THE STRENGTH AND FRACTURE OF COMPOSITE DIAMOND-BEARING TOOL MATERIALS

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ABSTRACT

The report deals with the results of theoretical and experimental studies of the strength and fracture of diamond-bearing tool composites. The account of residual stresses generated within the matrix and the diamonds embedded when cooling the composite from the sintering temperature to r.t. is of a great consequence in the proposed calculation scheme. These stresses are substantially dependent on a volumetric diamond concentration, the physicomechanical matrix properties and the phases binding conditions. The hereditary residual stresses substantially influence the strength and the fracture toughness of the material, that is why a knowledge and, in the long run, a relieving of them will make it possible to improve the composite properties as a whole.

KEYWORDS

Strength, fracture, toughness, diamond-bearing composite, residual stress, diamond inclusion, fatigue crack, diamond concentration.

INTRODUCTION

A great number of theoretical and experimental works (Brooksbank, 1969 ; 1972 ; Bock, 1975 ; Hoffman, 1980) have been dedicated to the problem of prediction of the strength of multiphase materials and the effect of thermal stresses on them. However, the prediction of the strength properties of composite materials using the basic principles of the above works is not possible at all.

The theoretical premises and the composite strength model

The composite material of this type could be described by mathematical model of stochastically reinforced bodies (Lange, 1974 ; Khoroshun, 1980). As the size of the embedded diamonds are by two orders of magnitude greater than that of matrix grains the matrix can be considered to be homogeneous.

The macroscopic thermoelastic constants for the composite material in the conformity with /6/ will have the form:

$$K^* = \langle K \rangle + C_1 C_2 K_2^2 (1 + C_1 K_2 + C_2 K_1 + \tfrac{4}{3} m)^{-1};$$

$$\mu^* = \langle \mu \rangle + C_1 C_2 \tfrac{2}{3} (C_1 \mu_2 + C_2 \mu_1 + R)^{-1};$$

$$\beta^* = \langle \beta \rangle + K_3^{-1} \beta_3 (K^* - \langle K \rangle); \qquad (1)$$

where $R = m\,(9n + 8m)\,[6\,(n + 2m)]^{-1}$;

$n = K_1 K_2 (C_1 K_2 + C_2 K_1)^{-1}$; $m = \mu_1 \mu_2 (C_1 \mu_2 + C_2 \mu_1)^{-1}$;

$K_3 = K_1 - K_2$; $\mu_3 = \mu_1 - \mu_2$;

K_i, μ_i, β_i, C_i $(i = 1.2)$ are the bulk and shear moduli, the thermal stress coefficient and the volumetric concentration of the i-th component, accordingly (diamond is indexed by 1 and matrix by 2).

The Young modulus E^*, the Poisson ratio ν^* and the linear thermal expansion coefficient α^* are expressed by the relation (1) as follows:

$$E^* = 9K^* \mu^* (3K^* + \mu^*)^{-1}; \quad \nu^* = \frac{E^*}{2\mu^*} - 1;$$

$$\alpha^* = \beta^* (3K^*)^{-1}. \qquad (2)$$

Using (1,2) and the principles described in works (Maslov, 1982 ; Majstrenko, 1982), we write down the strength criterion of the composite in the form:

$$\langle \sigma^2 \rangle_\theta - \langle \sigma^2 \rangle_M = \sigma_0, \qquad (3)$$

where $\langle \sigma^2 \rangle_\theta$ and $\langle \sigma^2 \rangle_M$ are average stresses generated in the matrix as a result of the temperature and mechanical impacts correspondingly ; σ_0 is the matrix strength.

On the basis of the corresponding criteria calculation the (4) could be given the final form:

$$\langle \sigma \rangle_c = A\,(\sigma_0 + B\,\theta), \qquad (4)$$

where $A = 3C_2 \left[\frac{K_2}{K_3 K^*} (K^* - K_1) + 2 \frac{\mu_2}{\mu_3 \mu^*} (\mu^* - \mu_1) \right]^{-1}$,

$B = - \left[\beta_2 + \frac{K_2}{C_2 K_3} (\langle \beta \rangle - 3K_1 \alpha^*) \right]$,

$\langle \sigma \rangle_c$ is the calculated strength of the composite under uniaxial compression, θ is the temperature that is uniform throughout the entire volume.

