EFFECT OF MEAN STRESS ON SHORT CRACK GROWTH IN FATIGUED 316L STAINLESS STEEL

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Abstract

Short crack growth mechanism and kinetics were studied in cylindrical specimens with a shallow notch in 316L steel cycled under constant plastic strain amplitude and constant mean stress. Cyclic creep strain, resulting from mean stress application, increases the density of slip makings in individual grains. Fatigue cracks initiated along strain localized areas and crack linking was the main mechanism of the early crack growth. Two different regimes were identified in short crack growth rate. In the first regime, initiated cracks grow with constant growth rate which is independent of the crack length. Later, the linear increase of the crack growth rate with the crack length can represent experimental data. The short crack growth rate in both regimes increases with increasing tensile mean stress.

Introduction

Materials of engineering components and structures are often subjected to cyclic loading with a positive mean stress. The positive mean stress results in accumulation of a unidirectional plastic strain (cyclic creep). The cyclic creep strain and the synergism of cyclic and static strain component can cause additional material damage, resulting in premature fracture. The effect of positive mean stress on the fatigue life reduction has been well documented, e.g. Polák [1], Dowling [2].

The whole fatigue process can be divided into several important and partly overlapping periods, i.e. strain localization, crack initiation, short and long crack growth. Obrtlík et al. [3] have shown that in austenitic 316L stainless steel, the fatigue life in low cycle fatigue domain is dominated by the period of short crack growth. However, the effect of mean stress on short crack growth has been reported rarely. Pippan et al. [4] Wang and Miller [5] and Bache [6] found that positive mean stress increases the short crack growth rate. Moreover, the growth rate of very small cracks, of the order of 10 μm, does not depend on the stress ratio R [4].

If a high density of cracks is produced under high-amplitude elastic-plastic cyclic loading, the crack interaction can be important. In order to characterize fatigue damage of a material the notion of an equivalent crack was introduced by Polák and Liškutín [7]. The equivalent crack is defined by the length of the presently largest crack in a specified area.

It is generally accepted that plastic strain amplitude represents a decisive parameter, which determines the fatigue life of crystalline materials. Moreover, the short crack growth rate was shown to be an unambiguous function of plastic strain amplitude in symmetric

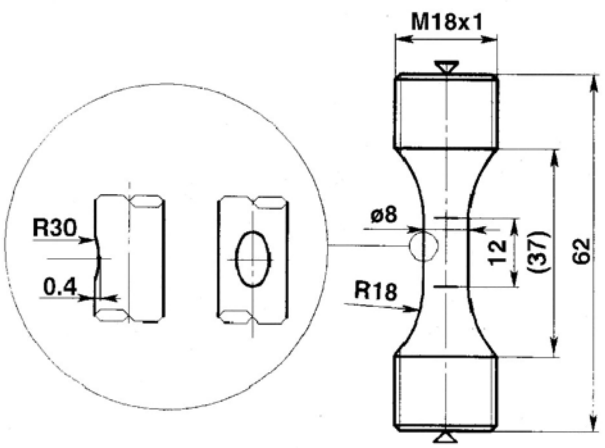

FIGURE 1. Shape and size of the specimen (in mm).

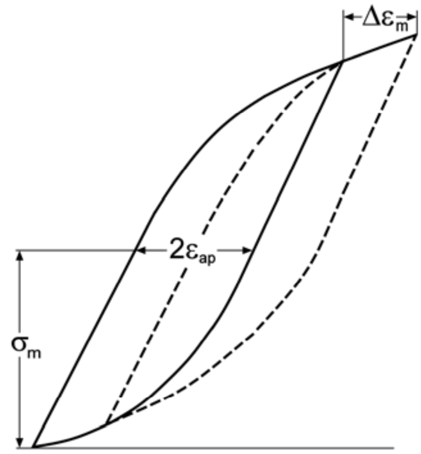

FIGURE 2. Scheme of two consecutive hysteresis loops in the start-up ramp.

cycling [3]. Therefore, the aim of the present work was to study the effect of mean stress on short crack growth mechanism and kinetics under combined plastic strain amplitude and mean stress control.

Experimental details

Material and specimens

Austenitic 316L stainless steel (Uddeholm, Sweden) was obtained in the form of a 25 mm thick plate with the following chemical composition (in wt. %): 0.018 C, 0.42 Si, 1.68 Mn, 0.015 P, 0.001 S, 17.6 Cr, 13.8 Ni, 2.6 Mo, rest Fe. The material was used in the as-received conditions, i.e., solution annealed at 1080°C and then water quenched. The heat treatment resulted in an average grain size of 39 μm (found using the linear intercept method without counting twin boundaries) and a hardness HV 10 = 145.

