REDUCTION OF MODE I FATIGUE CRACK GROWTH RATE AFTER A MODE II LOAD

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Abstract

The effect of mode II loading on subsequent mode I crack growth is experimentally investigated on steel AISI 01. The results show that the mode I crack growth rate decreases after a single mode II load cycle. This effect remains also after the crack has propagated through the mode II plastic zone. The crack growth reduction is shown to be caused by crack closure due to tangential displacement of crack-surface irregularities. The durability of this reduction has a decisive and favourable influence on fatigue life when the mode I *R*-ratio is not as high as to keep the entire load cycle above the closure level.

Introduction

In several applications where crack growth occurs, the growth problems involve bi- or even tri-modal loading of fatigue cracks. The modal loads seldom vary proportionally or with constant amplitude. Instead, the loads can appear in sequential blocks, where one loading occur in a large number of cycles and another only sporadically. The crack growth will then adjust itself to be of mode I type, according to the first type of loading. Then, the sporadic loading will give raise to another loading than mode I on the crack. In this paper, occasional mode II loading will be investigated. Nayeb-Hashemi and Taslim [1] studied the effects of mode I and II overloads on subsequent mode I crack growth in AISI 4340 and spherodized AISI 1090 steels using three- and four point bending specimens. The results show that mode II loads give rise to crack growth acceleration for a very short distance, much smaller than the mode II transient plastic zone size, with no reduction afterwards. Gau and Upul [2] investigated the effect of non-proportional overloading on a medium carbon steel (quenched and tempered 0.4% C - 1% Cr and a yield stress of 1039 MPa), using four point bending. Particular attention was drawn to mode I crack growth rate, $\mathrm{d}a/\mathrm{d}N$, after mode II overloading. Gau and Upul [2] recorded a reduction of crack growth rate with a remarkably long recovery distance until $\mathrm{d}a/\mathrm{d}N$ reverted to its original value before the overloading. This loading case has been carefully examined in the present study, using experiments. An obvious motivation for the present study is the importance of bi-modal loading and the contradictory results of [1] and [2] regarding crack growth rate. Gau and Upul [2] used a block of overloads consisting of ten mode II load cycles in a row. In this study a single mode II load cycle is used. The experimentally observed results exhibit a reduction of crack growth rate with a recovery distance, RD, that turn out to be even longer than what Gau and Upul [2] reported. It should also be noted that in [2] the experiments were interrupted at an early stage and the recovery distance was only approximated.

Scope of the investigation

In this investigation, the effect of a single mode II load cycle on subsequent mode I crack growth is studied. The crack growth rate is strongly connected to the effective stress intensity factor range, $\Delta K_{\mathrm{I,\,eff}}$ [3]. The idea of introducing an effective stress intensity factor range is that it should correspond to the actual loading range in the vicinity of the crack tip. The effective stress intensity factor range is defined as

$$\Delta K_{I,eff} = K_{I,\max} - K_{I,closure} \quad if\ K_{I,closure} > K_{I,\min}\ . \tag{1}$$

Experiments were performed with different magnitude of mode II loads in order to capture the typical behavior of mode I crack growth rate after a mode II load. The crack growth rate and the load-displacement relation (compliance) were continuously recorded during the experiments. These recorded data were used to determine the crack closure levels. The closure level, $K_{\mathrm{I,\,closure}}$, can be estimated experimentally in two ways. Either by the load-displacement relation, when the compliance curve deviates from a linear behavior [4], or by the measured crack growth rate, da/dN. When the second method is employed, $K_{\mathrm{I,\,closure}}$ is determined by combining a Paris law alike equation, used with data free from closure,

$$\frac{da}{dN} = C\left(\Delta K_{I,eff}\right)^n \tag{2}$$

and Equation 1

$$K_{I,closure} = K_{I,\max} - \left(\frac{da}{dN}\frac{1}{C}\right)^{\frac{1}{n}} \quad if\ K_{I,closure} > K_{I,\min} \tag{3}$$

where da/dN is the experimentally measured crack growth rate, $K_{\mathrm{I,\,max}} = \Delta K_{\mathrm{I}} / (1\text{-}R)$, $R = K_{\mathrm{I,\,min}} / K_{\mathrm{I,\,max}}$ (nominal data), C and n are the closure free material parameters. The experiments exhibit a long-lasting reduction of mode I crack growth rate after the mode II load. The mechanisms responsible for this reduction are investigated.

