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Journal of the European Ceramic Society 29 (2009) 261–266

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# Modelling transparent ceramics to improve military armour

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Available online 12 May 2008

**Abstract**

The dominant materials solution used for ballistic transparency protection of armoured 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 armoured windows to the soldier. Due to the high cost of testing transparent ceramics, a modelling approach has been undertaken in parallel with ballistic testing to validate armour designs based on a transparent magnesium aluminate spinel, $MgAl_2O_4$, striking-ply backed by polycarbonate. A key purpose is to characterize the influence of defects on the failure of laminates, both statically and dynamically tested. Finite element modelling is used to predict unsuccessful designs and reduce number of laminate configurations in experimental testing. A notional ceramic armour system based on spinel/polycarbonate assemblies is used to report results on the effect of surface and interior, equal area defects on the ballistic behavior of a laminates.
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*Keywords:* Armour; Modelling; Spinel; Failure analysis; Defects

## 1. Introduction

Transparent armour systems using ceramics as the striking face have been explored since the early 1970s because they potentially provide superior ballistic protection to conventional glass-based transparent armour systems.[1] However, commercial manufacturers have not experienced a demand for large transparent (>1290 cm$^2$) ceramic plates for commercial markets in point-of-sale scanners and fluorescent lighting. Therefore, the development of large and thick ceramic plates for transparent armour applications has not proceeded to commercial maturity. 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.

As large transparent ceramic materials are available commercially in sizes up to 900 cm$^2$, progress in ballistic designs has offered substantial increases in performance in transparent armour design. Among the potential ceramic materials considered for armour – sapphire, edge-form-growth sapphire, magnesium aluminate spinel, aluminium oxynitride – one was selected for the current pursuit, magnesium aluminate spinel ($MgAl_2O_4$). Although individually, single impact testing has shown small variations in ballistic efficiencies (<10%) of ceramics, to achieve multi-hit performance, all of the ceramics are effectively equivalent. technology assessment and transfer (Annapolis, MD, USA) is providing ceramic spinel plates produced via hot-pressing in sizes up to 28 cm × 36 cm × 1.5 cm for this report.[3]

Finite element modelling 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 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 used to recalibrate the models.[4,5] However, the recalibration method of modelling lacks many of the physical properties and failure mechanisms associated with real-world materials. Therefore, often recalibrated models lack the ability to predict within statistical error future failures over any substantial ranges, 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. Despite apparent limitations, recalibration of existing materials models has proven effective in minimizing the number of simulation iterations and in producing more successful predictions. Regardless

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0955-2219/$ – see front matter. Published by Elsevier Ltd.
doi:10.1016/j.jeurceramsoc.2008.03.010

of methodology, 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.[5]

## 2. Experimental

Due to the sensitive nature of ballistic test results, surrogate materials were assembled that do not represent current or future armoured designs.

### 2.1. Ballistic coupons

Experimental coupons for ballistic testing consisted of laminated layers of spinel bonded Deerfield 4700 (or Huntsman 399 equivalent) polyurethane adhesive to Bayer Makrolon polycarbonate. The laminate sandwich was assembled in an autoclave at 93–121 °C for 4 h. To reduce the variables in the investigation, the backing layer thickness was fixed at 1.27 cm of polycarbonate. The ceramic striking material is varied between 1.1 and 1.5 cm, depending on the density of flaws introduced. The bonding layer is typically 0.10 cm. Experimental samples were evaluated only to attain penetration velocity to confirm the model parameters. Otherwise, all results and discussion are based on simulation analysis.

### 2.2. Modelling

The ballistic behavior of the ceramic spinel, polyurethane and polycarbonate stack 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 modelling 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 1 atm pressure. Some of the strength material models of the laminated target materials had been previously recalibrated using existing ballistic data. The numerical modelling of undamaged armour coupons was carried out in two and three dimensions. The projectile applied in the models was a 3.0 cm long, 1095 steel projectile, of conical frustum geometry, (6 mm large base, 1.0 mm small base), using two-dimensional axi-symmetric and plane symmetry models. Depending on the geometric complexity of the laminated target and the existing pre-processing capability of the solver, smooth particle hydrodynamics (SPH), Lagrange and Euler solvers were used. In particular, when the SPH solver was used the target and the projectile were discretized by SPH with a particle size of 0.2 mm. 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 was simulated by all three solvers. All solvers produced similar results. Results were obtained by simulating projectiles impacting the targets at the experimental velocities ranging from 500 to 1000 m/s.

