CONTIGUITY AND THE FRACTURE PROCESS OF WC-Co ALLOYS

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ABSTRACT

This work is an attempt to explain qualitatively the dependence of the strength and toughness of WC-Co alloys on the contiguity of the carbide grains by establishing a correlation between these properties and the average size of WC-WC boundaries, as measured on a random plane section.

INTRODUCTION

Contiguity is defined as the average fraction of surface area shared by a carbide grain with all neighbouring grains of the same phase (Gurland, 1963). Its value obviously varies between 0 and 1 and depends on both the grain size and the volume fraction of the carbide phase. From the results available in the literature it appears that the transverse rupture strength (TRS) of WC-Co increases when contiguity decreases from 1 to ∿ 0.5 but decreases when contiguity decreases from ∿0.5 to 0. Therefore the TRS is maximum at a contiguity value of ∿ 0.5 (Chermant and others, 1977). The fracture toughness (K_{IC}) of WC-Co is also a function of contiguity,namely it increases when contiguity decreases (Chermant and Osterstock, 1976). Having long been observed that WC-WC boundaries are sites of stress concentration (Bartolucci and Schlössin, 1966; Lee and Gurland, 1978), an attempt is made here to explain the dependence of TRS and K_{IC} on contiguity by establishing a correlation between grain boundary characteristics and fracture properties.

EXPERIMENTAL

Contiguity is determined from metallographic measurements on polished plane sections as

$$C = \frac{2I_{WC-WC}}{2I_{WC-WC} + I_{WC-Co}}$$

where I_{WC-WC} is the number of intercepts between a random line of unit length and the WC-WC boundaries and I_{WC-Co} is the number of intercepts between the same line and WC-Co interfaces (Lee and Gurland, 1978).

In this investigation, however, new parameters have been introduced and measured in order to evaluate the influence of grain boundary features on the fracture process. The new parameters are the following: 1) N, the average number of WC-WC boundaries (or "contacts") per unit area of a plane section; 2) L, the average total length of WC-WC boundaries in a unit area; 3) G, the average number of carbide grains per unit area.

These parameters have been measured on random plane sections of specimens ranging from 5 to 15 wt.% Co and having average grain size of 2.5-3.0 μ. At this grain size the TRS reaches a maximum at ∿ 15 wt.% Co (Luyckx, 1968), which corresponds to a contiguity of ∿ 0.5. This investigation has been limited to grades having $C \gtrsim 0.5$ because - as is shown below - at lower contiguity values the fracture mechanisms which depend on contiguity operate only at high stresses, therefore cannot be the controlling mechanisms. Optical and TE micrographs (replicas) of random plane sections have been divided into squares of equal sizes. The parameters defined above have been measured in each square and averaged. The measurements have been repeated over a number of areas, there being a large scatter in the grain size distribution.

The parameters defined above have been used to determine the following ratios: 1) N/G, the average number of contacts between a WC grain and the neighbouring grains of the same phase, on a random plane section; 2) L/N, the average length of a WC-WC boundary on a random plane section; 3) L/G, the average length of the boundary of one grain which is shared with neighbouring grains of the same phase, on a plane section. L/G can provide relative measures of contiguity for alloys of equal grain sizes, since the ratio between L/G values, within the range of cobalt contents examined, is the same as the ratio between the contiguity values reported by Gurland (1979). (See Fig. 1).

On a plane section two types of WC-WC contacts are encountered, viz: "point contacts" (N_p), which are sections of threedimensional contacts between a face of one grain and an edge or a vertex of another grain, and "line contacts" (N_ℓ) which are sections of threedimensional contacts between a face of one grain and a face or an edge of another grain. The parameter N includes both types of contacts, while L is only the length of line contacts.

WC-WC contacts have been also examined by the following techniques: a) thin foils have been studied by transmission electron microscopy and b) polished plane surfaces have been indented by Vickers diamond indentors and subsequently studied by transmission electron microscopy (TEM) of replicas and by scanning electron microscopy (SEM).

Finally, the role of large carbide grains in the fracture process has been studied by examining fracture surfaces by TEM of replicas and by SEM.

