

FUNDAMENTAL INVESTIGATION OF HIGH-VELOCITY IMPACT OF DUCTILE PROJECTILES ON CONFINED CERAMIC TARGETS

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ABSTRACT

To aid the Army's transformation into a more mobile, rapidly deployable, and highly survivable force, researchers at the Army Research Laboratory (ARL) have undertaken a program aimed at supporting the development of lighter weight ceramic armors with greater protection capabilities. One goal of this program is to improve the capabilities of computational tools for the design and analysis of ceramic armors, which offer greatly enhanced protection capabilities at reduced weights. Given the multitude of design variables, the development of optimized ceramic armors is a resource-intensive process that relies on predictive simulations. The use of validated computational design tools in conjunction with ballistic experimentation and post-mortem system characterization are keys to improving upon this process. This approach has not been widely adopted mainly because of justified concerns with the validity of computational tool predictions. The program at ARL will assess the capabilities of current computational tools by generating benchmark data on the time-dependent response of simplified ceramic armor targets and armor ceramics, and quantify ceramic damage responsible for these responses. The ability for current computational tools to match such data will identify model weaknesses and therefore expedite improvements. The experimental capability for determining the time-dependent response of simplified ceramic armor targets and some recent results for an armor-grade silicon carbide are presented. In addition, preliminary efforts examining the validity of a computational tool based on Sandia National Lab's (SNL) GeoModel (Fossum and Brannon, 2004), and implemented into ALEGRA (Carroll et al., 2004) are reported.

1. INTRODUCTION

For the combat vehicles envisioned under the U.S. Army's Future Combat Systems (FCS) Program, the development of ceramic armor technologies that meet both the weight constraints and protection requirements is a difficult challenge.

One reason for the challenge is that ceramic armor developers lack validated computational tools that are

simultaneously robust and accurate for predicting the performance of lightweight ceramic armor. In the hands of an experienced user with a good understanding of computational mechanics and ballistics, current computational tools can be effectively used to gain insight into the effects of specific design variables on various indicators of performance including overall performance. However, our understanding of the fundamental phenomena (such as contact, penetration, fragmentation, inelastic behavior, and failure) that are encountered in a ballistic event is still limited. This has been due in part to our failure or inability to accurately or directly study these complex phenomena under relevant conditions and at the length-scales required. Consequently, accurate prediction of the performance of ceramic armors is still a challenge.

Researchers at the ARL, in collaboration with members of academia, national laboratories, and TARDEC, have undertaken a research program whose goal is to develop robust computational tools for analysis and design of ceramic armor. Current efforts are focused on assessing the capabilities of existing computational tools by generating data on the fundamental response of ceramics to ballistic and dynamic loading, as well as on the mechanisms responsible for such behavior, utilizing both traditional and advanced techniques in the areas of terminal ballistics, dynamic behavior of materials, and materials characterization. One of the cornerstone efforts within this program is the study of the interaction between a projectile and ceramic target (Projectile/Target Interaction or PTI). The purpose of the PTI effort is to quantify the effect of both ceramic and ceramic armor parameters on fundamental performance metrics, as well as to recover targets for post-mortem damage characterization.

Traditional performance metrics used to evaluate the efficiency of either ceramic armor designs (i.e. V50) or armor ceramics (i.e. DOP) are insufficient for assessing the capabilities of computational tools, as well as the potential ceramic material itself. Significantly more challenging are performance metrics that yield detailed insight into the time-varying response or penetration resistance of the ceramic target. Figure 1 depicts the normalized penetration-rate (u/v) as a function of impact velocity (v) of a ductile penetrator interacting with a ceramic armor target. That curve is characterized by a

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transition velocity region, above which there is penetration into the ceramic, and below which there is no penetration (i.e. dwell). This transition region is characterized by the dwell/penetration transition velocity, $V_p^{Transition}$, and a width Δv over which the dwell duration, τ_{dwell} , varies from complete dwell (left limit) to no dwell (right limit). The dwell/penetration transition velocity, dwell duration, and penetration rate provide detailed information on the connection between the design parameters of the ceramic armor target and penetration resistance during the different phases of the ballistic event.

