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Cyclic plasticity, cyclic creep and fatigue life of duplex stainless steel in cyclic loading with positive mean stress

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Abstract

Austenitic-ferritic duplex stainless steel was cycled with three constant stress amplitudes and different mean stresses and cyclic stress-strain response and fatigue life were measured. Fatigue hardening/softening curves and cyclic creep curves were recorded. Saturated plastic strain amplitude was plotted vs. stress amplitude to obtain cyclic stress-strain curves for different mean stresses. The dependence of the cyclic stress-strain curve on the mean stress was established. Cyclic creep rate decreases progressively during the fatigue life leading to saturation of the mean stress. Fatigue life decreases with the mean stress and different representation of the fatigue life curves were presented and discussed in terms of crack initiation and growth.

Key words: cyclic plasticity, cyclic creep, mean stress, fatigue life, duplex steel

1. Introduction

The effect of the mean stress on the fatigue behaviour of materials attracts considerable interest since engineering components are often subjected to cyclic loading involving mean stress. The positive mean stress usually results in shortening of fatigue life, and therefore the mean stress effects should be taken into account in fatigue life prediction. Positive mean stress in uniaxial cyclic loading results in an increase of the mean strain that is described as cyclic creep or ratcheting. Considerable interest has been devoted to the study of the ratcheting at high cyclic stresses at ambient and elevated temperatures [1–5] since it results in inacceptable changes of the shape of the component or even in the tensile fracture.

Higher practical importance represents the presence of the mean stress in cyclic loading, which results in fatigue fracture. Several empirical approaches were adopted to take into consideration the presence of the mean stress in fatigue life evaluation. Most popular are the stress based relations used originally for stresses close to the fatigue limit, like Goodman, Soderberg or Gerber relations [6] or Smith and Haigh diagrams [7]. In finite life domain the SWT parameter [8] and Walker parameter [9] were adopted with considerable success to present unified fatigue life curve for different mean stresses. Kujavski and Ellyin [10] demonstrated the inadequacy of SWT parameter in cycling pressure vessel steel with high mean stress and proposed a modified equation containing average ratcheting strain per cycle. Kwofie [11] proposed exponential stress function for predicting fatigue strength and life due to mean stresses. Kwofie and Chandler [3] recently modified Kwofie's original proposal [11] and derived a master curve for stress-controlled low cycle fatigue behaviour under tensile mean stress condition where cyclic creep occurs.

The majority of the proposed life estimation procedures in conditions incorporating mean stress are based on phenomenological approaches using correlation of fatigue lives with the parameters of the cyclic loading for a specific material. More basic approach to develop reliable relations describing the dependence of fatigue life on the mean stress represents an attempt to study in detail all relevant implications of the presence of the mean stress on the damaging process. This comprises the study of the effect of mean stress on the cyclic stress-strain response and also the study of the kinetics of cyclic creep.

The prediction of fatigue life in the presence of the mean stress requires the knowledge of the effect of

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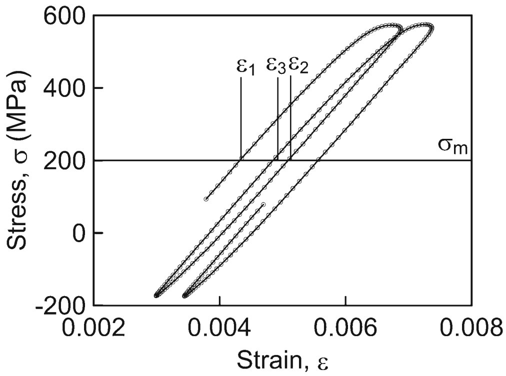

Fig. 1. Stress-strain path during two consecutive cycles with positive mean stress.

the mean stress on the cyclic stress-strain behaviour. Several papers studied different aspects of the effect of mean stress on the cyclic stress-strain response in polycrystalline copper [12–14], in polycrystalline nickel [15], in carbon and alloy steels [16–20], in austenitic stainless steels [21] and in ferritic-martensitic steel [22, 23]. In most cases the presence of the mean stress resulted in an increase of the plastic strain amplitude during the whole life and in cyclic creep acceleration. The simultaneous effect of the mean stress on the cyclic stress-strain response and on the fatigue life has not been studied systematically.

We have undertaken a systematic study of the effect of the positive mean stress on the cyclic stress--strain response, cyclic creep and resulting fatigue life of an austenitic-ferritic duplex stainless steel under conditions leading to fracture in the interval of fatigue lives from 10^4 to 10^7 cycles.

