CRACK CLOSURE: MECHANISMS, EXPLANATION AND PREDICTION

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ABSTRACT
A summary of recent studies concerning the similarities and differences in the explanation of plasticity induced crack closure and roughness induced crack closure is presented and the effect of the results on the predictability will be discussed.

1 INTRODUCTION

Despite the vast amount of studies devoted to crack closure which are impossible to cite here (see for example [1, 2, 3]) there exist many discrepancies concerning the contribution of the individual mechanisms and their origin. Furthermore, the predictability of the crack closure load is extremely limited. The present paper summaries our recent studies on plasticity induced crack closure and roughness induced crack closure and discusses their influence on the predictability.

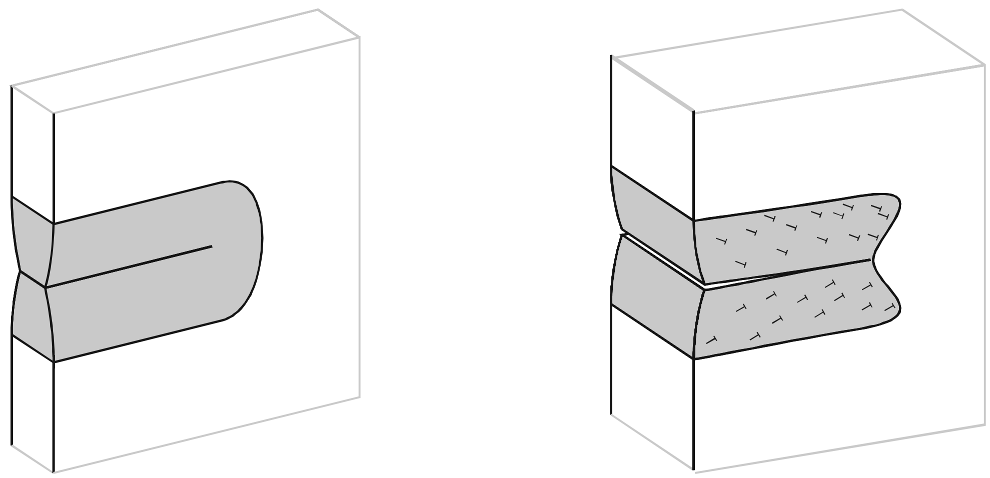
2 PLASTICITY INDUCED CRACK CLOSURE

Only for the plasticity induced crack closure under plane stress conditions a very simple explanation exists. The out of plane flow in the plastic zone results in a residual displacement of the crack flanks, which can be represented as a wedge filled into the crack. This effect is properly described by the models of [4, 5, 6], and can be easily used in the prediction of closure stress intensity.

The situation for plasticity induced crack closure under plane strain conditions is quite different. The crusial point is that there seems to be no source for the required extra material: out of plane flow is per definition not allowed and the plastic deformation does not change the volume of material involved. Despite the discrepancies [7, 8, 9, 10] it could be shown [11, 12] by dislocation mechanics as well as continuum mechanics that the elastically constrained plastic deformation during fatigue crack propagation gives rise to a rotation of the material in the wake, which leads to a transport of material to the crack tip. Because it is an elastic effect, no extra material layer remains on the crack flanks. The wedge which is produced by the "elastic rotation" follows the tip during the motion through material. Fig 1 illustrates the formation of the wedge in the plane strain case and the plane stress case. The size of this wedge under plane strain condition is about the same size as the size of the plastic zone. An analysis of the shielding capacity of a wedge reveals that even such small wedges are able to shield considerably a crack tip from the remote loading [12]. These results suggest furthermore, that the experimental verification of crack closure concept is limited by the ability of the various methods to detect such small but nevertheless efficient wedges. The closure stress intensity under plane strain is smaller than under plane stress condition. The shielding capacity in the plane strain case is about ½ of the plane stress case, which has been shown by finite element simulation [13-15] as well as by experimental observations [16].

3 ROUGHNESS INDUCED CRACK CLOSURE

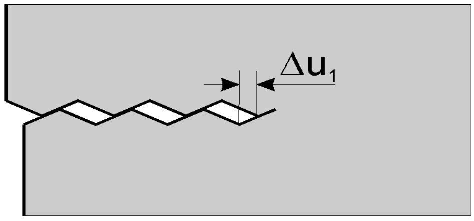
Roughness induced crack closure is denoted as the premature contact of the fatigue fracture surface caused by the misfit of the microscopically rough fracture surfaces. It has been proposed in the early 1980's [17, 18, 19]. Fig 2a stretches the usually used explanation for the occurrence of the roughness induced crack closure. Due to the micro structural inhomogenity and anisotropy, a local mode II deformation at the crack tip can take place, which results in a local mode II