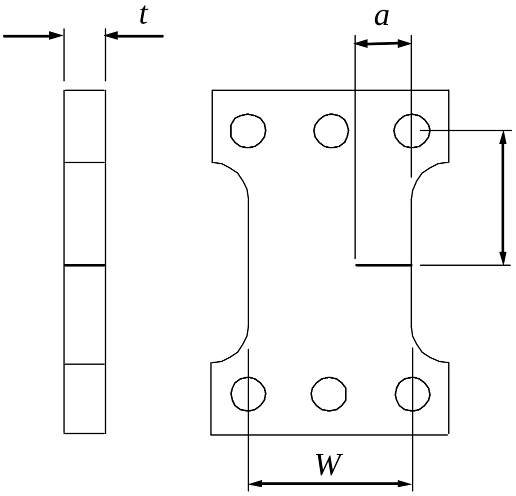

Figure 1. The geometry of the specimen used in the experiments.

Specimen setup and preparation

The geometry of the specimen used in the present investigation is shown in Figure 1. This is a version of the compact-tension-shear (CTS) specimen which is often used when mixed-mode crack growth is investigated.

Experiments

Four experiments were performed, test 1-4. The crack propagation rate da/dN as a function of the crack length was recorded during every experiment. The size of the specimens used in these experiments was: $W = 0.07$ m, $t = 0.01065$ m and $c = 0.05$ m, see Figure 1.

Material

The material used for the experiments is steel SS2140 (AISI 01). This material is a work tool steel of high and uniform quality. The mechanical properties are: Young's modulus $E = 208$ GPa, yield strength $\sigma_y = 440$ MPa, Poisson's ratio $\nu = 0.3$ and the Paris law data expressed in the form of Equation (2) are $C = 0.00468$ and $n = 3.13$ (closure free material parameters), where ΔK should be expressed in MPa$\sqrt{m}$ and da/dN in nm/cycle. The average grain size is approximately 16 μm.

Pure mode I loading with constant ΔK_I

In this paper the effect of a single mode II load cycle on subsequent mode I crack growth is studied. To be able to evaluate the particular effects caused by the mode II load in the forthcoming experiments it must be absolutely clear how pure mode I crack growth, da/dN, behaves without a mode II load, for the present setup. Hence, an experiment with constant mode I loading range has been performed with $\Delta K_I = 20$ MPa$\sqrt{m}$, $R = 0.1$. It turns out that the da/dN will not be constant, but vary slightly with the crack length, a, for this experiment. This is not to be expected from Paris law, since the test is performed with constant ΔK_I. However, this effect has been observed in the laboratory during previous experiments. A computer-control system continuously updates the load during the tests using measurements of the crack mouth opening displacement with a clip-gage. There can be several reasons for da/dN to vary with a, although ΔK_I is constant. The most straightforward explanation is that higher order stress terms in the crack tip field, *i.e.* T-stress, will influence the crack growth rate. Another reason could be three dimensional effects, *i.e.* curved crack front, which here means discrepancy in compliance between the compliance estimated from two-dimensional FE-simulations (which the computer-control program is based on) and the actual compliance measured in the experiments. It is not the purpose of this paper to investigate further the reasons for the da/dN variation. Instead it is accepted as an inherent property of the specimen and loading.

Test 1-3

Three experiments were performed with the intention to capture the typical behavior of mode I crack growth rate after a mode II load. All experiments started with $\Delta K_I = 20$ MPa$\sqrt{m}$, $R = 0.1$ and $a = 20$ mm (refers to machined notch depth). The cracks were first propagated to $a = 24.5$-25 mm. Then, the initiation area of the cracks were removed by electro-erosion, about 1 mm, *i.e.* the notch depth was extended from 20 to 21 mm. This procedure was performed in order to get rid of surface irregularities in the crack initiation region. This is important because the crack path in the initiation region appears to be quite different from one specimen to another. This in turn, affects the effective mode II load that is actually transmitted all the way to the crack tip. After the electro-erosion procedure, the experiments were resumed with the same load as before and the cracks were propagated to $a = 27$-28 mm. After that, the mode II load was applied. In the tests, K_{II} = 20, 30 and 40 MPa$\sqrt{m}$ were used, respectively. After the mode II loading, the experiments were resumed with the same loading as before and the cracks were propagated to a = 60 mm.

