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Crack branching and fracture mirrors in cemented tungsten carbide

S. BARTOLUCCI LUYCKX, A. SANNINO*
*Schonland Research Centre, and *Physics Department, University of the Witwatersrand, Johannesburg 2050, South Africa*

Fracture mirrors are investigated in several WC–Co grades with the aim of determining crack branching criteria. The size of the mirrors is found to increase with increasing cobalt content and with decreasing carbide grain size. The results are explained in terms of the dependence on cobalt content and grain size of the free surface energy and the elastic strain at fracture.

1. Introduction

"Fracture mirrors" are smooth, circular areas surrounding the fracture origins in brittle materials fractured in tension [1]. The perimeter of the fracture mirror is the locus of the points of first bifurcation of the propagating crack.

In the attempt to determine the causes of crack bifurcation, fracture mirrors have been studied in many brittle materials (e.g. glass [2], sapphire [3], ceramic single crystals and polycrystalline ceramics [4], etc.) and the following empirical relationships have been generally agreed upon:

$$\frac{r}{c} = \text{constant} \qquad (1)$$

where r is the fracture mirror radius and c is the size of the fracture-initiating flaw, and

$$\sigma_f r^{1/2} = \text{constant} = A \qquad (2)$$

where σ_f is the fracture stress and A is the symbol often used for the constant $\sigma_f r^{1/2}$ (e.g. [4]).

From Equations 1 and 2 it follows that

$$A = CK_{IC} \qquad (3)$$

where K_{IC} is the critical stress intensity factor (or fracture toughness) of fracture mechanics and C is a dimensionless constant.

The present work was undertaken in order to determine whether the above relationships are applicable to cemented tungsten carbides (WC–Co) and, if so, whether A and C vary with cobalt content and/or carbide grain size.

2. Experimental details

The WC–Co grades tested during this investigation are listed in Table I. Some grades have approximately equal WC grain size but different cobalt content, others have equal cobalt content but different WC grain size. The grain sizes in Table I are the average grain sizes quoted by the manufacturer.

The samples were rectangular beams of dimensions 0.5 cm × 1 cm × 4 cm and were tested in a four-point bending apparatus. The tensile face of each beam was polished and a surface flaw was introduced in the centre of each polished face in the form of a standard Vickers indentation. The depth of the indentation was assumed to be c (see Equation 1), i.e. the size of the fracture-initiating flaw. This assumption implies that the difference in the residual stresses associated with different indenting loads was neglected.

After each bending test the transverse rupture strength was recorded (σ_f in Equation 2) and the fracture mirror measured. Mirrors were measured on micrographs taken by means of a Leitz stereomicroscope at $\sim \times 30$ magnification. Each of the two fracture surfaces was photographed under four different lighting conditions, as shown in Fig. 1. In both cases the angle between incident light and fracture surface was small ($\sim 20°$) in order to enhance the visibility of the mirror boundary. Each fracture mirror diameter, r, reported below is, therefore, the average of eight measurements (four from each fracture surface).

Two sets of tests were carried out. The first set aimed at determining whether the ratio r/c (see Equation 1) is constant. For this purpose samples of the same grade were indented at different loads, i.e. were provided with fracture-initiating flaws of different size c. At least six samples were tested under each condition. Table I reports the range of the flaw depth in the grades used for this set of tests, i.e. grades H8, H12, G10, G15, E30 and J10. The range of flaw depth was limited by the following facts: too small indentations would not act as fracture-initiating flaws

TABLE I The characteristics of the WC–Co grades tested, including the depth of the indentations from which fracture initiated

WC–Co grade	Co content (wt %)	WC grain size (μm)	Flaw depth range (μm)
H8	8	~ 4	$42.8 \leqslant c \leqslant 51.3$
H12	12	~ 4	$39.8 \leqslant c \leqslant 53.3$
G10	10	~ 4	$44.8 \leqslant c \leqslant 54.3$
G15	15	~ 4	$40.2 \leqslant c \leqslant 52.9$
E30	30	~ 4	$68.3 \leqslant c \leqslant 74.7$
J10	10	5–6	$41.4 \leqslant c \leqslant 52.1$
WCS15	15	~ 2	48
WCS20	20	~ 2	48
WCS25	25	~ 2	48