2. Experimental

Experimental material was the same as used earlier [24, 25], i.e. austenitic-ferritic SAF 2205 type duplex stainless steel supplied by Sandvik, Sweden as rods of 30 mm in diameter. The chemical composition (in wt.%) was: 0.016 C, 22.0 Cr, 5.4 Ni, 3.1 Mo, 0.16 N, the rest Fe. The structure of the steel was formed by the islands of austenite elongated in the rolling direction that were embedded in a ferritic matrix. The volume fraction of austenite was 46 % and the cross section of the austenitic grains in the plane perpendicular to the specimen axis was about 200 μm^2.

Cylindrical specimens of the gauge length 12 mm and of the diameter 8 mm were manufactured and their central part was ground to achieve a smooth surface. They were subjected to sinusoidal loading with constant nominal stress amplitude and constant nominal mean stress with a frequency 5 Hz in a computer controlled electrohydraulic testing system. 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. Figure 1 shows schematically the stress-strain path during two cycles in stress controlled cycling with constant stress amplitude σ_a and positive mean stress σ_m. From the record of two subsequent hysteresis loops we have evaluated for selected cycles three strains corresponding to mean stress σ_m, chronologically ε_1, ε_2, ε_3. In the presence of positive mean stress the plastic strain range in the tensile half-cycle $\Delta\varepsilon_{pT} = \varepsilon_2 - \varepsilon_1$ is higher than the plastic strain range in the compression half-cycle $\Delta\varepsilon_{pC} = \varepsilon_2 - \varepsilon_3$.

The cyclic creep rate ε_c can be defined as the strain increment in a cycle

$$\varepsilon_c = \Delta\varepsilon_{pT} - \Delta\varepsilon_{pC} = \varepsilon_3 - \varepsilon_1. \tag{1}$$

The definition of the plastic strain amplitude is not unequivocal. The first possibility is to define plastic strain amplitude ε_{ap} as the half of the average of the plastic strain range in tensile half-cycle, $\Delta\varepsilon_{pT}$, and that in compressive half-cycle $\Delta\varepsilon_{pC}$, i.e.

$$\varepsilon_{ap,non} = \frac{2\varepsilon_2 - \varepsilon_3 - \varepsilon_1}{4}. \tag{2}$$

However, the completely reversed plastic strain range is only the strain range in compressive half-cycle, and therefore plastic strain amplitude in the following was defined as half of the reversed strain range, i.e.

$$\varepsilon_{ap} = \frac{\varepsilon_2 - \varepsilon_3}{2}. \tag{4}$$

The nominal mean strain is defined as

$$\varepsilon_m = \frac{\varepsilon_3 + \varepsilon_1}{2}. \tag{4}$$

The cyclic creep rate ε_c and the nominal mean strain ε_m characterize the kinetics of cyclic creep. Since in cyclic loading the nominal stress amplitude and the nominal mean stress were kept constant the true stress amplitude and true mean stress are systematically higher than the nominal values and are proportional to the $(1 + \varepsilon_m)$.

3. Results

Three stress amplitudes (340 MPa, 360 MPa and 380 MPa) and six levels of the mean stress (0 MPa, 50 MPa, 100 MPa, 150 MPa, 200 MPa and 250 MPa) were chosen. They result in fatigue lives in the interval 2×10^4 to 5×10^6 cycles. Figure 2 shows typical

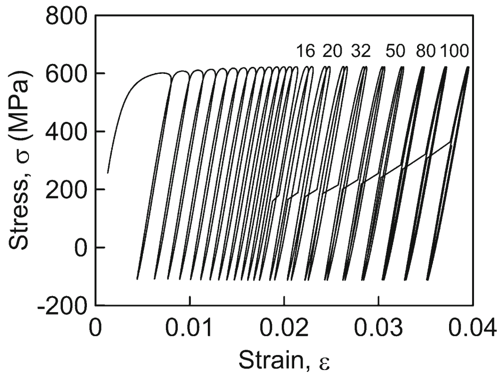

Fig. 2. Typical stress-strain record of the first cycles in cycling with high mean stress.

example of the stress-strain record of selected cycles up to 100 cycles. Initially all hysteresis loops were recorded, later at selected number of cycles (approximately corresponding to geometrical series) two consecutive loops were recorded and plastic strain amplitude, mean strain and cyclic creep rate were evaluated. Figure 2 shows that when the programmed maximum stress in a cycle is well above the yield stress the relaxation of the strain in cycling with frequency 5 Hz does not allow reaching this programmed level from the onset of cycling and the desired maximum stress is reached only at around 12 cycles.

