Effect of mean stress on short crack growth and fatigue life in austenitic-ferritic duplex steel

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Abstract

Effect of mean stress on the cyclic stress-strain response, fatigue life, short crack growth and crack initiation of austenitic-ferritic duplex steel has been studied. Cycling with mean stress results in mean strain relaxation and more pronounced initial cyclic softening that does not saturate as in symmetric loading. The mean strain relaxation results in hardening and for high mean stresses long-term cyclic hardening follows. Short crack growth is characterized by crack linkage. The kinetics of short crack growth is similar for symmetric loading and loading with mean stress. The concept of equivalent crack was used to describe the crack growth. The presence of mean stress accelerates crack initiation, which contributes to the decrease of the fatigue life.

1. Introduction

Effect of mean stress on the fatigue life of materials has been investigated mostly phenomenologically by measuring the fatigue life curves at different mean stresses. The most pronounced effect of the mean stress on fatigue life is in the domain of high cycle fatigue, close to the fatigue limit. Fatigue strength or fatigue limit expressed as the stress amplitude for a chosen number of cycles to fracture decreases with increasing mean stress. E.g. Haigh or Smith diagrams show the dependence of the fatigue limit in terms of the stress amplitude on the mean stress. In the domain of finite fatigue life more attention has been paid to the cyclic creep or strain ratcheting (see e.g. [1-3]).

In austenitic–ferritic duplex stainless steels, in spite of their increasing application in industry, the effect of mean stress has not been studied yet. These steels become an advantageous replacement of austenitic and ferritic stainless steels due to higher mechanical properties and equal or higher corrosion resistance. Standard fatigue properties of duplex stainless steels were subject to numerous investigations. Low cycle fatigue [4, 5], high cycle fatigue [6], long crack growth [6] and the initiation and growth of short cracks [8-10] were studied.

In the present contribution the effect of mean stress on the cyclic stress-strain response, fatigue life and short crack growth in austenitic-ferritic superduplex steel is reported.

2. Experimental

Austenitic-ferritic SAF 2507 type duplex stainless steel was supplied by Sandvik, Sweden as rods of 30 mm in diameter. The chemical composition (in wt. %) was: 0.02 C, 23.0 Cr, 7.0 Ni, 3.8 Mo and 0.27 N, the rest Fe. The structure of the steel was formed by the islands of austenite elongated in the rolling direction embedded in a ferritic matrix. The volume fraction of austenite was 53 %. The average cross section of the austenitic and ferritic islands in the plane perpendicular to the specimen axis is about 255 $(\mu m)^2$.

Cylindrical specimens of the gauge length 12 mm and the diameter 8 mm were manufactured and their central part was ground to achieve a smooth surface. These specimens were used to obtain fatigue hardening/softening curves and cyclic creep curves. For the study of crack initiation and short crack growth shallow notch in the central part of the cylindrical surface was made. The notch was produced by grinding a cylindrical surface 60 mm in diameter to a depth of 0.4 mm in the middle of the cylindrical gauge section of a smooth specimen. The central part of the notch could be observed during cycling using a long distance optical microscope. The stress and strain concentration in the centre of the notch can be evaluated from the theoretical stress concentration factor $K_t = 1.15$ estimated from finite element analysis.

The probability of crack initiation in the central part of the notch was slightly increased due to stress and strain concentration but it was still close enough to the conditions of a smooth cylindrical specimen except for the lowest amplitudes. This is confirmed by the fact that at all amplitudes the cracks also initiated and started to grow outside the area of the notch. The cylindrical surface of the shallow notch was further mechanically and electrolytically polished. Fine marks were engraved on the area of the notch in order to facilitate identification of the cracks.

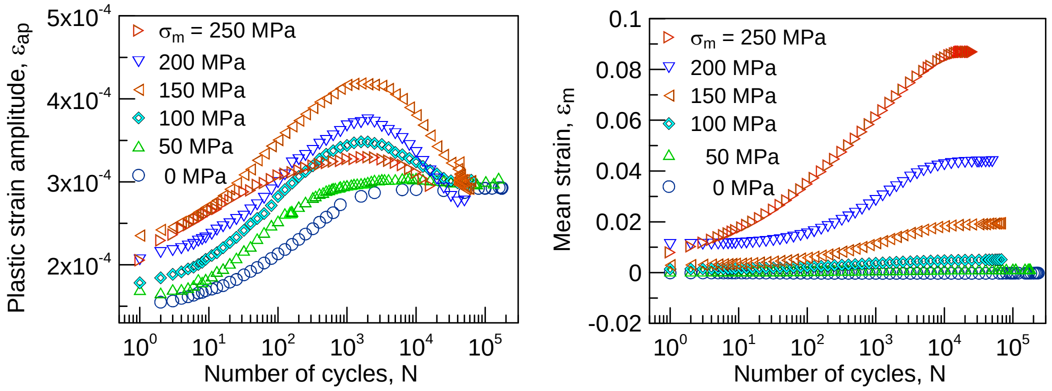
Sinusoidal loading with constant nominal stress amplitude and constant nominal mean stress with a frequency 0.5 Hz was applied. The strain was measured using extensometer with 12 mm gauge length positioned in the central part of the specimen. The hysteresis loops were recorded and plastic strain amplitude and mean strain were evaluated also in notched specimens neglecting the presence of the shallow notch.

