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FRACTURE OF WC-Co HARD METALS

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INTRODUCTION

WC-Co hard metals have been used and studied for many years. In spite of their simple structure the mechanism of fracture has still not been finally established. In order to obtain further information we have studied the characteristics of fracture in bending, compression and toughness testing for 18 combinations of carbide grain size and volume fraction of cobalt. Six volume fractions of cobalt for each of the three grain sizes d_{WC} (2.2 - 1.1 and 0.7 μm) were studied.

Since the microstructure has a strong influence on the mechanical properties each specimen was characterised by the following quantitative microstructural parameters:
- volume fraction of the cobalt phase, V_V (Co)
- mean diameter of the carbide crystals, d_{WC}
- mean free path in the cobalt phase, l_{Co}
- contiguity of the carbide phase, C_{WC}

At first we related the mechanical characteristics to the microstructural parameters to establish which were the most important parameters. Subsequently, an hypothesis of the mechanism of fracture necessitated the introduction of a more complex parameter.

RESULTS

We shall treat briefly the results for the critical stress intensity factor, K_{IC}, the behaviour in bending and compression and the microfractographic features.

Critical Stress Intensity Factor

The toughness was determined by three point bending tests on notched specimens. The force displacement curves are perfectly linear and it was possible to determine the critical stress intensity factor directly from the force at rupture.

The values of K_{IC} obtained were fairly small. The variation of K_{IC} and G_{IC} with the volume fraction of cobalt is fairly regular with however a marked influence of the mean diameter of the carbide crystals.

A study of the K_{IC} values as a function of the microstructural parameters [1] reveals the role of the two constituents in these materials. Thus the linear dependence of K_{IC} on l_{Co} at constant d_{WC} is evidence of the

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ductility of the cobalt which retards the propagation of the crack. On the other hand the fragile nature of the carbide phase is underlined when K_{IC} is plotted against the contiguity of the carbide phase (Figure 1). The contiguity appears therefore to be a determining parameter of the crack propagation.

In Figure 2 the parameters which can be obtained from the K_{IC} values are plotted against the volume fraction of cobalt: the critical crack size for fracture, a_c, and the size of the plastic zone, r_y. The knowledge of these quantities leads to a better appreciation of the formation of microcracks and their growth leading to fracture. The values of a_c calculation from the rupture stress in bending, σ_{fb}, are very small and of the order of a few crystals only. It can be observed that there are minima which obviously correspond to the maxima in the fracture stress in bending. The radius of the plastic zone has been calculated from the values of σ_y 0.05%. Only at sufficiently high cobalt volume fractions can the plastic zone extend over several carbide crystals.

Behaviour in Bending and Compression

The variation of the fracture stress in three point bending, σ_{fb}, as a function of the mean free path in the cobalt phase has a characteristic form: - rapid increase of σ_{fb} at low values of l_{Co}, passing over a maximum and slowly decreasing with further increase in l_{Co} [2] [3] [4]. In compression testing the same behaviour is observed but with higher values of rupture stress. Also the position of the maxima appears to be displaced towards low values of l_{Co}. This has already been reported by H. Doi [3], who also observed a shift of the maximum to high l_{Co} values for tensile tests.

This behaviour for the variation of the fracture stress is evidence of different fracture mechanisms. In this respect, it is necessary to note certain aspects in the variation of fracture stress characterised by the respective values of the fracture stress and the elastic limit of the material:

- purely elastic fracture corresponding to the region in which σ_{fb} increases rapidly with l_{Co}.
- fracture preceded by very little plastic deformation, the fracture stress being in the same range as the elastic limit of the material.
- fracture after appreciable plastic deformation, thus the fracture occurs at a stress significantly greater than σ_y. In this domain the fracture stress decreases with increasing l_{Co}.

The fracture stress depends therefore on the elastic limit and on the capacity of the material to undergo plastic deformation.

The deformation of the material before fracturing depends on the interaction of the cobalt and the carbide phases. The influence of the deformation on the fracture stress can be demonstrated by plotting these two quantities one against the other [4]. In compression much higher degrees of plastic deformation are achieved due to grain boundary sliding of the carbide crystals and slip in the crystals [5] [6].

Microfractographic Features

A microfractographic study of the initiation of fracture in bending has already been undertaken by J. Gurland [7]. The investigation shows that fracture propagates from isolated fractured carbide crystals. Measurements made along the fracture path on the tensile surface of the bend specimen show that it passes through the largest carbide crystals. On the other hand in notched bend specimens the distribution of the size of crystals fractured on the propagation surface corresponds to the normal distribution in the material [8].

As far as propagation of the crack is concerned, Figure 3 shows certain characteristic trends. It appears that the crack advances in two stages: in the plastic zone there is rupture of the carbide crystals, the probability of rupture, being amongst other things a function of the size of the crystal. Isolated fracture sites are then joined firstly by decohesion of the crystals and then rupture of the cobalt phase. The fact that rupture of the cobalt phase occurs last emphasises the influence of the contiguity of the carbide phase in the propagation of the crack.