The cyclic stress-strain behaviour showing the plastic strain amplitude, the mean stress and cyclic creep rate vs. number of loading cycles for all levels of the stress amplitude and mean stress is shown in Figs. 3, 4 and 5. Plastic strain amplitude at all levels of the stress amplitude and mean stress increases (initial fatigue softening). For symmetric cycle and for low mean stresses (< 50 MPa) the initial softening is followed by saturation of the plastic strain amplitude. For higher mean stresses the maximum plastic strain amplitude is reached and mild long term hardening or also saturation follows. After initial softening that is in all cases completed within 1000 cycles the variation of the plastic strain amplitude up to the end of the fatigue life is very small and the plastic strain amplitude corresponding to one half of the number of cycles to fracture characterizes very well the applied stress amplitude and the mean stress.

The effect of the mean stress on the plastic strain amplitude shows Fig. 6. For the lowest stress amplitude (340 MPa) the plastic strain amplitude increases appreciably with increasing mean stress, for the medium stress amplitude (360 MPa) the increase is very mild and for the highest stress amplitude (380 MPa) plastic strain amplitude decreases with increasing mean stress. This dependence has an important impact on the slopes of the cyclic stress-strain curves at various mean stresses. The plot of the ap-

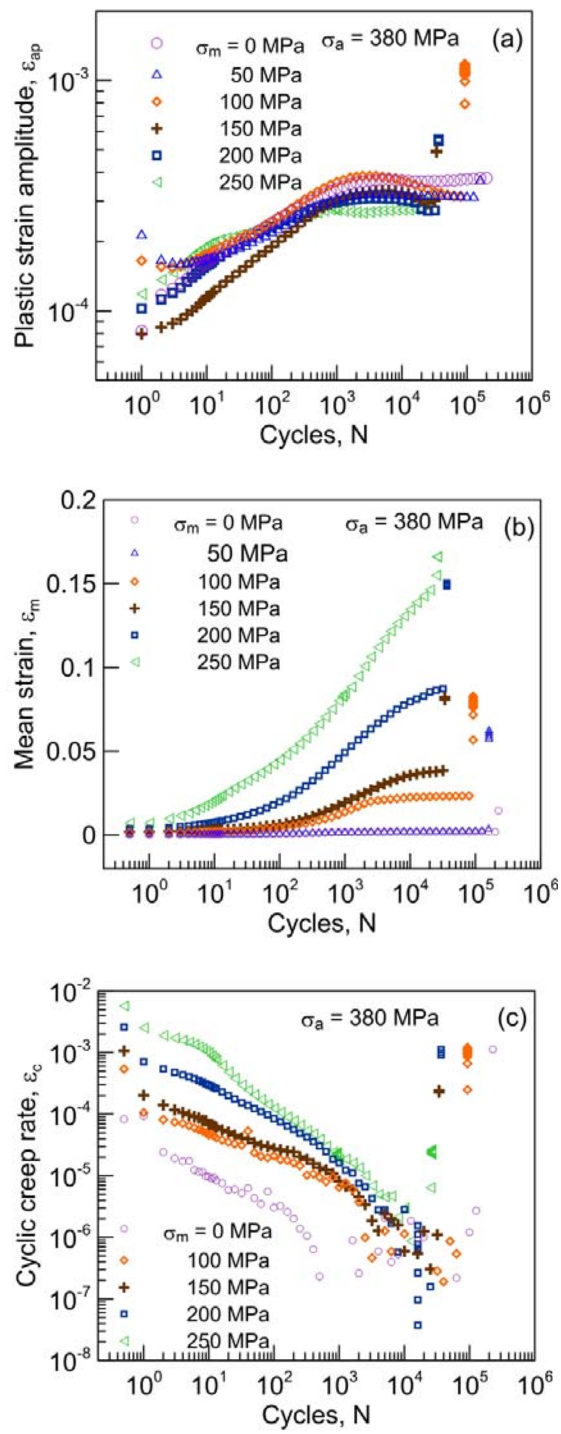

Fig. 3. Plastic strain amplitude (a), mean strain (b) and cyclic creep rate (c) in cycling with stress amplitude 380 MPa and different mean stresses.

plied stress amplitude vs. the plastic strain amplitude at half-life for various mean stresses in bilogarithmic coordinates is shown in Fig. 7. Though only three points for each mean stress were available, the power law

