COMPUTER-AIDED SIMULATION OF CRACK PROPAGATION IN CUTTING TOOLS

V.N. Kulakovskiy*, G.I. Chepovetskiy*, A.L. Maistrenko*

A procedure of computer-aided simulation of crack extension in a plane problem under combined stress conditions using the FEM is described. The procedure is intended to evaluate the residual durability of cutting tools made from brittle materials from fatigue failure diagrams. It is illustrated with the calculation of hard metal milling cutter service life.

INTRODUCTION

The present work deals with fracture of products made from cemented carbides and superhard materials (SHM). Tool-making industry is the main field of application of the mentioned materials. Cutting tools, drills, milling cutters, etc. used for high speed and precision machining are being tipped with cemented carbides and SHM because of their high wear resistance and relatively high heat resistance. The efficiecy of such tools, however, is restricted with low resistance of these materials to crack propagation (fracture toughness K_{Ic} of cemented carbides and superhard materials of the grades most applicable in tool-making industry ranges from 2 to 10 MPa$\sqrt{m}$). The materials under study show a tendency to brittle fracture which is responsible for relatively small sizes of critical defects causing extension of instable main cracks. It should be noted that cutting tools being in service are effected by a variety of thermomechanical loads, as a result of which a crack grows under combined stress conditions, i.e. the crack extension is defined by a mixed type of straining.

* Institute for Superhard Materials of the UkrSSR Academy of Sciences, Kiev, USSR

CALCULATION PROCEDURE

A design and experimental procedure is developed to measure strength and durability of cemented carbide and SHM tools in view of crack-like defect growth in the materials.

To construct an extending crack trajectory in the tool the FEM calculations of stress-strain state were used (1,2). Computer packaged programs developed allow computer-aided simulation of infinitesimal crack extension. The construction of a crack trajectory in materials under study involves a number of methodical features. This is related, in the first place, with small crack dimensions and with relatively short subcritical crack length. Therefore, the most general method for the crack growth simulation was chosen which involves the reconstruction of the network of triangular finite elements at each of the crack length increment, as other methods (e.g. double noding technique or equating to zero the mechanical constants of the crack-tip material) fail as they require preliminary knowledge of the crack trajectory. To shorten calculating time as well as to raise flexibility of the computing technique a special region was used in simulation which comprises both a subregion surrounding a cracked zone and a transition subregion which allows matching of the region with a high concentration of finite elements around a crack with the rest part of a construction (Figure 1) (3,4). The value of the finite elements concentration at the crack tip is given when inputting initial data and may change arbitrarily. There are eight singular triangular finite elements at the crack tip. When calculating the stress state these finite elements are given from functions which take into account stress field features at the crack tip (5). This offers the possibility of using the developed technique for any calculating procedure of FEM in which routine linear finite elements are used.

Crack extension angle, θ_o, was measured from the maximum tensile stress criterion which is the most acceptable one for the materials under study (6).

$$\theta_o = 2 \operatorname{arctg} \frac{1 - \sqrt{1 + 8\lambda^2}}{4\lambda} \quad \ldots\ldots\ldots\ldots (1)$$

K_I and K_{II} were calculated near the crack tip by displacement field (7):

$$U_i = \frac{1}{2G}\sqrt{\frac{r}{2\pi}}\left[K_I F_i(\theta) + K_{II}\varphi_i(\theta)\right] \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

The occurrence of the critical state of a construction is defined from the comparison between the effective K_{Ief} and the experimental critical K_{Ic} or K_{fc} of the material depending on the service conditions for the tools.

RESULTS

The reliability of SIF determination procedure was verified by solving a test example about the diametral compression of a disk specimen containing a central crack (8). The orientation of the initial crack at various angles about the load-axis permits calculation of K_I and K_{II} at a variety of their combinations in the range of the angle variation from 0° (K_{II}=0) to 27° (K_I =0), the error of SIF calculation was 8%.

The procedure developed was used to analyze the fatigue fracture of working elements of a combined worm milling cutter with throw-away tips from 15TiC-6Co-79WC alloy (mass-% are given). Cutting forces were measured in gear cutting in a steel spline shaft and amounted P_z = 1230 N and P_y = 320 N. Pre-calculation of a crack-free milling cutter indicates that maximum tensile stress occurs at the front face of the tool, outside its contact region. The maximum tensile stress zone was pre-cracked, the crack size being 0.1 mm which is an order of magnitude higher than that of carbide grains and, consiquently, the problem may be solved using linear fracture mechanics.