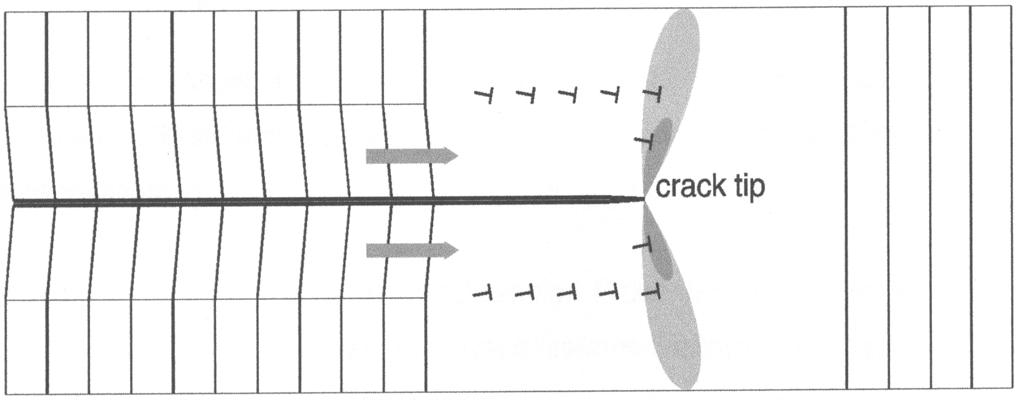
(a) (b)

Fig 1. Schematical representation of the mechanisms to explain the plasticity induced crack closure under plane stress condition (a) and the plane strain condition (b).

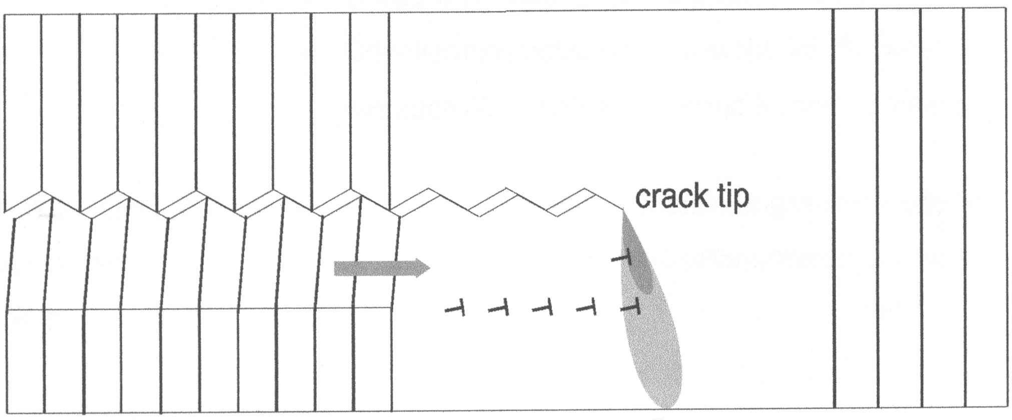
deformation and subsequently results in a residual displacement at the crack tip in the propagation direction. In polycrystalline materials the local mode II (and in reality also the local mode III) deformation vary along the crack front. Hence, the effect of the actual local residual displacement at the crack tip should not cause a shift of the whole crack flank, it should be cancelled out at relatively small distances behind the crack tip. However the asymmetry in the deformation at the crack tip can generate a misfit of the fracture surface after crack propagation far away from the crack tip [20]. The explanation is very similar to the plasticity induced crack closure under plane strain conditions. As mentioned above the constrained plastic deformation of a propagating crack induces a rotation of the volume elements in the crack propagation direction, which results in a displacement of the crack flanks in the crack propagation direction. If the deformation is asymmetric – as usual near the threshold of stress intensity range, where the plastic zone size is in the order of magnitude of the characteristic microstructural dimensions – the displacement in the crack propagation direction of the crack flanks will be different which causes a misfit of the fracture surfaces. The extreme cases are schematically illustrated in Fig 2b and 2c. Fig 2b shows the symmetric deformed crack wake which leads to plasticity induced crack closure under plane strain conditions (symmetric transfer of the material to the crack tip) and Fig 2c shows the case where the deformation took place only on one side of the crack flank, which leads to a maximum in the difference in the displacement (misfit) of the crack flanks. For more details, the experimental verification, the dependence on loading and microstructural parameters see [20].
The stress intensity, where the fracture surfaces come into contact, depends on both the geometry and the lateral displacement (misfit) of the fracture surfaces. This geometrical aspects are extensively discussed in [1, 19, 21]. Fatigue fracture surfaces are rough on different scales. The largest fluctuations are in the order of the grain size. Especially in the near threshold regime smaller fluctuations also occur which can be induced by dislocation-dislocation interaction [2] or by microstructural features much smaller than the grain size [2]. The smallest deviations are in the order of lattice spacing. They are caused by the remaining ledges formed by dislocations generated