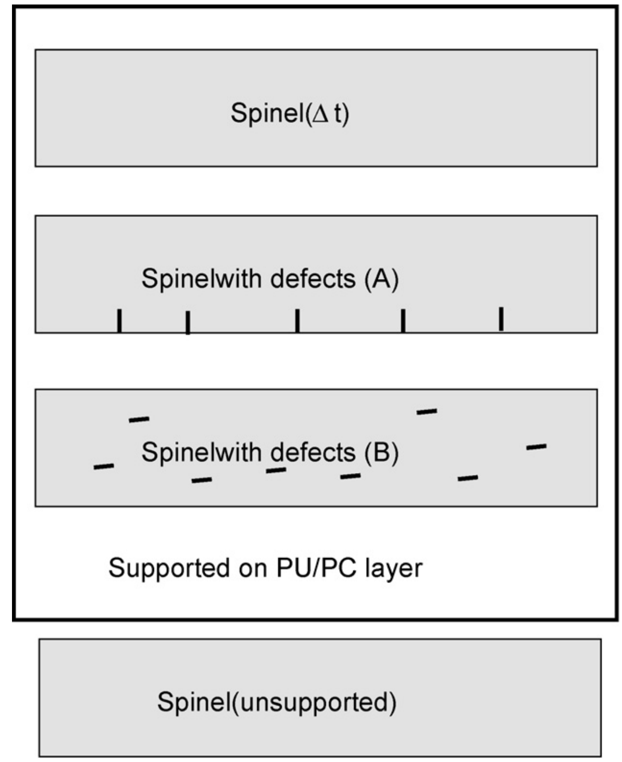


Fig. 1. Types and locations of various defects explored using the experimental and ANSYS/AUTODYN simulation tools for defects in ceramic spinel. Defects were located either at the surface (A) or at the interior (B) of the spinel layer of the laminated construction. The polymer layers are kept constant throughout. Voids are simulated as ideal gas air.

### 2.3. Defect models

One of the advantages of modelling 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 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 modelling 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 modelling approach, which had been validated previously by experimental data for the case of surface introduced discontinuities, defined also as defects, is employed.

Consideration of defects in calculating the failure probability of ceramic articles with short-term loading has been reported by Gorbatsevichl et al.[7] The effect of various shapes and locations of defects of equal cross-sectional area was studied by simulation of the impact. Fig. 1 shows pictorially the various defect types and locations of defect investigated. The location of the defects at either surface or interior to the sample is

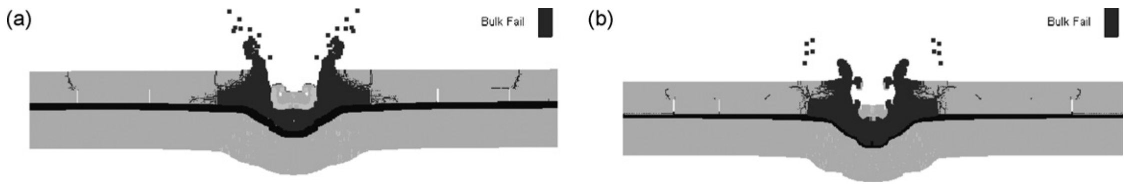


Fig. 2. Snapshot images from simulations showing damage propagation into spinel/polycarbonate stacks after 11 μs with slug moving 1000 m/s with (a) 7 surface defects and (b) 11 surface defects.

considered, and defect shapes from elliptical to square to circular are explored. Due to limitations of the SPH solver preprocessor, for this study the Lagrange and Euler solvers were used. However, the Lagrange solver was not able to be used for all shapes, due to its known sensitivity to the erosion of cells of shapes with sharp corners, like the elliptical and rectangular cross-sectional areas defects. The Euler solver produced results for all defect shapes. To ensure compatibility of our previous results produced by the SPH solver and between the Lagrange and Euler solvers as well, we compared the results of the impact simulation for a target without defects, which were run under identical impact and boundary conditions. All three solvers produced similar results. In the interest of computational consistency, defect results were compared using residual velocities based on a constant initial velocity.

