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Indentation fracture of WC–Co cermets

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Indentation fracture of a series of well-characterized WC–Co cermets was studied with a Vickers diamond pyramid indenter. The resulting crack length–indentation load data were analysed in terms of relations characteristic of radial (Palmqvist) and fully developed radial/median (half-penny) crack geometries. The radial crack model gave a better fit to the data on all the alloys studied. Crack shapes determined by repeated surface polishing confirmed the radial nature of the cracks. An indentation fracture mechanics analysis based on the assumption of a wedge-loaded crack is shown to be consistent with the observed linear relation between the radial crack length and the indentation load. The analysis also predicts a simple relation among the fracture toughness (K_{Ic}), the Palmqvist toughness (W) and the hardness (H) of the WC–Co alloys.

1. Introduction

Cemented carbides are extensively used in applications that demand wear resistance, for example, cutting tools, drilling and mining equipment, and components of valves designed to handle erosive slurries [1]. The excellent wear resistance exhibited by the cemented carbides is due to their unique combination of high hardness and moderate levels of fracture toughness. The bulk mechanical properties and wear resistance of cermets are strongly affected by their composition (binder volume fraction, f) and microstructural parameters (binder mean free path, λ, and the carbide grain size, $\bar{d}$) [2]. Thus, for example, the bulk hardness (Vickers diamond pyramid hardness) increases monotonically with decreasing binder volume fraction and binder mean free path [3], while the fracture toughness exhibits a reverse trend [4] for WC–Co alloys of the same carbide grain size. The relationships between wear resistance and the compositional and/or microstructural parameters are generally more complex. In abrasive slurry erosion the wear resistance increases monotonically with decreasing binder volume fraction, reaches a maximum at a low optimum binder level (approximately 5%), and then decreases with further decrease in the binder volume fraction [5, 6]. A systematic change in micromechanisms of wear from one of preferential binder extrusion (high binder alloys), to uniform transgranular wear (optimum composition alloys), to brittle intergranular wear (low binder alloys) has been noted on the eroded surfaces of these alloys. Despite the complex role of the microstructure it is clear from these studies that both hardness and fracture toughness are influential mechanical properties that determine the wear resistance of cermets.

The present paper on indentation fracture of WC–Co cermets evolved as a result of an effort to use diamond pyramid (Vickers) indentation tests to assess both the fracture toughness and hardness in connection with a study of the erosion behaviour of cermets and ceramics [5–7]. Indentation data obtained on selected, well-characterized WC–Co alloys are critically examined in light of the large body of literature that is now available on this topic (this literature is briefly reviewed in the following section). An important part of the paper is the development of an approximate fracture mechanics analysis whose predictions are quantitatively consistent with the experimental observations in the lower-binder alloy grades. The limitations of this analysis and of the overall practice of indentation testing for fracture toughness measurements are also discussed.

1.1. Indentation fracture of cemented carbides – literature review

Palmqvist initiated and developed the idea of testing the toughness of cemented carbides using

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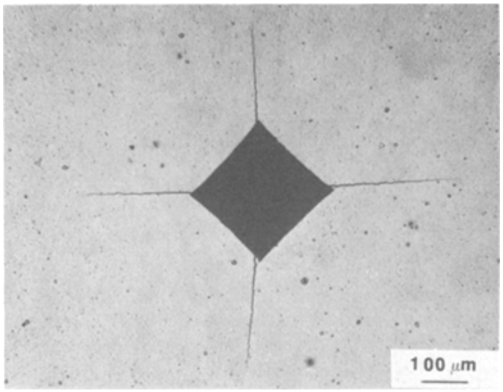

Figure 1 Vickers indentation (Palmqvist) cracks in WC–10.1% Co cermet indented with 800 N load.

as a measure the sum of the crack lengths at the four corners of a Vickers hardness indentation [8, 9] (Fig. 1). Dawihl and Altmeyer used the crack lengths associated with the indentation as a measure of the residual stresses on ground surfaces of cemented carbides [10]. It was Exner, however, who defined a crack resistance, W, based on the observed linear relationship between indentation load (P) and the sum of the radial (also called Palmqvist) crack lengths at the corners of the Vickers hardness impression [11]:

$$W = \frac{P}{4\bar{a}} \tag{1}$$

where $\bar{a}$ is the mean radial crack length. Fig. 2 shows an example of the experimentally obtained linear relationship between $\bar{a}$ and P for a WC–7.6% Co cermet. The crack resistance parameter, W, is now often referred to as the Palmqvist toughness.