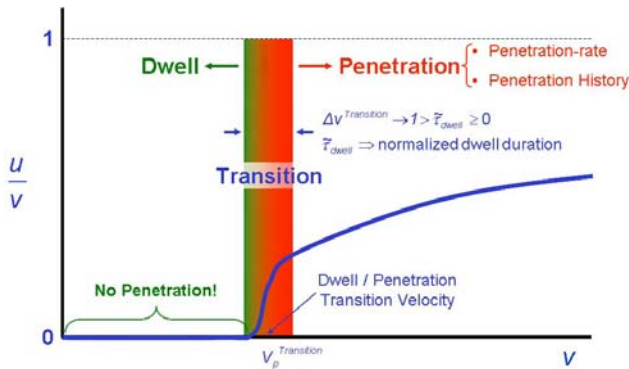


Fig. 1. Normalized penetration-rate (u/v) as a function of impact velocity (v), illustrating dwell (i.e. no penetration) and penetration stages typical of ballistic impact of a ductile penetrator on a ceramic armor target.

In this paper, recent results on the effect of ceramic thickness (a ceramic armor design parameter) on the dwell/penetration transition velocity and penetration rate will be presented. In addition, the experimental set-up, post-mortem ceramic damage characterization, and preliminary computational tool validation efforts will be discussed.

2. PTI SET-UP & PROCEDURES

Motivated by early work of Hauver et al. (1994, 2005) on confined ceramic armor, Orphal and Franzen (1997), Lundberg et al. (2000, 2004), and most recently, Holmquist et al. (2005), have investigated the time-dependent penetration of ceramics by ductile penetrators using flash X-rays. The work by Lundberg et al. (2000) has been used as benchmark validation experiments for computational ceramic models (Holmquist and Johnson, 2002; Templeton et al., 2002).

Based upon this work of Hauver et al. (2005) and Lundberg et al. (2000), a forward-ballistic experimental capability using three 1 MeV flash X-ray systems was developed at ARL to support the PTI effort. Figure 2 illustrates the components of the instrumented experimental set-up for the PTI effort: two orthogonal

pairs of striking 150 keV X-rays (to determine pitch/yaw and impact velocity), three separate 1 MeV penetration X-rays in one plane (to determine penetrator position and penetration rate), complimentary film cassettes, and break-screens for timing (used for triggering X-rays) and sabot-stripper. Additionally, a fully shielded fixture was created to protect equipment, as well as a robust target holder for recovery. Lastly, to improve the accuracy and reliability of timing with respect to the 1 MeV penetration X-ray equipment, an improved electronic set-up was developed which used optical isolation and false trigger detection.

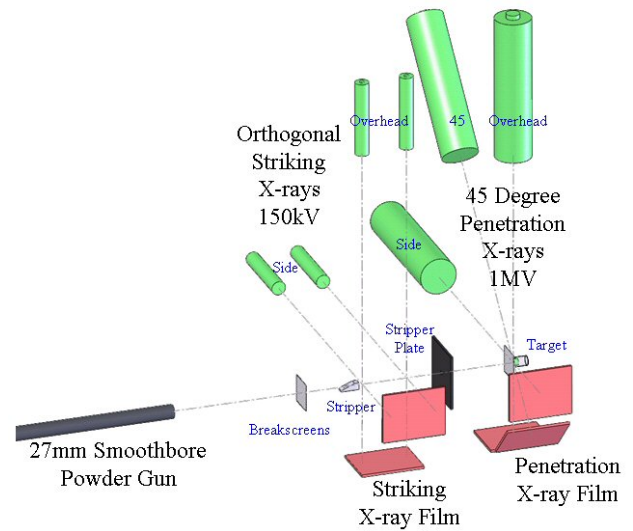


Fig. 2. Schematic of the experimental set-up for the PTI effort showing number and position of X-rays.

