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Modeling of Defects in Transparent Ceramics for Improving Military Armor

by C. G. Fountzoulas, J. M. Sands, G. A. Gilde, and P. J. Patel

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Vol. 2, pp. 760–767, New Orleans, LA, 22–26 September 2008.**

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14. ABSTRACT

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ABSTRACT

The dominant materials solution used for ballistic transparency protection of armored tactical platforms in commercial and military applications is low cost glass backed by polycarbonate. Due to the high cost of testing transparent ceramics, a modelling approach has been undertaken in parallel with ballistic testing to validate armor designs based on a transparent magnesium aluminate spinel, $MgAl_2O_4$, striking-ply backed by polycarbonate. Finite element modelling is used to predict unsuccessful designs and reduce number of laminate configurations in experimental testing. The purpose of this report is to demonstrate the importance of modeling tools in advancing ceramic transparent armor materials to fielded applications. The effect of various shape defects, located at various locations on the surface and in the interior of spinel hard face of the laminate target, on the failure of the transparent material will compared with relative available experimental data and they be discussed in detail.

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INTRODUCTION

The dominant materials solution used for ballistic transparency protection of armored tactical platforms in commercial and military applications is low cost glass backed by polycarbonate. Development of next generation ceramics is critical to offering enhanced protection capability and extended service performance for future armored windows to the soldier. Light armor was initially studied by M: L. Wilkins C. **A.** et al [1]. Transparent armor systems using ceramics as the striking face have been continuously explored since the early 1970's because they potentially provide superior ballistic protection to conventional glass based transparent armor systems [2]. The U.S. Army has invested heavily in the development of next generation materials, including ceramics, for military systems [3]. 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, aluminium oxynitride — one was selected for the current pursuit, magnesium aluminate spinel ($MgAl_2O_4$). Technology Assessment and Transfer (Annapolis MD, USA) is providing ceramic spinel plates produced via hot-pressing in sizes up to 28 cm x 36 cm x 1.5 cm for this report [4].

Finite element modeling has progressed substantially in the ability to predict failure of materials under extreme dynamic loading conditions. One of the limitations of predictive models is lack of a complete dynamic materials properties database which is needed for materials models for each of the materials in the simulations. In order to compensate for parameters whose dynamic values were extrapolated from their static or quasi-static properties, baseline experiments are often used to recalibrate the models [5, 6]. 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, when robust models are created [6].

The objective of this effort is to study the effect of various shape defects, located in the interior and on the surface of spinel, on the failure of the transparent material.

EXPERIMENTAL

Due to the sensitive nature of ballistic test results, surrogate materials were assembled that do not represent current or future armored designs. Experimental coupons for ballistic testing consisted of laminated layers of spinel bonded using Huntsman 399 polyurethane adhesive to Bayer polycarbonate. To reduce the variables in the investigation, the backing layer thickness was fixed at 12.7 cm of polycarbonate. The ceramic striking material for this investigation was 11 mm. The bonding layer is typically 1 mm. Experimental samples were evaluated only to attain penetration velocity to confirm the model parameters. However, the experimental results were also used to compare the actual cracking pattern with the produced from the simulation one. In addition, square cuts of 1.5 mm width and 5 mm height, and cones of 4 mm diameter and 4 mm height were introduced into the surface of the spinel. The density of the surface defects varied and it represented a 2% and 4% mass loss of the solid spinel. Since we have not been able to introduce actual defects in the interior of the spinel, all results and discussion on them are based on simulation analysis and they are compared to the surface defects simulation analysis, which was validated experimentally. The internal defects represented a 4% mass loss of the solid spinel.