As an example of the composite strength prediction for a composite on the basis of diamond concentration data consider the material containing 400/315 μm diamond grains and having the following thermoelastic properties of components :

- diamond – $E_1 = 10.5 \cdot 10^5$ MPa, $\nu_1 = 0.1$; $\alpha_1 = 1.3 \cdot 10^{-6} K^{-1}$;
- sintered carbide – $E_2 = 6.35 \cdot 10^5$ MPa, $\nu_2 = 0{,}22$;

$\alpha_2 = 5.0 \cdot 10^{-6} K^{-1}$; $\sigma_0 = 1400$ MPa.

Figure 1 shows the strength values for the composite in question that have been obtained by testing cylinders of 10 mm in diameter under compression and the subsequent calculation on the basis of the expression (4). The dependence of the theoretically defined thermal stresses within the matrix $\langle \sigma^2 \rangle_\theta$ is also presented here. The calculation were carried out for the $\theta = -1000$ K.

The data presented bear witness that the experimental results confirm the theoretical premises and the feasibility of the proposed criterion for the strength prediction of a diamond-bearing composite. In addition, a conclusion of far-going practical consequences could be drawn that the volumetric diamond concentration should not exceed 0.31 because the thermal stress value at this concentration is practically equal to the total composite strength and at $C_1 > 0.56$ there arises a spontaneous microscopic fracture in it, even without external loading what conforms well with the production experience for the materials of this class.

The fracture toughness of the diamond-bearing composite

In addition to the above stated on the composite strength prediction based on the theory of stochastically reinforced bodies it is possible by alternating the Lange's concepts (1974) to consider the same problem using the fracture mechanics approach. It was indicated in works (Lange, 1974; Davidge, 1968) that the total composite strength is related to the energy of the material fracture, the elastic modulus and the defect size. Bearing the above structure peculiarities in mind it would be incorrect to apply the conventional approach based on the linear fracture mechanics to the evaluation of the fracture energy of the composite.

The evaluation of the crytical stress intensity factor is based in this work on the hypothesis of the piecewise continuous body, i.e. the difinition of the ultimate equilibrium of a crack interacting with a single rigid inclusion. This problem was previously solved in a number of well-known works (Berezhnitsky, 1979 ; Atkinson, 1972 ; Tamate, 1968). In those works, however, there are no solutions with allowance for the thermoelasticity, that is, without taking into consideration the hereditary stresses which, as it follows from the earlier results, are one of the decisive factors reflecting the actual composite state.

Due to the complexity of the boundary conditions of the conjugation between a diamond inclusion and the matrix in the sintered carbide and the specimen loading scheme the solution of the problem was carried out through the numeric simulation by the finite elements method of a rigion represented by a disk (10 mm in diameter) with a diametric crack near the tips of which at a distance inclusions were present (cylinders of a unitary thickness and 0.5 mm in diameter having the elastic modulus and Poisson ratio equal to those of diamond (Novikov, 1981).Due to the symmetry a quarter of the disk has been analysed,the latter was divided into 940 triangle elements and 511 grid units.

