THE EFFECT OF THE TEST TEMPERATURE AND THE STRAIN RATE ON THE FRACTURE TOUGHNESS OF SINTERED CARBIDES

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ABSTRACT

The results of the in-depth study of the effects of high temperature and the strain rate on the fracture toughness of WC-Co-type alloys as a function of their structure state are reported in this paper.

Unlike the current fracture toughness assessment practice for sintered carbides and ceramics, the sintered carbide specimens have been tested after generating a fatigue crack in them. The strain rate was varied within the technical potentials limits of the mechanical and servohydraulic testing installations and also of an impact testing machine ($1.6 \cdot 10^{-6}$ to 5 m/s). Heating to 1300 K was carried out in a vacuum chamber in an optical furnace.

The effect of the structure parameters on the sintered carbide fracture toughness have been assessed over a wide cobalt content range, the grain size of the carbide phase varying from 2 to 9.3 μm.

KEYWORDS

Strain rate, fracture toughness, fatigue crack, temperature, cobalt content, grain size.

INTRODUCTION

A range of sintered carbide-based wear-resistant composite diamond-bearing tool materials have appeared lately (Novikov, 1983). The development and the improvement of these materials were provoked by a necessity to fit rock-crushing, dressing and other tools that were to work under extremely severe temperature and power load conditions. According to the Davidge and Green conception (1968) the actual strength properties of composite materials wherein particles are dispersed throughout a brittle matrix depend on the matrix fracture energy, the thermal expansion of constituents and the temperature of the composite production. Bearing the existing problem in mind the authors took on the task consisting in the definition of the fracture energy for hard WC-Co-type sintered carbides over a test temperature range to 1300 K and the strain rates to 5 m/s with the allowance for WC grains variation from 2 to 9.3 µm and that for the cobalt content from 5 to 20 mass %.

Apart the above specific task the problem of a correct sintered carbide fracture toughness assessment is self-sufficient and very significant. Thus, lately a number of works (Ingelström, 1975 ; Chermant, 1976 ; Almond, 1978 ; Hubner, 1978 ; Pickens, 1978 ; Kenny, 1971) has been dedicated to this problem wherein various methodological approaches to the sintered carbide fracture toughness assessment and various interpretations of the fracture mechanisms have been proposed. However, the data of the test temperature and the strain rate influences on the fracture toughness, i.e. the factors assisting to bring the material test conditions possibly closer to the real working situation have been so far accumulated only at the Institute for Superhard Materials of the Ukrainian Academy of Sciences (Novikov, 1981 ; 1982 ; Devin, 1982).

EXPERIMENTAL PROCEDURE

The experiments were carried out with specimens of home-made WC-Co-based sintered carbides (BK-type) having cobalt content of 5, 10, 15 and 20 mass % and the average carbide phase grain size of 2.0, 3.9 and 9.3 µm. Twelve sets of specimens were prepared altogether, the structure state in each of which represented a combination of the above cobalt content and WC grain size parameters. All the blanks were subjected to a normalizing sintering at temperatures up to 1450 K. The porosity of the specimens prepared did not exceed 0.1%.

SENB (single-edge notched bend) specimens of 5x5x35 mm and disks of 10 mm in diameter and 2.5 mm in thickness were prepared for testing. The preliminary stress raisers in specimens were initiated by the spark-erosion technique using a tungsten wire of 60 mm in diameter. As the initial defects in the works (Ingelström, 1975 ; Chermant, 1976 ; Almond, 1978 ; Hübner, 1978 ; Pickens, 1978 ; Kenny, 1971) were generated by different methods including mechanically performed sharp notches, spark-erosion technique, indentation with various types of indenters and so on, the K_{1c} values obtained by the authors had a 2.5-fold disagreement even for alloys of practically identical structure states (Novikov, 1982 ; Majstrenko, 1981). This could be explained not only by differential hystories of the preliminary defect initiation but also by the damage inflicted to the whole specimen cross-section when being fractured. Since the known standard specifications (E-399-72, 1972 ; RD 50-260-81 , 1982) strictly require the provision of a fatigue crack when testing for K_{1c} evaluation, the authors have developed a special fatigue crack initiation technique for specimens that are in the extremely brittle state (Konovalenko, 1980 ; Gille, 1982). This

technique is based on the principle of shifting the natural vibration resonance curve for a specimen loaded on frameless machines fitted with a system for generation forced vibrations (vibrator). The implementation of the technique developed permitted to initiate fatigue cracks of a desirable length in sintered carbides specimens at $\Delta K_1 < 0.5 K_{1c}$. The static tests were carried out on "Instron TT-KM" and "MTS 810" machines and the dynamic ones were performed on the upright impact testing machine working on the principle of Hopkinson measuring rods (Devin, 1982 ; Novikov, 1979).