Equation 1 is generally found to be valid for low-binder content cermets (approximately less than 10%). There is some dispute, however, regarding its validity for higher binder content alloys. Exner [11] and Viswanadham and Venables [12] are of the opinion that in carefully surface finished specimens, the $\bar{a}$–P relation extrapolated from high loads does pass through the origin, even though high-binder alloys may not exhibit cracking at low indentation loads. The experimental results of Ogilvy *et al.* [13] and Perrott [14] suggest, however, that for high-binder content alloys Equation 1 should be modified to

$$W = \frac{(P - P_0)}{4\bar{a}}, \tag{2}$$

where P_0 is a threshold indentation load for cracking. Perrott has also given a detailed analysis of elastic–plastic indentation which suggests that the threshold load, P_0, is an intrinsic property of the cemented carbides related to hardness, yield strength and elastic modulus [15].

Indentation fracture studies in recent years have been mostly focused on developing a fracture mechanics interpretation of the crack length–load relations of Equations 1 and 2 and also the relationship between the Palmqvist crack resistance parameter, W, and the linear elastic fracture

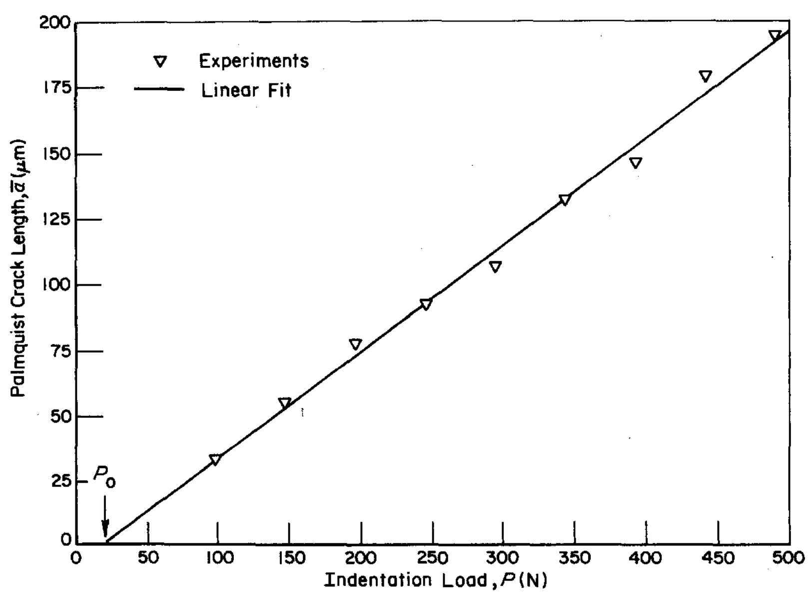

Figure 2 The relation between the mean radial crack length ($\bar{a}$) and indentation load (P) in a WC–7.1% Co alloy.

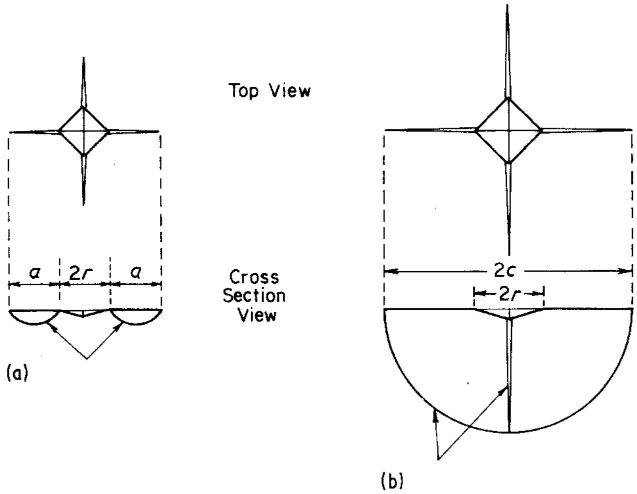

Figure 3 Geometries of (a) radial (Palmqvist) and (b) radial/median (half-penny) cracks (arrowed) produced by a Vickers indentation.

mechanics parameters, G_{Ic} (critical energy release rate) or K_{Ic} (critical stress intensity factor or more commonly referred to as fracture toughness) [16]. Based on correlations of W and G_{Ic} independently with either hardness or binder mean free path, Viswandaham and Venables [12], and subsequently Peters [17], suggested a direct linear relationship between W and G_{Ic}:

$$W = \alpha G_{Ic}. \quad (3)$$

The nondimensional proportionality constant, α, was, however, empirically derived from experimental correlations. Indentation and fracture mechanics data obtained on the same WC–Co alloy specimens by Exner *et al.* [18] and Perrott [14], however, indicated that the linear relationship was valid only for low-binder alloys. For higher-binder alloys significant nonlinearity was observed and Equation 3 overestimated G_{Ic} predicted from W.

