Oral Reference: ICF0387

# ON THE FATIGUE CRACK TIP DRIVING FORCE: ROLE OF CRACK TIP PLASTICITY

K. Sadananda[1], R. L. Holtz[1] and A. K. Vasudevan[2]

[1] Code 6323, Materials Science and Technology Division,
Naval Research Laboratory, Washington D.C. 20375
[2] Office of Naval Research, Washington D.C. 22217

## ABSTRACT

The role of crack tip plasticity on fatigue crack growth is examined using dislocation concepts. Plastic flow originating from a crack will only open the crack. This is also reflected in the crack tip driving force due to plasticity. The dislocations in the plasticity induce a shielding effect when the zone is ahead of the crack and a very small antishielding effect when the zone moves into the wake. The interaction of the monotonic plastic zone provides a source for $K_{max}$ threshold, retardation due to overloads and acceleration due to underloads. No crack closure however results from plasticity, that is in the crack wake.

## Keywords

Fatigue crack growth, plasticity, $K_{max}$ threshold, dislocation model, crack closure, overload effects, residual stresses, unified approach

## INTRODUCTION

Elber [1] proposed that plasticity in the wake of the crack could cause premature closure of the crack. Hence the actual or effective stress intensity amplitude, $\Delta K_{eff}$, is only a fraction of the applied amplitude, $\Delta K$. Crack growth dependence on load ratio, R, has been attributed to crack closure. Rice [2] had analyzed earlier the crack tip plasticity under cyclic load and showed that crack closure can occur, but only under compression when the reverse plastic strain is equal to that of forward plastic strain. This requirement ensures that the crack tip opening displacement (blunting component) during tensile loading is canceled causing the two mating surfaces to come in contact. Elber [1] dismissed Rice's argument of non-closure with a statement that it "applies only to an idealized crack which is not propagating", indicating that crack closure can occur from plasticity for a propagating crack i.e. from the plasticity in the wake of the crack. Weertman [3] subsequently has shown using elegant dislocation analysis that plasticity cannot contribute to crack closure in a plane strain incompressible solid. Elber established closure based on the load-displacement curves, since it is difficult to prove or predict analytically. But unfortunately, the changes in the macroscopic load-displacement curves arise from several sources and cannot be attributed solely to crack closure due to plasticity. Observations of premature contact of mating surfaces in SEM or TEM are common. These surface observations on somewhat thin samples neither prove nor disprove the plasticity induced crack closure. Any wake-interference could be result of asperities or overlapping hills resulting from faceted mode of crack growth. Such mode of crack growth arises mostly in planar slip materials and is not a general phenomenon. In addition such a wake-interference cannot be attributed to any compressive forces resulting from plasticity in the wake.

## PLASTICITY INDUCED CRACK CLOSURE

Budianski and Hutchinson [4] have shown that plasticity in the wake can contribute to crack closure only under plane stress but not under plane strain. Intrinsic in their analysis are the assumptions that (a) a residual stretch of previously yielded material is attached to the crack surfaces and (b) upon unloading, this residual stretch leads to contact over the entire length of the fatigue crack. This residual stretch should have an equivalent crack opening displacement (ledge displacement) that should be greater than their closing displacements. The residual stretch can cause closure if the tensile stretch is replaced by reverse plastic flow that removes the ledges that are left in the crack wake that would otherwise keep the crack open [2].

Under plane stress, there is a lateral flow of matter from the sides contributing to pinching effect. Presumption is that the matter that flows inwards causing a dimple at the surface flows into the crack causing closure. It was, however, shown [5] that this flow of matter into the crack is energetically unfavorable. Polishing of the dimpled surface, the shear lips and the crack tip curvature at the surface accentuates the crack growth rates temporarily. These experiments neither prove nor disprove that the retardation at the surface is due to premature contact of the crack surfaces.

Furthermore at low $\Delta K$ values close to threshold, the stress state is predominantly under plane strain than plane stress. Hence load ratio dependence of threshold cannot be due to plasticity induced closure. Hence, other forms of closure such as oxide induced closure[6-14] roughness induced closure[15-20] etc, have been proposed. These can contribute in the reduction of the stress intensity amplitude as they prevent crack tip unloading by keeping it open rather than closed. Freezing of the crack tip from unloading provides the mechanism for the reduction in the effective amplitude at the crack tip.

