Numerical Study of Damage Propagation and Dynamic Fracture in Sapphire

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NUMERICAL STUDY OF DAMAGE PROPAGATION AND DYNAMIC FRACTURE IN SAPPHIRE

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Sapphire, a single crystal of aluminum oxide, is of interest to U.S. Army and one of the candidate materials for use as the hard strike face of a transparent laminated armor. Strassburger et al studied monolithic single crystal sapphire plates (100 mm x 100 mm x 10 mm) in crystallographically controlled directions, such as the (0001) basal plane, the r-plane (10 \(\overline{1}\)) rhombohedral plane and (10 \(\overline{\overline{1}}\)) prismatic plane, impacted at about 450 m/s with both steel solid cylinders and spheres. The edge-on impact (EOI) ballistic behavior of these plates is simulated using the non-linear AUTODYN commercial package by using three-dimensional, 180 degrees (reflective) modeling and simulation. This study reports on the ability and the modification of existing strength and failure material models of Al\(_2\)O\(_3\) to be used as sapphire models for duplication of the experimental fracture and wave propagation in sapphire of different crystal orientation with respect to the line of impact.

INTRODUCTION

Transparent armor systems using ceramics as the striking face have been explored since the early 1970’s because they potentially provide superior ballistic protection to conventional glass based transparent armor systems [1]. The U.S. Army has invested heavily in the development of next generation materials, including ceramics, for military systems [2]. The result of the on-going investments is a critical understanding of ceramics strengths and weaknesses for military platforms.

Among the potential ceramic materials considered for armor — sapphire, edge-form-growth sapphire, magnesium aluminate spinel, aluminum oxynitride — one was selected for the current pursuit, magnesium aluminate spinel (MgAl\(_2\)O\(_4\)). Although single impact testing has shown small variations in ballistic efficiencies (<10%) of individual ceramics, in the case of multi-hit performance, all of the ceramics are effectively equivalent [3].
Strassburger et al [4] studied with the aid of using a Cranz-Schardin high speed monolithic single crystal sapphire plates (100 mm x 100 mm x 10 mm) in crystallographically controlled directions impacted at about 400 m/s with both steel solid cylinders and spheres. Thorough understanding of the various parameters influencing the projectile penetration mechanism is necessary to optimize the performance of multi-layer, ceramic faced transparent armor. The high ballistic resistance is dependent upon the projectile deformation and erosion, which in turn depends on the damage and failure mechanisms in the target materials. Since part of transparent armor consists of brittle materials, the fragmentation of the ceramic and glass layers plays a key role in the resistance to penetration [4, 5, 6].

Fountzoulas et al [4] used computational modeling to predict the effects of defects on failure in ceramic materials. The increasing density of flaws, simulated as cuts or slits of various equal area shapes, resulted in a significant reduction in apparent local stiffness in the composite laminates and significant changes in the virtual performance of the laminate stacks. According to the study, the surface grooves represented only a 2% reduction in the materials mass in the samples, yet they resulted in 7% reduction in performance. Internal defects resulted in less performance reduction, with the elliptical flaw causing 3.5% reduction in performance. Overall, the report showed that the presence of surface flaws and defect location relative to impact site were more detrimental to performance of spinel than internal defects (Fig. 1).

Finite element modeling has progressed substantially the ability to predict failure of materials under extreme dynamic loading conditions. One of the limitations of predictive models is the lack of a complete dynamic materials properties database, which is needed for each of the materials in the simulations. To compensate for parameters whose dynamic values were extrapolated from their static or quasi-static properties, baseline experiments are often used to recalibrate the static models at higher rate [5, 6]. However, the recalibration method of modeling lacks many of the physical properties and failure mechanisms associated with real-world materials. Therefore, recalibrated models often lack the ability to predict within statistical error future failures over any substantial ranges due to the existence of defects, and materials substitutions often lead to new calibration requirements. The desired approach is to validate a fully characterized materials database with one calibration model, and subsequently apply the model to modified designs. However, despite its apparent problems, recalibration of existing materials models has been proven to be an effective tool in the hands of the modeler by minimizing the number of simulation iterations and resulting in more accurate predictions. Regardless of methodology, when robust models are created finite element tools can be applied effectively to reduce the variability between impact tests and can be used to validate designs with fewer experimental failures[6].

The objective of this paper is to study the capability of the commercial non-linear software AUTODYN [8] to duplicate the experimental results for future cost savings.

