A NEW MODEL FOR THE PLASTICITY-INDUCED CLOSURE UNDER PLANE STRAIN CONDITION

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The plasticity-induced crack closure is associated with the flow of material to the flanks in the wake of the tip of a growing fatigue crack. Since plastic flow does not change the volume it is difficult to envisage the origin of the plasticity induced crack closure under plane strain conditions. A new model, which is based on the nonlinearity of the crack path, is proposed to explain the development of a plasticity-induced wedge. If the plastic zone size is in the order of magnitude or larger than the characteristic length of the crack deflection the plastic deformation changes the shape of both crack flanks in different ways. This causes a residual displacement on the crack flanks. Different examples for the development of such a plasticity induced closure are shown.

INTRODUCTION

The plasticity-induced crack closure (Elber [1]) is associated with the development of a residual wedge on the flanks of an advancing fatigue crack. Under plane stress conditions it is easy to imagine that this wedge results from material coming from the side faces of the specimen. But it is difficult to envisage the origin of this plastic wedge on the crack flanks under plane strain conditions (because plastic flow does not change the volume of a material except in cases of deformation induced phase transformation or void growth).

In the last 20 years many mechanical analyses and experimental studies have been performed , see for example Suresh [2], McClung et al. [3], Ewalds and Fornée [4], Fleck and Newman [5] and Pitoniak et al. [6]. But the most significant question – does crack closure occur under plane strain conditions – is not solved.

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The different analyses assume a plane crack, but fatigue cracks are usually rough. The purpose of this paper is to present a simple explanation of a plasticity induced wedge under plane strain conditions if crack deflections or a meandering of a crack occurs.

THE MODEL

The path of a fatigue crack often shows deflections from the macroscopic propagation direction or branches; often it looks like a meander or shows a zig-zag shape. A residual mode II deformation causes the well known roughness induced crack closure which plays an important role for the fatigue behavior in the near threshold region (Suresh [7], Minakawa and McEvily [8]). Hereby the geometrical shape of both flanks are assumed to be identical. In other words, if no residual mode II displacement between the crack flanks occured, the crack flanks fit perfectly (see Fig.1) and no crack closure would appear.

If the size of the plastic zone is comparable to or larger than the characteristic size of the deflections the plastic deformation changes the shapes of the two crack flanks in different ways. The widths of the convex parts (hills) become smaller and their heights increase. Contrarily, the widths of the concave parts (valleys) increase. As schematically drawn in Fig. 1c this leads to an increase of the "amplitude" of the meanders and to a formation of "cavities" between the side flanks of the hills and the valleys. This is a simple mechanism to explain the formation of a wedge under plane strain conditions.

An explanation for the formation of the "cavities" is easy to find. Under plane strain condition a very large triaxial stress state appears in the vicinity of a crack tip. If the crack tip is near a deflection point and the plastic zone size is in the order of magnitude or larger than the length of the deflection a plastic flow (a material transfer from the deflected part of the crack flanks) in the x_1 direction at the convex part of the crack flank will reduce this triaxiality and form a cavity at the deflected part of the crack path.

EXPERIMENTAL OBSERVATIONS

Fig. 2 shows the profile of a fatigue crack near the midsection of a CT 1 specimen (25mm thick) made of a high strength quenched and tempered steel SAE 4340 with a yield strength of 1195 MPa, an ultimate tensile strength of 1290 MPa and a fracture toughness $J_{IC} = 134\,\mathrm{KJ/m^2}$. The profile was obtained by means of stereophotogrammetric analyses (see Kolednik [9]) of the two corresponding crack surfaces. The specimen was pre-fatigued (part A of the profile) and subsequently subjected to 50 load cycles with $\Delta K = 75\,\mathrm{MPa}\sqrt{\mathrm{m}}$ and $R = 0$ at the room temperature (part B). It should be noted that the size condition for the plane strain fracture toughness test was fulfilled. After the total unloading from the 50th load cycle the specimen was post-fatigued in liquid nitrogen at a small ΔK (part C) and finally broken in liquid nitrogen (part D). Due to this procedure the fatigue crack produced at room temperature remains undisturbed and can be analysed. Fig. 2 shows that the crack is closed in the vicinity of the tip, i.e. the actual crack tip opening displacement of the fatigue crack at the unloaded state is zero. The details concerning the crack tip deformation is described by Siegmund et al. [10] and Pippan et al. [11]. The other important observation is that the profiles of the specimen halves do not fit perfectly.

The crack path is tortuous whereby the "hills" are generally narrower than the corresponding "valleys" on the opposite flank. This causes the contacts of the upper and the lower crack flank at larger distances behind the crack tip.

A similar example is shown in Fig. 3. The pre-fatigued specimen (SAE 4340 steel) was subjected to 200 load cycles with $\Delta K = 75\,\mathrm{MPa}\sqrt{\mathrm{m}}$ and $R = 0$. The unloaded specimen was cut into two halves in the midsection by spark erosion. The "midsection surface" was polished and subsequently ion sputtered in order to show the unadulterated profile of the crack. A scanning electron micrograph of some parts of the crack path is shown in Fig. 3. One can see that some parts of the flanks at larger distances behind the crack tip are in contact. Most of these contacts are caused by the deformation of the"hills" and the "valleys" of the crack surface.

It should be noted that the used stess intensity range used in the present experiments was large. The crack tip opening displacement and the cyclic crack tip opening displacement are in the sizes of a few micrometers [11], hence the residual deformations and the sizes of the "cavities" between the side flanks of the hills and the valleys have the same order of magnitude.