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 area density of the spinel is less than 5%. Simulation images 11 μs after impact are shown in Fig. 2 demonstrating the damage progression for a target with seven and eleven surface defects are similar. The defects were investigated both at the exposed surface and positioned on the interlayer (or directly on PC when the bonding layer is excluded). The interior defects were introduced along the geometric centreline of the spinel layer, spaced equally from each other. The projectile impacted the target in the following ways: (a) perpendicular to the centre of a defect and (b) perpendicular to the target but in-between two defects. Analysis of the experimental tests and the simulations includes evaluation of extent of damage and residual velocity after impact.

The material models used for the polycarbonate, urethane interlayer, and steel projectile were obtained from the AUTODYN material library.[6] The PC was modelled using a shock equation of state (EOS), piecewise Johnson–Cook (JC) strength model, and a plastic strain failure criterion. The urethane was modelled using a linear EOS and a principle stress failure criterion. The projectile steel was modelled using a shock EOS and a JC strength model. The spinel, however, was modelled using a recalibrated form of the AUTODYN library $Al_2O_3$ material model, which included a polynomial EOS and Johnson–Holmquist (JH2) strength and failure models. The recalibrated model was used to successfully predict within 3% the performance of specific target systems when compared with experimental results. The air was modelled using ideal gas EOS, with no strength and failure models.

## 3. Results

### 3.1. Experimental coupons versus model predictions

The minimum impact velocity for the surrogate steel projectile into the baseline, defect free spinel/polycarbonate target was calculated as $V_{simulation} = 975$ m/s. The result is validated using the experimental target with excellent agreement. The simulation results were completed more than 30 days prior to experimental testing and agreement was within 3% ($V_{experiment} = 1005$ m/s). Therefore, the failure criteria and confidence in the material parameters is excellent. 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. During the impact, failure modes were assessed and appeared consistent between experiment and model, including types of damage observed. Therefore, the 2D model shows an effective and rapid method of evaluating laminate constructions for failure criteria.

The experimental investigation of defects is much more challenging to explore. The uniqueness of targets with prescribed defects in conjunction with the statistical nature of ballistic testing results in a high level of difficulty. Despite the limitations, an experimental velocity was calculated for two defect conditions that were subsequently simulated. In one defect design, grooves were ground into the surface of a spinel plate. These grooves consisted of channels cut using a diamond saw at 25 mm spacings along one axis of the spinel surface to a depth of 4 mm. An experimental impact velocity of 850 m/s was found by testing six experimental coupons. An additional experimental target consisted of holes drilled into an array in the spinel surface. The ballistic limit for this target was higher, but the damage area induced in the sample was significant with substantial cracking of the surface do to point defects. Evaluating the performance of these samples in comparison to the Autodyn models showed excellent correlation. The approach taken was to characterize performance using a constant input energy and measure the exit velocity of the projectile using the models. This approach is referred to as the residual velocity method of assessment. For the target with holes, a simulation residual velocity of 19 m/s was determined. In addition to defects, the effect of reducing the mass of spinel in front of the projectile by reducing thickness was considered. All of these test results are plotted for simulations and experiments in Fig. 3. Fig. 3a shows the loss in ballistic efficiency as a function of mass reduction by changing spinel thickness. Fig. 3b shows the loss in performance due to

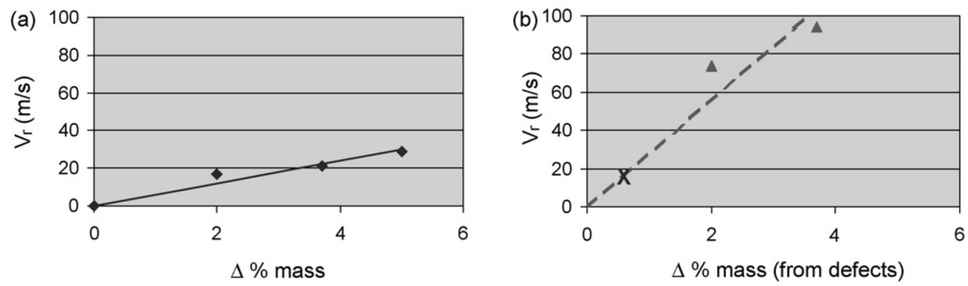


Fig. 3. Ballistic efficiency loss (as determined by residual velocity, $V_r$) demonstrating efficiency loss due to (a) reduced spinel thickness and (b) surface defects as a function of mass reduction.

defects. It is evident from the two figures that defects have a more dramatic effect on the performance at the examined thickness ranges.