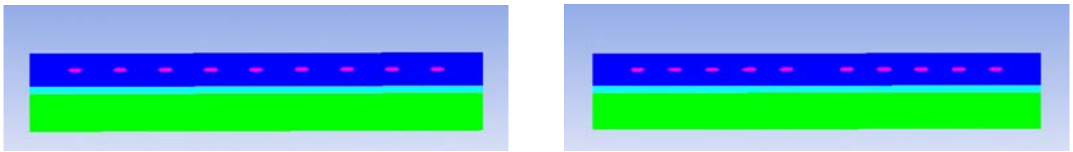
MODELING

The ballistic behavior of an identical to the actual target geometry, which was consisted of spinel, polyurethane (PU) and polycarbonate (PC), and impacted by a surrogate projectile, was simulated using the non-linear ANSYS/AUTODYN commercial package (7). The material models used were obtained from the AUTODYN library. The 2-D modeling laminated target consisted of panels of spinel, polyurethane, and polycarbonate of 900 cm^2 cross sectional area (30 cm in 2D models). The defects were filled with air at one atmospheric pressure. Due to the lack of the strength and failure material models of the spinel, these were obtained by modifying the existing at the AUTODYN materials library alumina (Al_2O_3) strength and failure model by using existing experimental ballistic data. The projectile applied in the models was a 3.0 cm long, steel projectile, of conical frustum geometry, (6 mm large base, and 1.0 mm small base). It was simulated using two-dimensional axisymmetric models. Smooth Particle Hydrodymamics

(SPH) solver was used for the simulation of the solid laminated target. Due to the pre-processing limitations of the SPH solver, the 2-D targets with interior defects were simulated only by Lagrange and Euler solvers. For increased modeling accuracy, the particle size for both the target and the projectile was 0.2 mm particle size for the SPH solver. The element size used for the 2D Lagrange and Euler solver was 0.25 mm. Since each of those solvers has its own characteristics, to ensure result compatibility a target containing no defects, for which there were experimental data available, was simulated by all three solvers. All solvers produced similar results. Results were obtained by simulating projectiles impacting the targets at the experimental velocity of 975 m/s. The PC was modeled using a shock equation of state (EOS), piecewise Johnson-Cook (JC) strength model, and a plastic strain failure criterion. The urethane was modeled using a linear EOS and a principle stress failure criterion. The projectile steel was modeled using a shock EOS and a JC strength model. The spinel, however, due to lack of existing material model, was modeled using a recalibrated form of the existing AUTODYN library Al_2O_3 material model, produced from existing experimental data and consequently validated many times by predicting within 3% results of new target design, which included a polynomial EOS and Johnson-Holmquist (JH2) strength and failure models. The air was modeled using ideal gas equation of state, with no strength and failure models.

Defect Modeling

One of the advantages of modeling methods is the ability to create physically challenging architectures to investigate effects of point defects on failure. The sensitivity of ballistic measurement tools is typically less than ±10% due to the range of available failure modes invoked in the high energy exchange between projectile and target. Additionally, capturing the real-time failure modes in the impact event requires highly specialized video equipments. These factors contribute to a very difficult and expensive set of experiments for investigating small flaws and the impact on performance in the experimental realm. By using modeling tools, however, the effects of macroscopic flaws and the location of these flaws can easily be investigated in a model that correctly captures the physics of failure in the materials. Therefore, to enhance the understanding of flaws and the behavior of spinel with defects, the modeling approach, which had been validated previously by experimental data for the case of surface introduced discontinuities, defined also as defects, is employed. Figures 1a and 1b show equal area surface 9 and 10 elliptical internal defects introduced at the centerline of the spinel.



(a) (b)

Figure 1. Target containing (a) 9 internal elliptical defects; and (b) 10 internal elliptical defects

Consideration of defects in calculating the failure probability of ceramic articles with short-term loading has been reported by Gorbatsevich et al (8). The effect of the various shapes and location defects of equal cross sectional area was studied by simulation of the impact. The location of the defects was at the striking and exit surface of the spinel, 2-mm below the front impact surface and 2-mm before the exit face of the spinel, clustered at and away the impact axis, which passes through the midpoint of the spinel width (Fig 1a and 1b), and at the geometric centerline of the spinel (Fig. 1). The shape of the defects explored were elliptical, square, circular and rectangular.

The effect of surface flaws on the ballistic performance of the target was studied by introducing square cuts into the surface of the spinel of 1.5 mm width and 5 mm height and comparing the results against a target without defects. The effect of the defects on areal density of the coupons is less than 1%. The "defects" were investigated both at the exposed surface and positioned on the interlayer (or directly on PC when the bonding layer is excluded). Five and nine "defects" were introduced on the spinel, corresponding to 2% and 4% mass loss respectively. The equal area interior defects were introduced were spaced equally from each other, the farthest from the middle of the target being at 13-mm from the edge, in agreement with the surface defects architecture.