## PLASTICITY VERSUS ROUGHNESS INDUCED CLOSURE

Fig. 1 shows schematically comparison of the load-displacement curves and crack surface profiles for asperity induced closure and plasticity induced closure. The reduction in the effective stress amplitude from the applied $\Delta K$ that the crack tip region experiences during loading and unloading can be justified if displacement at the crack tip is frozen at the point of deviation from linearity in the load-displacement curve, $K_c$. Then the load-displacement curve will have an infinite slope for a rigid asperity since the crack face displacements are frozen. Then the effective amplitude will be equal to $(K_{max} - K_c)$. For the plasticity induced crack closure, such is not the case. Even if one argues that due to compressive residual stresses in the wake the crack tip is closed prematurely, it is not a frozen-displacement condition at $K_c$ as is the case for the asperities. The crack tip region experiences full unloading, albeit prematurely. This is true even if the closing of the mating surfaces occurs

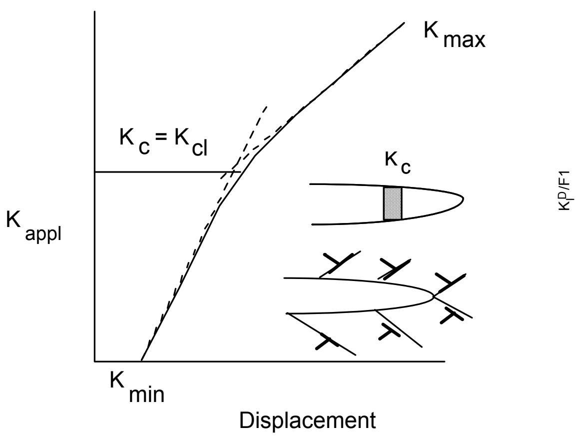


Fig. 1 Load-dislpacement curves - local asperity contact. No closure for stationary plastic crack. .

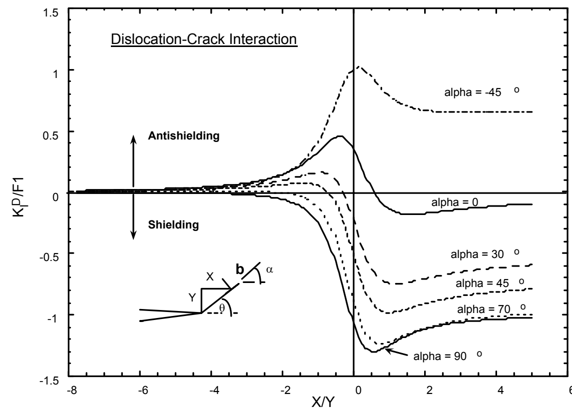


Fig. 2 Dislocation-crack interaction. X and Y are position coordinates and alpha defines dislocation orientation

gradually starting from the crack tip because of, say, some bending moments. Question essentially reduces to whether the material ahead of the crack tip is subjected to stress amplitude from $K_{min}$ to $K_{max}$ or not. If during unloading crack tip material goes from $K_{max}$ to compression and not just $K_{max}$ to $K_{cl}$, then it implies that full and not a fraction of the amplitude is encountered at the crack tip. Thus the loading and unloading conditions under the so-called plasticity induced closure are clearly distinct from that under asperity induced crack-wake interference as shown schematically in the insert in Fig. 1. It is therefore only a presumption rather than a fact that crack tip experiences reduction in amplitude by premature contact of the mating surfaces by plasticity, even if such contact occurs.

There have been several FEM analyses [21-27] of the problem and these conclude that plasticity induced closure can occur for propagating crack but not for a stationary crack. In addition, measurements of crack closure are mostly based on load-displacement curves presuming that changes in their slope correspond to crack closure. Besides the inaccuracies of these measurements [28], there is an inherent assumption that changes in the slope in the load-displacement curves are reflection of only crack closure. We have done extensive analysis of the crack behavior with and without asperities and the role of plasticity [29-30]. The asperity contributions depend on the position, size and width of the asperities but generally small of the order of 20% of $K_c$ value, where $K_c$ is point where the first contact occurs.