Perrott has derived a complex relationship between W, G_{Ic}, H and yield strength, Y, that also involves additional parameters from his elastic–plastic analysis of indentation [14]. The analysis appears to give a good correlation between the two toughness parameters, W and G_{Ic}, for a wide range of alloys. Chiang *et al.* have, however, questioned the validity of a key assumption involved in the analysis [19].

More recently, Niihara [20] and Warren and Matzke [21] have independently suggested a relationship of the form:

$$K_{Ic} = \beta(HW)^{1/2}, \quad (4)$$

where β is a nondimensional constant dependent, in Niihara's model, on the ratio of Young's modulus (E) and hardness. The value of the constant in Warren and Matzke's analysis is unspecified, but these investigators collected a large body of experimental data that showed good correspondence with Equation 4 for WC–Co alloys of fracture toughness up to 17 MPa m$^{1/2}$. It is interesting to note that although the two separate studies derived the same relationship, Equation 4, the bases of their development were quite different. Niihara [20] modelled the Palmqvist cracks as four independent semielliptical cracks, while Warren and Matzke [21] developed their semiempirical analysis on the basis of a centrally loaded through-crack.

Lankford [22] has disputed the analysis of Niihara [20] and Niihara *et al.* [23], and has argued that Palmqvist cracks behave in a manner identical to fully developed radial/median (half-penny) cracks (see Fig. 3). The half-penny cracks are typically observed in brittle ceramics at high indentation loads. The fracture mechanics analysis of the half-penny cracks is relatively more advanced and it has been discussed by Lawn *et al.* [24]. The half-penny indenter crack has been modelled as a centre-loaded surface crack on the basis of the following experimentally observed relation between the crack radius, c, and the indentation load, P [24]:

$$c = kP^{2/3}, \quad (5)$$

where the constant k is a function of the Young's modulus, hardness, and fracture toughness of the ceramic and the geometry of the indenter. The residual crack-opening force in equilibrium with the half-penny crack was derived by assuming that the hardness impression volume was accomodated

TABLE I Composition and mechanical properties of WC–Co cermets

Alloy	Cobalt volume fraction, f_{Co}	Carbide grain size, $\bar{d}$ (μm)	Hardness, H (GPa)	Fracture toughness, K_{Ic} (MPa m$^{1/2}$)
1	0.051	1.06	16.72	9.4
2	0.076	0.90	16.33	9.3
4	0.101	0.98	14.93	9.9
5	0.101	2.84	11.77	13.1
K-701			16.87	7.7*
K-703			15.06	8.1*
K-703M			16.75	9.6*
T-060			19.61	8.9*

*Values estimated from Equation 4 using the empirical correlation given by Warren and Matzke [21].

by an elastic compression of a hemispherical plastic zone. The final result of this model was

$$K_{Ic} = \xi \left(\frac{E}{H}\right)^{1/2} Pc^{-3/2} \qquad (6)$$

where the constant ξ was suggested to be independent of material properties. Lankford's argument was that Palmqvist cracks, despite their different geometrical shape and orientation relative to the plastic zones, exhibit the crack length–indentation load relation and fracture toughness relation characteristic of the fully developed half-penny cracks (Equations 5 and 6).

In the following sections we will examine indentation data obtained on WC–Co alloys by taking into consideration the differing viewpoints that exist in treating Palmqvist cracks.

2. Test materials and procedures

The WC–Co alloys used in this indentation study are listed in Table I. Alloys, 1, 2, 4 and 5 were provided by J. Gurland of Brown University. These alloys were extensively characterized by Pickens and Gurland as part of a study that investigated the influence of microstructure on fracture toughness [4]. The reported hardness values were determined with a Vickers diamond pyramid indenter at a load of 150 N while a single-edge-notch-beam technique was employed for measuring the fracture toughness [4].

Alloys K-701, K-703 and T-060 are commercial grades that were obtained from different companies. The mechanical properties of these alloys were characterized as part of the present study.

