Modelling of Subcritical Crack Growth in WC–Co Hard Metals

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ABSTRACT:

The subcritical crack growth data obtained by load relaxation tests on WC-Co system are modelled by means of tilting mechanism of crack deflection. The heterogeneity present in the system is believed to promote the extent of crack deflection. The model successfully predicts the shift in K_I - V data with Co content and also explains other effects of varying Co content on the subcritical crack growth behaviour of WC - Co system.

KEYWORDS:

Subcritical crack growth; WC - Co system; Crack paths; Tilting mechanism; Deflection conditions.

INTRODUCTION:

During recent years, considerable attention has been paid to the path of crack propagation during fracture tests of ceramics. Pletka and Wiederhorn (1982) showed that in the case of coarse alumina, the crack path is zig-zag in nature as opposed to the straight paths obtained in homogeneous materials. Similar observations were made in the case of SiC (Faber and Evans, 1983b), in ZrO_2 (Swain and Hannink, 1983) and in Al_2O_3 - SiC composites (Homeny et al., 1987). The phenomenon is observed in ceramic materials containing heterogeneities of various kinds e.g. - 1) wide distribution of grain sizes, 2) second phase of high aspect ratio, 3) transformable second phase and 4) deformable second phase. Therefore, one should try to understand - a) how these heterogeneities affect the crack path, b) if there is any improvement in fracture toughness due to crack - inhomogeneity interaction and c) the effect of heterogeneities on the subcritical crack growth behaviour.

First two questions are adequately described in the literature. Mechanisms of interaction of the crack with the heterogeneities have been identified and considerable modelling work is described. It is established that bridging takes place in coarse grained alumina (Swanson et al., 1987) and deflection takes place in SiC (Faber and Evans, 1983b). Several mechanisms e.g. bridging, deflection, pull-out may operate simultaneously in Al_2O_3 - SiC composites (Becher et al., 1986; Marshall and Cox, 1987; Chakraborty et al., 1989). In ZrO_2 based materials, transformation of metastable tetragonal phase into stable monoclinic phase gives rise to shielding effects.

The present paper specifically discusses the effect of heterogeneous microstructure on the subcritical crack growth behaviour in WC-Co hard metal composites. Fracture behaviour of these materials have been reported in the literature and have been reviewed by Fischmeister (1981). The review also covers the various theoretical models proposed to simulate crack growth behaviour. It is generally agreed that in WC-Co hard metals, four different types of fracture paths exist. These are - 1) transgranular fracture through the binder phase, 2) interface fracture along the carbide - binder phase boundary, 3) intergranular fracture through the carbide grain boundaries and 4) transgranular fracture through carbide crystals. Recent elaborate quantitative metallographic experiments (Sigl et al., 1986; Sigl and Exner, 1987; Sigl and Fischmeister, 1988) have determined the relative areas of these crack paths. However, these papers did not discuss the subcritical crack growth behaviour specifically. In the present paper, we describe a phenomenological model to simulate tortuous crack growth in WC-Co hard metals. The work described herein does not consider any specific mechanism but models crack growth in light of deflection. This type of modelling was carried out by the present authors in various heterogeneous ceramics (Eswara Prasad and Bhaduri, 1988) and in dual phase steels by Suresh (1985).

THE MODEL:

In the literature, various configurations of deflected cracks have been suggested e.g., forked, kinked, twisted etc.. However, the most important configurations are (1) Tilted crack and (2) Twisted crack (Fig. 1). Faber and Evans (1983a) have treated the synergistic effects of both the configurations to explain the increase in toughness. However, Suresh (1985) has shown that a simplified model considering tilting can explain fatigue crack growth data reasonably well. Therefore we follow the same approach here.

Tilting can be easily described by changing from cartesian to polar coordinates. Essential feature of tilting is that the crack tip has a model II component even though mode I loading takes place at the far end of the crack tip. Therefore, the crack actually propagates under mixed mode condition. For tilting, the stress intensity factors at the tip of the crack (Fig. 1) are given as

$$K_I' = K_I \operatorname{Cos}^3 \theta/2 \text{ and } K_{II}' = K_I \operatorname{Sin} \theta/2 \operatorname{Cos}^2 \theta/2 \qquad ...(1)$$

where K_I is the applied (pure tensile at the far end of the crack tip) stress intensity factor; K_I' and K_{II}' are the corresponding mode I and mode II stress intensity factors at the tip of the crack and θ is the angle of deflection. Using a simple coplanar energy release rate criterion, the effective stress intensity factor can be derived as $[(K_I')^2 + (K_{II}')^2]^{1/2}$. A tracing of the deflected crack path for WC-Co system is shown in Fig. 2a and the idealised crack path is shown in Fig.2b.