The mass loss of the internal defects corresponds to 4%. The elliptical and rectangular internal defects were oriented having their long axis and larger dimension respectively perpendicular and parallel to the line of impact of the projectile. Analysis of the experimental tests and the simulations includes evaluation of extent of damage, residual velocity after impact, and extent of deflection.

RESULTS

Surface Defects

The minimum penetration impact velocity for the steel projectile into the baseline, the solid defect free spinel/polycarbonate target was 802 m/s for a 9-mm thick spinel laminated target. The strength and failure models which were produced from this validated simulation were used for the simulation of the 11-mm thick spinel of the current investigation. This simulation result is on excellent agreement with available experimental data. It is noted that the simulation results were completed more than 30 days prior to experimental results and agreement was within 3%. Therefore, the failure criteria of the spinel and confidence in the material parameters are excellent. However, the extent of damage in the simulation result does not coincide precisely with the experimental coupons for this case. The simulation result shows potential edge effects that do not appear in the experimental system. It should be noted, however, that during the impact event, failure modes appear consistent. Therefore, the 2D model shows an effective and rapid method of producing laminate constructions for interrogation of failure criteria. The baseline results allow confident investigation of the defect models. That prediction disagreement may be attributed to the fact that a 2D defects, when expanded in 3D is not a localized 3D defect, but rather a groove. Therefore, more material is removed at a 2D simulation than the 3D respective simulation. Currently performed 3D simulation on targets containing conical surface defects tend to confirm this hypothesis. Moreover, the simulation almost duplicated the experimental surface cracking.

The effect of the urethane interlayer on the overall velocity changes in the baseline case is insignificant. The interlayer material does not add sufficiently to the mass of the system to impact performance metrics established.

When the defect targets are evaluated, the performance is dramatically lower. For a baseline target with no penetration, inclusion of 5 defects at the urethane surface, impacted by a projectile of initial velocity of 975 m/s, produced an exit velocity of 50 m/s. This is a 5% reduction in efficiency. Further, the damage area, as estimated by length of damage in the sample, appears to be comparable or larger with the defects. The effects are more dramatic as the number of defects is increased. The simulations show that addition of 9 defects at the same impact velocity of 975 m/s results in a residual velocity of 70 m/s, which corresponds to a 7% reduction in efficiency respectively. Figure 2a and 2b show damage extent on impact of 5 and 9 defect samples at 11 microseconds after impact.

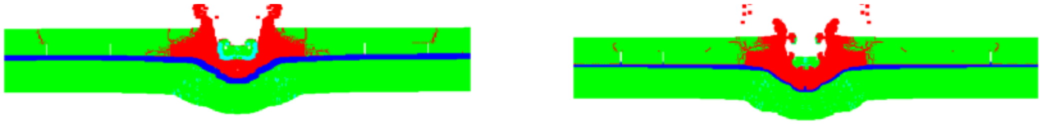

(a) (b)

Figure 2. Snapshot images of simulations of damage propagation into spinel-urethane-polycarbonate stacks after 11 s with slug moving 975 m/s with a) 5 notches and b) 9 notches

The experimental evaluation and numerical modeling of the impact of a laminated target with a spinel strike face and a polycarbonate backing showed that the resistance of the target to penetration deteriorates with the presence of surface defects. The position of these defects relative to a projectile did not appear to dramatically effect the performance reduction. The deterioration of the target seems to be related to the mass removed and to the properties like system stiffness, overall density and residual stress from the lamination process. However, the modeling also showed that the extent of the damage is only partially confined by the inclusion of intentional defects. The two dimensional slits employed in this analysis correspond to grooves in a three dimensional target. Since the target integrity depends on the material removal we anticipate that the 3D simulation of holes of same cross sectional area of the grooves will result in lower exit velocity and potentially different damage patterns.

The surface simulations indicated that the resistance of the ceramic hard face to the penetrating projectile depends mainly to the mass ahead of the projectile.

Internal defects

The simulation showed clearly that the internal defects have a reduced effect on the target resistance to penetration when compared to surface defects. The overall damage of the spinel at 100 μs appeared to be similar for all defect shapes.