The indentation fracture behaviour of cemented carbides is extremely sensitive to surface preparation. This sensitivity is due to the influence of compressive residual stresses that develop in a surface layer on ground surfaces [11, 25]. In the present study the influence of the compressive residual stresses on the Palmqvist crack length and shape was noted in the course of a metallographic investigation of the indenter crack shapes. In particular, it was desired to see if cemented carbides of sufficiently low binder contents (low fracture toughness) exhibit fully developed half-penny cracks at high indentation loads. Fig. 4 shows the subsurface crack geometry along a Vickers diagonal in the WC–5.1% Co alloy indented with 1200 N

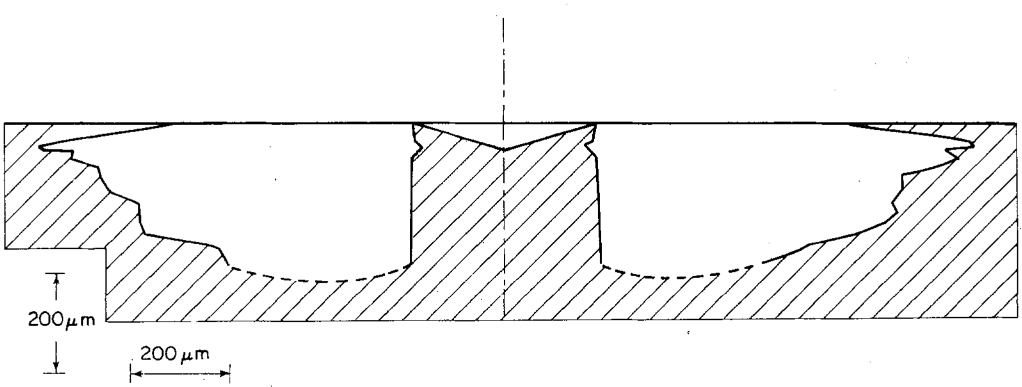

Figure 4 Palmqvist cracks in a WC–5.1% Co cermet indented at a load of 1200 N.

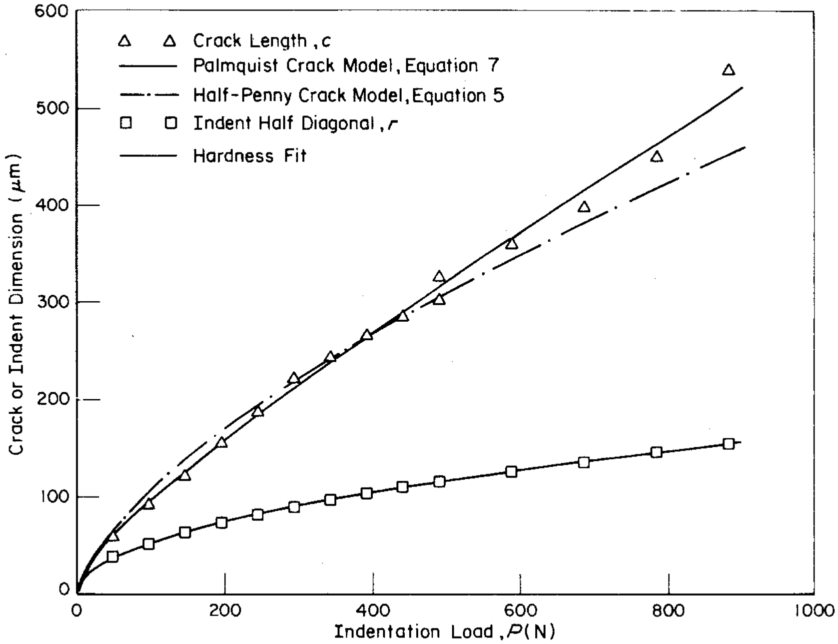

Figure 5 A comparison of the indenter crack and load data with the predictions of the Palmqvist (Equation 7) and the half-penny (Equation 5) crack models for WC–5.1% Co alloy.

load. The crack shapes were evaluated by sequential polishing with diamond grit while monitoring the surface removal with the aid of separate Vickers hardness impressions [11]. Two results in Fig. 4 are significant. The Vickers indenter cracks are radial or Palmqvist in nature even at the high indentation load used. It is safe to conclude from this result that typical WC–Co alloys (Co contents of 5% or greater) do not exhibit median cracking and the indenter cracks remain radial in nature. The second observation in Fig. 4 is the significantly reduced crack size on the surface relative to the subsurface crack extension. This apparent "crack pinching" effect is believed to be the result of the compressive residual stress near the surface which was not adequately prepared.

To eliminate the residual stress zones on the surfaces of WC–Co alloys a procedure recommended by Exner [11] was followed. This procedure involved three sequential steps of grinding on diamond-grit wheels; 15 min on 180 mesh, 15 min on 400 mesh, and 5 min on 600 mesh. This was followed by polishing for 10 min with 3 μm diamond, 5 min with 1 μm diamond, and a final polish with γ-alumina (0.25 μm) for 10 min. The whole procedure removed about 40 μm from the original rough-ground surface. Elimination of the compressive surface zone was ensured by indenting the surface at intermediate stages. The indenter crack lengths increased with each step in the early stages and became constant in the final polishing stages in a manner discussed by Exner [11].

