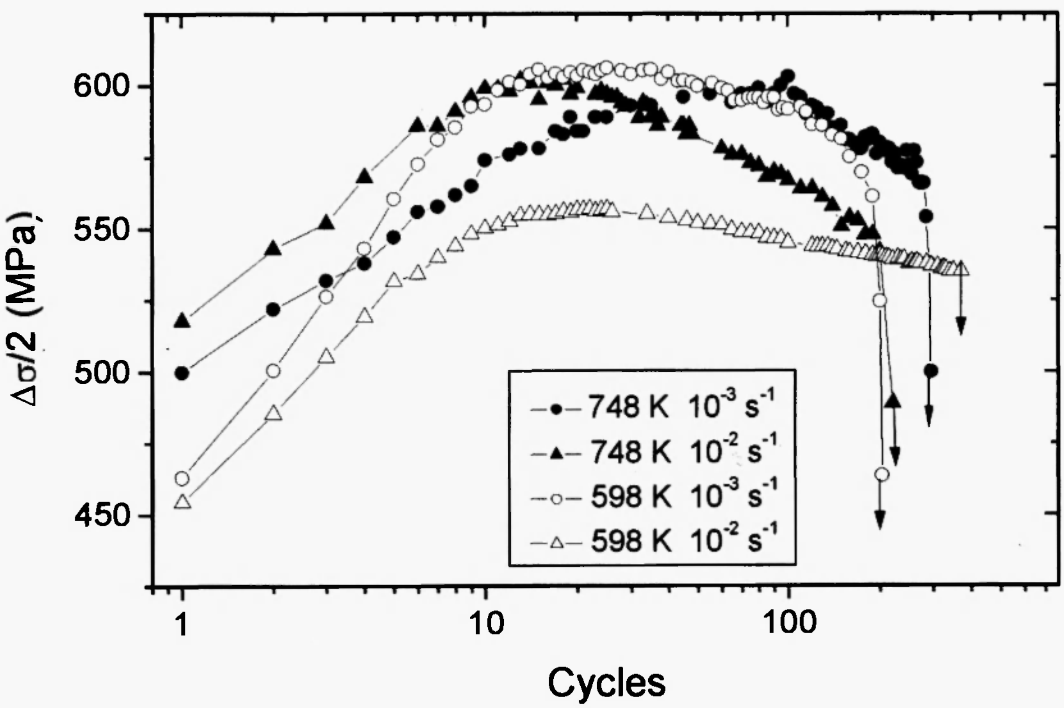

Fig. 1: Cyclic hardening-softening response of EN 1.4410 tested at $\Delta\varepsilon_t/2 = 9 \times 10^{-3}$ at 598 and 748 K.