The average stress intensity factor is given by

$$\bar{K}_I = \frac{\left(\sqrt{K'^2_I + K'^2_{II}}\right) D + K_I S}{(D+S)} \qquad ...(2)$$

where S and D are the lengths of undeflected and deflected crack paths. From equations (1) and (2)

$$\bar{K}_I = \frac{K_I\,(D \cos^2 \theta/2 + S)}{(D+S)} \qquad ...(3)$$

The average crack growth velocity is given by

$$\bar{V} = \frac{D \cos \theta + S}{D+S} V \qquad ...(4)$$

$\bar{V}$ is the measured average crack growth velocity, whereas V is the actual crack growth velocity in both the deflected as well as undeflected regions. Substituting equations (3) and (4) into a typical crack growth velocity relationship,

$$\bar{V} = A \; (\bar{K}_I)^N \qquad ...(5)$$

where A and N are constants. From equations (3), (4) and (5)

$$V = A\left[\frac{S+D}{D\cos\theta + S}\right]\left[\frac{D\cos\theta/2 + S}{D+S}\right]^N (K_I)^N \qquad ...(6)$$

which can be written as

$$V = A \; f(\theta) \; (K_I)^N \qquad ...(7)$$

where $f(\theta)$ is a simple trigonometric function as shown above and is a function of both θ, the angle of deflection and D/(D+S).

RESULTS AND DISCUSSION:

The aforementioned model was applied to the subcritical crack growth data on WC-Co as reported by Osterstock and Chermant (1983). The data were collected by performing load relaxation tests on double cantilever beam (DCB) specimens. K_I - V data thus obtained are shown in Fig. 3.. With increase in Co content K_I - V curves shift to higher stress intensity factor values. It can be argued that with increasing Co content the extent of deflection should increase (the angle of deflection should increase, even though, the micromechanism of crack growth may remain the same). We assume that in the material with least Co content the extent of crack deflection is minimum. The value of subcritical crack growth exponent, N is calculated to be 127 for WC-Co with 5% Co. Assuming this value of N, D/(D+S) = 1/2, various θ values and using equation (6) various curves are plotted and are shown in Fig. 4..

The close resemblence between Figures 3 and 4 is evident. This proves the conjecture that with increase in Co content, the extent of crack deflection increases. It is of interest to note here that the heterogeneity in this case is different from the heterogeneities considered in other cases as well. Co is a grain boundary phase as opposed to the second phases located inside the grains.

The above point explains the reason why Osterstock and Chermant did not find any correlation between the grain size of WC and N, the subcritical crack growth exponent. The correlation has to be sought between Co content and the average value of deflection angle. Further credence of our model can be obtained if we compare the present results with the microstructure of the crack paths presented elsewhere (Osterstock and Chermant, 1983). The calculations for the model predict an average angle of deflection as 41°. For the same material the microstructure present shows the deflection angle to be approximately 35° (average for over 10 readings). Therefore, the present model predicts deflection angle with reasonably good agreement.

Further the crack paths are modelled with constant D/(D+S) = 1/2. It should be noted here that Eq. 6 yields similar shift in K_I - V data with increasing D/(D+S) as in the case of increasing angle of deflection. However, in a physical system the crack deflection may not be as simple as it has been modelled here, but rather a mixture of both variations in θ and D/(D+S). It is intresting to note that increase in Co content increases the mean free path of crack in grain boundary Co phase (Sigl et al., 1986), thus directly affecting the D/(D+S) ratio. Therefore, we suggest that one should be careful while choosing the average values of D/(D+S) and θ to arrive at a meaningful averaging procedures. In this respect elaborate quantitative fractographic studies are very essential.

CONCLUSIONS:

1. The crack paths available in WC-Co system are zig-zag in nature and their extent of tortuosity increases with the increase in Co content of the system.
2. The proposed phenomenological model incorporating only tilting mechanism of crack deflection can explain the tortuous nature of crack growth and also the shift in K_I - V curves with Co content.
3. Close resemblence between the K_I - V data as well as average deflection angles as predicted by the model and the experimentally available data, proves that tilting mechanism can adequately explain the effects of Co content on the subcritical crack growth behaviour of WC-Co system.