All of the indentations were carried out on a Vickers–Armstrong hardness testing machine using loads typically in the range 100 to 800 N. Crack dimensions and hardness impressions were measured on optical photographs.

3. Results and analyses

3.1. Indentation load dependence of Palmqvist cracks

The first critical issue addressed in this study was the load dependence of Palmqvist cracks. Specifically, it was of interest to know which of the equations, Equation 2 or Equation 5, better described the load dependence of crack lengths in WC–Co cermets. In order to compare the two models with the experimental data on the same crack length–load plots, the Palmqvist crack model, Equation 2, was rewritten in the following way:

$$c = \bar{a} + r$$
$$= \frac{(P - P_0)}{4W} + \left(\frac{P}{2H}\right)^{1/2} \quad \text{for } P > P_0. \qquad (7)$$

The experimental data of apparent crack radius, c, as a function of indentation load, P, were then compared to the best fit predictions of Equations 5 and 7. Fig. 5 shows this comparison for the

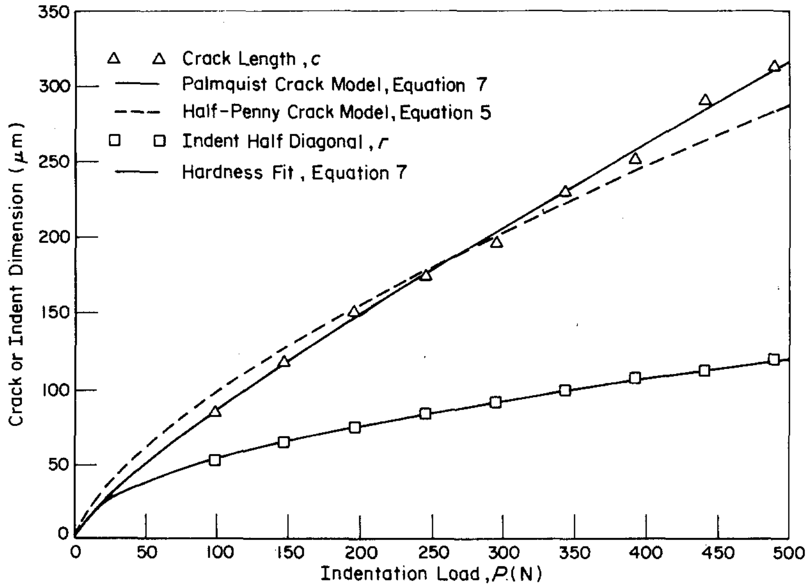

Figure 6 A comparison of the indenter crack and load data with the predictions of the Palmqvist (Equation 7) and the half-penny (Equation 5) crack models for WC–7.6% Co alloy.

WC–5.1% Co alloy. It should be noted that in deriving the best fit model prediction of Equation 7, least-squares fits were separately generated for the $\bar{a}$–P data (similar to Fig. 2) and the hardness fit (lower curve in Fig. 5). Fig. 5 shows that the predictions of the two models are surprisingly very close, but the Palmqvist model, Equation 7, gives a better fit overall than the half-penny crack model, Equation 5.

Indentation crack length data on all the alloys listed in Table I were analysed in the manner of Fig. 5. In every case the Palmqvist crack model was superior to the half-penny crack model in terms of overall agreement with the experimental data. There was a systematic trend, however, in these comparisons. In the high-toughness cermets, which had relatively shorter crack lengths, the difference in the model predictions was more apparent. This is illustrated in Fig. 6 which shows a comparison of the two models for the WC–7.6% Co alloy (Alloy 2). The Palmqvist crack model (Equation 7), is clearly superior to the half-penny model (Equation 5) for this alloy. With decreasing fracture toughness (i.e. increasing crack lengths in the same load range) the two models tended to give closer predictions (Fig. 5). This trend may explain the apparently different conclusions arrived at by Niihara *et al.* [23] and Lankford [22] in their work on ceramics. Because of their lower fracture toughness, ceramics probably behave like low-binder WC–Co cermets. The two models may, therefore, give apparently good fits if they are compared with the data independently as was done by Niihara *et al.* [23] and Lankford [22]. It would be difficult to distinguish between the two models without comparing them on the same plot as is done in Fig. 5.