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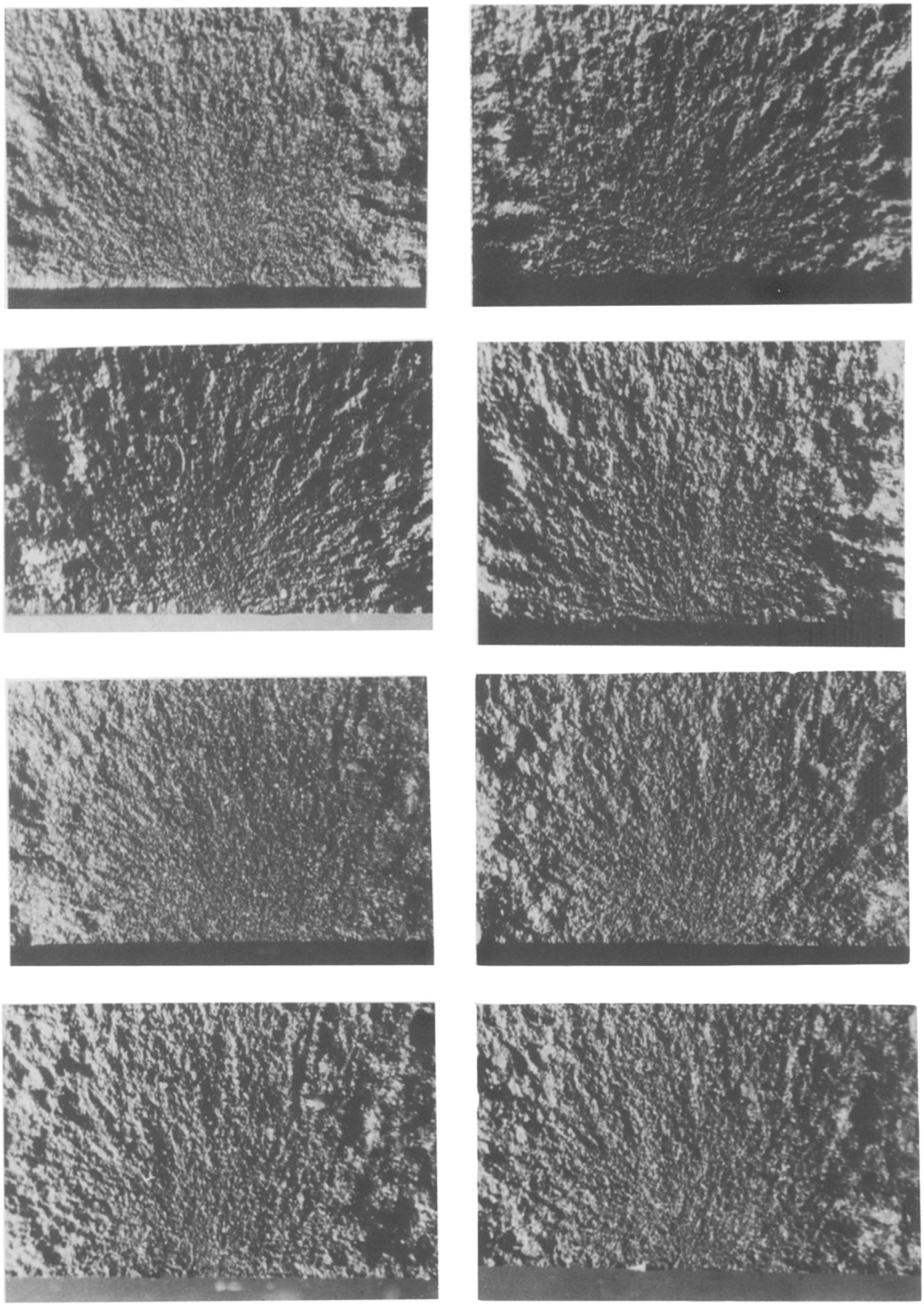

Figure 1 Examples of the eight micrographs used to measure the fracture mirror radius of a WC–Co specimen. The four upper micrographs are from the same fracture surface taken under different lighting conditions. The four lower micrographs are from the mating fracture surface.