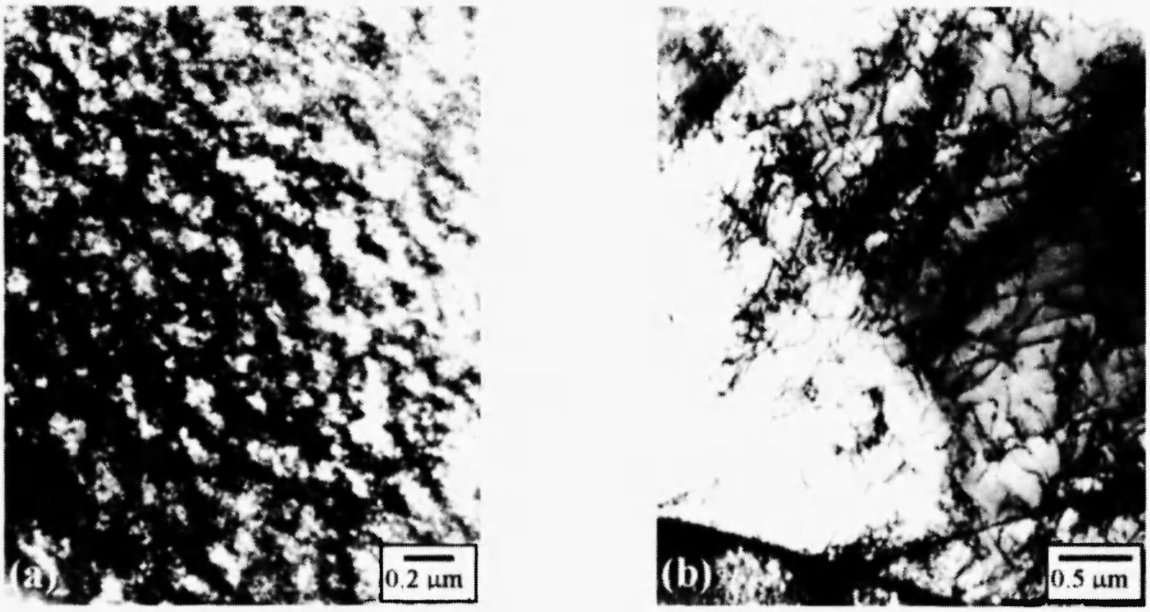

Fig. 2: Dislocations structures after cycling at 598 K, at $\Delta\varepsilon_t/2 = 9 \times 10^{-3}$ and at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$ developed in: (a) ferrite; (b) austenite.

difference can be attributed to the operation of DSA in ferrite that hinders the formation of three-dimensional dislocation structures /12/. On the other hand, the planar character observed in austenite for room temperature tests /11/ evolves towards wavier configurations, as evidenced for the tangles noticed at intersecting slip planes (Fig. 2b). This may be indirectly attributed to the DSA phenomenon, i.e. DSA mainly affects the ferritic phase restraining its plastic strain accommodation and, as a consequence, austenite is forced to contribute to plastic deformation by recourse to a transition towards a less planar-slip mode.

For the same temperature but higher strain rate, the substructural features are qualitatively similar in ferrite, although dislocation density is lower (Fig. 3a), whereas austenite glide remains quite planar (Fig. 3b). These differences are related with the lower effect of DSA due to the strain rate increase.

Concerning thermal ageing effects during tests at 598 K, they can be considered negligible because at this temperature its kinetics is very slow and long ageing times, i.e. thousands of hours, are necessary to produce appreciable changes on the mechanical properties /13,14/.

Tests at 748 K

The stress amplitudes corresponding to the first cycle of the cyclic hardening-softening curves of both tests performed at 748 K are about 60 MPa higher than the values measured at 598 K (Fig. 1). This circumstance is due to the influence of thermal ageing. At 748 K the kinetics of ageing is fast /8,9/, hence the time spent by the specimens in the heating chamber before starting the tests, i.e. 40 minutes for heating and 30 of holding, is long enough to induce a significant spinodal decomposition of the ferritic phase, and as a consequence higher stresses are required to deform the DSS.

Cyclic responses at 748 K (Fig. 1) are almost parallel for both strain rates up to the cycle 15, with the curve corresponding to the highest $\dot{\varepsilon}$ placed at higher stresses. Cyclic hardening, though less pronounced than that observed at 598 K, is noticed during this initial period. Both facts, i.e. positive strain rate sensitivity and low cyclic hardening, support the idea of absence of DSA operation at 748 K. Although at this temperature DSA effects have been reported for this DSS during tensile tests /10/, it should be taken into account that the

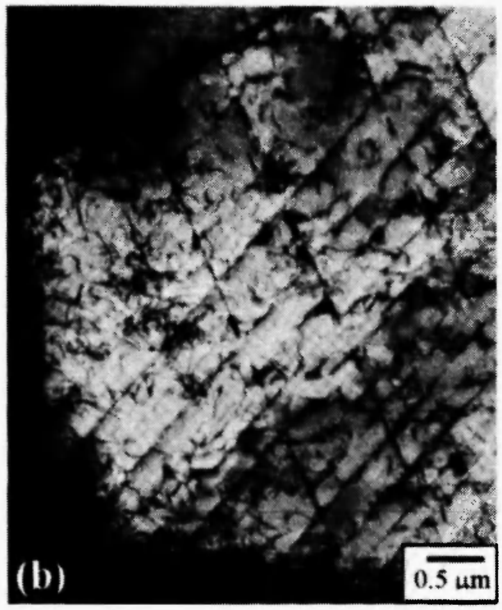

Fig. 3: Dislocations structures after cycling at 598 K, at $\Delta\varepsilon_t/2 = 9 \times 10^{-3}$ and at $\dot{\varepsilon} = 10^{-2}\ s^{-1}$ developed in: (a) ferrite; (b) austenite.

