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Stress induced cavitation in cobalt bonded tungsten carbide

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Tensile stress-strain curves of three grades of Co-bonded WC composite have been obtained near 1200° C. Extensive void formation is observed in specimens extended to failure. A qualitative model for deformation based on atomic migration of Co in the bonding Co phase is proposed to account for the observations.

1. Introduction

Until recently, the plastic properties of Co-bonded WC composites have been considered quite simply in terms of a hard non-deformable collection of WC particles embedded in a softer Co matrix. Gurland and Norton [1] suggest that the constrained Co matrix has a higher yield stress than that normally measured for Co metal but, nevertheless, the underlying assumption is that limited ductility occurs by a shear mechanism (dislocation glide) in the Co matrix. Precisely this model is used by Doi *et al* [2] to explain the behaviour of these composites under uniaxial compressive loading and anelastic cyclic loading at room temperature.

More recently, observations have been made which suggest that other deformation mechanisms may be important. For example, Almond and Roebuck [3] find extensive signs of deformation in carbide grains adjacent to hardness indentations formed at room temperature, although what proportion of the total deformation is taken up in this way is not known. However, indentation experiments by Brookes *et al* [4] suggest that deformation of the WC phase can be a dominant contribution to strain since it is found in some circumstances that Co-bonded WC composites are harder than pure WC crystals. In such cases, it has been proposed that the Co matrix acts as the hard phase which inhibits deformation in the WC grains, a model analogous to grain-boundary hardening.

In this paper, we consider another mechanism of deformation, that of stress assisted atomic diffusion, which leads finally to cavitation and fracture. That cavitation may be important in some cases is suggested from the work of Jonsson [5] who performed metallographic examinations of damaged regions in cutting tools subjected to turning experiments. The voids observed by Jonsson appear to form in regions where the cutting temperature is high and where large tensile stress components may be set up. To test the importance of cavitation we have performed high temperature tensile experiments on several grades of Co-bonded WC and the results of the study form the basis of the present paper.

2. Experimental procedure and results

Tensile specimens were machined from Co-bonded WC stock rods 7 cm long by 0.8 cm diameter. Three grades were examined; N, TT and R11 types having compositions and grain sizes as set out in Table I. Gauge lengths 13 mm long by 3 mm diameter were cut with a spark erosion lathe and screw threads for screwing specimens into the test grips were cut also using a spark erosion device.

Specimens were deformed in tension in an Instron apparatus equipped with an induction furnace. To ensure uniform temperature along the gauge length, specimens were located inside a cylindrical carbon susceptor and radiation heated. To prevent oxidation, purified argon was used as a protective atmosphere. Temperature was measured with an optical pyrometer and direct sighting of the specimens was made through a small hole in the susceptor. Stress-strain curves obtained at a strain-rate of 7×10^{-5} sec^{-1} and a temperature of 1200°C are shown in Fig. 1 for one each of the three

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TABLE I

Composite	(wt %) Co	WC grain size (μm)	Vickers hardness (kg mm^{-2})	U_1 (eV)	n	U_2 (eV)	v (Å^3)
N	6	2.0	1540 ± 25	2.1 ± 0.6	2.6 ± 0.8	3.0 ± 0.7	560 ± 50
TT	25	2.0	984 ± 25	—	—	—	—
R11	11	5.0	1175 ± 25	—	—	—	—

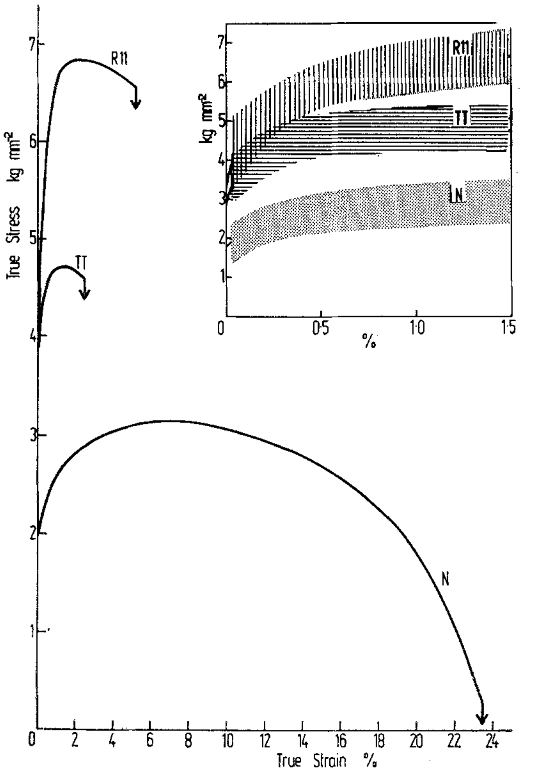

Figure 1 Stress-strain curves for three composite grades. Wide differences in flow stress are observed and approximate spreads are indicated by the shaded regions in the inset figure.

composite types studied. The temperature is 290°C below the melting point of Co and 120°C below the WC-Co quasi-binary eutectic temperature [6]. Although the overall shapes of the curves shown are typical of all specimens tested of each type, it was found that, within a given type, yield stresses and flow stresses varied considerably from specimen to specimen. The extents of these variations are indicated approximately by the shaded areas over each curve in the inset to Fig. 1. Although insufficient numbers of specimens have been deformed to warrant a full statistical treatment, it appears in general that the curves for R11 grade lie above those for TT grade which in turn lie above those for N grade. Ductilities for R11 and TT grades are low even at the high experimental temperature chosen and not all N grade specimens extended as much as the sample illustrated here. Fracture occurs in all specimens in a brittle manner in the sense that there is little or no necking.