RESULTS

a) Figure 1 summarizes the following results:

1) N_ℓ/G is ≃ 2 at all the cobalt percentages examined (Fig. 1a). In the present range it can be considered constant, however it must tend to a higher value (≃ 3) when the cobalt content tends to zero.

2) N_p/G increases slightly with increasing cobalt content (Fig. 1b), since at low cobalt percentages the grains are so closely packed that most contacts are face-to-face contacts.

3) As a result of 1) and 2), N/G (where $N = N_p + N_\ell$) increases slightly with cobalt content.

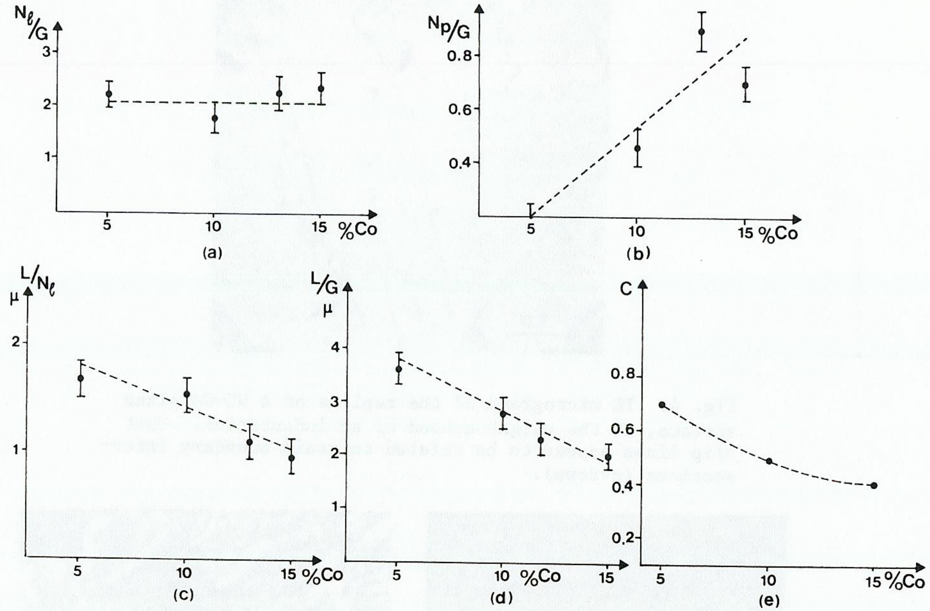

Fig. 1. Variation of the ratios defined in the text with cobalt content (a, b, c and d). "e" represents the variation of contiguity with cobalt content according to Lee and Gurland (1978). The ratios between L/G values (d) and C values (e) are equal for equal pairs of Co content values.

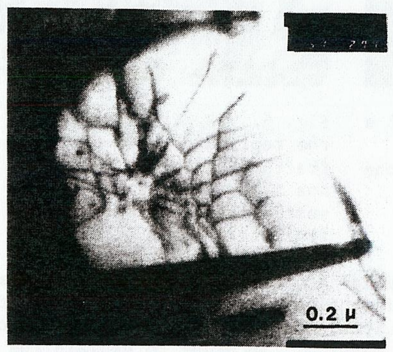

Fig. 2. TE micrograph of a thin WC-Co foil cut perpendicularly to the applied compressive stress. The dislocation network originated at a "point contact" between the grain in the picture and another grain.

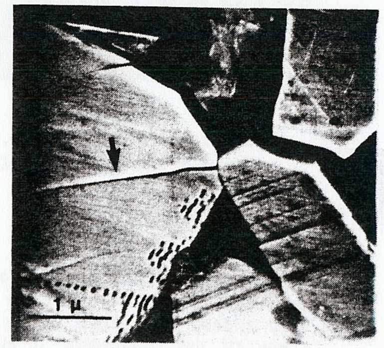

Fig. 3. SE micrograph from a WC-Co plane surface, in the neighbourhood of an indentation. The crack indicated by the arrow was nucleated at a "line contact".