DISCUSSION

The ductility of the cobalt phase and the appearance of plastic deformation prior to fracture enable the WC-Co materials to be classified as semi-brittle. In these kind of materials the fracture can be envisaged as taken place by a dislocation mechanism [2] [9]. H. Doi and coworkers have been able to show the presence of dislocations which are considered to be generated in the ductile cobalt phase [10]. At relatively low stresses these dislocations may be considered to pile up against the carbide crystals. It is possible in such a mechanism to take into account the interaction of the cobalt and the carbide phases, utilising their microstructural parameters.

One can therefore envisage a pile up mechanism of the type proposed by Petch [11]. A pile up of n dislocations:

$$n = (\sigma_{xy} - \sigma^{\circ}_{xy})\ l_{Co}/\mu b$$

has an energy per unit length, U, of:

$$U = (\sigma_{xy} - \sigma^{\circ}_{xy})^2\ l_{Co}^{\ 2}/4\ \pi(1 - \nu)\mu$$

This pile-up causes a carbide crystal to fracture if its energy is equal to the energy necessary to produce two new surfaces, $2\ \gamma_s d_{WC}$. The equality of the two energies leads to the microstructural quantity $l_{Co}^{\ 2}/d_{WC}$:

$$l^2_{\ Co}/d_{WC} = 8\ \pi\ \gamma_s(1-\nu)\mu/(\sigma_{xy} - \sigma^{\circ}_{xy})^2$$

This dislocation mechanism plays an important role in the initiation and the propagation of the crack.

We have observed that the initiation of fracture is caused by the rupture of carbide crystals and that the critical crack size is very small. Therefore, if the fracture of the crystals is due to a pile-up of dislocations there should be a direct relationship between the parameter $l_{Co}^{\ 2}/d_{WC}$ and the stress to fracture in bending which has been verified [1] [4]. In compression tests, where considerable plastic deformation takes place, the fracture stress becomes very high. The variation of the ratio of the rupture stress in compression to the rupture stress in bending, σ_{fc}/σ_{fb}, with $l_{Co}{}^2/d_{WC}$ (Figure 4) shows however that even in this case the initiation of fracture is likewise induced by pile-up of dislocations against carbide crystals.

The variation of the parameter G_{IC} can be used to describe the propagation stage of fracture. This parameter describes on the one hand the resistance to crack propagation and on the other hand the work done in the plastic zone, without making any assumptions about its shape and magnitude. The use of this energy can be described in terms of the model proposed by B. R. Lawn and T. R. Wilshaw [12]. In this plastic deformation zone there appears shear stresses the intensity of which decreases with increasing distance from the crack. The advance of the crack causes a plastic deformation to be formed in the cobalt phase. In the cobalt regions dislocations are produced which pile up against the carbide crystals and cause their fracture. The equilibrium situation is thus that as described above. This mechanism appears to be verified by the Figure 5 where one can see the very good correlation between $l_{Co}{}^2/d_{WC}$ and G_{IC}.

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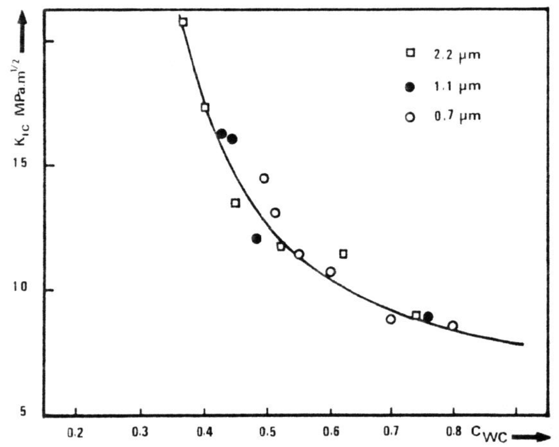

Figure 1 Variation of K_{IC} with the Contiguity of the Carbide Phase for Alloys with Carbide Grain Size of 2.2, 1.1 and 0.7 μm