An effort has been made to study the temperature and strain-rate sensitivities of deformation using the familiar trial relationships,

$$\dot{\epsilon} = K_1 \sigma^n \exp\left(-\frac{U_1}{kT}\right)$$

and

$$\dot{\epsilon} = K_2 \exp\left(-\frac{U_2 - v\sigma}{kT}\right) .$$

K_1 and K_2 are parameters which depend on internal structure, U_1 and U_2 are activation energies, n is a measure of the strain-rate sensitivity and v is an activation volume. U_1, U_2, n and v were evaluated by employing strain-rate changes during tests to find $(\partial\dot{\epsilon}/\partial\sigma)_T$ and also by changing the temperature during tests to find $(\partial\sigma/\partial T)_{\dot{\epsilon}}$. Strain-rate change data were obtained by increasing the strain-rate by an order of magnitude to 7×10^{-4} sec^{-1}. Temperature change data were obtained by decreasing the temperature by 100°C; a temperature decrease being preferred in an attempt to minimize annealing effects. Problems were encountered with both types of experiment. No clear yield point occurs after a change and, consequently, yields had to be defined by projecting back re-established steady state portions of curves to the strain at which changes were initially made. Furthermore, in the case of temperature change experiments, approximately 5 min elapsed before the new steady temperature was attained, during which time some annealing may have occurred. The reliability of the parameters governing temperature dependence and strain-rate sensitivity is in some doubt, therefore, and this is borne out by the spread of values obtained.

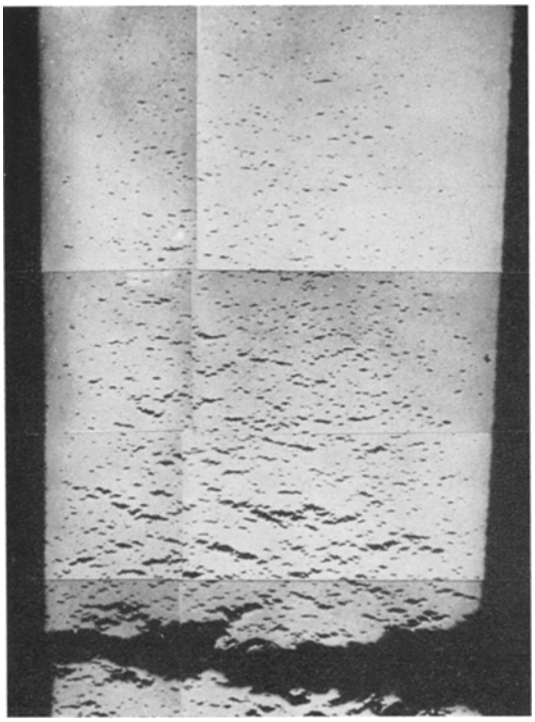

Figure 2 Optical micrograph of a longitudinal section through an N grade tensile specimen extended to failure.

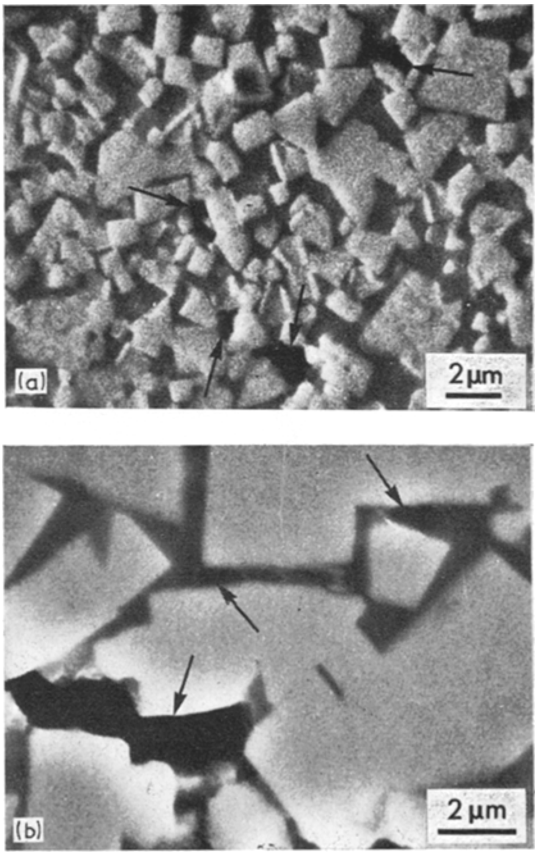

Figure 3 Scanning electron micrograph of specimens extended to failure showing the formation of voids between WC particles (a) TT grade, (b) R11 grade. Voids are indicated by arrows.