3.2. Palmqvist crack resistance (W) and fracture toughness (K_{Ic})

Since both the crack shapes (Fig. 4) and load dependence of crack lengths conformed to the more traditional Palmqvist crack treatments, further analysis of the data for all the alloys was made in terms of Equations 1 to 4. Table II summarizes the Palmqvist parameters, W and P_0, obtained from linear regression of data similar to those shown in Fig. 2. The crack resistance parameter W increased monotonically with increasing fracture toughness, K_{Ic}. The threshold load, P_0, was generally small (in relation to the applied indentation loads) for most of the alloys. But there was an apparent trend in P_0 with the alloy hardness and fracture toughness. Hard alloy grades, for example T060, exhibited a negative threshold load while the softer grades, example Alloy 5, showed positive threshold loads. A similar trend was apparent in the data of Exner *et al.* [18].

Following the suggestions of Niihara [20] and Warren and Matzke [21] the relationship of Equation 4 was examined for application to the

TABLE II Palmqvist parameters – crack resistance (W) and threshold load (P_0) measured for the WC–Co alloys

Alloy	Cobalt volume fraction, f_{Co}	Palmqvist crack resistance, W (10^5 J m^{-2})	Threshold load, P_0 (N)
1	0.051	6.24	− 11.6
2	0.076	6.14	17.4
4	0.101	7.83	− 8.9
5	0.101	20.80	85.9
K-701		4.50	10.2
K-703		5.61	49.3
K-703M		7.10	31.0
T-060		5.18	− 87.1

present data. Fig. 7 shows a plot of fracture toughness (K_{Ic}) against the hardness-crack resistance parameter, $(HW)^{1/2}$. In addition to the data obtained in this study, the data collected by Warren and Matzke [21] and those of Cutler *et al.* [26] are also plotted in Fig. 7. Equation 4 gives a reasonably good fit for WC–Co alloys of fracture toughness up to about 15 MPa m$^{1/2}$. A physical rationale for the functional dependence of Equation 4 is discussed in the following section.

3.3. An indentation fracture analysis of Palmqvist cracks

Unlike the case of the fully developed radial/median cracks which can be reasonably well represented by the model of a centre-loaded half-penny crack, Palmqvist cracks are difficult to model because of their complex crack geometry and orientation relative to the plastic zone. This difficulty is reflected in the widely different fracture mechanics analyses suggested by the previous investigators [20–22]. Our objective in this section will be to present an approximate fracture mechanics analysis that will explain the two significant experimental observations relating to the Palmqvist cracks:

1. the linear dependence of crack length on indentation load (Equation 1); and
2. the interrelationships between K_{Ic}, W and H given by Equation 4.

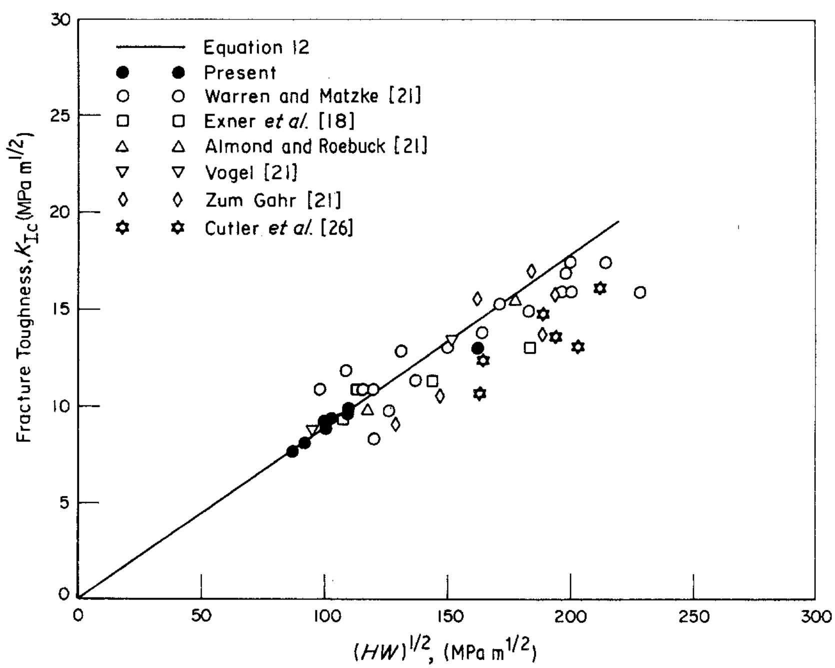

Figure 7 The relation between fracture toughness (K_{Ic}) and the hardness-crack resistance parameter $(HW)^{1/2}$ for WC–Co cermets. Data obtained by Almond and Roebuck, Vogel, and Zum Gahr were collected together by Warren and Matzke [21].