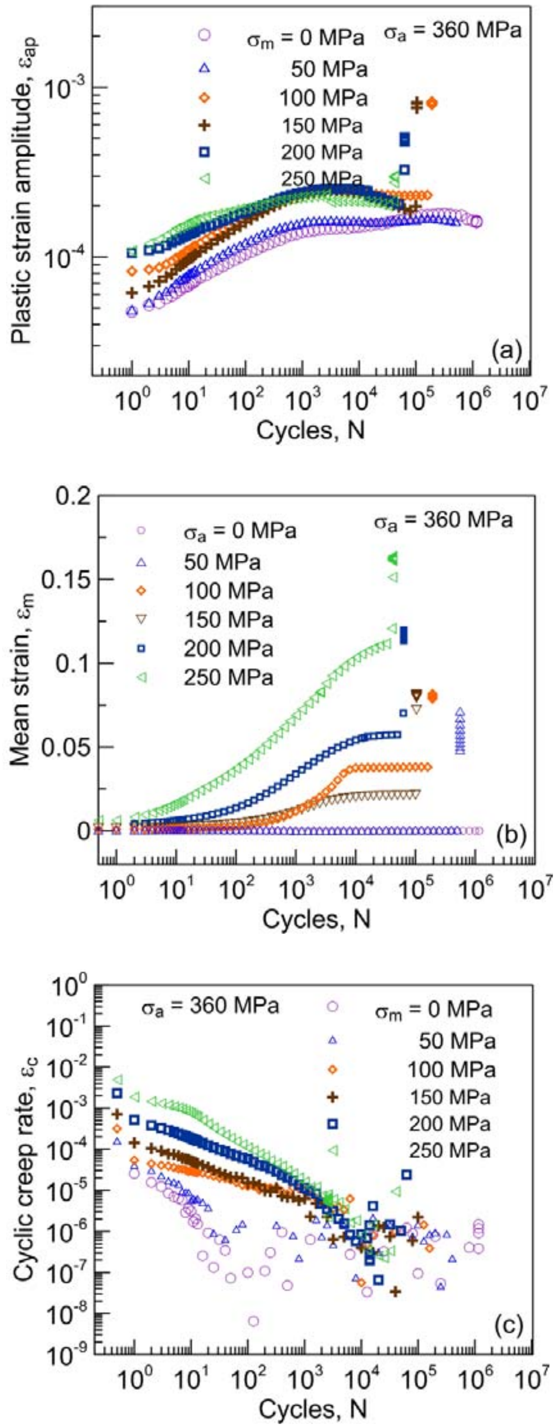

Fig. 4. Plastic strain amplitude (a), mean strain (b) and cyclic creep rate (c) in cycling with stress amplitude 360 MPa and different mean stresses.