Cycling was interrupted in predefined number of cycles and the central area of the notch was photographed using Navitar microscope with CCD MegaView IIIu digital camera. To document the surface evolution in the central area of the notch around 40 images were taken at each interruption of cycling. The growth of cracks was evaluated after finishing the experiment going back from the highest number of cycles to the nucleation. The history of all the cracks contributing to the formation and growth of all macroscopic cracks could be assessed. The crack length *a* was calculated from the half of the projected surface length to the plane perpendicular to the loading axis.

3. Results

Figure 1a shows cyclic hardening/softening curves and Fig. 1b respective plot of the mean strain vs. number of loading cycles for single amplitude of cyclic stress and different mean stresses. Cyclic straining under symmetric constant stress amplitude loading ($\sigma_m = 0$ MPa) results in cyclic softening. In the plot of the plastic strain amplitude vs. number of loading cycles (Fig. 1a) plastic strain amplitude increases and finally saturates. Plastic strain amplitude is saturated for most of the fatigue life. Mean strain in symmetric constant stress amplitude loading is approximately constant (Fig. 1b). In reality a small drift of the mean strain to the negative values ($-3\text{x}10^{-4}$) was observed, however, it is not apparent in Fig. 1b. The negative creep strain in symmetric loading is a specific feature of the duplex steel consisting of two phases having different yield stresses.

With increasing mean stress the initial cyclic softening is more pronounced and especially for high mean stresses instead of saturation long-term cyclic hardening follows (Fig. 1a). Cyclic softening rate was highest for mean stress 150 MPa. The development of cyclic softening/hardening behavior is related to the appearance of the cyclic creep (Fig. 1b). Appreciable increase of the mean strain during cycling with mean stress is apparent. Mean strain increases rapidly at the onset of cycling but there is a tendency to saturation for all mean stresses. The onset of saturation of the mean strain moves to higher number of cycles with increasing the mean stress.



(a) (b)

Fig. 1 Plastic strain amplitude (a) and mean strain (b) vs. number of loading cycles in constant stress amplitude loading (σ_a = 440 MPa) with different mean stresses σ_m.

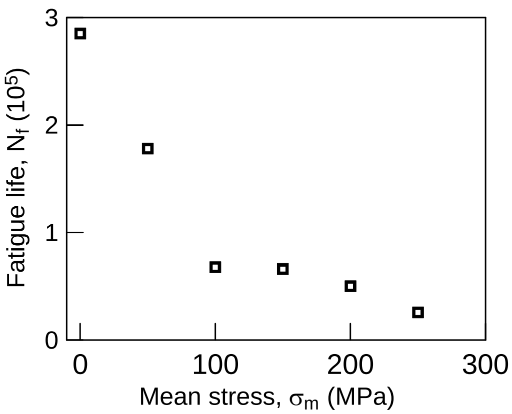


Fig. 2. Fatigue life vs. mean stress for cycling with constant stress amplitude σ_a = 440 MPa.

Figure 2 shows the plot of the fatigue life vs. the nominal mean stress. Appreciable decrease of fatigue life is observed with increasing nominal mean stress. The drop in fatigue life is highest for small mean stresses. When the mean stress increases further the decrease in fatigue life is already small in spite of the fact that the true stress amplitude increases during the test due to cyclic creep and resulting drop of the specimen diameter.

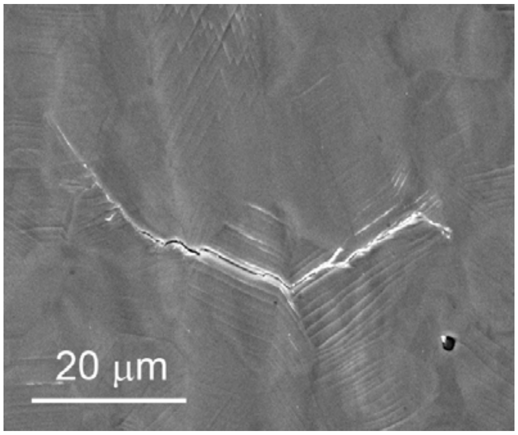


Fig. 3. Initiated crack in ferritic grain close to parallel monotonic slip step in constant stress amplitude loading with mean stress (σ_a = 440 MPa, σ_m = 150 MPa).