### 3.2. *Effect of adhesive interlayer*

When investigating the effects of the urethane interlayer, the overall velocity changes in the baseline case are insignificant. The interlayer material does not add sufficiently to the mass of the system to impact performance metrics established. Further, the thickness of the system, and the selected thickness of the interlayer do not provide significant attenuation of any blast or shock waves in the system. Therefore, the defect cases of the simulation are run with the interlayer present to adequately represent the thickness and stiffness effects of the experimental coupons.

### 3.3. *Effect of defect location and shape*

When the defect targets are evaluated, the performance is dramatically lower. The overall effect of performance has yet to be fully interrogated. However, in principal, a notched or defect-based target should allow localized failure in the ceramic strike face and, therefore, limit the extent of damage in neighbouring cells. On initial investigation, this conceptual hypothesis does not appear to hold true. However, the projectile receives a much lower interaction potential with the ceramic and is less eroded during the initial phases of the impact event. The resulting exit velocities of the projectile are dramatic. For a baseline target with no penetration, inclusion of 7 defects at the urethane surface, impacted by a projectile of initial velocity of 1000 m/s, produced an exit velocity of 70 m/s. This is a 7% 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 and 11 defects results in a residual velocity of 95 and 150 m/s or a 9.5% and 20% reduction in efficiency, respectively.

The experimental evaluation and numerical modelling 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 depend somewhat on the amount of defect in the target, which is related to the mass removed and to the properties like system stiffness, overall density and residual stress from the lamination process. However, the modelling 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 results in lower exit velocity and potentially different damage patterns. It is worth examining the effect of the defect orientation and size on the ballistic performance of the target. The simulations that were performed with PU interlayer indicate that the presence of the polyurethane provides an additional resistance to penetration for the samples with defects, but the overall effect did not alter the results in a measurable way.

In the case of the spinel surface consisted of conical defects the position of the defects relative to the line of impact produced different results. 2D and 3D simulations showed that for the case of the projectile impacting directly a cone, the exit velocity was close to the exit velocity from a spinel with no defect. However, when the projectile impacted the spinel between cones (aka in the valley) then the exit velocity was close to the exit velocity from a spinel-containing surface slit defects at the side next to the polyurethane.

The simulations also showed clearly that the internal defects have a reduced effect on the target resistance to penetration when compared to surface defects, as demonstrated by the summary

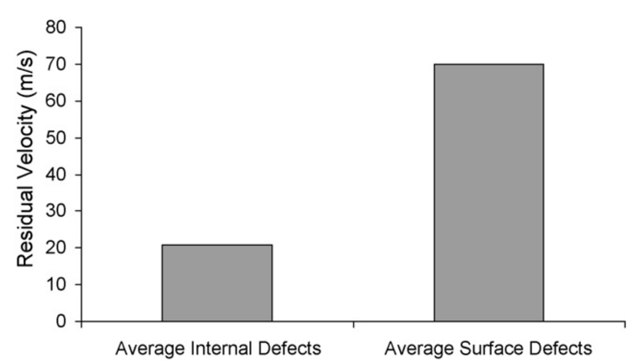


Fig. 4. Average residual velocity for spinel/polycarbonate targets impacted with a steel penetrator at 1000 m/s, where defects are modelled into the ceramic layer with a constant defect volume of 4%.