Test 4

The experiment was devoted to examine if the decrease in crack propagation rate in tests 1-3 were solely caused by crack closure. The experiment was performed under similar conditions as the above, except that the R-ratio, R = 0.48 was chosen. This R-ratio was intentionally chosen so that the entire load cycle should end up above the highest closure level. The crack closure level was estimated using the experimentally found crack growth rate da/dN, with the assumption that the entire reduction was caused by crack closure. If this assumption is true, the mode II load should not have any influence at all on subsequent mode I crack growth. The experiment started with ΔK_I = 15 MPa$\sqrt{m}$, R = 0.48. A precrack was prepared with the length of 33 mm. The crack was first propagated to a = 36 mm. Then, the mode II load was applied with K_{II} = 40 MPa$\sqrt{m}$. Thereafter the experiment was resumed with the same mode I loading as before the mode II load and the crack was propagated to a = 60 mm.

Results and discussions

Pure mode I loading with constant ΔK_I

The result of the experiment, concerning crack propagation rate, da/dN, under constant mode I stress intensity factor range for the present setup, is presented in Figure 2a. The crack growth rate is fairly constant from a = 20 mm to about 38-39 mm. Then the crack growth rate slowly decreases. Please note that ΔK_I = 20 MPa$\sqrt{m}$ and R = 0.1 are controlled to be constant throughout the experiment, from a = 20 to 60 mm. A curve has been fitted to the experimentally observed results using least square method. The curve is presented in Figure 2a. This curve is taken as a “reference” curve for the specimen and loading. The results from test 1-3 will be compared to this reference curve in order to clearly emphasize the effects of the mode II load.

Test 1-3

The results of the experiments, concerning crack propagation rate, da/dN, before and after a single mode II load cycle of different magnitudes, are presented in Figures 2b, 2c and 2d. The lower curves in Figures 2b-d show $\mathrm{d}a/\mathrm{d}N - (\mathrm{d}a/\mathrm{d}N)_{\mathrm{reference}}$. These curves are called the adjusted curves. Three load levels of mode II loading are shown. Before the mode II load is applied a constant crack growth rate of about 43-47 nm/cycle has been measured. When the mode I loading is resumed, after the mode II load, da/dN is reduced. Contrary to Nayeb-Hashemi and Taslim [1] a crack growth acceleration after the mode II load is not detected in this investigation. Instead, a substantial decrease in da/dN right after the mode II load is visible, thereafter the crack growth rate slowly increases. The results show that the reduction is stronger and more prolonged for larger mode II loads. If the mode II load is very small no reduction at all will occur. Thus, there exists a threshold value. This threshold value arises from the fact that under ordinary mode I loading conditions a wake of plastically deformed material develops around the crack. This wake is surrounded by elastic material. The elastic material forces the plastically stretched material in the wake together at zero load [5]. A zone of compressive stresses will therefore exist behind the crack tip when the mode II load is applied. This implies that the crack surfaces will remain in contact and rub together during the mode II load. Adding to this effect is also the fact that on a micro-scale, mode I crack growth is irregular. Therefore, the crack faces are wavy and not perfectly smooth. If the mode II load is insufficient, no relative tangential displacement will occur and the mode II load will not have any influence at all on the continued mode I growth. When the threshold value is exceeded, a permanent tangential displacement of the crack-surface irregularities will be the result, which causes roughness-induced crack closure. The fatigue life for $\Delta K_\mathrm{I} = 20$ MPa$\sqrt{m}$, $R = 0.1$ was increased with about 370000 cycles due to the single mode II load ($K_\mathrm{II} = 40$ MPa$\sqrt{m}$), according to a simple estimation from the results presented in Figure 2d. As a comparison, the number of cycles required to propagate the crack a distance of 32 mm, which is the Recovery Distance, RD (see Figure 2d), with constant $\mathrm{d}a/\mathrm{d}N = 45$ nm/cycle is 711000 cycles. In Figure 3, a photograph of the near-tip region after the mode II load can be seen. Here, grit marks makes the relative tangential displacement of the crack surfaces clearly visible.