The process of the specimens fracture was registered as a plot of fracture in terms of load versus crack opening displacement and in the dynamic tests the information obtained was registered by a storage oscilloscope in load- time coordinates.

The crytical stress intensity factor was calculated using the following expressions (RD 50-260-81,1982 ; Novikov, 1979; Yarema, 1976):
for a SENB-type specimen

$$K_{1c} = \frac{3F_c}{2tw^2} \left[1.93 - 3.07 \frac{1}{w} + 14.53 \left(\frac{1}{w}\right)^2 - 25.1\left(\frac{1}{w}\right)^3 + 25.8\left(\frac{1}{w}\right)^4 \right] \qquad (1)$$

and for a disk specimen

$$K_{1c} = \frac{1.01227F_c}{t\sqrt{\pi R}} \sqrt{\frac{\lambda}{1-\lambda}} \left(1 - 0.60387 + 1.67239\lambda^2 - 1.16988\lambda^3\right),$$

where F_c is the fracture load, L is the distance between the supports, t is the thickness, W is the width, R is the radius, 1 is the crack length in a SENB-type specimen, $\lambda = 21/D$ is the crack length versus disk diameter ratio.

The statistical analysis of the test results allowed to establish that the error in the K_{1c} value calculation when fracturing a batch of specimens consisting only of 4 pieces is no more than ± 6%, the confidence coefficient being 0.95.

The experiment performed permitted to establish a dependence of the sintered carbide K_{1c} value on the test temperature, various structure parameters and the strain rate, Fig. 1.

It follows from the above data that the fracture toughness within the investigated grain size range of the carbide phase up to 600 K could be considered practically constant. At temperatures above 600 K the K_{1c} value lowers which shows good agreement with the analytical model of two-phase medium fracture proposed in (Novikov, 1980). By solving the Prandtl plasticity problem related to the strain of a thin Co interlayer confined by rigid WC grains it was shown that the fracture toughness of a two-phase sintered carbide within a temperature range that does not lead to the phase structure modification of the matrix interlayer would be governed mostly by the yield strength and the thickness of the interlayer. This solution was approximated by a simple and descriptive expression of the following form (Novikov, 1980):

$$K_{1c} = \sigma_y \, (1.88+5.1\, f_{Co}^{-0.884}) \sqrt{\bar{d}_{wc} \cdot f_{Co}^{0.884}} \qquad (2)$$

where f_{Co} is the volumetric cobalt content (mass %).
$\bar{d}_{WC}$ is the average WC grain size.

The experimentally deduced σ_y correlations for Co within 300 to 900 K range confirmed the nature of curves in Fig. 1 and, consequently, the correctness of the proposed model.

With the further test temperature rise the fracture toughness increases. Obviously this effect is connected with the increase around the tip of the initial crack of the density of microcracks generated at the tungsten carbide grain boundaries wherein at temperatures above 900 K a drastic weakening of binding forces takes place. This accounts for a further energy dissipation which leads in a long run to the fracture toughness increase. This effect is well described by a dissipation fracture model proposed by Pompe W. (1978).

To evaluate the net effect of the test temperature, the cobalt content and the average WC grain size on the K_{1c} value the multiple regression analysis was used as a result of which the multifactor regression equation was obtained. This allowed to calculate K_{1c} values as a function of variation of one of the factors, i.e. temperature, cobalt content or WC grain size, or of variation of all the factors simultaneously (Novikov, 1981). The error emerging when calculating the K_{1c} value using the above equation as compared with the experimental data does not exceed 15%.

As can be seen from Fig. 2, the fracture toughness increases at the transition from the static loading to higher strain rates. At this, the sintered carbide K_{1c} value at strain rates to 50 mm/min, are independent of the strain rate. At the rates from 10^3 to 10^5 mm/min the fracture energy in sintered carbides substantially increases and those for BK25 alloy approaches the maximum at the rate of $5 \cdot 10^5$ mm/min.

Thus, the results obtained describe the cracking resistance of the sintered carbides with the allowance for their structure state over a wide high temperature range and make it possible to make a more reasonable choice of materials for specific working conditions or when developing composites based on them.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Dr. L.N.Devin and Dr. N.K. Konovalenko for their participation in carrying out the experiments.