(a)



(b)



(c)

Fig 2. Illustration of the standard explanation of the roughness induced crack closure caused by a residual mode II displacement at the crack tip (a), the material transfer to the crack tip due to symmetric arrangement of dislocations (or symmetric deformed wake) which causes displacement of both crack flanks in the crack propagation direction and the "localized" wedge at the crack tip (b) and the effect of asymmetric transfer of material which induces in addition a misfit of the fracture surfaces (c).

at the tip or entered on the fracture surface. Furthermore the lateral displacement vary locally, which makes the prediction difficult.
Finally it should be noted that the roughness induced crack closure is not only caused by lateral displacement of two geometrically identical fracture surfaces [23, 24, 25]. Due to plasticity the shape of the two rough fracture surfaces are not identical. This leads to a local contact at the top of the asperities. A simple explanation for this type of crack closure from the dislocation point of view is depicted in Fig 3a. Dislocations in the vicinity of the kink of the crack bend locally the crack flank, forming a hump. The contact of the crack flanks in this case starts at the top of the irregularity. Which mechanism dominates the roughness induced closure depend on the ratio between deflection length and plastic zone size, the asymmetry in the size of the plastic zone and in the asymmetry of the amount of plastic deformation. If the plastic zone size is very small in relation to the deflection length the plastic hump effect will determine the closure load. If the plastic zone is larger than the deflection length and the asymmetry in plastic deformation is large the mechanism caused by the shift of the crack flanks will dominate the roughness induced crack closure as schematically visualized in Fig 3b.

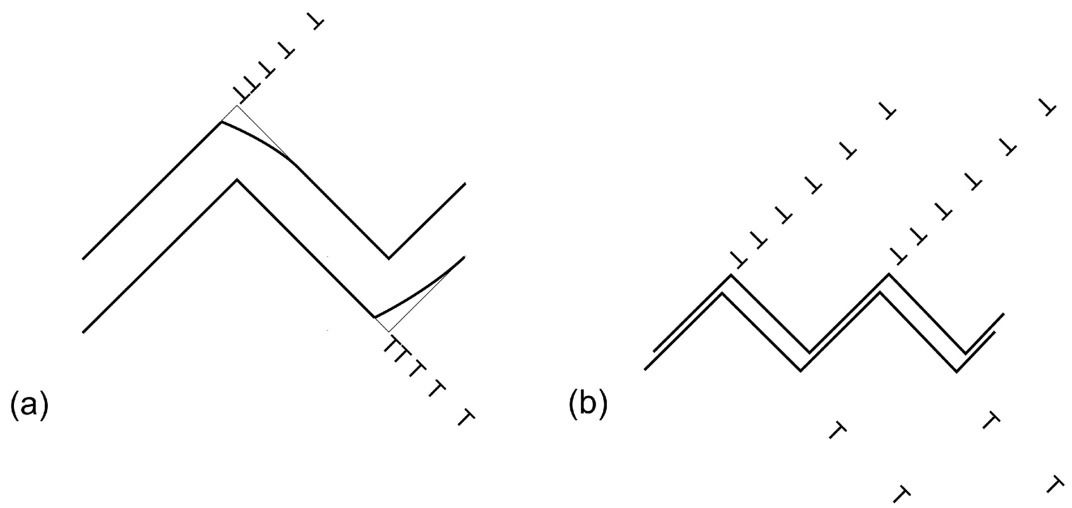


Fig 3. Schematic comparison of different types of roughness induced crack closure: a "plastic hump type" dominated closure (deformed and undeformed crack contour is indicated) (a), and a "shift of the crack flank" dominated roughness induced crack closure.

REMARKS ON PREDICTION OF CRACK CLOSURE

The prediction of crack closure is an important task in the life time prediction under variable amplitude loading and the short crack regime. From the engineering design point of view only plasticity induced crack closure can be directly taken into account.

- Prediction of plasticity under plane stress conditions is straight forward.
- In the plane strain case finite element methods in principle permits the prediction, however simplified tools have to be developed or improved and validated.
- The transition from plane strain to plane stress conditions is actually not well documented.
- In the short crack regime only for the idealized plane stress case [26] a simple description exists. For complex 3D problems of short cracks such analyses were not performed,

however they are needed for understanding as well as for a real life time prediction of components.

The prediction of roughness induced crack closure is far more complex and for my opinion it will not be directly used in design of components, however in the design of materials it will play an important role. However the tools (the methodology) are relative complex in this case, because microstructural features have to be taken into account. Furthermore, it takes place predominately in the near threshold regime, where the discrete nature of plasticity may play an important role. Hence, for a real understanding a multiscale modelling - involving discrete dislocation mechanics, crystal plasticity and micromechanics – is necessary.

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