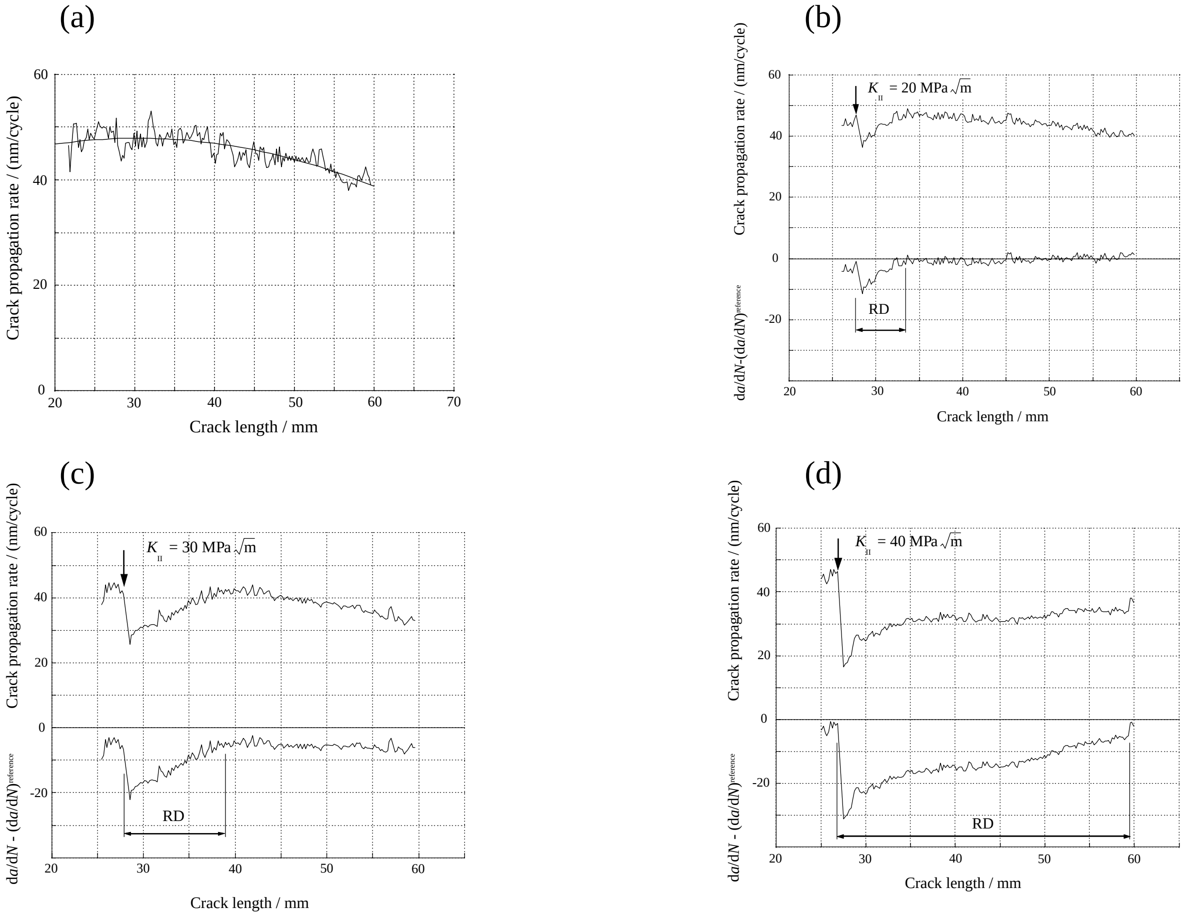

Figure 2. (a) Mode I crack growth rate under constant mode I loading with $\Delta K_\mathrm{I} = 20$ MPa$\sqrt{m}$ and $R = 0.1$, showing both experimental data and a fitted curve. The fitted curve is given by $\mathrm{d}a/\mathrm{d}N = 38.2386 + 0.633a - 0.0104a^2$ in units of the Figure. Mode I crack growth rates before and after a mode II load with (b) $K_\mathrm{II} = 20$ MPa$\sqrt{m}$, (c) $K_\mathrm{II} = 30$ MPa$\sqrt{m}$ and (d) $K_\mathrm{II} = 40$ MPa$\sqrt{m}$.