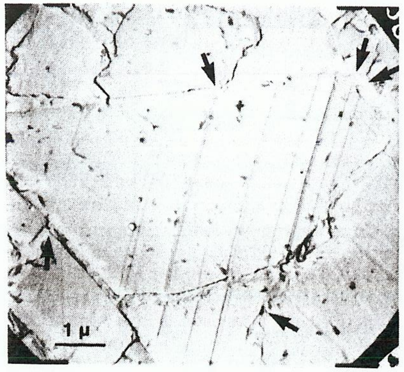

Fig. 4. TE micrograph of the replica of a WC-Co plane surface, in the neighbourhood of an indentation. Most slip lines appear to be related to grain boundary intersections (arrows).

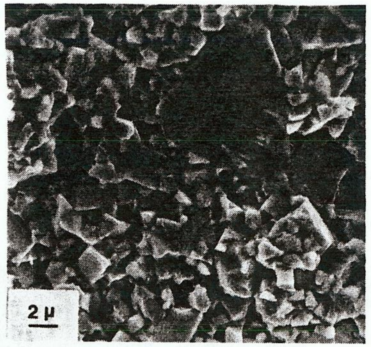

Fig. 5. SE micrograph of a WC-Co fracture surface. Grain A was the site of the main fracture origin.

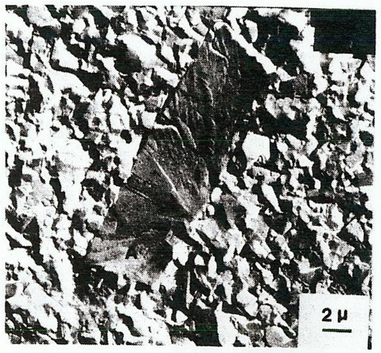

Fig. 6. TE micrograph of the replica of a WC-Co fracture surface. Grain A was along the path of the mostly intergranular fracture.

4) Both L/N and L/G (Figs. 1c and 1d) decrease with increasing cobalt, in agreement with the decrease of contiguity with increasing cobalt content. They appear therefore to be suitable parameters to correlate with the strength and toughness of the material, in order to explain the dependence of these properties on contiguity.

b) Examples of evidence pointing to WC-WC contacts as sites of stress concentration are given in Figs. 2-4.

Figure 2 is a transmission electron micrograph of a thin foil cut perpendicularly to the applied compressive stress. The dislocation network in the grain was originated at the "point contact" between the face of the grain in the picture and the vertex of another grain. This kind of feature has

not been found in foils cut parallel to the applied stress.

Figure 3 is a scanning electron micrograph from the plane surface of a WC-Co specimen, in the neighbourhood of an indentation. The crack indicated by the arrow was obviously nucleated at a "line contact" between two grains.

Figure 4 is the TE micrograph of a replica from the polished surface of a WC-Co specimen, in the neighbourhood of an indentation. Slip lines appear to have been mostly nucleated at grain boundary intersections.

c) Figures 5 and 6 are examples of intergranular failures exhibiting large fractured grains. Grain "A" in Fig. 5 was the site of the main fracture origin, which confirms that, in the absence of very large flaws such as pores or inclusions, fracture in WC-Co starts from grains larger than the average (Almond and Roebuck, 1977). Grain "A" in Fig. 6 was not found in the fracture origin region. It indicates that large grains offer less resistance to a propagating crack than the rest of the matrix.

DISCUSSION

Figure 1 indicates that bridges between WC particles remain the same in number (N/G) but decrease in size (L/N or L/G) when the cobalt content is increased up to ∿ 15 wt.%. At higher cobalt percentages (i.e. $C < 0.5$) the WC-WC bridges are expected to break down progressively and their role in the fracture process is expected to become less and less important.

The dependence of fracture toughness on contiguity can be explained in terms of the ratios reported in Fig. 1 by considering the schematic representation in Fig. 7.

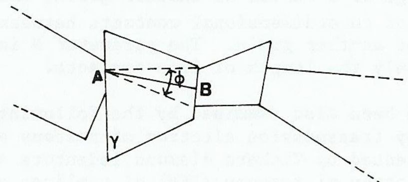

Fig. 7. Schematic representation of a chain of WC grains. AB is a crack in a grain γ. The average length of the grain boundaries is L/N.