strain rate was considerably lower as compared to the LCF tests here performed, and therefore DSA could take place easier. Afterwards, whereas at $\dot{\varepsilon} = 10^{-2}\ s^{-1}$ a pronounced softening up to fracture is observed, for the low strain rate test the hardening stage continues for 100 cycles. This long duration of the cyclic hardening may be related to the simultaneous development of spinodal decomposition associated with the longer duration of the test at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$, i.e. 3 hours as compared to 12 minutes spent in the highest $\dot{\varepsilon}$ test.

If Figures 4a and 5a, corresponding to the substructure developed in ferrite, are compared, it can be discerned that for the test at high strain rate a more developed substructure is obtained, mainly with more defined walls. Moreover, when comparing substructural features developed within austenitic grains, completely planar arrangements are observed for the fastest test (Fig. 4b), while the presence of dislocation tangles at the intersection of slip systems indicates a tendency towards a wavier character at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$ (Fig. 5b). This different degree of plastic strain share between the two phases as a function of the strain rate may be related to the development of spinodal decomposition. As a consequence, ferrite deformation becomes hampered and austenite contribution to slip accommodation gets enhanced. Also, the higher accumulated plastic strain, due to the longer fatigue life, accounts for the change on the slip character of austenite in the slowest test.

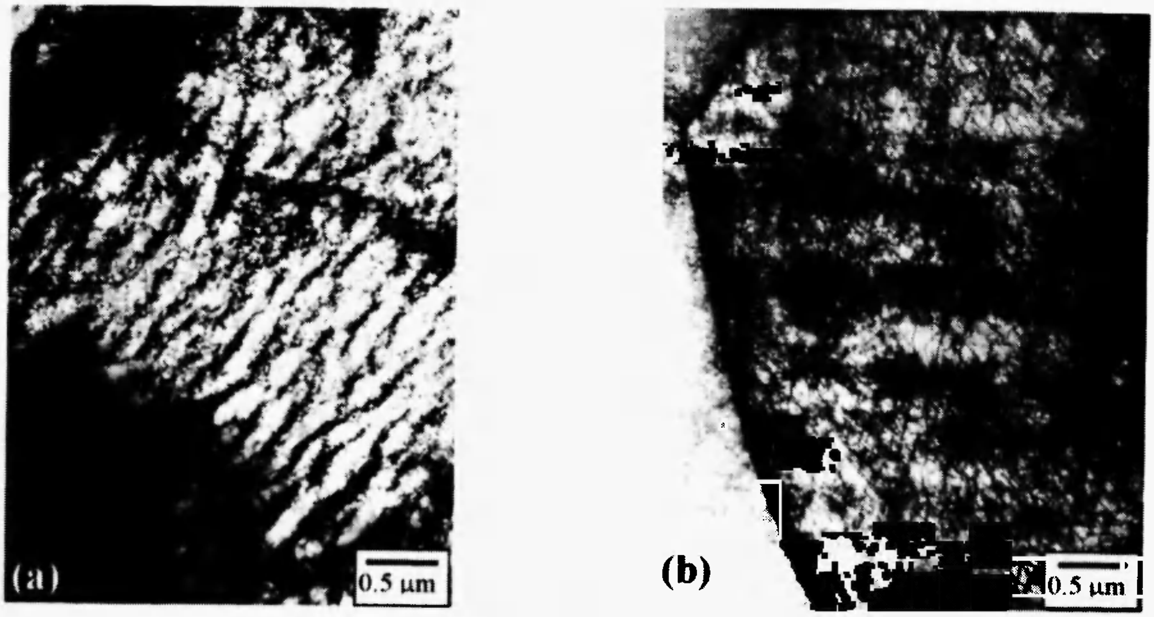

Fig. 4: Dislocations structures after cycling at 748 K, at $\Delta\varepsilon_t/2 = 9 \times 10^{-3}$ and at $\dot{\varepsilon} = 10^{-3}\ s^{-1}$ developed in: (a) ferrite; (b) austenite.