(i.e. fracture would start from larger pre-existing flaws whose geometry and position would not be directly comparable to those of the indentations); too large indentations would cause the formation of mirrors whose boundaries would be outside the fracture surface and so unmeasurable.

The second set of tests aimed at determining whether the fracture mirror size depends on the cobalt content. All samples of the grades used for these tests, i.e. grades WCS15, WCS20 and WCS25, were indented at a load that would produce a 48 μm deep indentation. Therefore, c was kept constant, as was the grain size (see Table I), so that r would be a function of cobalt content only.

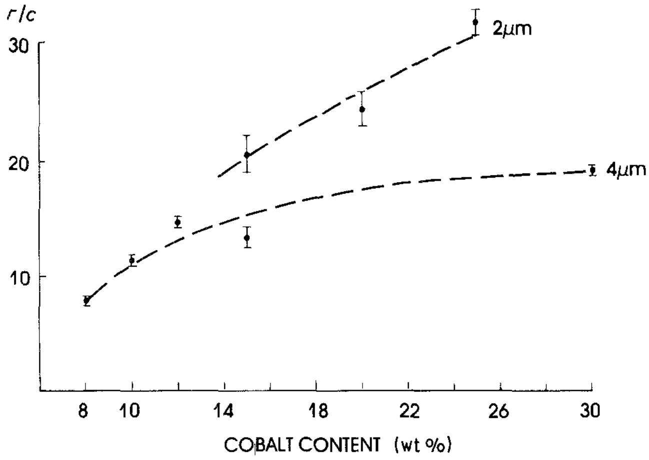

Figure 2 Variation of the r/c ratio with cobalt content in WC–Co for 2 and 4 μm WC grain sizes.

The results from both sets of tests were used to determine whether the product $\sigma_f r^{1/2}$ (see Equation 2) is constant for each grade and, if so, the constant $A = \sigma_f r^{1/2}$ is proportional to the fracture toughness of the material. Because direct measurements of fracture toughness, K_{IC}, could not be carried out, the hardness, HV30, of each grade was measured. In cemented carbides the inverse of the hardness (which for the sake of simplicity will be indicated as H_v^{-1}) is known to be proportional to K_{IC} as long as the grain size is constant [5], therefore A was plotted against H_v^{-1} for grades having equal grain size.

3. Results

The results of both sets of tests are summarized in Table II. The r/c ratio can be considered constant for each grade because the scatter in r/c values is small relatively to the average r/c value (see Table II), except for G15 and WCS15. The ratio r/c was plotted against cobalt content for the 2 and 4 μm grain size grades (Fig. 2). As seen in Fig. 2, r/c increases with increasing cobalt content and with decreasing grain size.

A can also be considered constant for each grade because the scatter in A values is small (see Table II), except for H8 and G15. A (Fig. 3) also increases with increasing cobalt content and with decreasing grain size.

When plotting A against H_v^{-1}, for both 2 and 4 μm grain size grades, reasonable straight lines are obtained (Fig. 4) within the range of grades tested. Assuming that these results can be extrapolated to grades of higher hardness (Fig. 4), it appears that the relationship between A and H_v^{-1} is of the type

$$A = CH_v^{-1} - D \qquad (4)$$

(where D is a function of grain size only) rather than of the type $A = CH_v^{-1}$ (i.e. $A \propto K_{IC}$) as was found for other materials (e.g. [4, 6]).

4. Discussion

The results summarized above show that the fracture mirror radius, r, increases with increasing $c(r/c =$ constant). The value of r/c increases with increasing cobalt content (Fig. 2) and increases with decreasing grain size (Fig. 2). The occurrence of crack branching, therefore, depends on the size of the fracture-initiating flaw, cobalt content and grain size.

The increase in r with increasing c has been observed in many brittle materials (e.g. [4, 6]). When c is large the specimen fractures at a low stress and so the energy supplied cannot create as many new fracture surfaces as in the case of small values of c. In the case of large values of c, therefore, bifurcation occurs late in the fracture process and r is large. The opposite occurs when c is small.