Simulations showed that internal defects of elliptical cross section seem to decrease the penetration resistance of the target more when compared to the circular and rectangular penetration. In addition, the simulation shows that a defect of elliptical cross section with its large axis parallel to the line of impact resulted in the largest exit velocity, thus smaller resistance to penetration. Our analysis indicate that the larger decrease of the resistance to penetration caused by the presence of the surface defects may be attributed to the damage wave traveling through intact spinel before its exit from the spinel to the polyurethane. The defects under or very close to the impactor initially became deformed during the impact and finally they collapsed. In opposite, the defects away from the line of impact did not collapse. For the case of the defects at 2 mm below the striking surface, the simulations also showed clearly that the failure of the target progresses towards its edge starting from the defect closer to the impact site and continuing to the next defect away from the point of impact.

The damage progression seemed to grow continuously until the midpoint of two neighboring defects. However, at this point the damage appeared at the next defect while it continued to grow. This phenomenon was more obvious at defects with sharp corners, such as elliptical and rectangular cross section. This may be attributed to the damage wave arriving at the sharp corners, points of stress concentration, faster than the progressing damage.

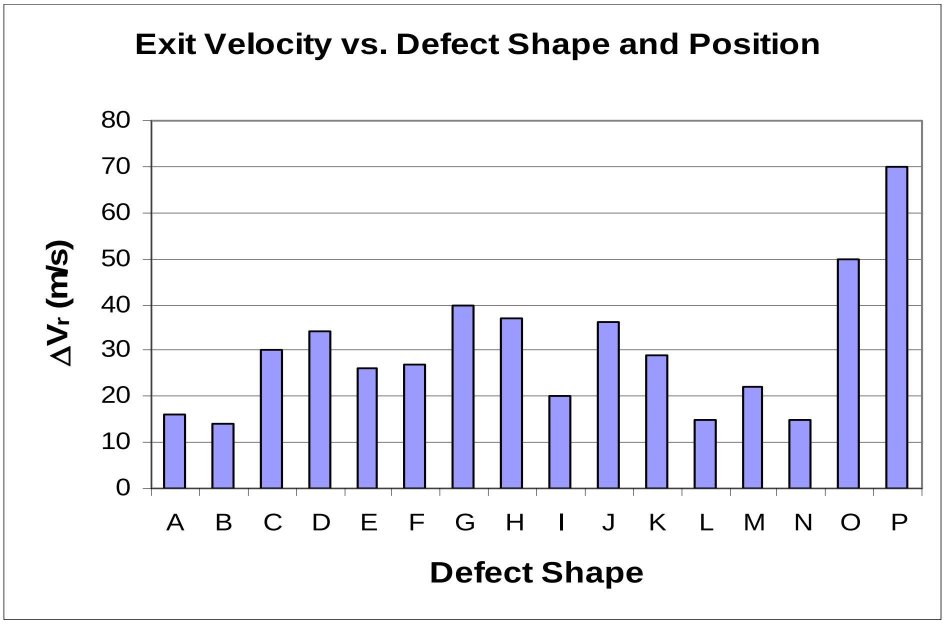


Figure 3. Comparison of residual velocity for spinel/polycarbonate targets impacted with a steel penetrator at 975 m/s, containing various shape defects. Advice Table I for symbol explanation.

The simulations showed that the surface defects decrease the resistance to penetration more than the internal defects. Figure 3 shows that the presence of surface defects reduced the resistance of the spinel more, which is indicated by the larger exit velocity even when compared to all the internal defects which correspond to a double mass loss. It also shows that the defects at the interface resulted in the next largest decrease of the penetration resistance of the target. Figure 4 shows the effect of clustering of various defects concentrated around the impact axis result in much higher projectile exit velocities, depending on the shape.