Figure 3 shows the relative geometries of the penetrator and confined ceramic targets. Each penetrator was a tungsten-based (93 wt.% tungsten) rod with a length of 63.7 mm and a diameter of 3.2 mm (i.e. $L/D=20$). Each penetrator was fired from a 27 mm smoothbore powder gun using launch packages which consisted of four-petal discarding sabot and a thin steel pusher with obturator. The launch package separates from the penetrator prior to impact on the ceramic target. Impact velocities were varied nominally between 1000 and 1600 m/s.

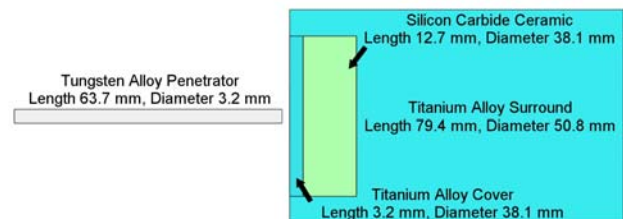


Fig. 3. Projectile and target geometry for ceramic thickness study (12.7mm thick ceramic target shown).

The axisymmetric targets consisted of a cover plate, ceramic, and a cup or backing. The cover plate and cup were made from a titanium alloy (Ti6Al4V). The cover plate was 3.175 mm thick (one rod diameter) and welded to the cup. The ceramic used in these experiments was the armor-grade variant of SiC known as SiC-N manufactured by BAE Advanced Ceramics Division. Table 1 lists some physical and mechanical properties for SiC-N. The columns in Table 1 represent the density, polytype, grain size, Young's modulus, Knoop hardness at a 4 kg load, fracture toughness and 4 point bend strength, respectively. The ceramics were of cylindrical geometry with diameters of 38.1 mm. Three different thicknesses, 12.7, 25.4, and 38.1 mm, were examined. The ceramic cylinders were seated into cavities machined into the cups. The cups were 50.8 mm in diameter and 76.2 mm in length. The length of the cups was chosen to approximate a semi-infinite backing for the ceramic cylinders. This was done in an attempt to minimize system effects and allow the effect of ceramic thickness to be examined exclusively. A tight slip-fit (0.025 – 0.050 mm) between the sides of the ceramic cylinders and cups was used to provide lateral confinement without pre-stress.

Table 1. Physical and Mechanical Properties of SiC-N

ρ (g/cm ³)	Polytypes	d (μ m)	E (GPa)	HK4 (GPa)	K_{IC} (MPa*m ^{1/2})	σ_{bend} (MPa)
3.22	6H, 15R, 3C	1.90	452	18.6	5.1	620

For each of the three ceramic thicknesses, two experiments were conducted at each nominal impact velocity. X-ray flashes were staggered in time and overlapped to obtain a more complete record of the projectile and target interaction during the ballistic event.

3. EXPERIMENTAL RESULTS

Figure 4 is a sequence of three flash X-ray radiographs showing the initial dwell and subsequent penetration of a rod impacting on a 12.7 mm thick ceramic target. The approximate location of the rod material is outlined in red, while that of the ceramic is indicated by black outline. At 16 μ s, the rod material can be seen mainly spreading over the top of the ceramic (i.e. dwelling). In addition, initial penetration of rod material can be seen. As well be shown later, this initial penetration (off-axis) is most likely penetration along tensile cone cracks that form. At 38 μ s, the rod has penetrated into the ceramic, while at 59 μ s, it has penetrated into the Ti6Al4V backing.

Figure 5 illustrates the potential impenetrability for ceramic armor systems against projectiles launched at typical ordnance velocities. In this figure, the rod dwells

along the surface and is completely eroded. The ceramic remains in place and provides additional multi-hit protection. Recovered ceramics from targets that exhibited complete dwell provide the greatest insight into the mechanisms that govern the dwell/penetration transition and penetration resistance of the ceramic, as will be shown later.