Cylindrical specimens with threaded ends had the gauge diameter and length of 8 and 12 mm, respectively. In order to facilitate the study of the crack initiation, crack interaction and growth, the shallow notch in the centre of the cylindrical surface was produced (see Fig. 1). The area of the shallow notch was mechanically ground by increasingly finer grit emery paper. Specimens were annealed at 600°C for 1h in vacuum and the notch area was electrolytically polished.

Fatigue tests and crack observation

Specimens were cycled in a computer-controlled electrohydraulic MTS machine under strain control with constant strain rate of $1.5 \times 10^{-3}\ s^{-1}$. The strain was measured and controlled with a 12 or 10 mm base extensometer (10 mm base was used in tests with high mean stress). Plastic strain amplitude, equal to the half of the hysteresis loop width, and the mean stress were kept constant with the help of the computer. Plastic strain amplitude was constant for the whole period of cycling. In order to prevent a large tensile plastic strain in the first half cycle the desired mean stress was reached gradually during a ramp. Fig. 2 shows scheme of two consecutive hysteresis loops within the ramp. The maximum shift

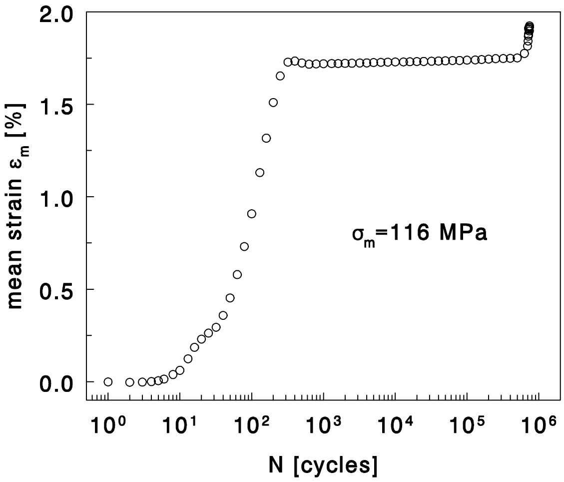

FIGURE 3. Mean strain ε_m vs number of cycles N, ε_{ap} =1x10^{-4}, σ_m = 116 MPa.

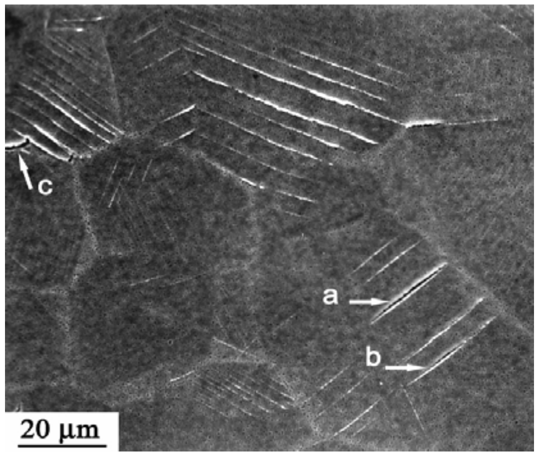

FIGURE 4. Surface relief of a specimen cycled to fracture with ε_{ap} =1x10^{-4} and σ_m = 0, SEM. Loading axis vertical.

$\Delta\varepsilon_m$ of consecutive hysteresis loops was limited to 50% of the controlled plastic strain amplitude using the computer program.

Surface relief evolution, crack initiation and growth were studied in the notch area by the use of the light microscope (LM) and the scanning electron microscope (SEM) on some specimens by interrupting a test and taking a specimen out of the testing machine for inspection in a microscope. Short crack growth was monitored systematically on specimens left in the testing machine with long-distance QUESTAR optical microscope coupled to camera and personal computer. The surface of the specimen was systematically photographed and the pictures were stored in the disc for later evaluation. It consisted in assessment of the length of the surface crack projected on the surface line perpendicular to the specimen axis. Since the shape of the crack was approximately semicircular the half of the projected length is equal to the crack radius and was taken as the crack length *a*.