Let us consider a crack which was nucleated at "A" by a high contact stress and which propagated through the grain "γ". Assuming $N/G = 2$ and therefore "γ" as being in contact with only two other grains, the probability that the leading edge of the crack impinges on a WC-WC boundary can be assumed to be proportional to $\mathrm{tg}\,\frac{\phi}{2}$ (where ϕ is the angle indicated in Fig. 7), therefore approximately proportional to $\frac{1}{2}\,\frac{L/N}{G^{-\frac{1}{2}}}$.

Since the fracture toughness of the carbide grains is lower than the fracture toughness of the binder layers in between the grains (Lindau, 1977), the higher is the probability of the crack impinging on a WC-WC boundary the lower is the fracture toughness of the alloy. One can therefore write:

$$K_{IC} = f(\frac{N}{L}, G^{-\frac{1}{2}}) \qquad [1]$$

which reads that the fracture toughness of the material is an increasing function of N/L and $G^{-\frac{1}{2}}$, i.e. K_{IC} increases by decreasing L/N and by increasing $G^{-\frac{1}{2}}$. This is in agreement with the experimental results, according to which K_{IC} increases with decreasing contiguity (Chermant and Osterstock, 1976) and K_{IC} increases with increasing grain size (Chermant and others, 1973).

In the present range of alloys (i.e. for Co % ≤ 15), WC-Co can be considered as almost perfectly brittle, therefore the stress σ required to propagate a crack of fixed length "C" can be assumed to be proportional to the fracture toughness K_{IC} ($\sigma \simeq K_{IC}/\sqrt{2\pi C}$). One can, then, write:

$$\sigma = f(\frac{N}{L}, G^{-\frac{1}{2}}) \qquad [2]$$

which reads that the stress required to propagate a crack of fixed length is also an increasing function of N/L and $G^{-\frac{1}{2}}$ i.e. σ increases with decreasing L/N and with increasing $G^{-\frac{1}{2}}$. This is in agreement with the experimental results, according to which σ increases when the contiguity decreases from 1 to ∿ 0.5 (Chermant and others, 1977) and σ increases with increasing grain size up to about 3 μ (Brewer and Pearson,(1963).

From [2] it follows that at high cobalt contents (i.e. low L/N values) and high WC grain sizes σ is high, therefore other mechanisms, not dependent on contiguity, will control the fracture process. High cobalt contents and large WC grain sizes correspond to contiguity values < 0.5, which is the contiguity range that was expected not to play a major role in the fracture process, as was mentioned above.

Since fracture, in this range of alloys, starts in the carbide grains, as a result of the high stresses at the contacts between the grains, σ must also be a function of the fracture stress of the WC crystals, (σ_{WC}),which decreases with increasing the size of the crystals (Pfau and Rix, 1952). One should,therefore, write

$$\sigma = f(\frac{N}{L}, G^{-\frac{1}{2}}, \sigma_{WC}) \qquad [3]$$

which is also in agreement with the experimental results, since it has been found that fracture starts preferentially from large grains (Fig. 5 and Almond and Roebuck, 1977). Consequently, it should also be:

$$K_{IC} = f(\frac{N}{L}, G^{-\frac{1}{2}}, \sigma_{WC}) \qquad [4]$$

i.e. K_{IC} should also increase with increasing σ_{WC}, which is confirmed by Fig. 6, since large grains such as "A" (which have low σ_{WC}) offer little resistance to a propagating crack, therefore can only lower the toughness of the material.

CONCLUSION

It is possible to explain qualitatively the dependence of strength and toughness of WC-Co on the contiguity of the carbide grains in terms of the average size of the WC-WC contacts, as measured on random plane sections.

ACKNOWLEDGMENTS

The author wishes to thank Professor F.R.N. Nabarro and Professor G.G. Garrett for their very helpful criticism. This work has been sponsored by Boart International Ltd., Johannesburg, South Africa.

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