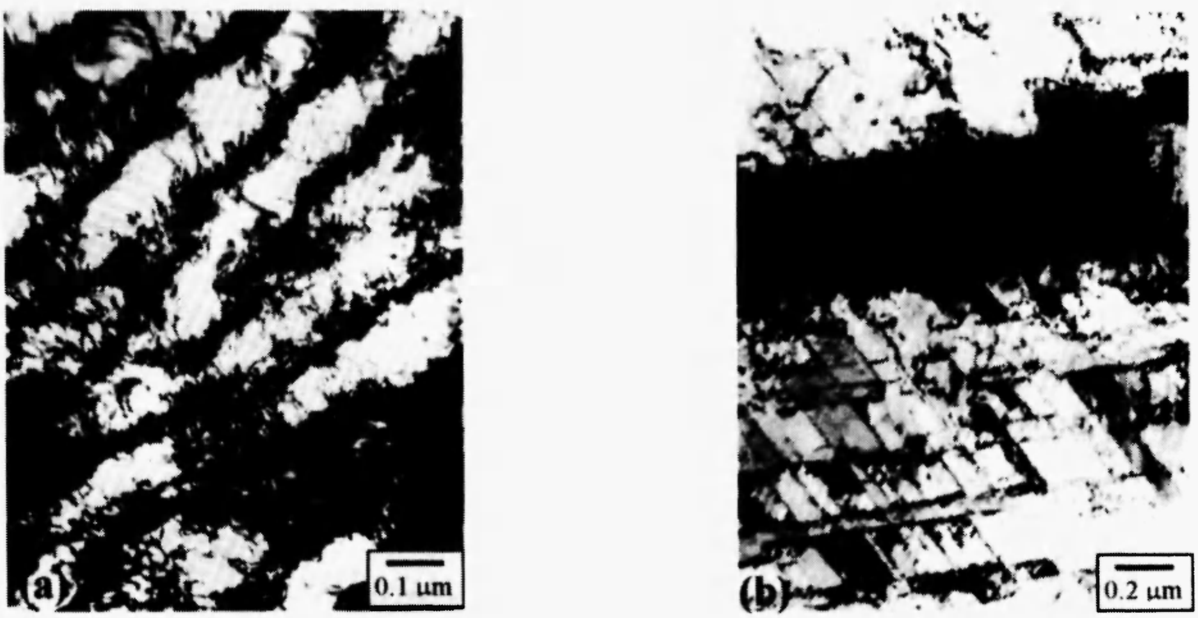

Fig. 5: Dislocations structures after cycling at 748 K, at $\Delta\varepsilon_t/2 = 9 \times 10^{-3}$ and at $\dot{\varepsilon} = 10^{-2}\ s^{-1}$ developed in: (a) ferrite; (b) austenite.

CONCLUSIONS

The following concluding remarks are outlined from the present study concerning the LCF response of DSSs at intermediate temperatures:

- Cyclic hardening-softening response at 598 K strongly depends on the activity of DSA mechanisms. The lower the strain rate, the more remarkable the DSA effects, and as a consequence initial hardening is stronger. The substructural evolution indicates the hindrance of three-dimensional dislocation arrangement due to DSA operation in ferrite.

  During LCF tests at 748 K, while DSA effects are negligible, thermal ageing influence must be taken into account. Low strain rate conditions lead to long duration tests and therefore spinodal decomposition of ferrite may be sufficiently developed to obstacle plastic strain accommodation in this phase.

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