K_{Ief} measurements at the first step of calculation showed that $K_{Ief} > K_{th}$ and, therefore, the calculation permits evaluation of the residual life of the tool design, K_{Ief} variation as a function of crack growth is given in Figure 2. The calculated critical crack length, l_{fc}, for given critical conditions is 0.245 mm. Integrating the equation which describes the diagram of a fatigue crack growth we evaluate the residual life of the milling cutter

$$N = \int_{l_{th}}^{l_{fc}} f\,(K_{Ief})\,dl \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

which equals to 2388 cycles, i.e. 8-min-service of the milling cutter.

CONCLUSIONS

The software versatility which is defined by the feasibility of predicting cracks of arbitrary dimensions and at various angles of their extension, as well as the use of triangular singular elements enable studies of fracture micromechanisms for cemented carbides and superhard materials nonhomogeneous in structure as well as measurements of the structural strength of tools.

The development of methods for evaluation of cutting tool durability will offer the possibility to choose the optimum tool design and service conditions to ensure reliability of working elements which is of particular importance when using them in flexible manufacturing systems.

SYMBOLS USED

θ_o	= crack extension angle
K_I, K_{II}	= stress intensity factors (MPa$\sqrt{m}$)
λ	= K_{II}/K_I
G	= shear modulus (GPa)
r	= distance from the crack tip (m)
$F_i(\theta)$, $\varphi_i(\theta)$	= trigonometric functions
U_i	= displacement (m)
K_{th}	= threshold stress intensity factor (MPa$\sqrt{m}$)
K_{Ief}	= effective stress intensity factor (MPa$\sqrt{m}$)
K_{Ic}, K_{fc}	= critical stress intensity factors (static and fatigue) (MPa$\sqrt{m}$)
l_{fc}	= critical crack length (m)
l_{th}	= threshold crack length (m)

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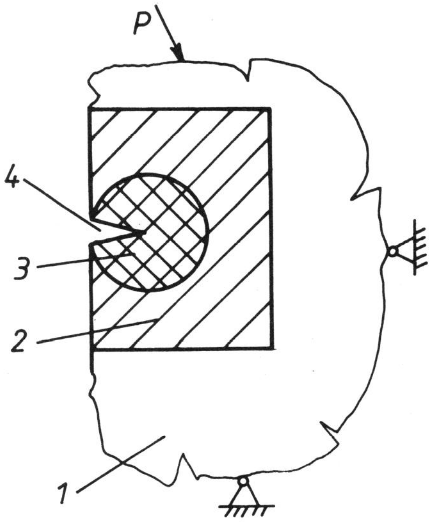

Figure 1 Utilization of the special region for calculating a crack-containing body

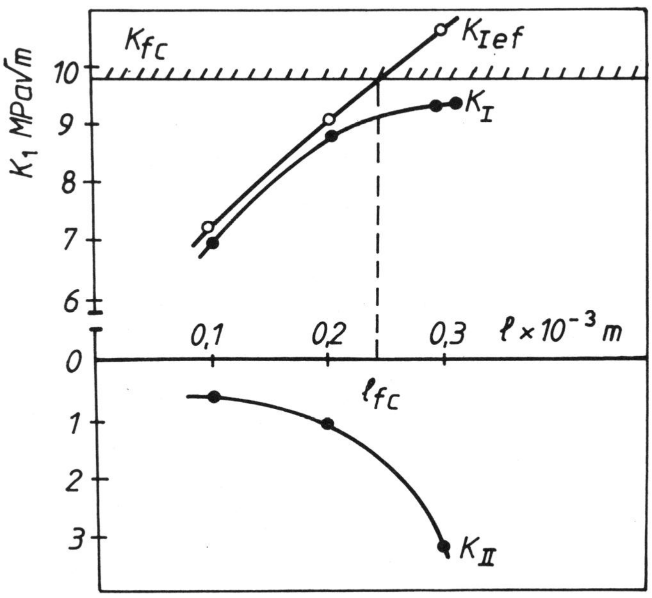

Figure 2 The change of the stress intensity factor with the crack growth in a tool