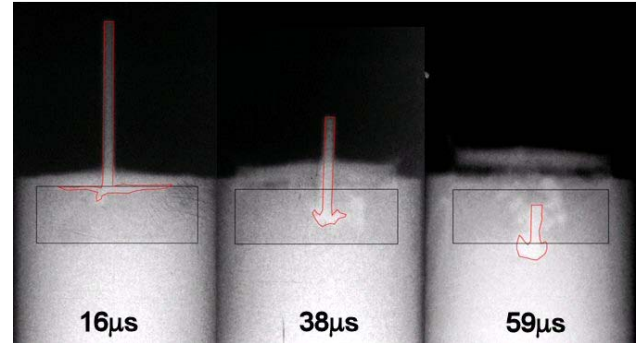


Fig. 4. Sequence of three flash X-ray radiographs showing the initial dwell and subsequent penetration into a 12.7 mm thick SiC-N ceramic target.

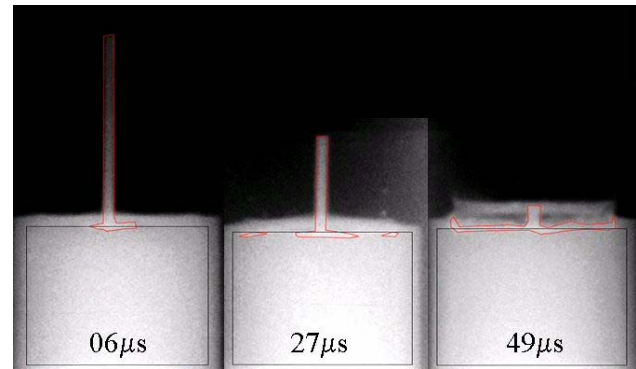


Fig. 5. Sequence of three flash X-ray radiographs showing complete dwell of the penetrator on a 38.1 mm thick SiC-N ceramic target.

3.1 Flash X-Ray Radiograph Data Reduction

Data that quantifies the ballistic event on a detailed and more fundamental level than a V50 or DOP value can be easily measured or derived from the flash X-ray radiographs shown in Figures 4 and 5. Correcting for image distortion, the position of the nose and tail of the rod at each specific time can be measured accurately. From such data, the rod penetration history is determined directly, allowing rod penetration and erosion rates to be calculated for each impact velocity.

Figure 6 shows rod penetration (p) histories with associated impact velocities for ceramic targets with 38.1 mm thick SiC-N cylinders. In this plot, the spatial positions (demarcated by lines parallel with the time axis) of the cover, ceramic, and backing (i.e. cup) are shown. Complete dwell was achieved at impact velocities of 1030

and 1207 m/s, while partial dwell followed by penetration was observed for impact velocities of 1209 m/s and higher. According to one-dimensional steady-state penetration equations, derived independently by Alekseevskii (1966) and Tate (1967), the slopes of the penetration histories should be insensitive to impact velocity (i.e. p should vary linearly with impact velocity). Hence, deviations from linearity may indicate that penetration was not steady-state. Non-steady-state penetration may be expected near the dwell/penetration transition velocity as observed by Lundberg (2002). Further experiments and analysis are needed to determine penetration velocities and other information more precisely and with increased certainty.

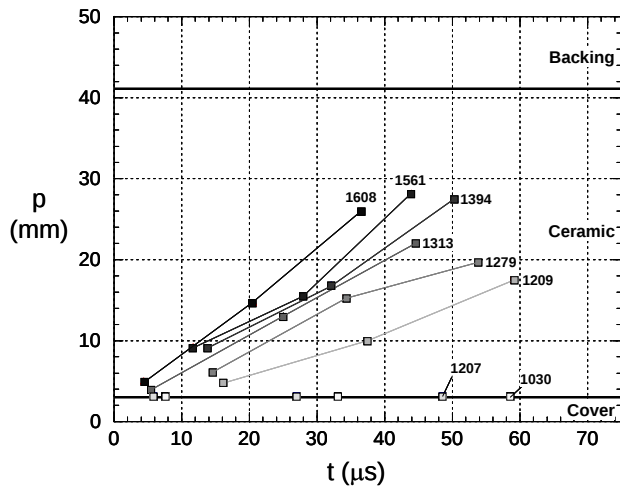


Fig. 6. Penetrator nose position vs. time for the 38.1 mm thick ceramic targets.