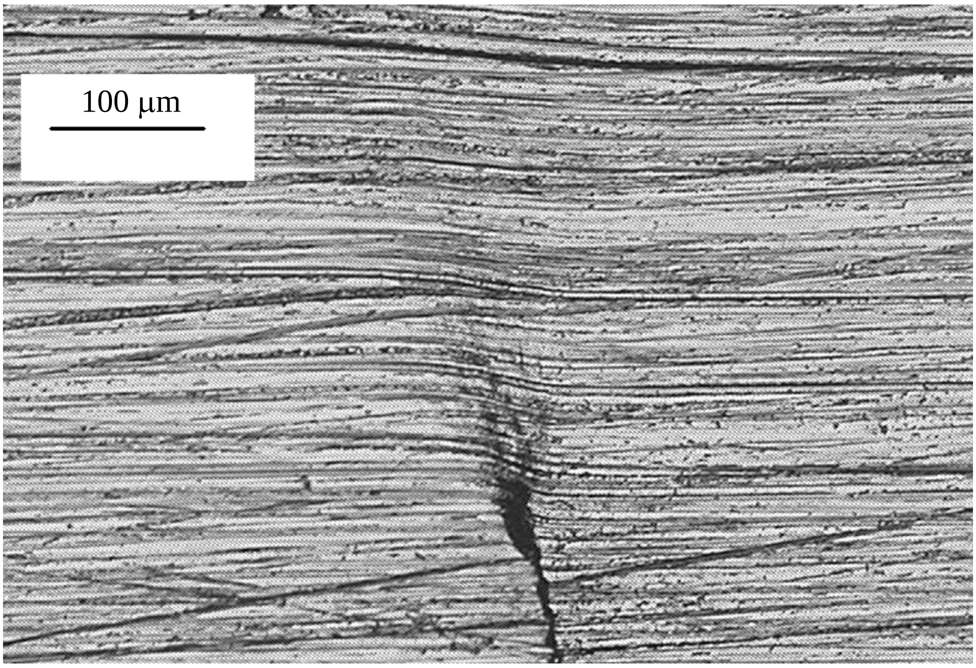

Figure 3. A microscopy photo of the crack tip, right after a mode II load (K_{II} = 40 MPa$\sqrt{m}$), showing the relative tangential displacement of the crack surfaces.

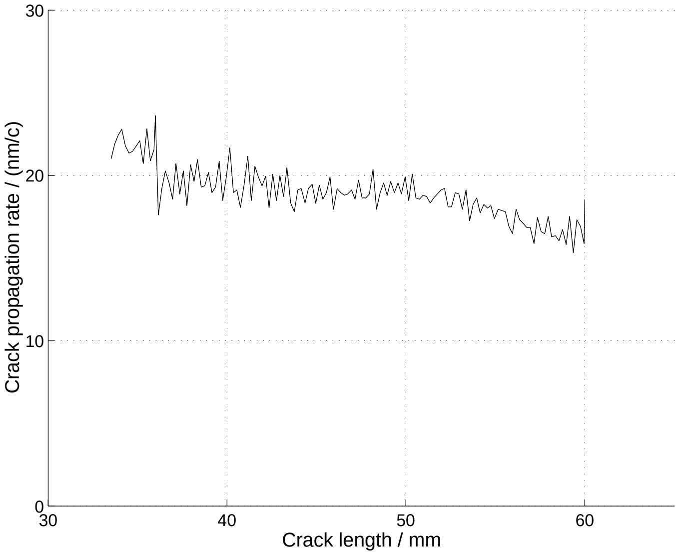

Figure 4. Mode I crack growth rate before and after a mode II load (K_{II} = 40 MPa$\sqrt{m}$). In this experiment $K_{I,\,min}$ was chosen to be larger than $K_{I,\,closure}$ (R = 0.48).