The increase in r/c with increasing cobalt content and with decreasing grain size follows a similar trend as the increase in A (see Figs 2 and 3) and can be explained in thermodynamic terms. By equating the potential strain energy to the energy required to produce four new fracture surfaces, one obtains [3] that crack branching is energetically possible when the applied stress is

$$\sigma_f = 4\left(\frac{E\gamma}{\pi r}\right)^{1/2} \qquad (5)$$

where E is the Young's modulus and γ the free surface energy of the material.

From Equation 5 it follows that at the onset of

TABLE II Summary of the results, as described in the text. r is the fracture mirror radius, c the size of the fracture-initiating flaw; $A = \sigma_f r^{1/2}$, σ_f being the fracture stress; H_v is the Vickers hardness

WC–Co grade	r/c	$\sigma_f(\mathrm{MN\,m^{-2}})$	$A(\mathrm{MN\,m^{-3/2}})$	$H_v(\mathrm{MN\,m^{-2}})$
H8	7.9 ± 0.3	1181.3 ± 82.5	24.4 ± 5	1211 ± 50
H12	14.7 ± 0.7	1588.7 ± 38.2	41.0 ± 2	1096 ± 50
G10	11.15 ± 0.6	1556.8 ± 56.5	36.8 ± 2	1207 ± 50
G15	13.2 ± 2	2089.8 ± 104.4	51.7 ± 10	1005 ± 50
E30	19.1 ± 0.2	2032.8 ± 44.8	75.0 ± 3	741 ± 50
J10	6.9 ± 0.4	1709.0 ± 24.0	29.6 ± 2	1087 ± 50
WCS15	20.6 ± 2.6	1875.0 ± 137.0	58.8 ± 4	1156 ± 50
WCS20	24.3 ± 2	2111.0 ± 61.1	71.9 ± 2	985 ± 50
WCS25	31.7 ± 1	2215.5 ± 46.5	86.4 ± 1	871 ± 50

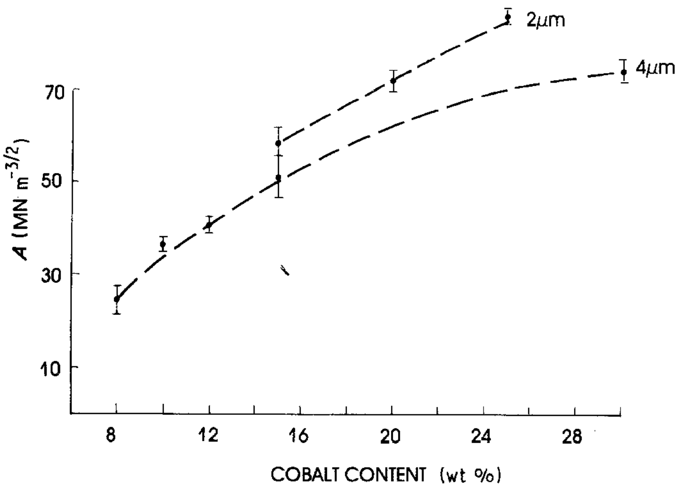

Figure 3 Variation of $A = \sigma_f r^{1/2}$ with cobalt content in WC–Co for 2 and 4 μm WC grain sizes.

crack branching

$$A = \frac{16E\gamma}{\pi\sigma_f} \qquad (6)$$

from which it appears that A increases or decreases according to whether E, γ and σ_f increase or decrease.

Table III summarizes the known experimental results on the dependence of E, γ, σ_f and A on cobalt content and carbide grain size. From the results in Table III it is possible to deduce that A increases with increasing cobalt content because the free surface energy, γ, must increase with cobalt content more rapidly than the ratio σ_f/E (i.e. the elastic strain at fracture). By contrast, A decreases with increasing WC grain size because the ratio σ_f/E must increase with grain size more rapidly than γ does. Experiments should be carried out to test this interpretation because the results available in the literature on γ and σ_f/E are from different sources and their rate of change are difficult to compare.