## DISLOCATION ANALYSIS OF PLASTICITY

We outline here the essence of our arguments why the plasticity that originated from the crack tip does not contribute to crack closure. In particular: (a) every dislocation that originates at the crack tip or due to crack tip stress field, has to be a loop that forms a ledge at the crack while the rest forms part of plastic zone. (b) The plastic opening displacement at the ledge will always be greater than the elastic closing displacement from its counterpart in the plastic zone. (c) Even if the dislocations sources are ahead of the crack tip, the part of the loop that opens the crack is attracted to the crack and the other part is repelled to form the plastic zone. (d) That the net displacement is positive is true for plasticity at the crack tip or behind the crack tip. In fracture mechanics terminology it is valid for both propagating and non-propagating cracks as well as loading and unloading conditions. (e) Dislocations that are not originated from the crack tip (pre-exiting ones due to notch tip stress fields etc. driven from sources other than the crack tip stress fields) can contribute to closure depending on their position and orientation with respect to the crack tip. In these cases their corresponding ledges are not at the crack tip to prevent the crack from closing. These arguments are in tune with the Rice continuum analysis [2]. This can also be ascertained by dislocation-crack interaction as deduced by Lin and Thomson [31]. Using their equation one can determine the stress intensity factor, $K_D$, due to dislocations stress field for various orientations and dislocation positions. As the dislocation glides towards the crack tip, the retarding force or shielding effect increases and reaches a maximum at $X/Y \approx 1$, where X and Y are coordinates of the dislocations in relation to the crack tip. As the dislocation bypasses the crack to form a crack-wake plasticity, the $K_D$ term changes to predominantly antishielding type but rapidly goes to zero as the dislocation moves behind the crack. That the effect dies down rapidly can be understood from the fact that spacing between dislocation and the free surface of the crack becomes increasingly smaller in comparison to dislocation distance to the crack tip. In the single dislocation case depicted in Fig. 2 the maximum effect is narrow region at $X \approx Y$. But in real plastic zone such as in the case of distributed dislocations of pile-up the maximum effect smears to larger range of X values that the crack must overcome to bypass the deformed region. As the fatigue crack moves continuously in a plasticity field, a continuous retarding force must be felt by the crack tip and the driving force must exceed this maximum retarding force for the crack to move forward.

The behavior is the same if one replaces a single dislocation by a dislocation array representing a pile up or plastic zone. The only difference is that the distributed dislocations in the pile up, in contrast to a superdislocation of equivalent Burgers Vector, will have the same maximum retardation effect (within 10%) when the plastic zone is ahead of the crack tip, but the antishielding effect reduces to zero much more rapidly as the dislocations move behind the crack tip [32]. These dislocation-crack crack tip driving force reemphasizes the fact that plasticity has a major role to play when the plastic zone is ahead of the crack tip. Its effect on the crack tip driving force rapidly reduces to zero as it moves behind the crack tip. The implication is that plasticity in the wake does not contribute to any crack closure since there is no shielding effect for the dislocations in the wake. In addition any closing contributions for dislocations which are closely behind the crack tip are compensated by the crack tip blunting formed during the crack tip plasticity. Secondly, the maximum retarding effect of plastic zone on crack tip driving force will be felt when the crack tip moves into the plastic zone. However for the crack to move forward it has to overcome this resistance force. This contributes to a $K_{max}$ threshold for crack growth. Note that this is not the $\Delta K$ threshold but $K_{max}$ threshold since it is required to overcome the force of retardation due to shielding effect of the monotonic plastic zone ahead of the crack tip. Experimentally this can be determined using the technique developed by Lang and Marci [33]. Further implication of this is that the retardation effect of overloads or the acceleration effects due to underloads also arises from the residual stresses from dislocations in the overload-underload plastic zones ahead of the crack tip and not due to plasticity induced crack closure. This also explains the fact that the FEM analysis found closure effects only for a propagating crack and not for stationary crack. The propagating crack has to encounter the retarding effect from dislocations as the crack moves forward into the monotonic plastic zone. Furthermore the delayed retardation effect encountered during the overload effects can also be accounted for since the maximum shielding occurs as the crack moves forward to $X/Y \approx 1$ as shown in Fig. 2.

A more detailed analysis of a moving crack with continuously forming plastic zone has been analyzed using the Lin-Thomson equations. The analysis only reinforces the conclusions drawn above since most of effects arise from the plasticity ahead of the crack tip than that behind the crack tip. Nevertheless it points out the fact that the plastic zone ahead of the crack tip is the primary factor for the source of $K_{max}$ threshold, while environment provides an additional factor influencing this driving force.

