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## *Stress corrosion cracking of a 6% cobalt/tungsten carbide hard metal*

In an experiment to examine the shape of cracks in indented specimens of a tungsten carbide/cobalt hard metal a staining technique was tried [1], and it was found that petal-shaped flakes broke away from the surface around a pyramid identation when a specimen was left exposed to hydrogen fluoride vapour overnight (Fig. 1). The damage around the indentation resembled the flaking and cracking observed in indentation tests on glasses and ceramics where the surface fractures as a result of the propagation of lateral vents generated by tensile stresses during unloading [2, 3]. Under normal conditions flakes do not form during indentation of hard metals, but cracks are found at the corners of indentations (Fig. 2) and these propagate radially during both loading and unloading [4] probably as a result of the growth of median vents initiated

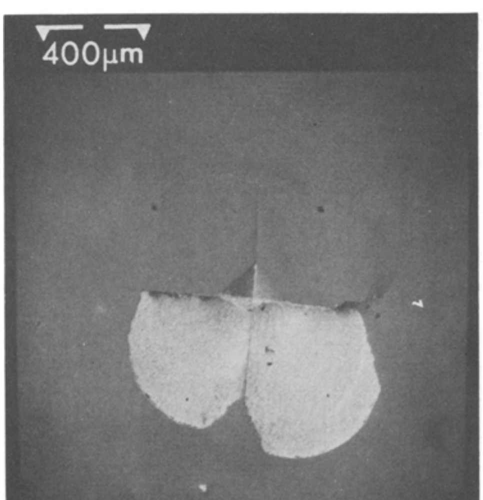


*Figure 1* Flakes formed around a pyramid indentation in a 6% Co/WC hard metal, indented with a 981 N load and exposed to HF overnight.

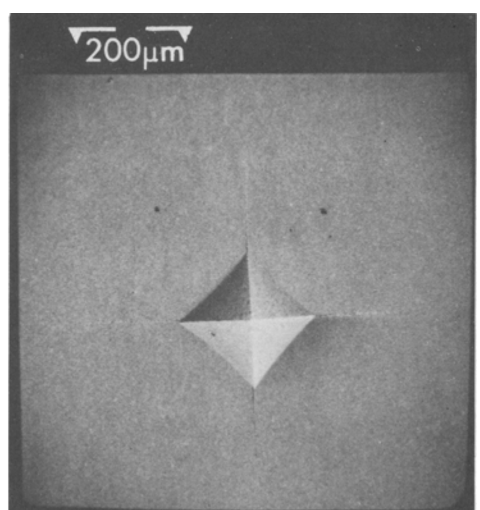


*Figure 2* Radial cracks at the corners of a pyramid indentation in a 6% Co/WC hard metal indented with a load of 589 N.

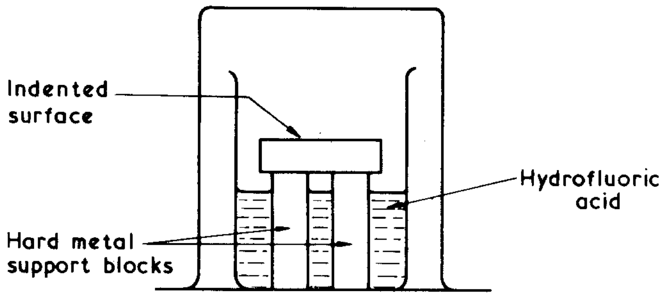


*Figure 3* The arrangement used for examining the effect of a corrosive environment on the extent of flaking and radial cracking in a 6% Co/WC hard metal.

below the apex of the indenter [3].

To examine the effect in hard metals of corrosion on flaking, and crack formation generally, a series of experiments was performed using a Vickers pyramid indenter and specimens of a 6% cobalt/tungsten carbide hard metal. Before testing, the specimens in the form of 20 mm x 6.5 mm x 5 mm blocks were diamond-ground on the upper and lower faces to remove the "sintered layer", and then diamond-lapped to remove any residual stresses that were introduced into the surface by grinding [5]. For studying the effect of a corrosive environment the specimens were supported on two hard metal blocks just above the surface of a 40% hydrofluoric acid solution, and the arrangement was covered with a beaker (Fig. 3).

For the first experiment, two specimens were indented using a 589 N load. One of the specimens was annealed at 800° C for 4 h in a vacuum, and then they were both exposed to hydrogen fluoride for 16 h. Flaking was only observed in the specimen that had not been given an annealing treatment. This demonstrated that the presence of residual stresses as well as a corrosive environment was necessary for producing flaking.

In the second experiment, measurements were made of the radial cracks in specimens that had been subjected to various sequences of annealing, indenting, and etching. Indentations were made using loads of 196 to 981 N, and the extent of radial cracking was defined as the sum of the lengths of the four radial cracks at the corners of the indentations. The reproducibility of the measurements was ± 40 $\mu$m. The values are given in Table I.