The evolution of fatigue damage on the specimen surface in symmetric loading and loading with mean stress was followed by systematically documenting the surface of the shallow notch using optical microscope with digital camera. The details of the surface relief and growing cracks were exemplified using scanning electron microscope (SEM). Fatigue cracks initiated both in ferritic and in austenitic grains within persistent slip markings (PSMs) produced by the localized cyclic straining in persistent slip bands (PSBs). Unidirectional strain developed during initial softening phase generated slip steps in which PSMs nucleated and thus cyclic creep contributed to the earlier development of the fatigue cracks. Figure 3 shows the surface area around the initiated crack in a specimen cycled with the mean stress 150 MPa. Several parallel slip steps in two neighbor ferritic grains are apparent. One of the monotonic slip steps served as a nucleus for the formation of the PSB leading to the creation of the PSM and later to the crack initiation.

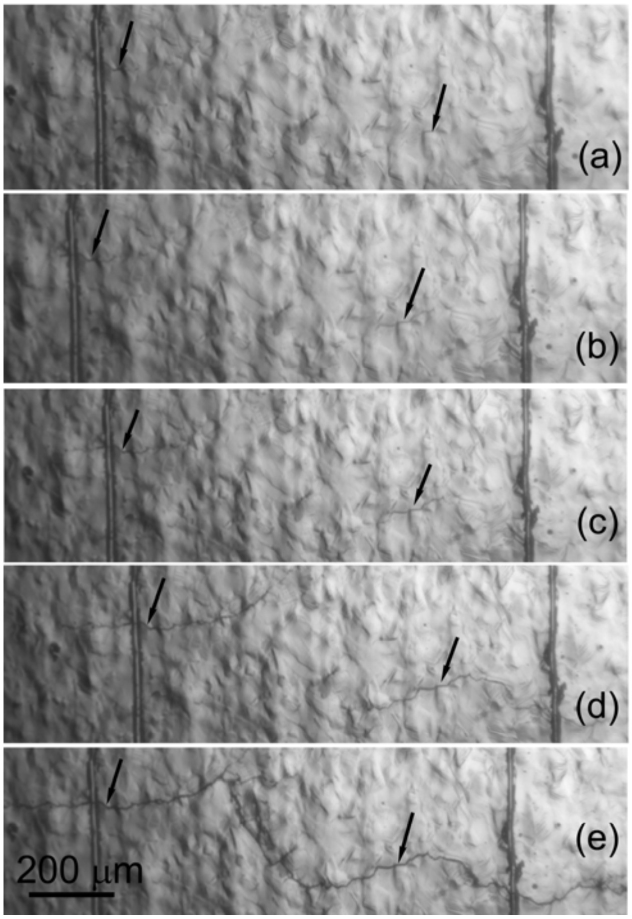
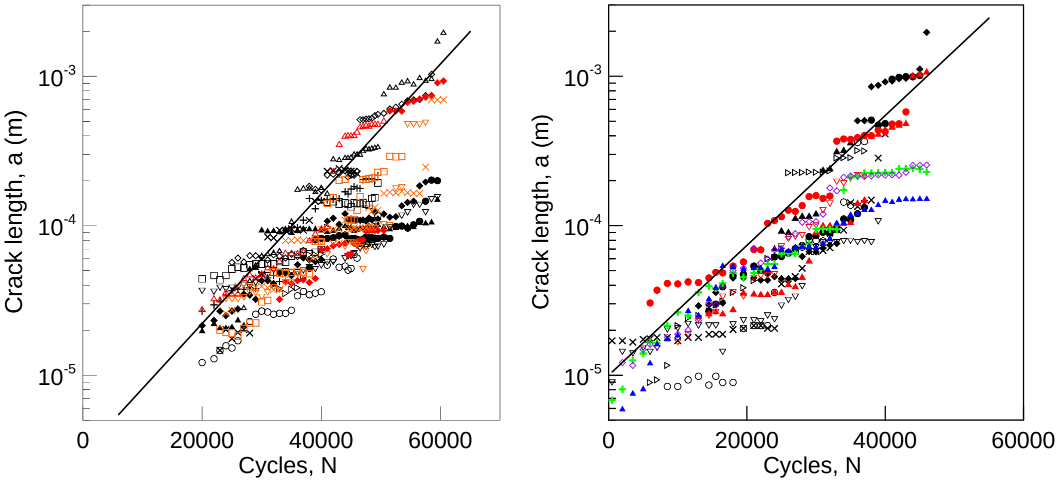