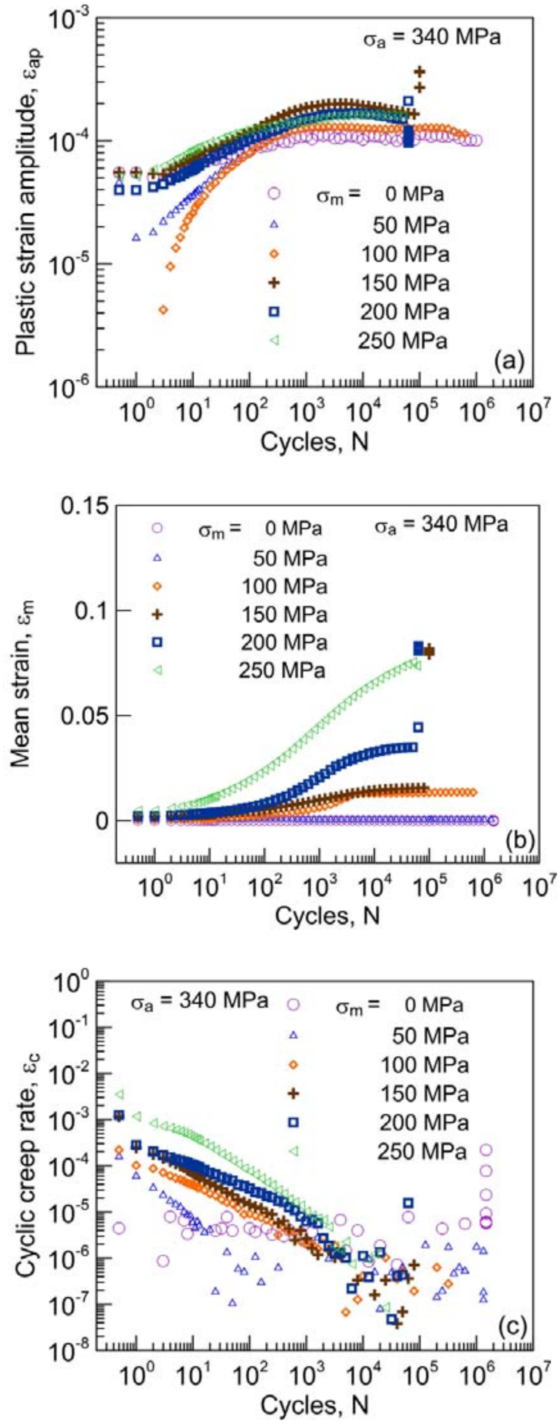

Fig. 5. Plastic strain amplitude (a), mean strain (b) and cyclic creep rate (c) in cycling with stress amplitude 340 MPa and different mean stresses.

$$\sigma_{\mathrm{a}} = K\varepsilon_{\mathrm{ap}}^{n} \tag{5}$$

has been fitted to each set of experimental data. In Fig. 7 for lucidity only two fitted straight lines corresponding to zero and 250 MPa mean stresses are plotted. However, it is evident that with increasing mean stress the slope of the cyclic stress-strain curve increases. Figure 8 shows the plot of exponent n of the dependence (5) fitted to each set of data corresponding to one mean stress vs. mean stress.

Mean strain remains approximately constant in symmetrical cycling and in cycling with low mean

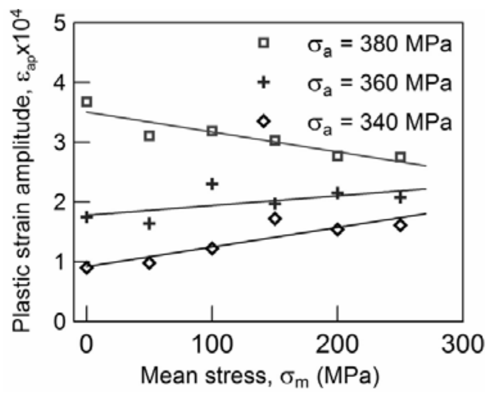

Fig. 6. Dependence of the saturated plastic strain amplitude on the mean stress for three stress amplitudes.

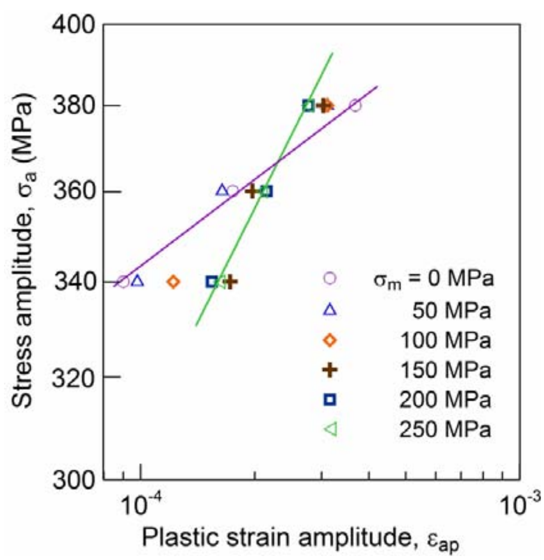

Fig. 7. Cyclic stress-strain curves plotted for different mean stresses.

stress (< 50 MPa). With increasing mean stress the mean strain increment (cyclic creep rate) in the first cycle becomes substantial. Cyclic creep rate decreases with the number of cycles until it reaches the values around 10^{-6} per cycle. The lowest cyclic creep rates evaluated from one cycle have appreciable scatter (Figs. 3c, 4c and 5c). The mean strain either saturates completely or has a strong tendency to saturation. Mean strain at half-life vs. mean stress is plotted in Fig. 9.

Fatigue life decreases appreciably with the increase of the mean stress for all three stress amplitudes as shows Fig. 10. When the data are plotted in a Wöhler plot (Fig. 11), individual plots can be approximated by the Basquin dependence

$$\sigma_a = \sigma_f'(2N_f)^b, \tag{6}$$

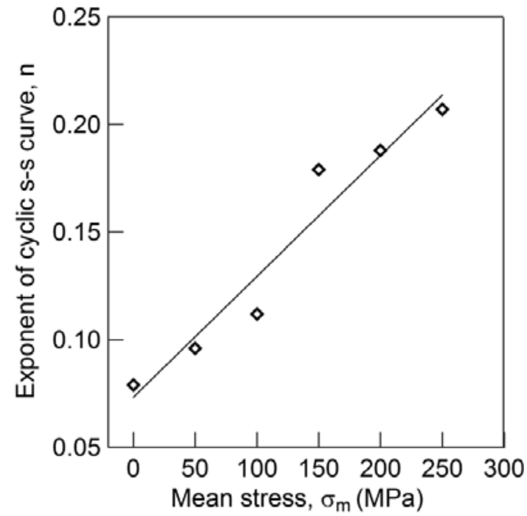

Fig. 8. Exponent of the cyclic stress-strain curve vs. mean stress.

