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13. ABSTRACT *(Maximum 200 words)*

The present investigation yields significant results in controlling crack formation in transparent ceramic crystals (LiF, MgO, ZrO_2, and Al_2O_3), as well as in amorphous solids (fused quartz and PMMA) through a series of systematic experimentations and theoretical modeling of the laser-solid interaction. The impact of such success is the extension of another dimension in the investigation of many mechanical and physical problems from the current two-dimensional simplifications to three-dimensional phenomena. The critical control of the formation of internal cracks allowed us, for the first time, to examine the interaction of three-dimensional cracks in PMMA and fused quartz, and to validate the general predictions of the available theoretical analyses. We also studied the interaction of a penny-shaped internal crack and dislocations in lithium fluoride single crystals, a phenomenon currently under renewed extensive investigation for fundamental understanding of the ductile vs. brittle behavior of solids.

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LASER-INDUCED CONTROLLED FLAW TESTING IN CERAMICS

Final Progress Report

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September 30, 1996

U. S. Army Research Office

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1. STATEMENT OF THE PROBLEM STUDIED

The present program, "Laser Induced Controlled Flaw Testing in Ceramics," started April 1, 1991, and was completed on August 30, 1996. The objective of this program was to understand and control the fracture characteristics and kinetics in the interior of a ceramic crystal. In the later stages of investigation, the study was extended to amorphous solids, in particular, glasses and polymers.

The present investigation provides significant results in controlling crack formation in transparent ceramic crystals (LiF, MgO, ZrO_2, and Al_2O_3), as well as in amorphous solids (fused quartz and PMMA) through a series of systematic experimentations and theoretical modeling of the laser-solid interaction. The impact of such success is the extension of another dimension in the investigation of many mechanical and physical problems from the current two-dimensional simplifications to three-dimensional phenomena. The critical control of the formation of internal cracks allowed us, for the first time, to examine the interaction of three-dimensional cracks in PMMA and fused quartz, and to validate the general predictions of the available theoretical analyses. We also studied the interaction of a penny-shaped internal crack and dislocations in lithium fluoride single crystals, a phenomenon currently under renewed extensive investigation for fundamental understanding of the ductile vs. brittle behavior of solids. Finally, we investigated the thermal healing phenomenon of internal cracks in lithium fluoride single crystals, as compared with the conventional investigations of surface cracks.

2. SUMMARY OF IMPORTANT RESULTS

a) Controlled formation of internal cracks in transparent solids

The dynamic stress fields caused by finite, instantaneous heat sources within a region of spherical and ellipsoidal shapes embedded in an infinite, isotropic elastic medium were analyzed. Based upon the theoretical results obtained and extensive experimentations, a laser technique composed of a cylindrical lens system has been developed. This technique provides the controlled generation of regularly-shaped internal cracks in both crystalline and amorphous transparent solids such as lithium fluoride (LiF), magnesium oxide (MgO), fused quartz (SiO_2), polymethyl methacrylate (PMMA), etc. In crystalline materials, the laser generated crack system consisted of cracks on all or some of the equivalent cleavage planes, and hardly on a single cleavage plane. In contrast, a single well-defined planar crack, close to an ellipse with nearly equal major and minor axes, can be formed in amorphous materials. The size and orientation of these cracks are controllable through the adjustment of laser energy and the optical system. It was found that the physical mechanisms responsible for laser energy absorption, inherent optical effects (particularly spherical aberration), the purity of the recipient material, and the geometry of the optical focal spot, determine the ultimate shape and orientation of the internal cracks. Some of the findings have been and will be published (See paper no. 3).

b) Experimental evaluation of three-dimensional crack interaction

The interaction of two internal cracks, produced by laser irradiation, with typical configurations such as coplanar, parallel, "T" and "H" cracks in PMMA, were experimentally investigated under tension. The results validated the general predictions of the available theoretical analyses for coplanar and parallel cracks, i.e., an enhancing effect and a shielding effect, respectively. On the other hand, the experimental and theoretical results showed a significant discrepancy in the actual value of the interaction strength for parallel cracks, with the experimental results indicating a much weaker interaction between the two cracks. For the T and H crack configurations where no theoretical analysis is available, the presence of the delamination cracks decreased the material strength, indicating an enhancing effect of the crack interactions similar to the case of coplanar cracks. The fracture morphology revealed a temporary crack arrest of the main crack by the delamination cracks. These results indicated that the effectiveness of crack retardation by delamination cracks (a toughening mechanism) is significantly weaker in the three-dimensional crack configuration than in the two-dimensional case. (See papers no. 1 and no. 2).

The interaction of "complex cracks" (or flaws) composed of numerous fragmentary cracks in coplanar and parallel configurations in fused quartz has also been investigated under compression. Surprisingly, the interaction strength between two flaws for these two configurations was found to be comparable to that between two cracks. The Griffith fracture criterion was also found applicable to this system. This finding validates the common practice in failure analysis of estimating the failure stress from the flaw size on the fracture surface. (See paper no. 4 and Li's dissertation).

c) Observation of new characteristic fracture features by internal cracks

A new characteristic fracture feature associated with the fracture of internal cracks in SiO_2 within a certain range of crack size was identified for the first time. This fracture marking was caused by a discontinuous change of the stress intensity in the dynamic process of the internal crack propagation. Along with other typical markings in brittle fracture (fracture mirror, mist, hackle, and branching), this characteristic marking can be used to identify the origin of the fracture and to estimate the size of the defect that causes fracture. The new result has been published (papers no. 4 and no. 5).

d) Thermal healing of internal cracks

A unique quantitative analysis of thermal healing of laser-induced internal cracks was made for LiF crystals without environmental contamination. It has been demonstrated that the evolution of crack morphology and healing kinetics are different from those of the surface cracks (subjected to environmental effects). In addition, hhree distinct stages of healing have been identified, and the healing process of internal cracks was controlled by volume diffusion of fluorine ions. (See paper no. 7).

e) Effectiveness of dislocations in hindering 3D crack propagation

The fracture study with lithium fluoride single crystals revealed that significantly less dislocations were associated with the crack propagation in the case of internal cracks than those associated with two-dimensional surface cracks. The stress intensity factor calculated from the fracture of internal {100} cracks was smaller than that calculated from two-dimensional surface cracks with crack front along the <100> directions. This result is consistent with the fact that the number of available slip systems which either contain or intersect the crack front changes along the crack front of three-dimensional cracks. The present study clearly demonstrated that the development of theoretical models of ductile vs brittle behavior should be based on the three-dimensional characteristics of materials rather than on the two-dimensional simplifications. These results will be reported shortly (paper no. S1).

3. PERSONNEL

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Prof. John P. Huennekens, Co-Principal Investigator

Graduate Students:

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Degrees conferred:

Ph. D. - Y.Z. Li (1996)

Ph. D. - B. Zhou (1995)

4. PUBLICATIONS

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7 Z. Wang, Y.Z. Li, M.P. Harmer, and Y.T. Chou, "Thermal Healing of Laser-Induced Internal Cracks in LiF Single Crystals," J. Am. Ceram. Soc. 70, 1596-1602 (1992).

Other Technical Article in Preparation:

S1 Y.Z. Li and Y.T. Chou, "Orientation Dependence of Stress Intensity Factor in LiF," to be submitted to the Materials Science and Engineering A, 1996.