The results show that the total crack length in specimens containing residual stresses increased by about 60% in a corrosive environment; however, there was no significant crack extension when the residual stresses around the indentation were removed by annealing prior to exposure to hydrogen fluoride.

These observations showed that exposure to a corrosive environment produced an increase in the length of radial cracks provided there was a residual stress field around the indentation.

As a third experiment, indentations were made in two specimens in a position midway along the length using a 590 N load. One specimen was annealed and then they were both exposed to hydrogen fluoride for 16 h. Both specimens were broken in a three-point bend rig with the indented surfaces in tension so that fracture initiated from the radial cracks and exposed the stained fracture surfaces. By comparing Fig. 4a and b it can be seen that the size but not the shape of the radial fracture zone was altered by the action of residual stresses and a corrosive environment. Since stress contours

TABLE I

| Specimen | Treatment | Crack length ($\mu$m) at different loads | | | | |
|---|---|---|---|---|---|---|
| | | 196 N | 392 N | 589 N | 785 N | 981 N |
| (a) | (i) Lapped, indented | 266 | 508 | 720 | 905 | 1095 |
| | (ii) As (i) and annealed | 272 | 513 | 714 | 939 | 1153 |
| | (iii) As (ii) and exposed to HF | 290 | 512 | 714 | 915 | 1157 |
| (b) | (i) Lapped, annealed, indented | – | 502 | 715 | 953 | – |
| | (ii) As (i) and exposed to HF | – | 1025 | 1138 | 1473 | – |
| (c) | Lapped, indented, exposed to HF | 450 | 881 | 1130 | 1503 | 1775 |

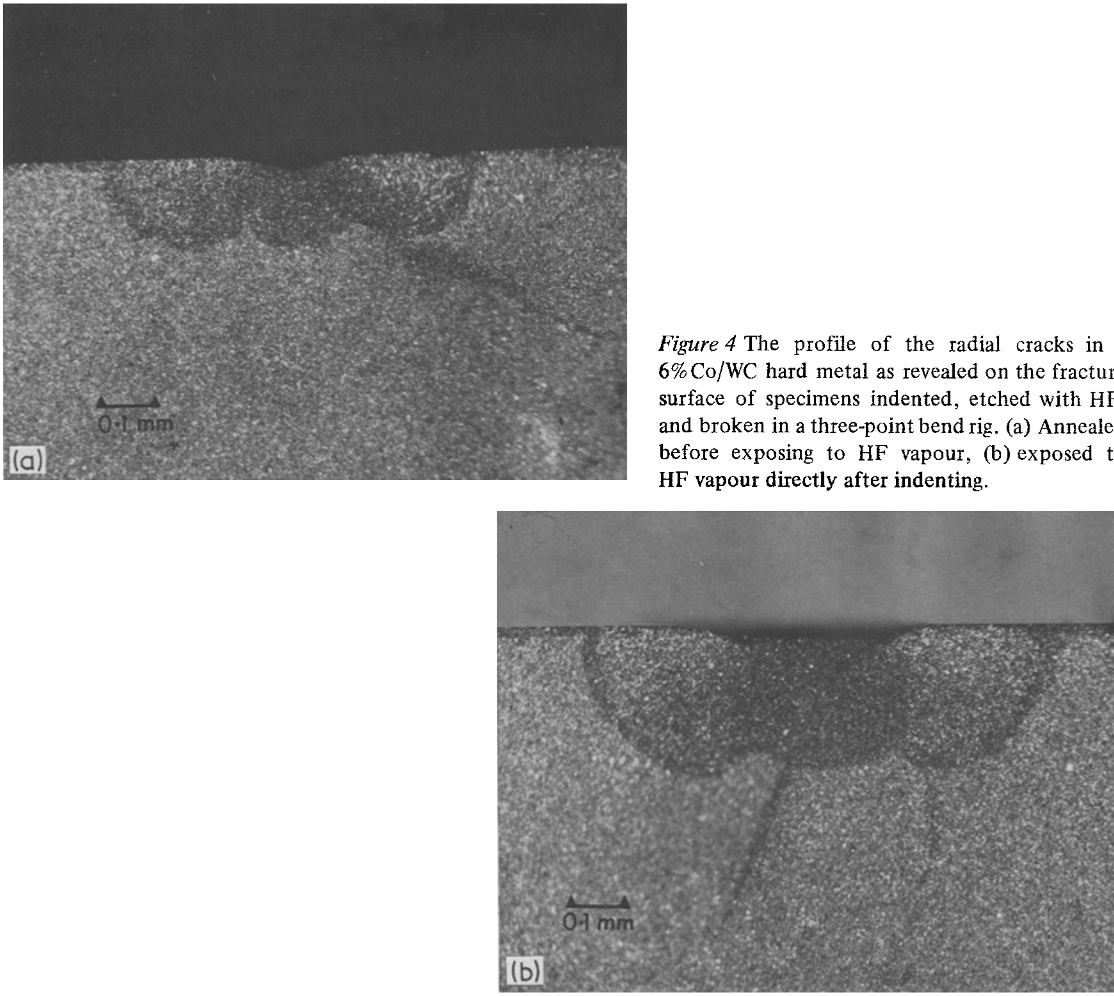


*Figure 4* The profile of the radial cracks in a 6% Co/WC hard metal as revealed on the fracture surface of specimens indented, etched with HF, and broken in a three-point bend rig. (a) Annealed before exposing to HF vapour, (b) exposed to HF vapour directly after indenting.