Results

Constant plastic strain amplitude cycling with constant mean stress results in cyclic creep. The characteristic cyclic creep curve in the representation of mean strain ε_m versus number of cycles N is shown in Fig. 3 for the mean stress σ_m = 116 MPa. Substantial growth of the mean strain during the start-up ramp is followed by the saturation as soon as the desired mean stress has been achieved. An increase of ε_m at the end of the fatigue life is apparent. Cyclic creep rate, defined as increment of the mean strain per one cycle, is high in the beginning of cycling. The saturated value of the mean strain is smaller than the mean strain achieved during sudden application of the mean stress thanks to the start-up procedure. The cyclic creep rate rapidly decreases after the mean stress attains its desired value and then slowly drops to a minimum cyclic creep rate followed by the final increase. The minimum cyclic creep rate grows with applied mean stress, e.g., from 3x10^{-10} cycle^{-1} for σ_m = 54 MPa to 1.3x10^{-9} cycle^{-1} for σ_m = 215 MPa.

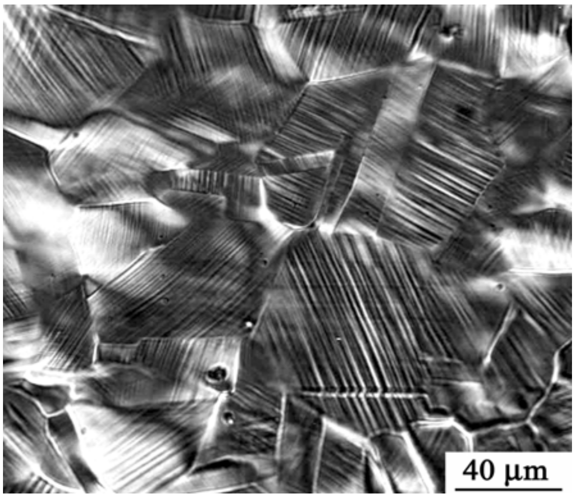

FIGURE 5. Surface relief of a specimen cycled with ε_{ap} =1x10^{-4} and σ_m = 215 MPa for N ~ 2%N$_f$, LM. Loading axis horizontal.

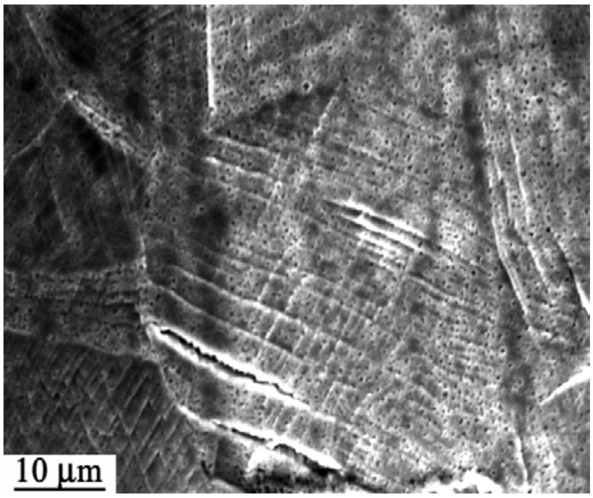

FIGURE 6. Surface relief with cracks initiated along slip markings in a specimen cycled to fracture with ε_{ap} =1x10^{-4} and σ_m = 116 MPa. SEM. Loading axis horizontal.

Fig. 4 shows the surface of the specimen strained in symmetrical cycle to the end of the fatigue life with plastic strain amplitude of 1x10^{-4}. Surface relief developed during cycling consists of persistent slip markings (PSMs). Pronounced PSMs appear only in some grains and cover small area of the grain surface. Fatigue cracks both along PSMs (arrows a, b) and at a grain boundary (arrow c) can be seen in Fig. 4. The surface developed in a specimen strained in pulsating cycle with ε_{ap} = 1x10^{-4} for 2%N$_f$ is shown in Fig. 5. First slip markings (SMs) were apparent already at 0.02%N$_f$. Their density increases with increasing number of cycles and early in the fatigue life the majority of grains is densely covered with SMs – see Fig. 5. Fatigue cracks initiated either along SMs or at grain boundaries both in symmetrical and asymmetrical cycling. An example of cracks along SMs in a grain of a specimen strained with ε_{ap} = 1x10^{-4} and σ_m = 116 MPa to fracture is shown in Fig. 6. Two slip systems are activated in the grain lying close to a large primary crack.