## CONCLUSIONS

The role of crack tip plasticity is examined using dislocation-crack interactions deduced by Lin and Thomson. It is shown that dislocations stress field induces maximum shielding effect when it is ahead of the crack tip. As the dislocation moves behind the crack tip, the effect changes to antishielding type. The shielding effect causes crack tip retardation and to induce crack growth one has to overcome this retarding force. The existence of $K_{max}$ threshold in the Unified Approach proposed by the authors is accounted for by this shielding effect of plasticity ahead of the crack tip. The analysis is in agreement with the experimental approach for the determination of $K_{max}$ threshold by Lang and Marci[33].

## REFERENCES


(1) Elber, W. Eng. (1970) Frac Mech. 2, 37.
(2) Rice, R. (1967) in Fatigue Crack Propagation, ASTM-STP 415, 247.
(3) Weertman, J. (1992) Phys. Stat. Sol., 172, 27.
(4) Budianski, B. and Hutchinson, J.W. (1978) J. Appl. Mech. 45, 267.
(5) Sadananda, K. Vasudevan, A.K. and N. Louat, N. (1997) "Dislocation Behavior Under Fatigue", in Recent Advances in Fracture, eds: Mahidhara et al., TMS, Warrendale, 395.
(6) Paris, P.C. Bucci, R.J. Wessel, E.T. Clark, W.G. and Mager, T.R. (1972) In Stress Analysis and Growth of Cracks, ASTM-STP, 513, 141.
(7) Ryder D.A. and Lynch, S.P.(1977) in The Influence of Environments on Fatigue, Institute of Mechanical Engineers, London, 21.
(8) Skelton R.P. and Haigh, J.R. (1978) Mater. Sci. Engrg., 36, 17.
(9) Tu, L.K.L. and Seth, B.B.(1978) J. of Testing and Evaluation, 6, 66.
(10) Ritchie, R.O. Suresh, S. and Moss, C.M. (1980) J. Eng. Mater. Tech., 102, 293.
(11). Stewart, A.T., (1980) Engrg. Frac. Mech., 13, 463.
(12) Suresh, S. Zamiski G.F. and Ritchie, R.O. (1981) Met. Trans. 12A, 1435.
(13). Vasudevan, A.K. and Suresh, S. (1982) Met. Trans., 13A, 2271.
(14). Liaw, P.K. Leax T.R. and Logsdon, W.A.(1983) Acta Metallurgica 31, 1581.
(15). Purushotthaman, S. and Tien, J.K. (1975) Scripta Met., 9, 923.
(16).Walker N. and Beevers, C.J.(1979) Fat. Engrg. Mat. Struc., 1, 135.
(17). Halliday M. D. and Beevers, C.J. (1981) J. of Testing and Evaluation, 9, 195.
(18). Ritchie, R.O. and S. Suresh, S. (1982) Met. Trans. 13A, 1627.

(19). Gray, G.T. Williams, J.C. and Thompson, A.W., (1983) Met. Trans. 14A, 421.
(20). Suresh, S.(1983) Met. Trans. A, 14A, 2375.
(21) Ohji, K. Ogura, K. and Yoshiji, O. (1975) Eng. Frac. Mech. 7, 457.
(22). Newman, J.C. (1976) in Mechanics of Fatigue Crack Growth, ASTM-STP, 590, 281.
(23). Newman, J.C. (1981) Methods and Models for Predicting Fatigue Fatigue Crack Growth Under Random Loading, STP 748, 53.
(24). Bloom A.F. and Holm, D.K. (1985) Engineering Fracture Mech. 22, 997.
(25). Fleck, N.A. (1986) Engrg. Frac. Mech., 25, 441.
(26). Fleck, N.A. and Newman, J.C., (1988) Mechanics of Fatigue Crack Closure, ASTM-STP, 982, 319.
(27). McClung, R.C. and Sehitoglu, H., (1989) Engrg. Frac. Mech., 33, 237.
(28) Donald, J.K. (1997) Int. J. Frac. 19, S191.
(29). Louat, N. Sadananda, K. Vasudevan, A.K. and Duesbery, M. (1993) Met. Trans., 24A, 2225.
(30) Vasudevan, A.K. Sadananda, K. Louat, N. (1994) Mat. Sci. Engrg., A188, 1.
(31) Lin I.H. and Thomson, R. (1986) Acta Met. 34, 187.
(32) Sadananda K. and Ramaswami, D. N. (2001) Phil. Mag., In Press.
(33) Lang, M. and Marci, G., (1997) Advances in Crack Closure, ASTM-STP, 1347. .