Fig. 4. Evolution of the surface relief in constant stress amplitude loading with mean stress (σ_a = 430 MPa, σ_m = 150 MPa); (a) 10 000 cycles, (b) 20 000 cycles, (c) 30 000 cycles, (d) 40 000 cycles, (e) 50 000 cycles, N_f = 61960 cycles.

Contrary to the case of symmetric loading where the first fatigue cracks appeared around 20% of the fatigue life loading with mean stress results in the early formation of cracks. High density of cracks was formed, and grew mostly perpendicularly to the specimen axis. The growth of individual cracks was initially independent of the other cracks. The growth of developed cracks was influenced by the presence of small cracks along their path and the linking of cracks contributed significantly to the crack growth. Crack linkage was usually decisive for the formation of a principal crack. Figure 4 shows five stages of the development of the principal crack in specimen cycled with constant nominal stress amplitude and constant nominal mean stress. Already at 10 000 cycles (N/N_f = 0.16) two cracks in the area shown in Fig. 4 can be detected using optical microscope (see black arrows in Fig. 4a). Both cracks grow slowly during the fatigue life and are linked together shortly before the end of the fatigue life (N/N_f = 0.81). The linkage of cracks resulted in rapid growth of some larger cracks and not a single physical crack was the longest crack during the whole fatigue life.

Kinetics of short crack growth was derived quantitatively from the numerous photographs of the specimen surface taken during the interruption of cycling in the area of the shallow notch. The crack length *a* was evaluated. It corresponds to the radius of the semicircle which approximates very well the shape of all cracks with the exception of very small, just nucleated cracks [11]. In Fig. 5 we have plotted the lengths of all cracks contributing to the formation of the principal crack resulting in fatigue fracture and also of five other largest cracks vs. the number of loading cycles. For very small cracks it was difficult to distinguish between the PSM/PSB and the crack. The length of crack *a* in this case corresponds to the half of the surface length of PSM/PSB which later developed into a crack.



(a) (b)

Fig. 5 Length of all cracks contributing to the formation of six longest cracks including principal crack vs. number of cycles; (a) symmetric loading (σ_a = 440 MPa, σ_m = 0 MPa), (b) loading with mean stress (σ_a = 440 MPa, σ_m = 150 MPa). Black symbols correspond to the cracks contributing to the growth of the principal crack.

In symmetric cycling the first cracks or PSMs/PSBs start to develop at around 20% of fatigue life. Though the first cracks could be identified using optical microscope already at 20% of fatigue life, the first quantitative evaluation was performed at 20 000 cycles. With increasing number of cycles individual cracks grow and are linked later, some of them forming a principal crack. Majority of growing cracks stop. They stop either at the grain boundaries, due to screening effect of larger cracks or simply because they achieved only certain length when the specimen failed due to the growth of a principal crack. The growth rate of individual cracks could be evaluated from this plot; however, since most individual cracks stop and others are linked with neighbor cracks it would be erroneous to characterize the damage of the body by these individual crack growth rates. Linkage of two cracks increases immediately the surface length of a linked crack but it takes some time before the semicircular shape is again achieved. As a result the crack length *a* calculated from the surface length immediately does not increase for a considerable period of cycles after linkage of two cracks (see Fig. 5).

In cyclic loading with mean stress (Fig. 5b) similar plot of the crack length vs. cycle number was obtained. The first cracks were detected much earlier than in symmetric loading, at around 1% of the fatigue life. Due to appreciable mean strain developed during cyclic creep in the early stage of cycling (see Fig. 2), PSMs/PSBs and cracks started to develop much earlier in life. Also here the linkage contributed to the crack growth and numerous cracks stopped while the growth of the principal crack resulted in fatigue fracture. Similar apparent retardation of crack growth rate as in symmetrical loading was observed after linkage of two cracks.