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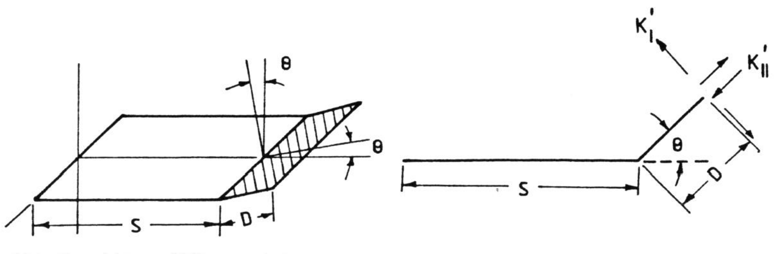
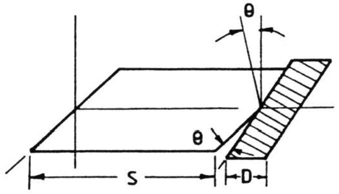
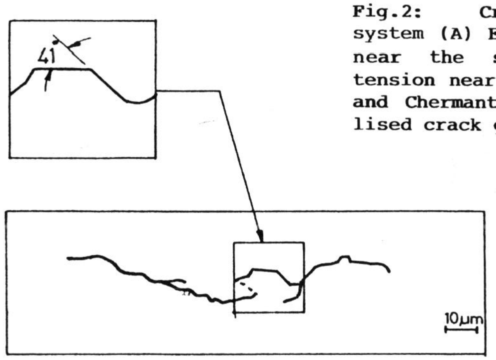


(A) TILTED CRACK



(B) TWISTED CRACK

Fig.1: Schematic diagram showing the two basic modes of deflection (A) Tilting mechanism (along with the line diagram) and (B) Twisting mechanism.



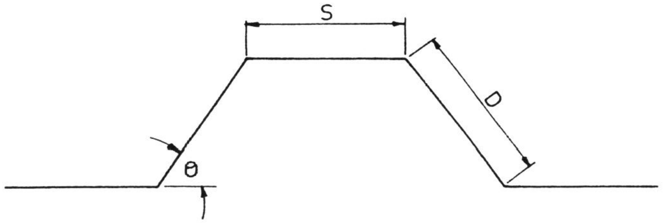


Fig.2: Crack paths in WC-Co system (A) Experimentally obtained near the surface subjected to tension near crack tip (Osterstock and Chermant, 1983) and (B) Idealised crack geometry.

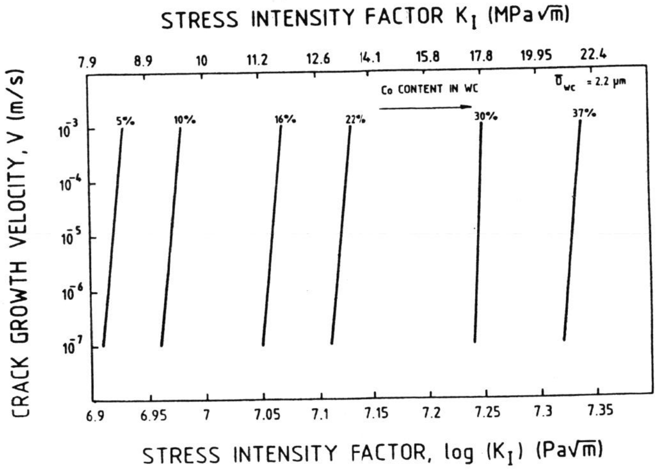


Fig. 3: Subcritical crack growth data of WC-Co composites with varying amounts of Co (After Osterstock and Chermant, 1983).

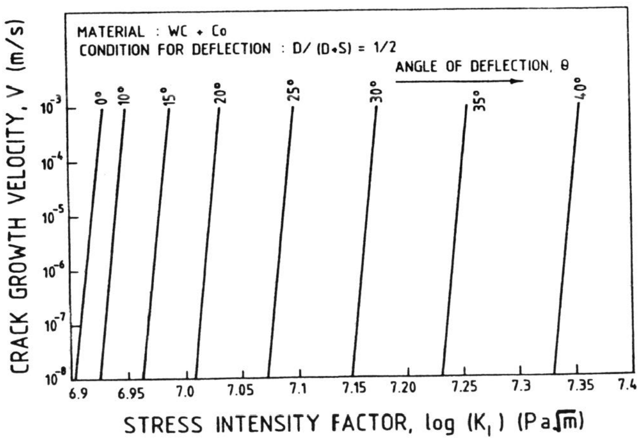


Fig.4: K_I – V data obtained for idealised crack growth in WC-Co composite system with varying angles of deflection (Average WC particle size of 2.2 μm).