Fig. 7 shows the variation of crack length *a* vs number of cycles N in specimens cycled with ε_{ap}= 1x10^{-4}. The diagram for symmetrical test is shown in Fig. 7a and that for asymmetrical test with a mean stress of 116 MPa in Fig. 7b. Several cracks were observed to grow in the notch area at this plastic strain amplitude. The growth rates of all growing cracks in both specimens differ only slightly until one crack becomes a dominant crack. Fig. 7 shows three longest cracks that propagated in both specimens. In the beginning of symmetrical cycling (Fig. 7a), crack b is the longest, later the crack a becomes the longest and then both cracks a and b link to form a dominant crack. Finally the crack c join the dominant crack. In the asymmetrical cycling (Fig.7b) individual cracks a, b, c, alternate in the role of the largest crack. But they finally stop and another crack that is not shown in the diagram becomes a dominant crack. The concept of equivalent crack [3,7] was used in order to describe the evolution of an assembly of interacting cracks. The equivalent crack was taken as the instantaneous largest crack in the area of observation.

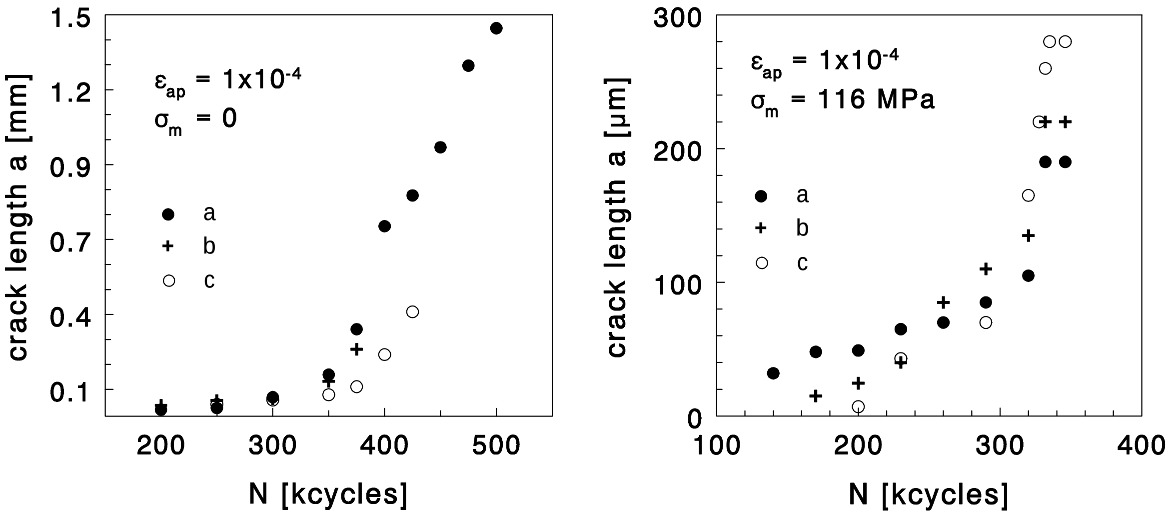

FIGURE 7. Crack length a vs number of cycles N, $\varepsilon_{ap} = 1 \times 10^{-4}$. (a) $\sigma_m = 0$, (b) $\sigma_m = 116$ MPa.

Fig. 8 shows the length a of an equivalent crack vs the number of cycles N for experimental data plotted in Fig. 7 for two mean stress levels. The dependence of the length of the equivalent crack on N for all specimen tested can be separated into two regimes I and II. In the first regime, ($a<a_t$, where a_t is the transitional crack length equal to 90 μm for σ_m = 116 MPa), the dependence of a vs. N can be represented by a straight line

$$a = a_o + v_I\, N. \tag{1}$$

It implies the constant initial crack growth rate v_I in the regime I. In the second regime ($a>a_t$) an exponential function

$$a = a_{II} \exp\,(k_{II}\, N) \tag{2}$$

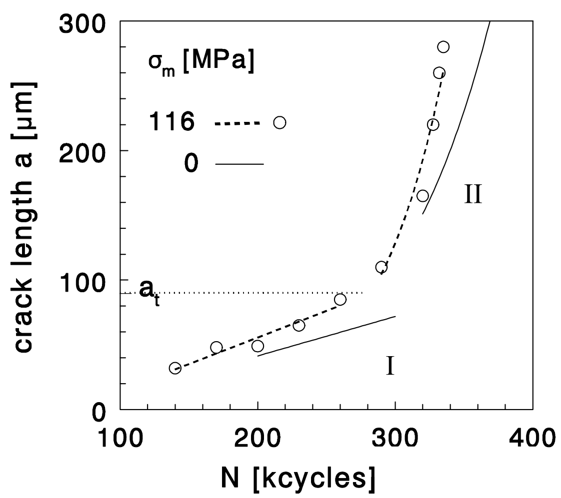

FIGURE 8. Equivalent crack length vs number of cycles for two mean stress levels, $\varepsilon_{ap} = 1 \times 10^{-4}$.