The optical micrograph of a longitudinal section through the gauge length of a fractured N grade specimen is shown in Fig. 2. The main feature is the presence of voids which are not characteristic of the undeformed material. Over most of the section the voids are randomly arranged, but in the vicinity of the fracture surface they can be seen coalescing to form fissures. Clearly, it is this agglomeration of voids which has ultimately led to the fracture. Furthermore, this sort of widespread tearing action can slowly reduce the effective area of the specimen, which explains why necking is not seen in that part of the stress-strain curve where stress is decreasing. Excess voids were also found in the R11 and TT grades, but the void density was lower. Also the void density was uniform throughout the gauge length and not highly localized in conical regions about the fracture surface as was found in N grade.

3. Discussion

In Table I, room temperature Vickers hardnesses obtained at 30 kg load are given for the three composite grades studied here. Clearly for this group of materials hardness falls as the proportion of Co phase increases. This one might expect from the relative softness of Co with respect to WC, although according to the work of Gurland and Bardzil [7] this trend is fortuitous as the more important parameter controlling hardness is the interparticle spacing. In tension at high temperature the situation is different. The N grade which has the highest WC concentration has the lowest values of flow stress. It is of particular value to compare the results of N and TT grades because both have the same average grain size and only the Co proportion differs. In spite of the fact that the N grade has nearly 20% more of the hard WC phase than the TT grade, the latter has a higher yield stress and a higher ultimate tensile stress. We propose an explanation for this result in terms of a vacancy flow in the Co phase, in which vacancies are produced at WC-Co interfaces lying perpendicular to the applied stress axis and migrate to interfaces lying parallel to it. The mechanism is essentially similar to Nabarro-Herring creep [8].

The experiments performed on N grade to evaluate activation energies are neither accurate enough nor do they cover a sufficiently wide range of temperatures and strain rates to determine which equation (1 or 2) is the better description of the flow process. However, as both equations lead to activation energies close to the activation energy for self diffusion in Co, namely 2.9 eV, it seems evident that deformation is governed by flow of vacancies within the Co phase. As the flow of Co progresses, WC grains will gradually come into contact with each other and oppose the lateral shrinkage. In regions where this occurs, further transfer of Co atoms, which takes place in the reverse direction to vacancy flow, then leads to tensile stresses in the Co phase perpendicular to the applied stress. The vacancy flow will consequently be slowed down as the stress in the Co phase approaches a condition of hydrostatic tension. In the absence of cavitation, this hydrostatic stress would reach a value equal to the applied tensile stress. In fact, under high tensile stress this stage is not reached. Instead the vacancy concentration rises sufficiently that vacancies coalesce to form voids.

The rate at which this whole process proceeds depends upon the total interfacial area per unit volume between the two phases and on the average thickness of the Co phase between the WC particles. (Both parameters are functions of particle size and Co fraction. For example a reduction in particle size increases interfacial area and reduces Co thickness.) Larger interfacial area per unit volume means more efficient vacancy sinks and sources which leads to easier mass transfer. Cavitation should occur more readily in materials which have only thin Co films between grains because this condition ensures that the transverse tensile stresses required to slow down vacancy flow will develop more readily. This model explains qualitatively both the low flow stress and the high density of voids observed in N grade. In a qualitative sense, the R11 grade fits in with the overall scheme since, with an interfacial area per unit volume approximately three times less than N and TT grades, it exhibits the highest flow stresses.

The coalescence of vacancies to nucleate voids probably occurs at the interfaces. An examination of the deformed regions using the scanning electron microscope partially supports this view. The SEMs of Fig. 3 show that small voids, which we assume to be newly nucleated, are in contact with carbide phase. Furthermore, in an extensive examination of many voids, none was ever observed which was not in contact with a carbide grain.

In the cutting tool experiments of Jonsson [5] referred to earlier, it was found that during high-speed turning operations tool temperatures can rise to 1100° C. This temperature is within the range where we expect diffusion and cavitation to become important. It seems likely, therefore, in the light of present evidence that in high-speed conditions cavitation may play an important role in determining the life of Co-bonded WC cutting tools.

4. Conclusion

At temperatures just below the Co-WC quasi-binary eutectic temperature Co vacancy diffusion is thought to be a dominant deformation mechanism in tensile testing of Co-bonded WC composites. It is found that for two composites with the same carbide grain size the composite with the smaller proportion of soft phase Co exhibits the lower yield stress. To explain this result a qualitative model is proposed in which the rate of vacancy flow increases as the interfacial area between the two phases increases and as the Co film thickness decreases. The model also leads to the prediction that for a given Co proportion, material consisting of fine WC particles will exhibit a lower yield strength than coarser grained material. In the later stages of deformation, the evidence suggests that voids nucleate at WC-Co interfaces and grow into the Co phase.

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