As a result of the numerical solution of the above singular problem for a crack located at various distances from an inclusion and also at the process of its growth across a diamond a dependence has been obtained for variations of the relationship between the stress intensity factor $K_I^{\wedge}$ and the stress intensity factor K_I for a homogeneous region of analogous shape but devoid of inclusions,for which an accurate solution is available (Yarema, 1976).The calculated dependence for the distance between the crack tip and the inclusion is shown in Fig. 2, whence it follows that the contribution of the inclusion into the stressed crack state could be neglected at the distance of 1.8 d. Suppose that in this case defines the distance between the tip of the crack emerging from the nearest inclusion and the inclusion located at the crack trajectory extension.On the basis of the stereological analysis of the true composite structure in question that was carried out on the television image analyser "Quantimet-720" it was possible to obtain a distribution for the relation of distances between diamonds and their diameters and volumetric concentration that could be approximated as follows:

$$\bar{\lambda} = \frac{3}{14}\cdot\frac{d^3(1-C_1)\left|\operatorname{Ln}\left(C_1+1-\pi/2\sqrt{3}\right)\right|}{(1-d)^2 C_1} . \qquad (5)$$

Taking into account the relation (1) and the data from (Erdogan, 1972) that at the interface of the phases having different moduli the ratio K_I/K_I' for the case considered is within a limit quantitatively equal to the finite ratio $E_2(1-\nu_1^2)/E_1(1-\nu_2^2)$, we can write down the dependence in Fig. 2 as follows:

$$\frac{K_I}{K_I'} = \left\{\frac{E_2(1-\nu_1^2)}{E_1(1-\nu_2^2)} + \left| e^{-\bar{\lambda}/2d} - 1\right|\right\} . \qquad (6)$$

This ratio reflects the stressed state intensification rate in the vicinity of the crack tip with the approach to the diamond inclusion and clearly reflects the contribution of the volumetric concentration of inclusions within the composite.Thus, taking into account the self-similarity conditions for the ratio obtained for various specimen loading schemes, it is possible to evaluate the fracture toughness K_{Ic}^* of the composite using known solutions of the linear fracture mechanics for continuous media with a sole correction for the presence of the finite number of inclusions located along the initial crack front and corresponding to their volumetric concentration in the composite, namely,

$$K_{Ic}^* = K_{Ic}\left(1 + C_1\cdot\frac{K_I}{K_I'}\right). \qquad (7)$$

Figure 3 shows the experimental data for the fracture toughness of the diamond-bearing composite having various diamond concentration (0 to 0.437), the grain size being 400/315 µm (the reduced diameter being 0.364 mm).The specimens have been prepared in conformity with the requirements for generally accepted SENB (single-edge notched bend)-type specimens and contained an initial fatigue crack.The tests were carried out on a mechanical installation with the rate of 0.5 mm/min at room temperature. The preliminary fracture toughness values were calculated using the solutions for the elastic case (RD 50-260-81, 1982), and are shown in Fig. 3 (the curve 1).Furthermore,the effective fracture toughness K_{Ic}^* of the composites investigated were calculated using the relationships (6) and (7) (the curve 2).As it follows from the figure, the extent of correction with the allowance for inclusions located along the front of the initial crack at C_I = 0.437 amounts to 17.3 %. By approximation of the curve 2 by the following simple functions

$$K_{Ic}^* = K_{Ic}^M\left[1 + \frac{1}{2}\left(\frac{K_I}{K_I}\right)\sin\frac{41}{5}C_1\right] \qquad (8)$$

(K_{Ic}^M is the fracture toughness of the sintered carbide matrix) in this particular case we find that the K_{Ic}^* values attain their maxima at the volumetric diamond concentration of 0.15. This agrees with the predictions developed in (Claussen, 1976). When the volumetric diamond concentration is over 0.37 the K_{Ic}^* values become less than K_{Ic}^M which is in the practical aspect quite undesirable.

The expression (8) makes it possible to conduct a preliminary fracture toughness prediction for the composite of the above type using the matrix fracture toughness and the volumetric diamond concentration data that gives to the industrial engineers a certain freedom of choice when developing composites in question.

It should be noted that the conducted evaluation of the effective fracture toughness value K_{Ic}^* of the composite is of a partial nature as the K_I/K_I' ratios were obtained for the boundary conditions of a real composite. But when calculating the function (7) for the other boundary conditions of the phases conjugation it becomes possible to extend this value on other composites reinforced with dispersed particles.