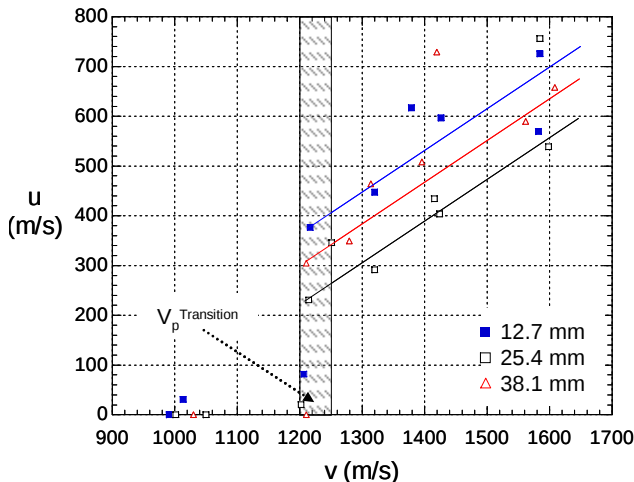


Fig. 7. Penetration rate (u) as a function of impact velocity (v) for each ceramic thickness.

The penetration histories of the 12.7 and 25.4 mm thick ceramics were similar to that shown in Figure 6. As mentioned previously, rod penetration-rate can be calculated from the rod penetration history. Figure 7 shows the rod penetration-rate as a function of impact

velocity for the 12.7, 25.4, and 38.1 mm thick ceramics. As can be seen, for the thicknesses examined, the nominal dwell/penetration transition velocity (1200 – 1250 m/s) is not strongly dependent on ceramic thickness, which suggests that the transition velocity is determined primarily from material properties, not by experiment geometry. However, penetration-rate does appear to be influenced by ceramic thickness. As expected, the scatter in penetration-rates is large given the deviations in linearity of the penetration histories. Surprisingly, the penetration-rates are higher in the 38.1 mm thick ceramic compared to the 25.4 mm thick ceramic. That is, the penetration resistance in the 25.4 mm thick ceramic is higher than in the thicker ceramic. Further experiments will be conducted to determine if this behavior is repeatable, or merely an outlier artifact of scatter in the data.

3.2 Depth of Penetration (DOP) Data

Figure 8 shows static X-ray radiographs for 12.7, 25.4, and 38.1 mm thick ceramics. Impact velocities for each ceramic target are listed. Static X-ray radiographs are useful for determining the final depth-of-penetration (DOP) of the rod in the ceramic targets.

Clearly, DOP data cannot reveal deformation histories during penetration or, in particular, how long the rod dwelled at the top surface of the ceramic. Matching DOP is a necessary *but not sufficient* validation of computational models. By “tuning” parameters, it is fairly easy for any model to match DOP results. It is clearly more valuable to assess the underlying physics that distinguishes one model from another by testing how well they each (using a *fixed* parameter set) predict time-resolved penetration data in a variety of impact scenarios, including these PTI experiments.

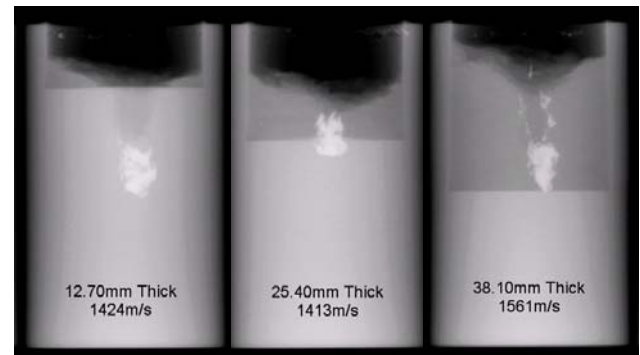


Fig. 8. Depth-of-penetration images for the three different target geometries with a variety of striking velocities.