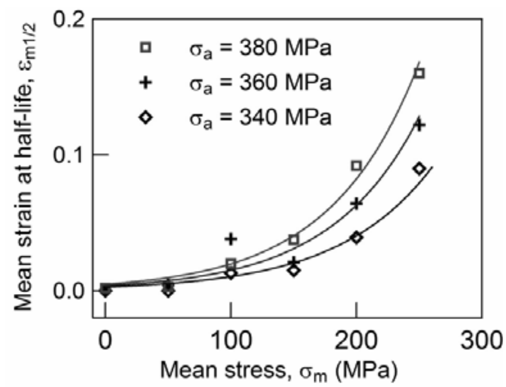

Fig. 9. Mean strain at half-life vs. mean stress in cycling with different stress amplitudes.

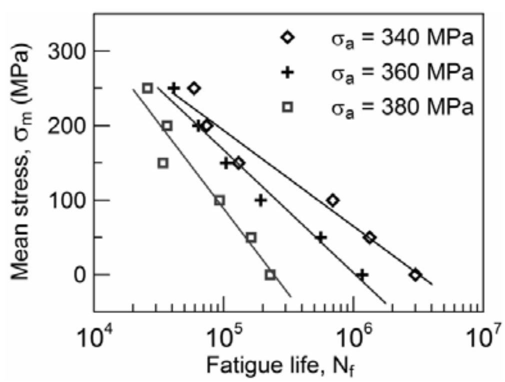

Fig. 10. Mean stress vs. fatigue life for different stress amplitudes.

where σ_f' and b are parameters. It is evident that with increasing mean stress Basquin curve is shifted to

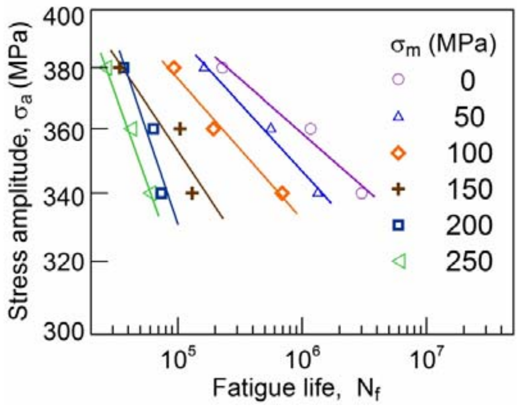

Fig. 11. Wöhler plot for different mean stresses.

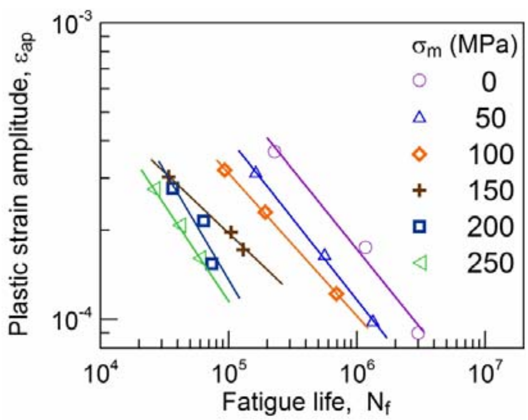

Fig. 12. Manson-Coffin plot for different mean stresses.

lower fatigue lives. The absolute value of the fatigue strength exponent b increases with increasing mean stress.

The plot of the fatigue life vs. plastic strain amplitude at half-life in the Manson-Coffin plot (Fig. 12) was fitted to the Manson-Coffin law in the form

$$\varepsilon_{\mathrm{ap}} = \varepsilon'_{\mathrm{f}}(2N_{\mathrm{f}})^{c}, \tag{7}$$

where $\varepsilon'_{\mathrm{f}}$ and c are parameters. The curves are also shifted with increasing mean stress to lower fatigue lives. The fatigue ductility exponent c is, however, approximately the same for all mean stresses and the average value is -0.56.