below indentations do not alter markedly with increase in depth [3] this result indicates that the controlling factor that limits the extent of crack growth in a corrosive environment is probably the same as in a non-corrosive environment, and it is most likely some function of the stress field [2, 3]. Further evidence to support this conclusion is given in Fig. 5 where the mean values of crack lengths before and after exposure to hydrogen fluoride have been plotted from the data for experiment 2. Here it can be seen that for both sets of results there is the characteristic linear relationship between load and crack length that is commonly observed in materials where fracture toughness (or stress intensity) determines the extent of radial cracking.

The combined evidence from the experiments establishes that flaking and crack growth in the tungsten carbide/cobalt hard metal were caused by stress corrosion cracking and the observations have several important fundamental and practical consequences. Thus the geometry of the flakes, the shape of the cracks, and the directions taken by the cracks provide strong evidence that the stress distribution around an indentation in a hard metal is similar to that observed in glasses and ceramics [3].

Secondly, the fact that hard metals are susceptible to stress corrosion indicates that the resistance of a hard metal to corrosion in an unstressed condition may not be a good guide to the performance of the material under load in a hostile environment in, for example, a wear application where a lubricant or coolant is used. Likewise, present attempts to use fracture mechanics concepts as a guide to the potential performance of different hard metals

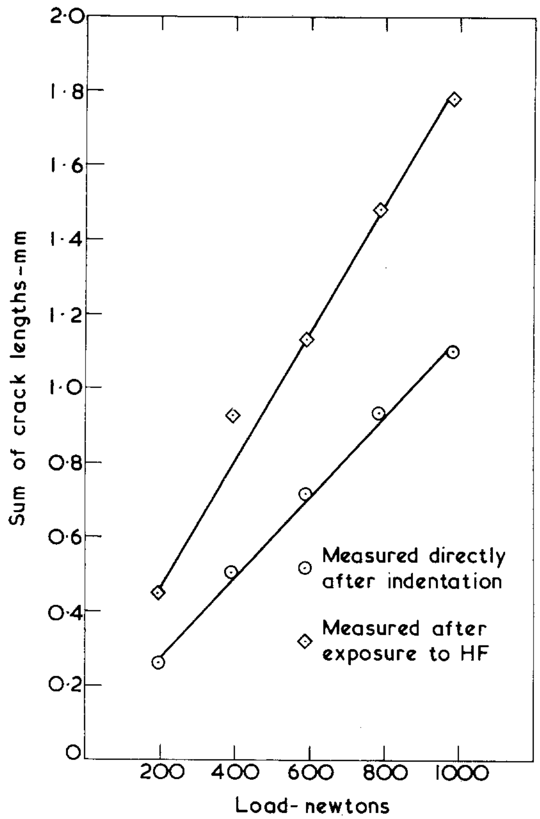


*Figure 5* Variation in the average total crack length with load on indenter for 6% Co/WC hard metal specimens before and after exposure to HF vapour.

[6] will be misleading and lead to over-estimates of toughness unless they take into account the possible effects of environment in reducing the fracture toughness of the material.

Finally, the simplicity of the above experiments suggests that an easy and useful test for determining the susceptibility of a low-ductility material to stress corrosion cracking would be to indent the specimen under standard conditions and then measure the length of the radial cracks around the indentations before and after exposure to the suspect environment. The percentage increase in crack length could then be used to compare the effects of different environments.

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## *Transverse cracking in cross-plied composites*

One of the major limitations of high-performance composites, made of aligned continuous strong fibres in a resin matrix, is that the strengths are quite low at substantial deviations from the fibre direction. Consequently, in multi-ply configurations, the layers containing fibres aligned transversely to the imposed loads are apt to fail at low stresses.

The failure takes the form of cracking in the resin between the fibres, with the crack running more or less across the thickness of the ply and parallel to the axis of the fibres. Although the laminate will still be intact, the stiffness decreases and the permeability increases, thus limiting the durability of the component.

The cause of this transverse cracking has been identified by Kies [1] and Schultz [2] as the strain concentration effects of the fibres. Because the fibres are much stronger and stiffer than the resin, most of the longitudinal strain in the transverse ply must be borne by the thin layer of resin between the fibres. Kies estimated that in glass-fibre composites the resin may be subjected, in service, to a strain of about 40%, which is well above the failure strains of epoxide resins normally