In order to correlate the growth of short cracks with the fatigue life of a body it is advantageous to use the concept of “equivalent crack” introduced earlier [12]. Equivalent crack is given by the instantaneous longest crack and need not to be always the same physical crack. The growth of the equivalent crack can be very well represented by a straight line in Fig. 5. It was drawn by hand and passes through the data which correspond to crack lengths corresponding approximately to semicircular cracks (just before the linkage with another smaller crack). Straight lines in Fig. 5 represent an exponential dependence

$$a = a_i \exp\left(k_g N\right) \tag{1}$$

where k_g, the crack growth coefficient, is a non-dimensional parameter. a_i, the apparent initial crack length, is the extrapolated value of the crack length to zero cycle. This dependence is in agreement with previous results for the growth of individual cracks in symmetric constant plastic strain amplitude loading [8]. Straight lines plotted in Fig. 5 correspond to the same crack growth coefficient $k_g = 1\text{x}10^{-4}$ but different apparent initial crack lengths a_i. For symmetric loading $a_i = 3\text{x}10^{-6}$ m and for loading with mean stress $a_i = 1\text{x}10^{-5}$ m were fitted. The apparent initial crack length in loading with mean stress is very close to the length of a nucleated crack. The very low apparent initial crack length in case of symmetric loading indicates that crack nucleation stage represents appreciable fraction of the fatigue life.

4. Discussion

Stress controlled loading with mean stress of austenitic-ferritic duplex steel results in cyclic creep. Unidirectional mean strain develops mostly in the early period, during cyclic softening. Cyclic creep rate decreases quickly and saturation of the mean strain is achieved. Saturation of the mean strain is reached later for higher mean stresses. Development of the mean strain in cycling with mean stress results in hardening of the material. While in symmetric cycling plastic strain amplitude increases (cyclic softening) and saturates early (see Fig. 1a), with increasing mean stress initial cyclic softening is more pronounced but it is followed for most of the fatigue life by appreciable cyclic hardening. As a result of a more pronounced cyclic softening and following long-term cyclic hardening the resulting plastic strain amplitude at half-life is for all tests with different mean stresses approximately the same.

Fatigue life of smooth specimens decreased appreciably when small asymmetry (σ_m up to 100 MPa – see Fig. 3) is introduced. Further increase of the mean stress leads only to a small additional decrement of the fatigue life. This small additional decrease of the fatigue life at higher means stresses can be explained by hardening of the material due to unidirectional strain that result in the drop of the plastic strain amplitude for most of the fatigue life (cyclic hardening). Since plastic strain amplitude is a governing factor of crack growth rate [8] fatigue life does not decrease further.

More insight into the effect of the mean stress on the fatigue life can be obtained from the observation of surface damage and quantitative evaluation of short crack growth and initiation. Limited experimental data show that the initial unidirectional cyclic creep strain and accompanying cyclic softening results in higher initial plastic strain amplitude and early crack nucleation. This can be one factor contributing to the decrease of the fatigue life due to the presence of the mean stress.

The kinetics of short crack growth studied for the mean stress equal to 150 MPa shows, however, that the crack growth coefficient k_g is similar for symmetric cycling and cycling with mean stress. This can be understood since due to long-term cyclic hardening plastic strain amplitude is for most of the fatigue life similar in both cases. Shorter fatigue life measured on a specimen with shallow notch that was fatigued with positive mean stress 150 MPa is thus caused predominantly due to shortening of the crack nucleation stage. The drop in the fatigue life of smooth specimen with increasing mean stress is, however, larger than in a specimen with a shallow notch. This difference can be understood by the concentration of the mean strain in the area of the shallow notch and resulting higher long-term cyclic hardening as observed for higher mean stresses on smooth specimens.

The role of long-term cyclic hardening due to cyclic creep in the presence of appreciable mean stress needs a more thorough study since the fatigue life can be significantly influenced by resulting monotonic hardening. Mean strain resulting from cyclic creep has twofold effect: (a) it shortens the crack nucleation period and initially cyclically softens the material; both phenomena result in the decrease of the fatigue life, (b) it also leads to long-term cyclic hardening, which is the cause why the drop in fatigue life at high mean stresses nearly saturates.

5. Conclusions

Experimental study of cyclic stress-strain response, fatigue life and short crack growth of austenitic-ferritic duplex stainless steel led to the following conclusions:

(i) Cyclic loading with mean stress results in more intensive cyclic softening followed by long-term cyclic hardening contrary to saturation in symmetric cycling.
(ii) Fatigue life decreases with increasing mean stress appreciably for mean stresses smaller than 150 MPa. Further increase of mean stress leads to appreciable cyclic creep, long-term cyclic hardening and therefore fatigue life decreases only mildly.
(iii) Kinetics of short crack growth in mildly notched body is similar in symmetric cycling and cycling with mean stress and approximately follows exponential law.
(iv) Mean monotonic strain due to the presence of the mean stress contributes to earlier nucleation of fatigue cracks.

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