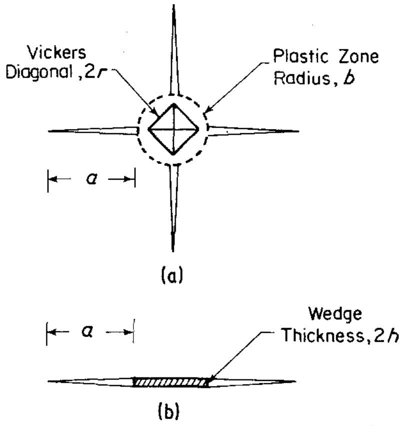

Figure 8 The Palmqvist indentation crack (a) and the equivalent wedge-loaded crack analogue (b) used in the fracture mechanics analysis.

Metallographic evaluations of Palmqvist crack shapes as shown in Fig. 4 suggest that crack extension under increasing indentation load occurs predominantly along the surface [13]. Crack penetration below the surface appears to correspond roughly to the plastic zone depth. This observation suggests that Palmqvist cracks are more realistically represented as two-dimensional through cracks rather than three-dimensional surface cracks. This assumption is similar to the one made by Warren and Matzke [21]. Furthermore, we suggest here that Palmqvist cracks in equilibrium with the post-indentation crack opening due to the residual plastic zone are equivalent to a through crack in equilibrium with a wedge of height, $2h$, as illustrated in Fig. 8. For the fracture mechanics analogue of Fig. 8b the equilibrium critical stress intensity factor or fracture toughness is given by Barenblatt [27] and Tweed [28] as

$$K_{\mathrm{Ic}} = \frac{Eh}{(1-\nu^2)(2\pi\bar{a})^{1/2}} \qquad (8)$$

where ν is the Poisson's ratio. The equivalent wedge height for the indentation problem can be estimated along lines similar to those adopted by Lawn *et al.* [24]. We suggest that the wedge thickness is given by the radial (plastic) expansion of the plastic zone beneath the hardness impression required to accommodate the hardness impression volume. Now, for diamond pyramid indentations with the standard Vickers geometry (apex angle, $2\psi = 136°$) on a variety of elastic–plastic materials the plastic zones are hemispherical with the zone radius, b (Fig. 8) given by the approximate relation [24]:

$$\frac{b}{r} = \left(\frac{E}{H}\right)^{1/2} \frac{1}{(2^{1/2}\pi \tan\psi)^{1/3}}. \qquad (9)$$

The assumption of hardness impression volume accommodation by a uniform spherical expansion of the plastic zone is equivalent to

$$\tfrac{2}{3}\pi\,[(b+\delta b)^3 - b^3] = \delta v = \frac{2^{1/2}r^3}{3\tan\psi}, \qquad (10)$$

where the right-hand side of Equation 10 is the hardness impression volume. On simplifying Equation 10 by neglecting higher-order terms one can get

$$2\delta b = 2h = \frac{2^{1/2}r^3}{3\pi b^2 \tan\psi}. \qquad (11)$$

Equations 9 and 11 can now be substituted into Equation 8 to give the final result

$$K_{\mathrm{Ic}} = \frac{1}{3(1-\nu^2)(2^{1/2}\pi\tan\psi)^{1/3}} \frac{(HP)^{1/2}}{(4\bar{a})^{1/2}} \qquad (12)$$

or

$$K_{\mathrm{Ic}} = \beta(HW)^{1/2} \qquad (13)$$

It is noted that the final result derived in Equation 12 is completely consistent with the two requirements listed at the beginning of this section. Moreover, the constant β in Equation 13 has a very simple interpretation in terms of the indenter geometry, ψ, and the Poisson's ratio, ν. For $\nu = 0.22$ (typical of WC alloys) and $2\psi = 136°$ for the standard Vickers indenter $\beta = 8.89 \times 10^{-2}$. The straight line drawn in Fig. 7 corresponds to this value of β. It is seen that the analysis and its quantitative prediction are in good agreement with the experimental data.

4. Discussion

Results and analyses of this study have established that Palmqvist cracks in cemented carbides follow the linear dependence of crack length on indentation load (Equations 1 or 2) rather than the 2/3 power dependence expected for the half-penny cracks (Equation 5). The regression analysis of the indentation data in terms of the two models (Fig. 5) also demonstrates a fact not recognized before. On an equal basis of comparison the two models do give very similar predictions, especially for the low-binder cemented carbides. This similarity may well be the reason for the apparent validity of different analyses that have been presented for analysing Palmqvist cracks in ceramics [22, 23].

