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ScienceDirect
Journal of the European Ceramic Society 29 (2009) 261–266
www.elsevier.com/locate/jeurceramsoc

Modelling transparent ceramics to improve military armour

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

U.S. Army Research Laboratory, Survivability Materials Branch, 4600 Deer Creek Loop, AMSRD-ARL-WM-MD, APG, MD, USA

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.
Published by Elsevier Ltd.

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

* Corresponding author. Tel.: +1 410 306 0878; fax: +1 410 306 0806.
E-mail address: james.m.sands@us.army.mil (J.M. Sands).

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.

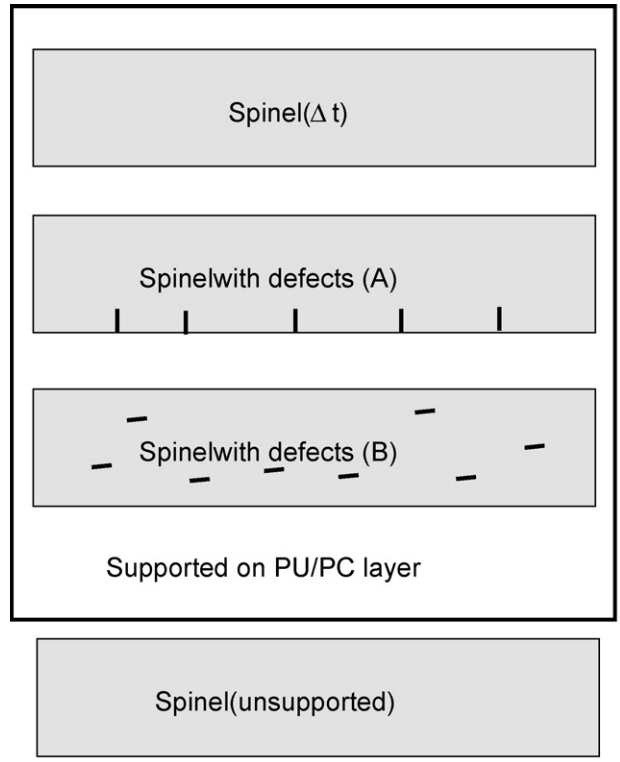

Fig. 1. Types and locations of various defects explored using the experimental and ANSYS/AUTODYN simulation tools for defects in ceramic spinel. Defects were located either at the surface (A) or at the interior (B) of the spinel layer of the laminated construction. The polymer layers are kept constant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

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