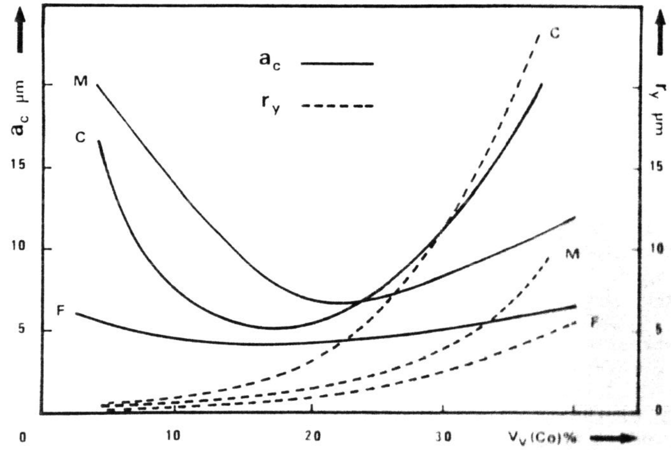

Figure 2 Variation of the Critical Size Defect, a_c, and the Plastic Zone Radius, r_y, with the Volume Fraction of Cobalt for the Alloys C : d_{WC} = 2.2 μm, M : d_{WC} = 1.1 μm and F : d_{WC} = 0.7 μm

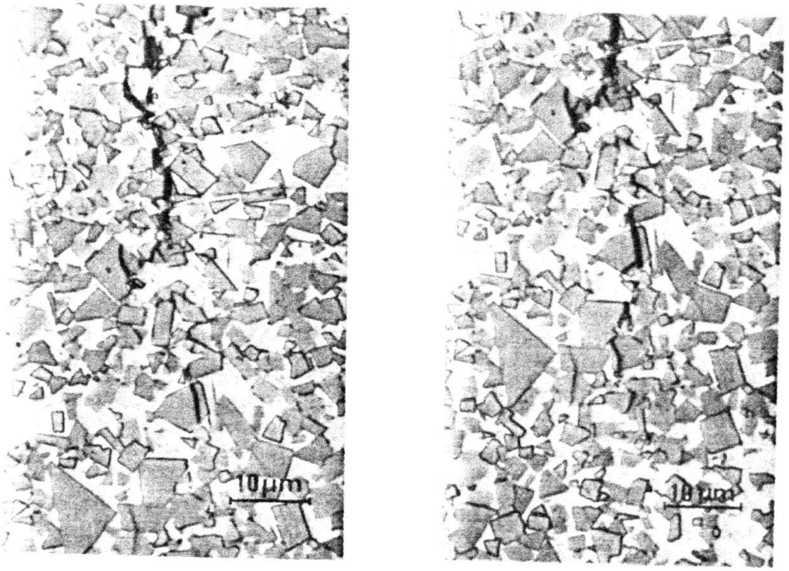

Figure 3 Micrographs of Different Stages in the Crack Propagation in a WC-37 Volume % Co Alloy

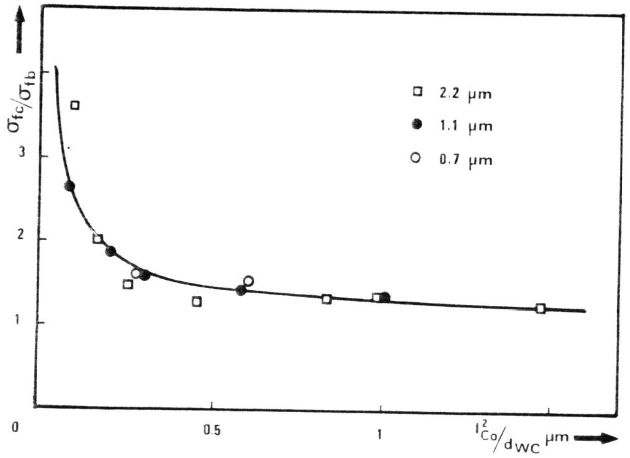

Figure 4 Variation of the Ratio of Rupture Stress in Compression to Rupture Stress in Bending with $l_{Co}{}^2/d_{WC}$ for Alloys with Carbide Grain Size of 2.2, 1.1 and 0.7 μm

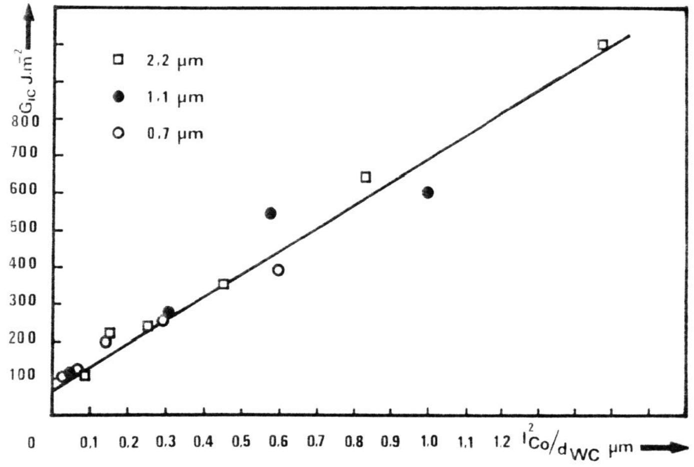

Figure 5 Variation of G_{IC} with $l_{Co}{}^2/d_{WC}$ for Alloys with Carbide Grain Size of 2.2, 1.1 and 0.7 μm