4. Discussion

4.1. Cyclic creep and cyclic plastic strain

Austenitic-ferritic duplex steel consists of two phases with different yield stresses and substantially different effective stresses [26]. The approach using statistical theory of the hysteresis loop [27] can be applied also in case of cyclic loading with positive mean stress. The effective stresses of the elementary volumes and the critical internal stresses with the highest probability in austenite are considerably lower than respective quantities in ferrite. It is therefore predominantly the ferrite which determines the cyclic stress-strain behaviour in stress controlled loading with positive mean stress. The plastic strain increment in tensile direction $\Delta\varepsilon_{\mathrm{pT}}$ is determined by the integration of the strain rate under the action of positive effective stress in tensile half-cycle. Effective stress component is equal to the difference of the total stress and internal stress. Due to cyclic creep resulting in unidirectional straining (the increase of the mean strain) both the austenite and ferrite are hardened, which results in an increase of the internal critical stresses. In terms of statistical theory the peak of the probability density function of the internal critical stresses is shifted to the higher values of the internal critical stresses. As a result of the increase of the internal critical stresses the effective stress decreases and plastic strain increment in tensile direction, $\Delta\varepsilon_{\mathrm{pT}}$, decreases steadily during the fatigue life.

The plastic strain increment in compressive direction $\Delta\varepsilon_{\mathrm{pC}}$ represents reversible cyclic plastic strain and is the result of the localized plastic straining in specific volumes of the material, in persistent slip bands. It is determined primarily by the applied stress range. Since localization of the cyclic strain into persistent slip bands starts very early in fatigue life [28] the plastic strain amplitude increases initially and stabilizes later for most of the fatigue life (Figs. 3a, 4a and 5a). Contrary to single phase alloys [22], where appreciable increase of the plastic strain amplitude up to the fracture was observed, the two phase austenitic-ferritic steel is stable. The fracture is due to the initiation of fatigue cracks in persistent slip bands and slow growth of fatigue cracks under approximately constant plastic strain amplitude regime.

The cycling with higher mean stress at all stress amplitudes results in an increase of the maximum stress in a cycle, and therefore in the increase of the cyclic creep rate with mean stress (Figs. 3–5). Nevertheless, in all cases the cyclic creep rate decreases during the fatigue life resulting in a tendency of the mean strain to reach saturation.

Much more interesting is the effect of the mean stress on the plastic strain amplitude. The increase of the plastic strain amplitude with increasing mean stress for lower stress amplitudes (340 MPa and 360 MPa, see Fig. 6) can be explained by the fact that unidirectional slip lines promote the formation of persistent slip bands (PSBs) and thus cyclic slip localization. Formation of PSBs is most difficult for low stress amplitudes and numerous unidirectional slip

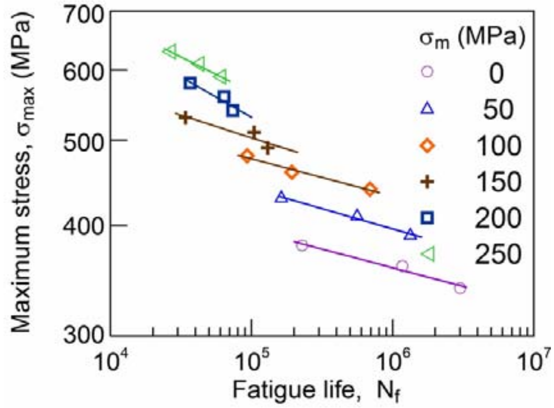

Fig. 13. Maximum stress vs. fatigue life for different mean stresses.

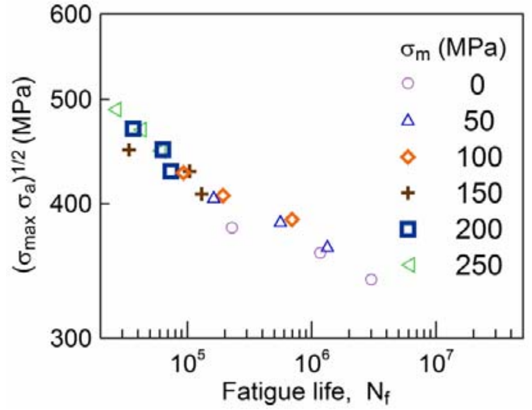

Fig. 14. SWT parameter vs. fatigue life for different mean stresses.

bands resulting from the cyclic creep facilitate the creation of a high density of PSBs. The high density of PSBs results in an increase of plastic strain amplitude. In case the initial unidirectional strain in a cycle (initial cyclic creep rate) is so high that it results in double slip in majority of grains it leads to the hardening of the material and to the blocking of PSB formation due to activation of secondary slip. The effect of the hardening in cyclic loading with high amplitude can be thus higher than the effect of softening. Therefore, for cycling with stress amplitude 380 MPa plastic strain amplitude decreases with increasing mean stress.