Table I. Symbol explanation of Figure 3

Defect Shape	**ΔV_r (m/s)**	
A	16	Circle 9
B	14	Circle 10
C	30	Ellipse 9
D	34	Ellipse 9 long axis parallel to line of impact
E	26	Ellipse 9 -2mm under the striking face
F	27	Ellipse 9 -2 mm from the exit face
G	40	Ellipse 9 long axis parallel to line of impact-2mm under the striking face
H	37	Ellipse 9 long axis parallel to line of impact-2mm before the exit face
I	20	Ellipse 10
J	36	Ellipse 10-long axis parallel to line of impact -2 mm under the striking surface
K	29	Ellipse 10 long axis parallel to line of impact -2mm before the exit face
L	15	Rectangle 9
M	22	Rectangle 9 long dimension parallel to line of impact
N	15	Rectangle 10
O	50	Rectangular Surface Groove 5
P	70	Rectangular Surface Groove 9

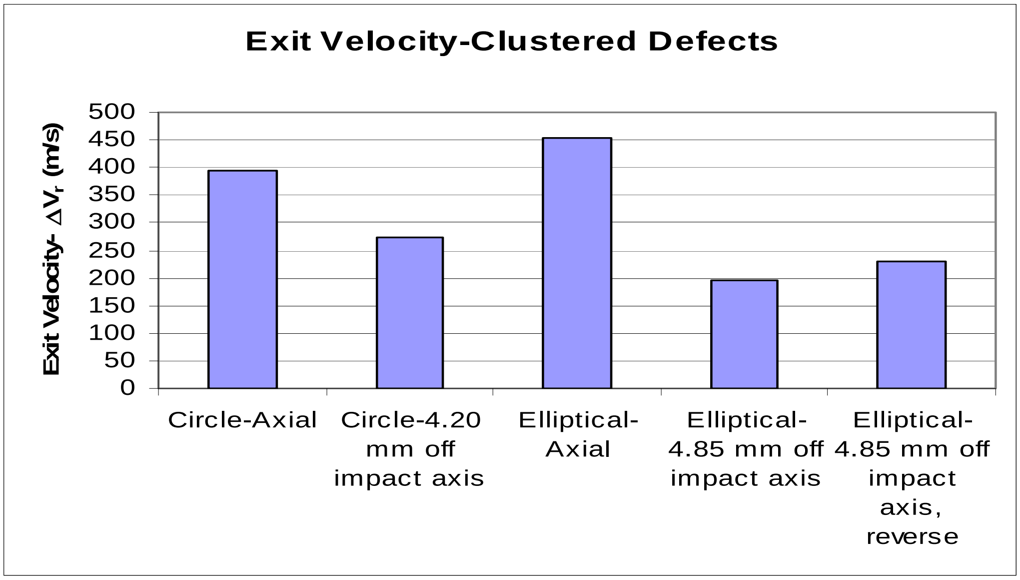


Figure 4. Effect of clustering of circular and elliptical cross-sectional area defects on the projectile exit velocity

CONCLUSIONS

While the need for advanced materials solutions for protection of vehicles from ballistic threats continues to grow, the ability to predict materials performances using advanced modeling tools increases. The current efforts underway in the U.S. Army include the use of ballistic modeling, ballistic testing, and historic knowledge of ballistic design to create structural armors for the transparent armor needs of the U.S. military. The current paper has demonstrated the powerful use of 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, which are located at carefully selected points of the spinel, resulted in a significant reduction in apparent local stiffness in the composite laminates, and resulted in significant changes in the virtual performance of the laminate stacks. These results were verified using ballistic testing to demonstrate the complex nature of the ballistic environment. While the surface grooves represent only a 2-4 % reduction in the materials content in the samples, they resulted in 5% and 7% reduction in performance, and compare this with the maximum 3.5% reduction in performance caused by the elliptical internal defect. This is consistent with previous research that shows that ceramics with flaws demonstrate reduced mechanical performance during static testing, and validates the potential use of random flaws in model systems for predictive performance in dynamic validations using simulation. The presence of surface flaws in conjunction with the defect relative position with respect to the line of impact was more detrimental to the damage resistance of the spinel when compared to the internal of equal area defects. The simulations showed that the presence of voids or the mass decrease caused by defects, and especially higher local void concentration, results in decreased resistance to penetration, smaller for internal defects and relatively larger for surface defects of equal cross-sectional area. However, we believe that as the defect density increases the resistance to penetration and the ceramic deterioration will be accelerated. It is worth studying the effect of defect density, defect shape irregularity, orientation and size of the defect, inclusions of various nature materials rather only air and the minimum size of the defect which can influence the resistance of the target.

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