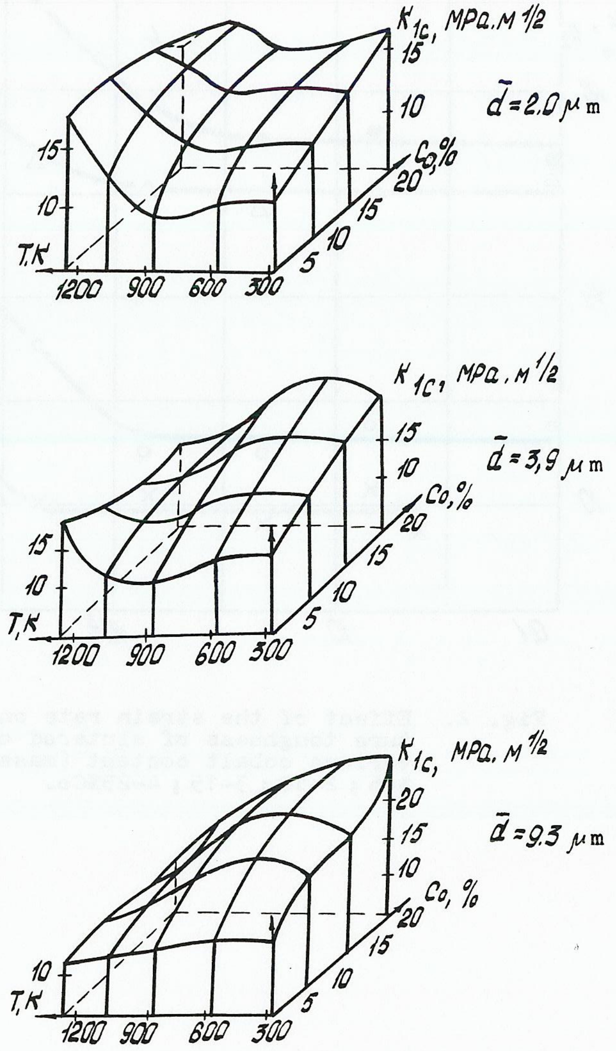

Fig. 1. Effect of Co-content (mass %) and test temperature (K) on the fracture toughness of sintered carbide with various grain sizes.

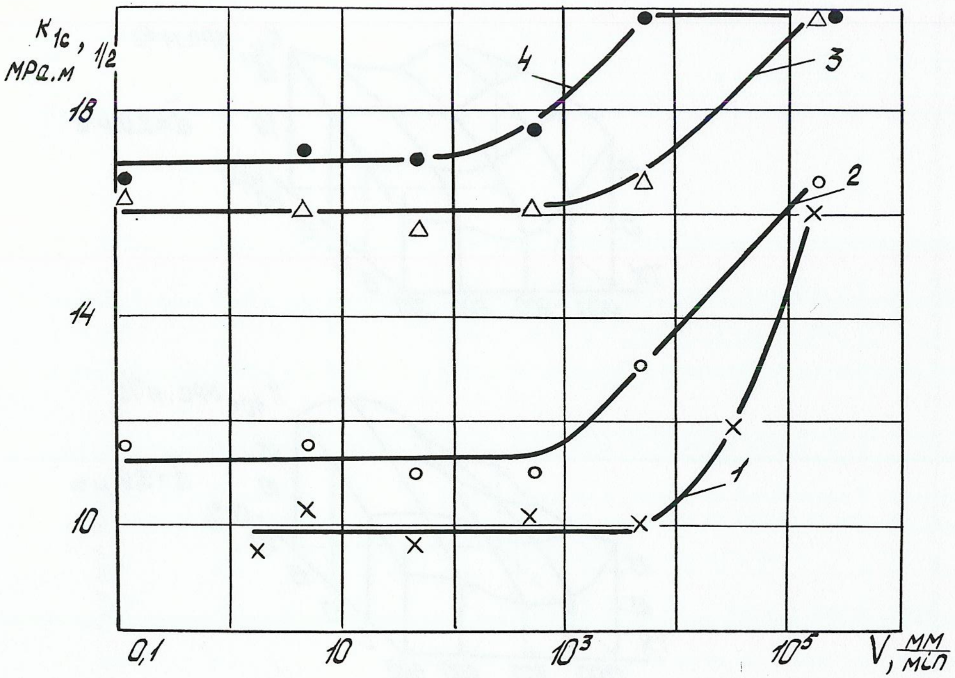

Fig. 2. Effect of the strain rate on the fracture toughness of sintered carbide with various cobalt content (mass %): 1-6 ; 2-10 ; 3-15 ; 4-25%Co.

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