The effect of the mean stress on the saturated plastic strain amplitude shows on the slope of the cyclic stress-strain curve at different mean stresses (Fig. 7). The result must be, however, taken with caution since this dependence has been determined for each mean stress using only three data points and only in a narrow interval of the plastic strain amplitudes.

4.2. Fatigue life

Mean stress results in a decrease of the fatigue life (Fig. 10). Plotting the stress amplitude vs. fatigue life in Fig. 11 we can see the shift of fatigue life to lower lives with increasing mean stress. The slope of the Basquin curve (power law dependence) increases considerably with the increasing mean stress. The plot of the maximum stress in cycle vs. fatigue life in Fig. 13 shows that for equal maximum stresses the increase of the mean stress leads to the higher fatigue life. The plot of the fatigue life vs. some combination of the maximum stress and stress amplitude can yield one curve. Walker [9] proposed to use the parameter $\sigma_{\max}^{\nu}\sigma_{\mathrm{a}}^{(1-\nu)}$, where ν can be adjusted to yield unequivocal dependence on the fatigue life for all maximum stresses and stress amplitudes. For majority of materials ν is close to 1/2. In this case the Walker approach reduces to SWT approach [8] provided the plastic strain component is small. SWT parameter is plotted vs. the fatigue life in Fig. 14 and single curve can be fitted to all experimental data. Nevertheless, both Walker and Smith et al. approaches represent only phenomenological descriptions that contribute too little to fatigue life prediction in cycling with mean stress. The attempt to apply other phenomenological procedures e.g. proposed by Kujavski and Ellyin [10] or by Kwofie [11] and Kwofie and Chandler [3] to our experimental data were only partially successful.

In order to explain the effect of the mean stress on the fatigue life the plot of the fatigue life vs. plastic strain amplitude is of primary importance since plastic strain is a decisive factor both in fatigue crack initiation and in early crack growth [29]. It was found that the dependence of the saturated plastic strain amplitude on the mean stress is very weak (Fig. 6). Nevertheless, since this dependence is different for small and for high stress amplitudes the slope of the cyclic stress-strain curve is changed appreciably (Figs. 7 and 8). Eventually the Manson-Coffin curves derived from cycling with different mean stresses (Fig. 12) have approximately the same slope (the average value of the cyclic ductility exponent is −0.56). It indicates that the process of fatigue damage leading to fracture is similar in cycling with different stress amplitudes and mean stresses. Mean stress influences the fatigue life equally when cycling with high or low stress amplitudes in our interval of cyclic lives. With increasing mean stress the Manson-Coffin curve is shifted to lower fatigue lives. Mean stress 250 MPa results in lowering the fatigue life more than an order of magnitude. Most probably both the crack initiation and short crack growth are affected by the mean stress; nevertheless, the same slope of Manson-Coffin curves indicates that the mean stress affects primarily the rate of short cracks. The separation of the effect of the mean stress on the fatigue crack initiation and the early crack growth is the subject of further study on the initiation and growth rates of short cracks [30].

5. Conclusions

Experimental study of the cyclic plastic stress--strain response and fatigue life of duplex austenitic-ferritic stainless steel under stress controlled loading with positive mean stress leads to the following conclusions:

(i) Cyclic loading with mean stress leads to initial cyclic softening followed by the saturation of the plastic strain amplitude.

(ii) Mean strain increases with the number of cycles but cyclic creep rate decreases rapidly and either saturation or at least a strong tendency to mean strain saturation is apparent.

(iii) Saturated mean strain increases with the mean stress; saturated plastic strain amplitude increases mildly with the mean stress for small stress amplitudes while it decreases mildly with the mean stress for the highest stress amplitude.

(iv) Cyclic stress-strain curve is substantially influenced by the mean stress; the exponent of the cyclic stress-strain curve increases with increasing mean stress.

(v) Fatigue life decreases considerably with increasing mean stress. SWT parameter or Walker parameter can be used to take into consideration mean stress effect.

(vi) Manson-Coffin curves at different mean stresses give more insight into the mechanisms responsible for fatigue life reduction in the presence of positive mean stresses. With increasing mean stress they are shifted to lower fatigue lives with approximately the same slope.

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