**EXPERIMENTAL**

Experimental details are presented in ref [4]. An Edge-on Impact (EOI) test method coupled with a high speed Cranz-Schardin camera, with frame rates up to
107 fps, has been developed at the Fraunhofer- Institute for High-Speed Dynamics, EMI, to visualize damage propagation and dynamic fracture in structural ceramics. Details of the experimental setup [4] are shown in Figures 1 and 2. Impact tests at approximately equivalent velocities were carried out in transmitted plane (shadowgraphs) and crossed polarized light. Both steel solid cylinder (mass 127 g, diameter 30 mm) and spherical impactors (mass 39.1 g, diameter 15.9 mm) have been used at a velocity of $\approx 450$ m/s on 100 mm x 100 mm x 10 mm plates.

Table I shows a summary of the EOI test performed. Crystallographic details are shown in Fig. 3.
TABLE I. EOI TEST MATRIX [4]

<table>
<thead>
<tr>
<th>Config. #</th>
<th>Impact Direction</th>
<th>Large Surface</th>
<th>Projectile</th>
<th>EMI Test #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>a-axis (parallel)</td>
<td>c-plane</td>
<td>sphere</td>
<td>17074</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cylinder</td>
<td>17071</td>
</tr>
<tr>
<td>2)</td>
<td>a-axis (parallel)</td>
<td>r-plane</td>
<td>sphere</td>
<td>17075</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cylinder</td>
<td>17069</td>
</tr>
<tr>
<td>3)</td>
<td>c-axis (parallel)</td>
<td>a-plane</td>
<td>sphere</td>
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<tr>
<td></td>
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<td></td>
<td>cylinder</td>
<td>17070</td>
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<tr>
<td>4)</td>
<td>c-axis (perpendicular)</td>
<td>a-plane</td>
<td>sphere</td>
<td>17077</td>
</tr>
<tr>
<td>5)</td>
<td></td>
<td>Edge surface</td>
<td>sphere</td>
<td>17359</td>
</tr>
</tbody>
</table>

Figure 3. Sapphire (α-Al2O3) crystal mineralogical nomenclature and Miller-index notation from Schmid and Harris [7]

RESULTS

Modeling

The EOI ballistic behavior of a target geometry that consisted of sapphire plate, impacted by a sphere and cylinder projectiles respectively was simulated using the non-linear ANSYS/AUTODYN commercial package [8]. The modeling of the target consisted of a sapphire plate, 100 mm x 100 mm x 10 mm. The projectiles applied in the models were a 4340 steel spheres and cylinders of identical geometry to the actual projectiles used in the EOI experiments. The numerical modeling was carried out in three dimensions (3D). Reflective symmetry (180º) was used. Only configurations 1 and 2 (EMI tests 17075, 17071, and 17075) (Table I) were modeled and simulated. In particular, the 17075 test was simulated by an oblique impact on the edge of the target at an impact angle of 32.4 º with respect to the Z-axis of the plate (long axis of the edge of the plate). The impact velocity was 453 m/s.

Smooth particle hydrodynamics (SPH) and Lagrange solvers were used. Sapphire equation of state (EOS) and strength and failure material models were not available in the AUTODYN materials library. The existing in the library Al2O3 material models were modified according to certain values such as density and tensile strength of the sapphire in the open literature, and they used for the modeling and simulations. The $K_{IC}$ toughness and cleavage energy of configuration
2 (r-plane, Fig. 3) were obtained from reference 4 as 2.38 MPa m$^{1/2}$ and 6.45 J/m$^2$ respectively. The sapphire plate was discretized with SPH and Lagrange solvers. The element size for the Lagrange solver was 0.5 mm; and he particle size for the SPH solver 0.5 mm. The steel projectiles were discretized by SPH only with particle size of 0.5 mm.

Simulations using SPH solver for the plate were unsuccessful for impact velocities greater than 200 m/s (Fig. 4a and 4b). Simulations with impact velocities greater than 250 m/s resulted in bulk failure of the target, which was not observed in the experiments. Various attempts to modify various parameters of the strength and failure models of sapphire, such as the parameters of the intact and failed material models and by varying the hydro tensile limit (HTL) of the sapphire from 0.5 to twice its published value in the AUTODYN library resulted again in the bulk failure of the sapphire.

Simulations using Lagrange solver were successful in cracking the sapphire plate without bulk failure at the experimental impact velocity of 453 m/s. The sapphire was modeled using a polynomial equation of state (EOS), and Johnson-Holmquist (JH2) strength and failure models with or without crack softening [8]. The projectile steel was modeled using a linear EOS and Johnson-Cook (JC) strength and failure materials models [8].