The linear dependence of crack lengths on load suggests that the characteristic toughness parameter from indentation measurements is the Palmqvist crack resistance, W. The fracture mechanics analysis of the Palmqvist cracks in terms of an analogue of a wedge-loaded through-crack leads to a very simple interpretation of the relationship between the Palmqvist crack resistance, fracture toughness, and hardness. A surprising aspect of this analysis, which is based on several simplifying assumptions, is the fact that it not only predicts the correct relationship between the materials properties, but also gives a quantitative agreement (without any arbitrary adjustable parameter) with a large body of indentation data. The theoretical prediction is well within the experimental range for WC–Co alloys ranging in toughness up to about $15\,\mathrm{MPa\,m^{1/2}}$. In spite of this agreement, several limitations can be pointed out with respect to the fracture mechanics analysis. The major limitation is that Palmqvist cracks are in reality three-dimensional surface cracks while the analysis treats them as two-dimensional through-cracks. A rigorous analysis should treat them as surface cracks with a changing aspect ratio with increasing indentation load. Such an analysis would be quite complex since the fracture mechanics of surface cracks is still a subject of much controversy [29]. The second limitation of the analysis is with respect to the formulation of the crack-driving force of the residual plastic zone. We have treated the plastic zone as elastically rigid and all of the hardness impression volume mismatch to be taken up by a crack opening. This assumption over-estimates the crack opening, i.e. the wedge height. In reality, part of the hardness impression volume is taken up by some displacement of the material to the surface (i.e. surface pileup). Also, the plastic zone probably undergoes some elastic compression. In this sense the plastic zone is equivalent to a compressed elastic spring with a finite stiffness. An analysis of half-penny indenter flaws with the residual plastic zone modelled as a compressed-spring has been presented by one of the authors [30]. The assumption of a wedge in the present analysis is equivalent to a spring of high stiffness (relative to the stiffness of the crack).

To the best of the authors' knowledge there have been only two earlier attempts to model Palmqvist cracks. Niihara [20] has treated Palmqvist cracks as four independent semielliptical surface cracks. His analysis, however, does not take into account a change in aspect ratio of the elliptical crack. It is, therefore, questionable that an elliptical crack of the same shape can exhibit a linear dependence of size on indentation load. In other words, an elliptical crack internally loaded should also exhibit a 2/3 power dependence somewhat analogous to that of the half-penny cracks. Warren and Matzke [21] suggested an analysis of Palmqvist cracks in terms of a two-dimensional through-crack, but they did not explicitly formulate the crack driving force.

Leaving aside the fundamental fracture mechanics aspects of the indentation problem, the practical objective in this study was to examine critically the different relationships and choose an appropriate one for estimating fracture toughness, K_{Ic}, from the indentation data. In this respect Equation 4 appears to give reasonable estimates of K_{Ic} at least for WC–Co alloys of K_{Ic} up to about $15\,\mathrm{MPa\,m^{1/2}}$. For higher fracture toughness alloys the data in Fig. 7 indicate a deviation from the relation of Equation 4. Specifically, the fracture toughness values estimated from Equation 4 appear to be greater than the actual bulk fracture toughness values. This deviation is qualitatively consistent with one of the limitations of the wedge-crack model discussed previously. It was pointed out that the analysis gave an over estimate of the wedge height and therefore the fracture toughness, because it assumed a total accommodation of the hardness impression volume by the radial expansion of the plastic zone. It is possible that in the high-toughness cermets surface pileup and elastic compression of the plastic zone are more significant and this may account for the increasing deviation of the bulk fracture toughness from the indentation analysis in Fig. 7.

The large scatter that is typically observed in the experimental data has discouraged a wider use of the indentation technique for estimating fracture toughness of cermets. This scatter is reflected in the wide band of the data in Fig. 7. Clearly, inadequate surface preparation which leaves a residual compressive stress on the surface is a major cause of this scatter. Fig. 4 shows an excellent demonstration of the adverse effect of this compressive stress in underestimating the Palmqvist crack lengths. The effects of threshold load, P_0, also complicates the analysis of the data. While some investigators found the threshold load to be negligible [12, 17], our study has shown that

P_0 is finite at least for the very low binder and the high-binder grades. In this respect the negative threshold loads observed for the low-binder grades are physically illogical. This is simply a consequence of the extrapolation of the high-indentation load behaviour. Palmqvist crack lengths do approach a threshold at small indentation loads. Careful preparation of surface and a uniform analysis of the experimental data should enable the indentation technique to be a viable practical method for estimating fracture toughness of cermets.

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