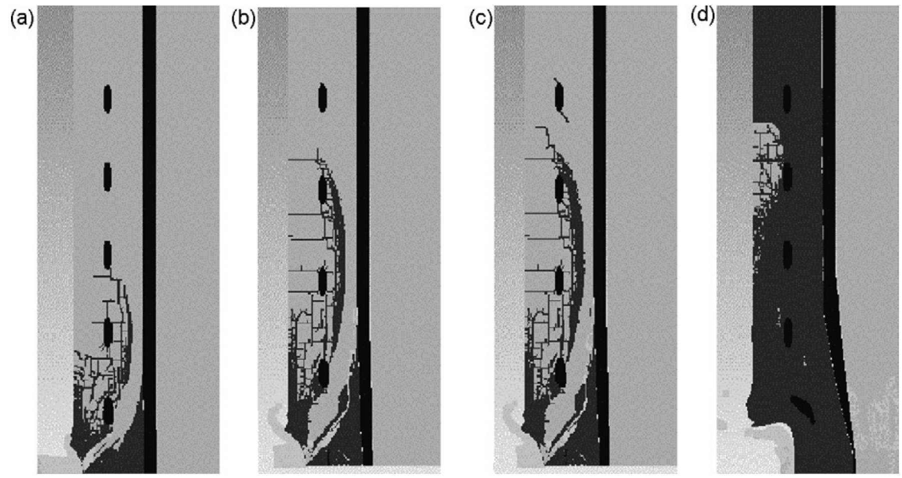


Fig. 5. Damage progression in a spinel/polycarbonate laminate with 4% elliptical defects internally inserted along the center line of the spinel after (a) 16 μs, (b) 30.37 μs, (c) 32 μs, and (d) 52 μs. The damage progression appears to grow at the sharp edges of the defects until complete failure of the ceramic. Note that the damage does not penetrate the void areas, but is initiated at the boundaries.

chart in Fig. 4. The average residual velocity of projectiles into defect targets shows a three times increase in residual velocity with surface defects as compared to internal defects. Simulations were used to further evaluate the different stress concentrations by varying the defect types between rectangular, elliptical and circular defects. The simulations showed that internal defects of elliptical cross-section seem to increase the residual velocity the most when compared to the circular and rectangular defects internal to the spinel. In addition, simulations show that a defect of elliptical cross-section with its large axis parallel to the line of impact resulted in the largest exit velocity. Fig. 5 shows time slices from the impact into an ellipse-based defect target showing the progression of damage. 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. The phenomenon may be attributed to the damage wave arriving at the sharp corners, i.e., points of stress concentration, faster than the progressing damage.

## 4. 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 modelling tools increases. The current efforts underway in the U.S. Army include the use of ballistic modelling, ballistic testing, and historic knowledge of ballistic design to create structural armours for the transparent armour needs of the U.S. military. The current paper has demonstrated the powerful use of computational modelling 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 resulted in significant changes in the virtual performance of the laminate stacks. These results were verified using ballistic testing. While the surface grooves represent only a 2–3% reduction in the materials content in the samples, they resulted in 7% and 20% reduction in performance. 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 aligned along the penetration axis was more detrimental than the internal defects of equal area. The simulations showed that the presence of voids, or the mass decrease caused by defects, 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.

Although this report explored the defect tolerance of spinel ceramics subjected to ballistic loading, some generalized conclusions can be offered based on the experimental and simulation results. First, surface defects, regardless of placement, are most detrimental to the performance of the ceramic in a ballistic event. Therefore, protecting the ceramic from circumstantial impacts and damage is considered essential to preserving the ballistic performance of these materials. Second, inclusion of localized defects for the purpose of controlling the spread of damage in the target does not appear to have valid support. While ballistics is a statistical science, evidence from experiments and modelling did not support the hypothesis for controlling damage growth through localized defect inclusion. Finally, although the intent of the characterization in this report is to demonstrate the importance of defects on failure modes in ceramics, the importance of defects may be smaller than initially perceived. The defects probed in this study are large by the standards applied to ceramic fabrication. In fact, the approach here would result in non-transparent defects that would negatively impact the optics of the systems. The resulting defects caused only a small decrease in the ballistic efficiency of the systems, unless the defects were located immediately under the impact zone and oriented along the axis of impact. Therefore, one can conclude that unless the transparent ceramic contains large defects that are visually observable, the performance of transparent spinel ceramic armour is likely to achieve design goals. Therefore, ceramic transparent armours are still a very viable technology for armour applications for future platforms.

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