3.3 Post-Mortem Sectioning

To gain insight into the possible mechanisms responsible for the penetration onset of the ceramic, post-

mortem characterization was conducted. After careful removal from their Ti6Al4V cups, the ceramics were sectioned and metallographically prepared. Cross-sections were examined using optical microscopy.

Figure 9 shows the cross-section for a 38.1 mm thick SiC-N ceramic target that was recovered. As shown in Figure 5, this ceramic target exhibited complete dwell. Numerous shear- and tensile-driven discrete cracks can be seen throughout the cross-section. Such discrete damage is challenging for continuum-based brittle solid material models to accurately capture. While it may be argued that this type of damage is unimportant (and doesn't need to be modeled), the results shown in Figure 7 when compared with the previous results of LaSalvia et al. (2001) and Lundberg et al. (2004) would suggest otherwise. Even if the current results are ignored, it must be acknowledged that the effects of fracture (i.e. tensile- and shear-driven cracks) must be captured accurately to properly model multiple-impact events on ceramic targets.

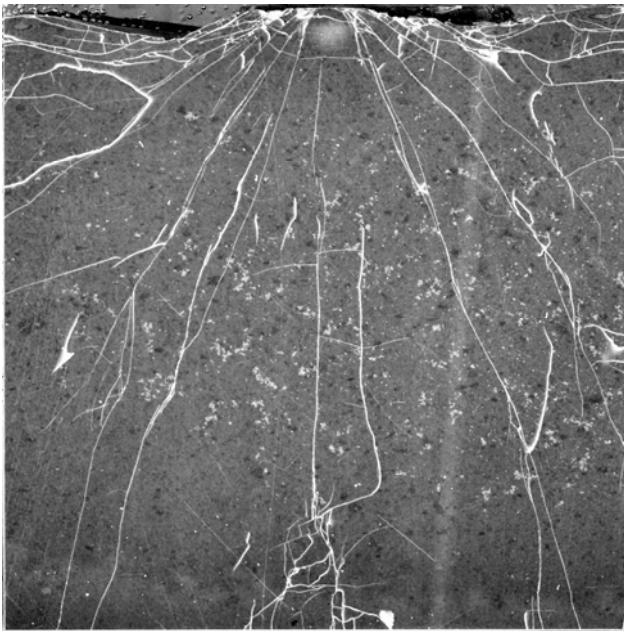


Fig. 9. Cross-section of recovered 38.1 mm thick SiC-N cylinder.

Figure 10 is a close-up of the region in the immediate vicinity of impact. The white round region immediately beneath the impact location is called the Mescall or comminuted region (McGinn et al., 1995). It is made up of a high-density of microcracks located along the grain boundaries of the ceramic (LaSalvia et al., 2001, LaSalvia et al., 2005). This region was also observed in many of the different types of ceramics that were recovered in the interface defeat experiments previously conducted by Hauver et al. (2005). However, a distinct difference between the damage shown in Figure 10 and that observed in Hauver's recovered ceramics (LaSalvia et al.,

2001), is the presence of high-angle cone cracks approximately half of a rod diameter out from the impact point. Figure 4 suggests that these high-angle cone cracks form very early in the ballistic event and that rod material can penetrate into them. This has been previously observed during penetration by Hauver et al. (2005) and most recently by Lundberg et al. (2005).

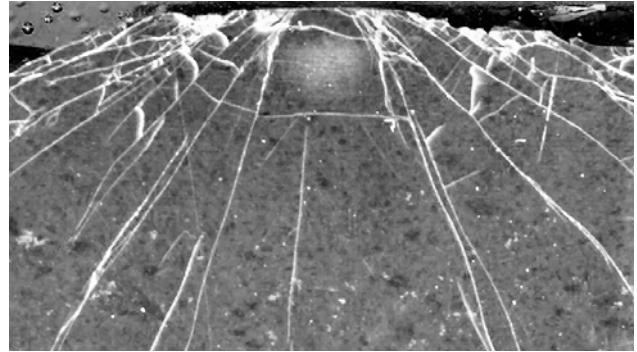


Fig. 10. Close-up of damage in the vicinity of impact.