Test 4

The result of the experiment, where $K_{\mathrm{I,\,min}}$ was chosen to be larger than $K_{\mathrm{I,\,closure}}$ ($R = 0.48$), is presented in Figure 4. Here, $K_{\mathrm{I,\,closure}}$ was estimated from the lowest d*a*/d*N*-value in Figure 2d. The crack propagation rate was slightly decreased right after the mode II load. Then, the propagation rate was almost constant to $a = 50$ mm. Thereafter, the propagation rate was continuously decreased. The cause of the latter decrease is probably the same as the one responsible for the decrease under constant mode I loading, without a mode II load. The crack growth rate reduction due to the mode II load is much more pronounced in test 3 ($K_{\mathrm{II}} = 40\ \mathrm{MPa}\sqrt{m}$) than in test 4. This shows that the main mechanism responsible for the reduction in tests 1-3 is without question crack closure.

General discussions

Based on the results from all experiments performed in this study, the course of events under one typical experiment can be summarized as: The crack is propagated in mode I to a crack length where the mode II load, in the form of the ratio $K_{\mathrm{II,\,eff}} / K_{\mathrm{II,\,nom}}$, is believed to be independent of the crack length. Then, the mode II load is applied. The plastically deformed area surrounding the crack tip is exposed to compression and extension in the tangential direction, above, respectively below, the crack surfaces. This leads to a relative tangential displacement of the irregularities at the crack surfaces which have been created previously during the mode I crack growth. When the crack is propagated further in mode I, the permanent tangential displacement causes mismatch between upper and lower crack faces, which in turn results in a higher degree of crack closure compared to the mode I growth before the mode II load. Even when the crack has propagated through the mode II plastic zone the tangential residual stresses will remain and continuing the displacement of the recently formed crack faces of which the enhanced closure level will remain. This is due to the permanently deformed regions on each side of the crack path where the crack tip was located when the mode II load was applied.

Every experiment in this study exhibit a changed crack path direction (a 4–6° kink) after the mode II load, except the experiment with $K_{\mathrm{II}} = 20\ \mathrm{MPa}\sqrt{m}$. The changed crack path direction was almost constant for a remarkably long distance (about 5-8 theoretical plastic zones (for $K_{\mathrm{II}} = 30\text{-}40\ \mathrm{MPa}\sqrt{m}$)) and then gradually returned towards the direction before the mode II load.

The effectiveness of the closure will depend on the “waviness” of the mode I crack already present. Hence, it is expected that different materials, with different grain size etc., will behave differently when considering the crack growth rate in mode I after a mode II load. This material dependence has not been investigated here, only one material has been used in this study.

We have not investigated how the professional engineer in common deals with sequential bi-modal loading of cracks. Three different methods can be used: (i) occasional mode II loads increases d*a*/d*N* (ii) mode II loads does not influence d*a*/d*N* at all (iii) mode II loads decreases d*a*/d*N*. In our investigation we have shown that (iii) is true in general, and (ii) is almost true at large *R*-values and that (i) is always wrong, when dealing with high cycle fatigue. More details about this investigation are presented in [6].

Conclusions

It has been shown that a single mode II load, larger than a certain threshold value, causes reduction on subsequent mode I crack growth on steel AISI 01 in high cycle fatigue. The main reason for the reduction is the plastic deformation caused by the mode II load. This results in a change of stress state, which affects the crack path direction and propagation rate. The plastic deformation also increases the degree of crack closure due to the tangential displacement of crack-surface irregularities. These displacements causes mismatch between upper and lower crack faces, which in turn results in a higher degree of crack closure (roughness-induced closure). The changed crack path direction and the increased degree of crack closure are effects that remain even when the crack has propagated far from the mode II plastic zone. The durability of this reduction has a decisive influence on the fatigue life when the mode I *R*-ratio is not as high as to keep the entire load cycle above the closure level.

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