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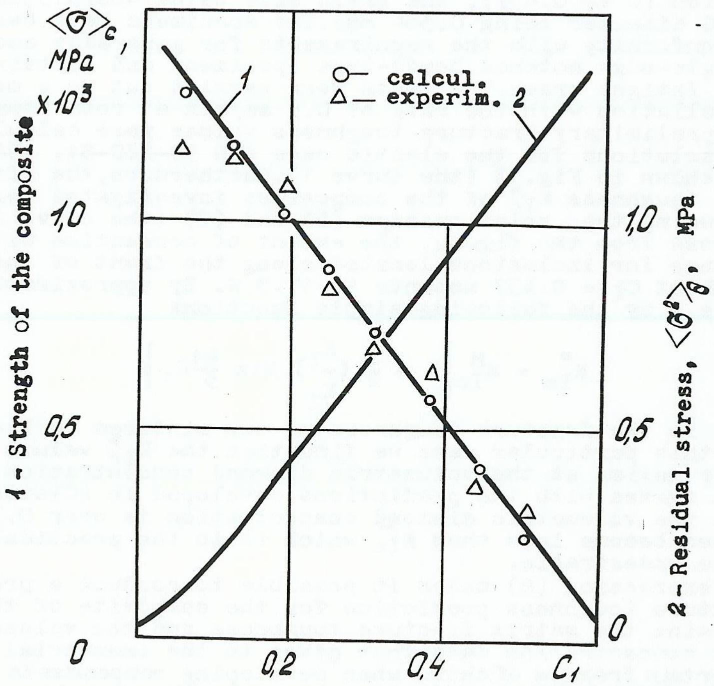

Fig. 1. Composite strength values v. volumetric diamond concentration C_1.

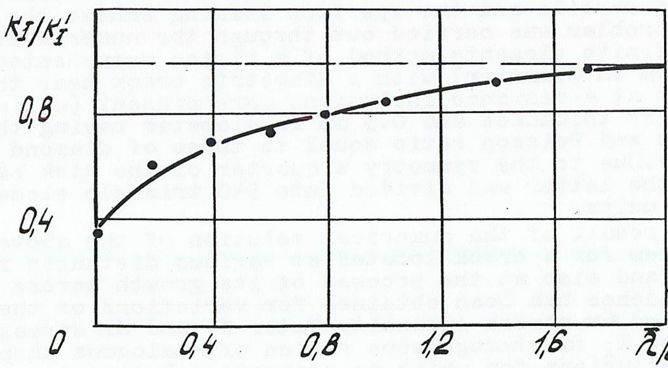

Fig. 2. Change of the dimensionless stress intensity factor as a function of distance between the crack tip and the diamond boundary.

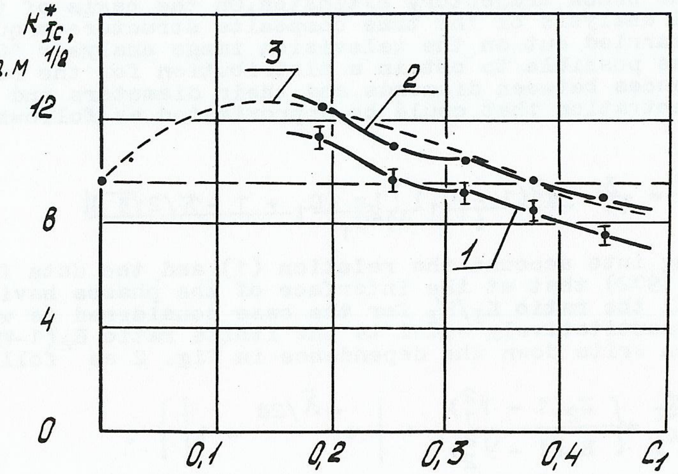

Fig.3. Dependence of the fracture toughness on the diamond content (1-experiment; 2-calculation K^*_{Ic} using the equation (7); 3-prediction of K^*_{Ic} according to the equation (8)).

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