Of particular interest to the numerical modelers is the appearance of similar features occurring in a wide variety of ceramic impact events. In both small- and large-scale experiments, with various target and projectile geometries, consistent failure patterns emerge. By recovering information from a variety of impact conditions, as well as from traditional dynamic experiments, it becomes possible to better evaluate computational tools for modeling and designing ceramic armors.

4. COMPUTATIONAL MODELING

Numerical modeling tools have been used for a number of years to capture the behavior of ceramics in systems of interest to the Army. The work of Johnson and Holmquist (1990) in the development of a constitutive ceramic model has been essential to furthering the understanding of how ceramics behave in an armor system. Current limitations in numerical tools have made it extremely difficult to apply the ceramic models developed in one code for a given experiment and then use it in a different application (Templeton et al., 2002). The brittle failure of ceramics and thus the extreme sensitivity to numerical code meshes and constitutive model implementations continually hamper efforts to obtain tractable and predictive ceramic tools.

One of the goals of this research effort was to obtain more specific information on the performance of a ceramic during a ballistic event, in order to improve ceramic constitutive models.

In parallel to these experimental methods, a comprehensive ceramic model development effort was

created by Brannon and others. One component of the Brannon Fossum Strack (BFS) model is a generalized plasticity model (Fossum and Brannon, 2004), which (because it was originally developed for geological materials) supports sophisticated third invariant dependence of strength that allows the failure criterion to vary *smoothly* from principal stress dominated failure at low pressure, Drucker-Prager behavior at intermediate pressures, and cap plasticity at extremely high pressure. To model ceramics, this geological model was enhanced to allow a smoothly evolving loss in strength, and concomitant degradation in elastic stiffnesses toward fully failed “sand-like” behavior. If used alone, any softening plasticity model will give mesh-dependent and therefore non-predictive results. Therefore, the BFS model includes an essential second component that imposes statistical uncertainties and scale effects to mitigate mesh dependence.

To approximate the overall effects of symmetry-breaking localized failure while minimizing mesh sensitivity, Brannon and Strack (2005), implemented a new failure distribution methodology that shares similarities to classic Weibull theory. In a sequence of indirect tension tests on SiC-N ceramics, Brannon and Lee (2005) demonstrated that median strength increases as sample size decreases, but absolute *uncertainty* in strength also increases with decreasing sample size. The BFS model applies these observed scale and statistical effects at the finite element level in such a way that failure probability (and net failure energy) for a finite domain is unaffected by whether or not that domain is subdivided into many or few elements. Incorporating realistic data-driven strength perturbations also gives a physical basis for the non-axisymmetric response (radial cracking) in an otherwise axisymmetric penetration event. Properly spaced radial cracking cannot be predicted without statistical perturbations (if radial cracks appear in a deterministic model, they are non-physical platform-dependent and mesh-dependent numerical artifacts).

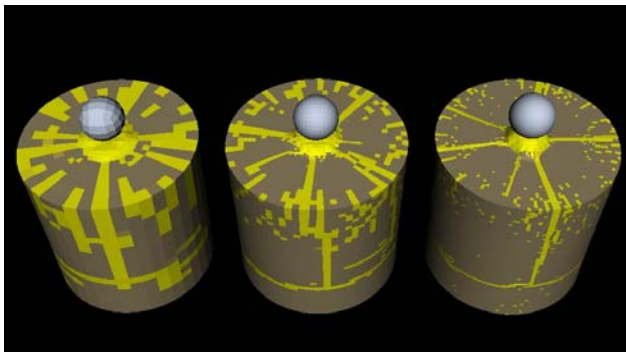


Fig. 10. Dynamic indentation simulation results showing mesh independence for three different mesh resolutions.