The relationship $A = CH_v^{-1} - D$ (Fig. 4) implies that at a critical hardness value $A = \sigma_f r^{1/2} = 0$, i.e. $r = 0$. This agrees with the observation that in hard grades fracture often propagates along more than one path from its origin (e.g. [9]). Very hard grades (e.g. 3% wt Co–WC) are known to fracture by multiple initiation (e.g. [9]). In these grades, therefore, crack branching occurs "outside" the specimen, which corresponds to the $A < 0$ values predicted by Equation 4.

Equation 4 has been obtained empirically for grades having equal grain size, in which case H_v^{-1} increases linearly with K_{IC} [5]. Thus at constant grain size A also increases linearly with K_{IC}, which is consistent with both A and K_{IC} increasing with increasing cobalt content (Fig. 3 and e.g. [10]).

If the grain size is varied, however, the relationship between A and K_{IC} is no longer a simple one because K_{IC} and H_v^{-1} are no longer linearly related. In this case the relationship between K_{IC} and H_v^{-1} has been established by Warren and Johannesson [10] and is as follows:

$$K_{IC} = 14.8E^{1/2}H_v^{-1} - 13.3 \qquad (7)$$

where E is the Young's modulus.

By combining Equations 7 and 4 one obtains a general relationship between A and K_{IC}, which is valid for varying cobalt content as well as varying grain size:

$$A = C\frac{K_{IC} + 13.3}{14.8E^{1/2}} - D \qquad (8)$$

Both C and D in Equation 8 are decreasing functions of grain size (Fig. 4). Equation 8, therefore, can reconcile the facts that A decreases with increasing grain size (Fig. 3) while K_{IC} increases (e.g. [10]).

5. Conclusions

In agreement with results from other brittle materials (e.g. [4, 6]), the ratio between the fracture mirror radius, r, and the size of the fracture-initiating flaw, c,

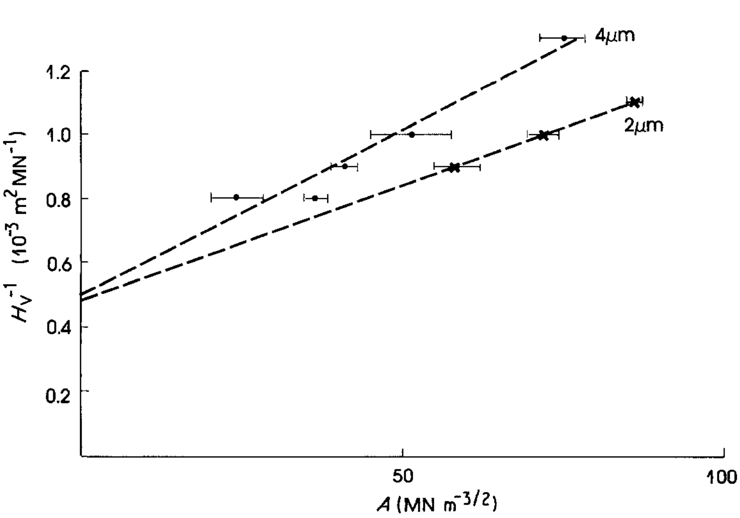

Figure 4 Variation of $A = \sigma_f r^{1/2}$ with the inverse of the Vickers hardness in WC–Co for 2 and 4 μm WC grain sizes.

TABLE III Summary of experimental results on the dependence of the Young's modulus (E), the free surface energy (γ), the transverse rupture stress (σ_f) and A on the cobalt content and WC grain size in WC–Co

	Variation with increasing cobalt content	Variation with increasing WC grain size
E	decreases [7]	decreases [7]
γ	increases [8]	increases [8]
σ_f	increases [7]	constant or decreases [7]
A	increases*	decreases*

*See Fig. 3 in present work.

is constant for each WC–Co grade and so is the product $\sigma_f r^{1/2} = A$, between the fracture stress and the square root of the mirror radius. In WC–Co it is found that the ratio r/c and the product $\sigma_f r^{1/2}$ increase with increasing cobalt content and decrease with increasing grain size. This is explained in terms of relative rates of increase of free surface energy and elastic strain at fracture.

Because the fracture toughness of WC–Co increases with increasing cobalt content and with increasing grain size, in this material the relationship between fracture toughness and the product $\sigma_f r^{1/2}$, which decreases with increasing grain size, is not as simple as in other brittle materials (e.g. [4, 6]).

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