EXPERIMENTAL AND NUMERICAL CRACK GROWTH IN A SPECIAL GEOMETRY

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Summary Experimental evidence on three-dimensional crack propagation is needed for a better understanding of the local mechanisms around the crack front in a motor grain geometry. The crack propagation and turning processes suggest that the role of the shear modes is important in the initial stages of growth and a two-dimensional plane strain finite element simulation is used to compare the SIF values as trying to assess the efficiency of such a simplified procedure.

INTRODUCTION

The desire to establish a three-dimensional framework for use in analyzing problems of stable mixed-mode crack propagation has received lately a considerable attention. The study of predicting crack paths under the most general possible hypotheses (three dimensions, arbitrary geometry of the body and of the crack, arbitrary loading) is an ambitious objective. Recently, Leblond [1] and Leblond, Lazarus and Mouchrif [2] established formulae which specify the general functional form of the successive terms of the expansions of the SIFs along the front of the extended crack and, as they underline, the formulation of the propagation criterion is an open problem only in the presence of mode III. Therefore, in a mode I+II situation, the widely accepted "principle of local symmetry" of Goldstein and Salganik [3] receives a general recognition. In fact, for the two-dimensional problem, Cotterell and Rice [4] presented an analysis for slightly curved or kinked cracks and accounted for the role of mode II in crack turning. Also Rubenstein [5], in analyzing test results, concluded that sharp kinks likely occur only in very brittle materials and that, more commonly, the change in direction during the crack growth is more of a gradual turning than a kink. In numerical experiments the FRANC3D code uses new concepts with a model that allows for the implementation of 3-D crack growth mechanics [6] with the support of both finite and boundary elements. Keeping in mind such beneficial developments, one should emphasize that for a specific geometry and loading we may obtain various experimental crack paths which are dependent on the local position of the initial crack, as any deviation from "symmetry" influences the future crack trajectory.

This study emphasizes some practical aspects which should be considered in the finite element modelling. One should analyze carefully results obtained from experimental observations, especially when a 3-D model is in view. A preliminary comparison with a FRANC2D/L analysis [7] gives higher numerical normalized SIFs than the experimental ones obtained at maximum depth penetration.

MODEL CONFIGURATION AND 3-D EXPERIMENTAL PROCEDURE

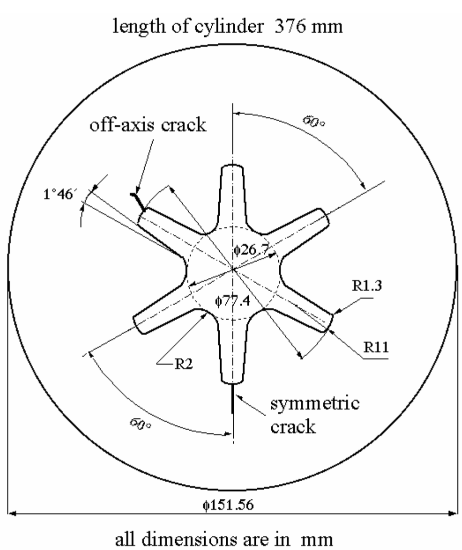

Fig. 1. Tested model geometry.

The geometry of the model studied here is shown in Fig. 1 and represents a motor grain configuration [8]. A model contained two starter cracks, a *symmetric* and an *off-axis* crack separated by an uncracked fin to avoid any interference. The *off-axis* crack (located at the coalescence of the two radii of 1,3 mm and 11 mm) can be inclined (as shown in Fig. 1) or straight-in – parallel with the fin axis. After inserting the starter cracks by striking a shaft with a blade at the end held normal to the inner fin surface, the models were capped with RTV rubber caps which were glued with PMC-1 adhesive and were subjected to the stress freezing cycle under internal pressure. The cracks were grown under internal pressure above critical temperature to desired size, after which the pressure was dropped to about 0,04-0,05 MPa and stress freezing was completed. After cooling, thin slices (around 1 mm thickness) were removed normal to the crack front and analyzed at maximum crack depth and in certain locations along the crack front, finally obtaining the values of the normalized stress intensity factors by using a two parameter algorithm valid within the linear elastic fracture mechanics (LEFM) constrains. Thus optical data (isochromatic fringes) can be converted into Mode I and Mode II SIFs, if the last one exists. All symmetric cracks remained in the plane of the axis of symmetry and grew as semi-elliptic cracks. If the cracks were off-axis straight-in parallel to the fin axis but (Fig. 1), a slight initial crack plane misalignment is possible due to the position of the blade or due to its bending after striking it, but the crack grows quickly by regaining its symmetry.