can be fitted to the experimental data (see Fig. 8). Since the best fit of the equivalent crack length vs. number of cycles is an exponential function, it implies the linear dependence of the crack growth rate v_{II} in the second regime on the crack length

$$v_{II} = da/dN = k_{II}\, a, \tag{3}$$

where k_{II} is the crack growth coefficient that determines short crack growth rate in the second regime. Experimental data on the equivalent crack growth represented by fitted curves for two values of mean stress in Fig. 8 shows that for given number of cycles the equivalent crack length increases with increasing mean stress in both regimes of short crack growth. Table 1 presents experimental data on the initial crack growth rate, v_I and the crack growth coefficient k_{II} for two plastic strain amplitudes and two mean stresses. It can be seen from Table 1 that the increase in plastic strain amplitude or in mean stress results in the growth of both characteristic parameters v_I and k_{II}.

TABLE 1. Parameters of short crack growth in 316L steel

ε_{ap}	σ_m [MPa]	10^{10} x v_I [m/cyklus]	10^5 x k_{II} [cyklus^{-1}]
1 x 10^{-4}	0	3.1	1.4
	116	4.1	2.0
5 x 10^{-4}	0	19	2.5
	120	40	23

Discussion

The experimental study of early fatigue damage under constant plastic strain amplitude cycling revealed a very important effect of mean stress on strain localization and short crack growth. Tensile mean stress results in cyclic creep with the cyclic creep curve (see Fig. 3) the character of which is affected by the limits pre-set for the creep rate in the start up ramp. The rapid drop in the creep rate is recorded as soon as the desired mean stress is achieved. In the domain of short crack growth the cyclic creep can be characterized by the minimum cyclic creep rate the value of which increases with increasing mean stress in a cycle.

Surface relief forms very early in the fatigue life as a consequence of plastic strain localization. It is closely connected to crack nucleation and plays also an important role in short crack growth. The cyclic creep manifests itself in the evolution of the characteristic surface relief (see Fig. 5). The majority of grains is densely covered with SMs usually of one slip system. The density of surface slip markings increases with growing cyclic creep strain for a given plastic strain amplitude. Since the essential amount of cyclic creep strain takes place during the initial ramp (Fig. 3) the SM density remains nearly unchanged for the rest of the fatigue life. Fatigue cracks initiate mostly along persistent slip markings both in symmetrical and asymmetrical cycling (see Fig. 4 and 6).

The experimental study of short natural crack growth under constant plastic strain amplitude and mean stress cycling revealed a very important effect of crack linking on the kinetics of individual crack growth as shown in Fig. 7. The crack density depends strongly on the plastic strain amplitude (see [8] for quantitative data in 316L steel). The fatigue damage, however, is very well represented by the length of the longest crack, independent of the density of the generated cracks. Therefore, the concept of an equivalent crack can be used for the analysis of the short crack growth data also under the asymmetrical loading.

Two regimes were distinguished in the growth of short cracks at all loading conditions used. In the first regime the initiated cracks grow with approximately constant crack growth rate v_I. The first regime is limited by reaching the crack transition length a_t, which is roughly equal to two average grain sizes. In spite of the fact that a_t is small, the first short crack growth regime represents an important fraction of the fatigue life (see Fig. 8) and for a material specimen is life determining. In the second regime (crack length greater than a_t) the linear increase of the crack growth rate with the crack length represents reasonably well experimental data and the crack growth rate is characterized by the crack growth coefficient k_{II}.

The analysis of short crack growth in 316L steel under symmetrical loading [3] revealed that fatigue life was inversely proportional to the initial crack growth rate v_I, namely $N_f = \pi a_g/2v_I$ where a_g is close to a_t. The present results show that the crack growth rate v_I and crack growth coefficient k_{II} increase with increasing mean stress. Therefore, the fatigue life derived on the basis of both parameters is reduced with the growing mean stress, which is in agreement with experimental data on the effect of mean stress on the fatigue life [1,2]. The present results also support the findings that the growth rate of microstructurally and physically short cracks is enhanced if tensile mean stress in a cycle is applied [5].

Conclusions

(i) Density of slip markings increases with cyclic creep strain. Fatigue cracks initiate preferentially along persistent slip bands.

(ii) Fatigue damage in the short crack domain can be represented by an equivalent crack, i.e. by the instantaneous largest crack.

(iii) Two regimes of short crack growth were found. Initial growth is characterized by constant crack growth rate. Later, the crack growth rate is directly proportional to crack length.

(iv) Tensile mean stress increases the crack growth rate in both short crack growth regimes.

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