CONCLUSION

- It is shown that the plastic deformation during fatigue crack growth changes the shape of both flanks in different ways. This causes an increase of the amplitude of the meanders of the fatigue crack and build up a plasticity induced wedge in the wake of the crack tip.
- The size of this plasticity induced wedge should depend on the size of the plastic zone and the characteristic geometrical parameters of the crack deflections and crack branches.

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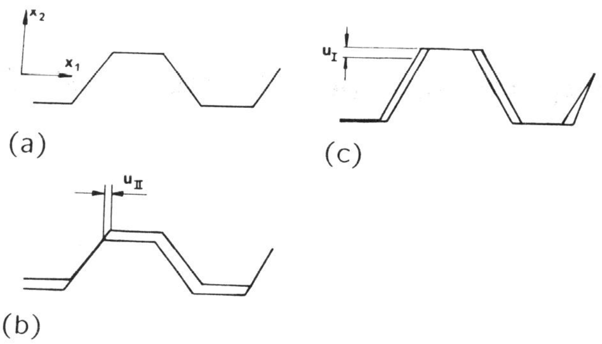

Figure 1: (a) Schematic representation of a deflected crack with periodic tilts without a lateral shift u_{II} of one crack face and (b) with a lateral shift of one crack face which leads to the roughness induced crack closure. (c) If the plastic zone size is larger than the characteristic length of the deflection the plastic deformation causes a reduction of the width of the convex parts of the crack flanks and an increase of the width of the concave parts of the crack flanks. This leads to a residual displacement u_I (a plasticity induced wedge).

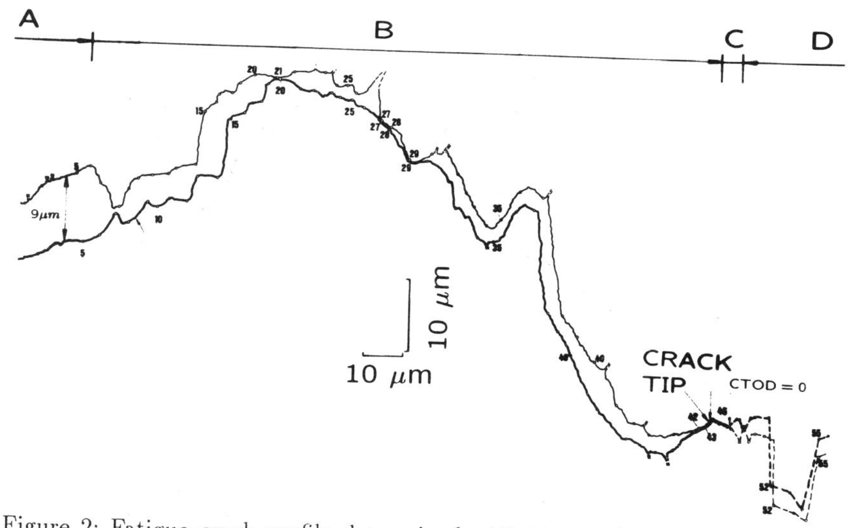

Figure 2: Fatigue crack profile determined with the method of stereophotogrammetry with the scanning electron microscope to demonstrate the formation of the plasticity induced wedge by a reduction of the width of the "hills" and an increase of the width of the "valleys".

a.

b.

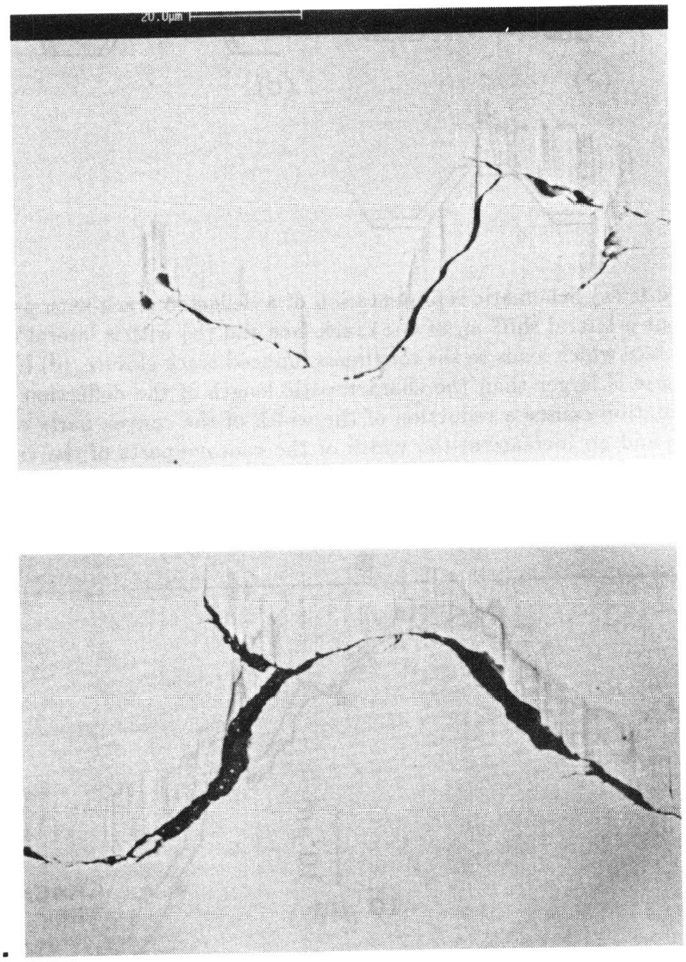

Figure 3: Scanning electron micrograph of a fatigue crack path from the mid-section of a specimen. (a) the vicinity of the crack tip, (b) at larger distances behind the crack tip.