Studies of 11 tests on the motor grain geometry [8, 9] covered cracks of projected a/c values (crack depth/half length of crack in fin tip surface) of 0,5 to 0,9 and a/t values from 0,2 to 0,6 (t = 37,08 mm is the cylinder wall thickness at fin tip). It appears that both SIF values and crack geometry during growth are quite variable due to shear modes for the off-axis inclined cracks. On the other hand, the symmetric cracks situated on the fin axis are quite predictable in their growth, as they tended to grow much more readily than the off-axis crack, always in the plane of the fin axis. It was found that the substantial delay in crack growth for the inclined cracks is also due to some initial misalignment of the blade with respect to the normal to the fin surface that is corrected by the turning of the crack as it grows and eliminates the shear modes.

NUMERICAL 2-D SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS

A FRANC2D/L plane-strain finite element analysis was performed on half model using triangular 6-node elements. The mesh has 988 elements with 2153 nodes. A refined mesh was used around the notches. The material constants used in the analysis were the same as of the photoelastic material.

The initial numerical study was to find the SIFs versus crack length for three different configurations: symmetric crack, off-axis straight-in crack and off-axis inclined crack. The remeshing by delete and fill algorithm was used, which requires: to delete a group of elements in a region around the crack tip, then the crack is extended into this region, singular elements are placed around the crack tip, [4]. The stress intensity factors were obtained using the Modified Crack Closure Integral method. A study of crack propagation of off-axis cracks was carried on. The numerical prediction of the direction of crack trajectory was based on the maximum principal stress theory.

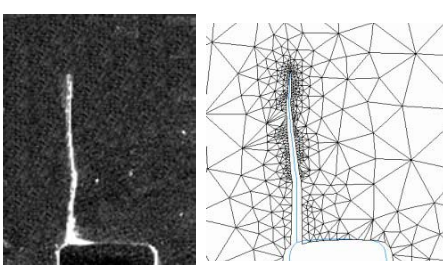

Fig. 2. Experimental off-axis straight-in crack and numerically simulated crack growth.

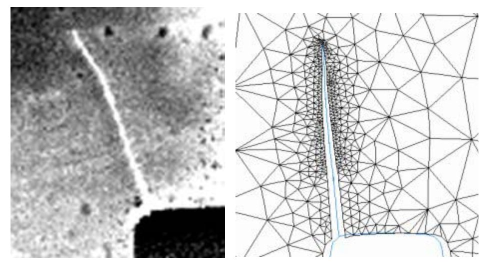

Fig. 3. Experimental off-axis inclined crack and numerically simulated crack growth in early stages.

The crack in Fig. 2 remains straight after some minor rearrangements, and Mode I is present. For the off-axis inclined crack, this one turns on a curved path (note path of mid-point at left of Fig. 3 in the experimental test), and after this limited amount of growth some Mode II as well as Mode I remained. Presumably, with further extension, the crack will straighten out and eliminate Mode II. The numerical simulation shows a rapid change of direction and presence of Mode I. At maximum depth all the experimental 3-D SIFs were smaller than the numerical 2-D corresponding values.

CONCLUSIONS

Off-axis cracks are retarded in growth by shear modes (II or II and III) and eventually gain their local and global symmetry. For three-dimensional numerical simulations mode III has to be considered. For two-dimensional simulations, one should remember that any local imperfections of crack location and loading will change at the beginning the crack trajectory, but later Mode I will be dominant.

Acknowledgements

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