Figure 10 shows an implementation of the BFS model with statistical variability using three different

meshes for one of the ceramic benchmark experiments. It was found that both onset and progression variability was required to accurately capture the failure of a ceramic target during this ballistic event (Brannon and Strack 2005). Radial cracking can clearly be seen in each of the resolutions. Subsequent modeling showed the progression of the radial and cone cracking, and favorably reproduced the results seen for a number of these dynamic sphere impact experiments reported by Normandia and Leavy, (2004, 2005); LaSalvia et al., (2005).

After calibration and testing of the BFS ceramic model for SiC-N was underway, it was applied to the current PTI experiments. Prior to testing, the entire suite of ceramic geometries and velocities was simulated using the Johnson-Holmquist One (JH1) ceramic model for SiC-N (Leavy et al., 2005). It was implemented in the Eulerian hydrocode CTH (McGlaun et al., 1990), based on Holmquist’s silicon carbide model (Holmquist and Johnson, 2002). The velocities for the experiments were initially chosen based on these simulations. Due to some of the issues mentioned above, the model over-predicted the performance of the ceramic in these configurations. The dwell transition velocity for the simulations was found to be about 100m/s greater than the experimental results, with some other ceramic predictive features unable to be accurately captured.

Currently, the parametrics are being repeated using the BFS SiC-N ceramic model with statistical variability in ALEGRA. Figure 11 shows the current status of the PTI simulations utilizing the BFS model. The cover and surround are not displayed in the figure. In the BFS model, “coherence” is regarded loosely as 1 minus damage. Damage from the simulation at 24 μ s is plotted from blue (intact) to red (completely damaged).

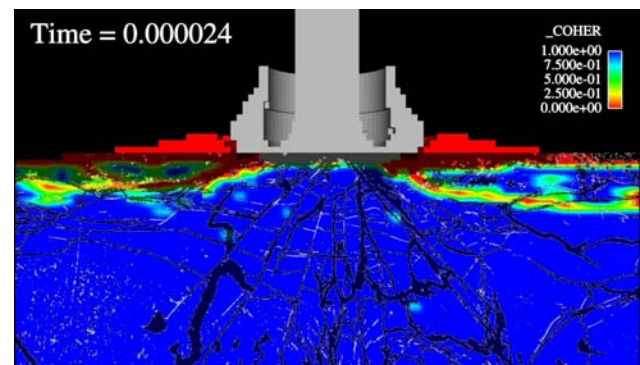


Fig. 11. A comparison of a radial mesh simulation of the 12.7 mm thick ceramic target versus a rod at 1000 m/s.

An overlay of the cross-sectioned experimental results was placed over the ceramic simulation results for a given time. By comparing the final crack morphology versus the progression of the simulation results, the authors are hoping to obtain calibration data for the rate

parameters of the model as well as a better understanding of how a ceramic fails in an armor system. The simulation used an Eulerian meshing scheme in order to capture the penetration event with rod erosion. Radial and traditional structured Eulerian meshes have been implemented. To reduce advection errors, which notoriously induce spurious “numerical healing” and which are even more severe with the high-frequency spatial variability essential for the BFS model, the ALEGRA framework is currently being revised to support Eulerian solutions to the momentum equation with Lagrangian tracking of spatially high-frequency history-dependent material variables. This work is a variant of the Material Point Method (Chen and Brannon, 2002).

Current efforts are also underway to improve the modeling of the other materials involved in these experiments. The time-dependent penetration of the rod into solid titanium, as well as system information like the dwell product behavior, and cover plate release, will all help improve the understanding of the ceramic armor systems being developed.

5. SUMMARY & CONCLUSIONS

A series of experimental and numerical methods has been introduced to enhance the Army’s understanding and development of lightweight ceramic armor systems.

Experimental equipment was developed to obtain time-dependent information on the behavior of ceramics in an armor system. In addition to this information, traditional DOP measurements, along with post-mortem sectioning and analysis were completed.

These experiments have been added to the suite of dynamic ceramic ballistic benchmarks that are used to assess the predictive capability of ceramic constitutive models. These experimental and numerical tools are essential for the Army’s current and future armor development programs.

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