**TEST: CONFIGURATION 1**

**Sphere Impact**

Figure 5 shows the experimental data (a) and the simulation results (b) – (d) from the impact of a steel sphere on the edge of a sapphire specimen at 453 m/s, parallel to a-axis (large surface (0001) plane. The simulated cracking shown in figures 5b was obtained by using the sapphire strength and failure models from the AUTODYN library. The simulated cracking shown in figures 5c and 5d was obtained by decreasing the hydro tensile limit to half the value in AUTODYN library and to introducing principal stress failure criterion with crack softening respectively. Decrease of the hydro tensile limit (fig. 5c) results in higher crack density when compared to as is (fig. 5b) and principal stress failure with crack
softening criterion (fig. 5d). The first simulated cracks appeared immediately after impact, cutting a cone with an angle ranging from about 120º (5b and 5c), which also was observed experimentally (fig. 5a) [4], to about 160º (fig. 5d) into the specimen. After about 2 μs simulated time a crack appeared to propagate straight into the impact direction, compared with a similar experimentally observed central crack at about 2.7 μs [4]. However, after 4 μs simulation time the simulated
cracking (fig 5b-5d) was different than the experimentally observed. (5a). While the simulation showed many individual cracks propagating along many directions into the sapphire target, experimentally the cracks appeared as broader cracks propagating in certain directions. Cone cracks and individual cracks branching off was observed experimentally and in simulations. It is the author’s believe that finer element mesh would have resulted in broader cracks, similar to the experimentally observed ones. The average simulated crack propagation velocities varied between 4200 m/s to 5500 m/s compared to the experimentally measured of 4590 m/s to 4934 m/s.

Cylinder Impact
The crack propagation experimentally and in simulation did not propagate along certain directions. According to Strassburger [4] the fracture due to steel cylinder impact exhibited many similarities to the fracture pattern observed with the polycrystalline transparent ceramic. The simulations showed that the crack formation starts along the edge of the projectile, where the shear stresses dominate (fig. 6a), which was also observed experimentally (fig. 6a). After 3 μs simulation time, while the central semicircular crack zone continuous propagating, a plethora of cracks evolves and propagates in any direction into the sapphire. The average speed of the fracture front in the first 4 μs was estimated to be about 8750 m/s compared to the measured speed of 8434 m/s [4].

Figure 6. a) Experimental Data: test # 17071 from impact with steel cylinder; (b); AUTODYN library strength and failure material models
TEST: CONFIGURATION 2

Sphere Impact

In this test, the sapphire plate was impacted with a steel sphere, parallel to the a-axis [large surface of plate r forming and angle with the a-plane of 32.4º (fig. 3)]. An oblique impact at an angle of 32.4º with the z-axis of the edge at 453 m/s speed was used to simulate the experimental impact. Two main simulated cracks were initiated at an angle of ±15º with the a-axis (fig. 7b and 7c), compared to the experimentally measured ±37.5º. The simulated black zone ahead of the projectile was much smaller than the experimentally observed zone. The simulated initial cracks after 6 μs branched off in two directions, parallel to and about ±30º to a-axis. After 10 μs cracks B and C continued branching off. The use of principal stress

Figure 7. a) Experimental Data: test # 17075; (b) AUTODYN library strength and failure material models; (c) Principal stress failure and crack softening.
failure and crack softening resulted in smaller crack density compared to using the AUTODYN strength and failure material models, as shown in fig. 7c and 7b respectively. The simulated cracking was different than the experimental one. This may be attributed to the smaller energy absorbed by the large r-plane due to the oblique impact, which resulted in smaller crack density.

Figure 8 and figure 9 show the experimental and simulated path time histories respectively. The slope of the trendline of the simulated path-time history multiplied by 1000 gives the speed of crack A as 5650 m/s (Fig 9), compared to the speed of 4949 m/s of crack A of the experiment #17075.

Figure 8. a) Nomenclature of fracture b) Bulk damage and cleavage controlled crack velocities in test # 17075

Figure 9. Path-time history of simulation impact of test 17075

\[ y = 5.6508x - 8.0733 \]
CONCLUSIONS

Simulation of selected edge-on impact tests of spherical and cylindrical projectiles on sapphire plates 100 mm x 100 mm x 10 mm, conducted at the Fraunhofer- Institute for High-Speed Dynamics, EMI, Germany, were performed by using the AUTODYN commercial software. The simulations duplicated to a satisfactory level the cracking pattern and crack propagation for the case of projectile moving parallel to the [1010] direction impacting the large surface of the plate [basal plane (1000) of the single sapphire crystal. However, cracking pattern of the impact of the r-plane (1011) rhombohedral plane was not successful. This may be attributed to the energy distribution for an oblique impact. The crack density can be duplicated better by using a finer element size, smaller than the 0.5 mm used for this study. In addition, the use of a modified Al₂O₃ EOS and strength and failure models as sapphire materials models have contributed to the less successful duplication of the experimental results. The current study showed, that while the software cannot recognize the cleavage of a single crystal, it can be used effectively by either an oblique impact of known direction with these crystallographic planes, or by making a composite target consisted of areas of different properties, such as fracture toughness and fracture energy.

REFERENCES
8 ANSYS/AUTODYN Vol 14.1, Manual, Century Dynamics Inc., Concord, CA