Advances in Ceramic Armor VIII

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Michael Halbig
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The American Ceramic Society

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A Collection of Papers Presented at the 36th International Conference on Advanced Ceramics and Composites January 22–27, 2012 Daytona Beach, Florida

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Advances in Ceramic Armor VIII

Preface

Ten years have passed since the first Armor Ceramics focused session was held at the 27th Annual Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites in Cocoa Beach, FL in January 2003. The 9/11 terrorist attacks and the subsequent military conflicts in Iraq and Afghanistan quickly made "armor ceramics" a hot research topic. This became very apparent at the first presentation of this initial session. More colleagues came to "A Brief History of Ceramic Armor Development" by S.R."Bob" Skaggs than the conference room could handle. People were sitting on the floor and standing in the hallway outside the room. This necessitated an immediate room change and Bob graciously offered to give his talk again at the end of day for those who were unable to hear his initial presentation. That focused session contained 32 presentations in Novel Material Concepts, Dynamic Test and Modeling, and Transparent Ceramics.

In the ensuing decade the growth of the "Cocoa Beach meeting" necessitated a venue change north to Daytona Beach and a name change to the International Conference on Advanced Ceramics and Composites. At the same time Armor Ceramics became a symposium with increased participation from colleagues in Europe and Asia as well as an increase in the number of annual presentations covering additional topics such as Nondestructive Characterization, High-Rate Real-Time Characterization and Multi-Scale Modeling and Manufacturing. The symposium has become one of the premier international conferences for the latest developments in the fabrication, characterization and application of ceramic materials to meet the needs of the armor community. It continues to foster discussion and collaboration between academic, government and industry personnel from around the globe. The manuscripts contained in these proceedings are from some of the 70+ presentations that comprised the 10th edition of the Armor Ceramics Symposium.

On behalf of the organizing committee I would like to thank all of the presenters, authors, session chairs and manuscript reviewers for their efforts in making the symposium and the associated proceedings a success. As always success of the Symposium would not be possible without the support and tireless efforts of Marilyn Stoltz and Greg Geiger of The American Ceramic Society.

JEFFREY J. SWAB
Symposium Chair

Introduction

This issue of the Ceramic Engineering and Science Proceedings (CESP) is one of nine issues that has been published based on content presented during the 36th International Conference on Advanced Ceramics and Composites (ICACC), held January 22–27, 2012 in Daytona Beach, Florida. ICACC is the most prominent international meeting in the area of advanced structural, functional, and nanoscopic ceramics, composites, and other emerging ceramic materials and technologies. This prestigious conference has been organized by The American Ceramic Society's (ACerS) Engineering Ceramics Division (ECD) since 1977.

The 36th ICACC hosted more than 1,000 attendees from 38 countries and had over 780 presentations. The topics ranged from ceramic nanomaterials to structural reliability of ceramic components which demonstrated the linkage between materials science developments at the atomic level and macro level structural applications. Papers addressed material, model, and component development and investigated the interrelations between the processing, properties, and microstructure of ceramic materials.

The conference was organized into the following symposia and focused sessions:

Symposium 1	Mechanical Behavior and Performance of Ceramics and Composites
Symposium 2	Advanced Ceramic Coatings for Structural, Environmental, and Functional Applications
Symposium 3	9th International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology
Symposium 4	Armor Ceramics
Symposium 5	Next Generation Bioceramics

Symposium 6	International Symposium on Ceramics for Electric Energy Generation, Storage, and Distribution
Symposium 7	6th International Symposium on Nanostructured Materials and Nanocomposites: Development and Applications
Symposium 8	6th International Symposium on Advanced Processing & Manufacturing Technologies (APMT) for Structural & Multifunctional Materials and Systems
Symposium 9	Porous Ceramics: Novel Developments and Applications
Symposium 10	Thermal Management Materials and Technologies
Symposium 11	Nanomaterials for Sensing Applications: From Fundamentals to Device Integration
Symposium 12	Materials for Extreme Environments: Ultrahigh Temperature Ceramics (UHTCs) and Nanolaminated Ternary Carbides and Nitrides (MAX Phases)
Symposium 13	Advanced Ceramics and Composites for Nuclear Applications
Symposium 14	Advanced Materials and Technologies for Rechargeable Batteries
Focused Session 1	Geopolymers, Inorganic Polymers, Hybrid Organic-Inorganic Polymer Materials
Focused Session 2	Computational Design, Modeling, Simulation and Characterization of Ceramics and Composites
Focused Session 3	Next Generation Technologies for Innovative Surface Coatings
Focused Session 4	Advanced (Ceramic) Materials and Processing for Photonics and Energy
Special Session	European Union – USA Engineering Ceramics Summit
Special Session	Global Young Investigators Forum

The proceedings papers from this conference will appear in nine issues of the 2012 Ceramic Engineering & Science Proceedings (CESP); Volume 33, Issues 2-10, 2012 as listed below.

- Mechanical Properties and Performance of Engineering Ceramics and Composites VII, CESP Volume 33, Issue 2 (includes papers from Symposium 1)
- Advanced Ceramic Coatings and Materials for Extreme Environments II, CESP Volume 33, Issue 3 (includes papers from Symposia 2 and 12 and Focused Session 3)
- Advances in Solid Oxide Fuel Cells VIII, CESP Volume 33, Issue 4 (includes papers from Symposium 3)
- Advances in Ceramic Armor VIII, CESP Volume 33, Issue 5 (includes papers from Symposium 4)

- Advances in Bioceramics and Porous Ceramics V, CESP Volume 33, Issue 6 (includes papers from Symposia 5 and 9)
- Nanostructured Materials and Nanotechnology VI, CESP Volume 33, Issue 7 (includes papers from Symposium 7)
- Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials VI, CESP Volume 33, Issue 8 (includes papers from Symposium 8)
- Ceramic Materials for Energy Applications II, CESP Volume 33, Issue 9 (includes papers from Symposia 6, 13, and 14)
- Developments in Strategic Materials and Computational Design III, CESP Volume 33, Issue 10 (includes papers from Symposium 10 and from Focused Sessions 1, 2, and 4)

The organization of the Daytona Beach meeting and the publication of these proceedings were possible thanks to the professional staff of ACerS and the tireless dedication of many ECD members. We would especially like to express our sincere thanks to the symposia organizers, session chairs, presenters and conference attendees, for their efforts and enthusiastic participation in the vibrant and cutting-edge conference.

ACerS and the ECD invite you to attend the 37th International Conference on Advanced Ceramics and Composites (http://www.ceramics.org/daytona2013) January 27 to February 1, 2013 in Daytona Beach, Florida.

MICHAEL HALBIG AND SANJAY MATHUR
Volume Editors
July 2012

Contents

OPAQUE MATERIALS

Modeling and Dynamic Behavior

MESOSCALE MODELING OF THE DYNAMIC RESPONSE OF ARMOR CERAMICS

T. Antoun, O. Vorobiev, E.B. Herbold and Scott Johnson

ABSTRACT

Continuum mechanics based constitutive models are widely used in simulations of the macroscopic response of armor ceramics. These models rely on fitting parameters to phenomenologically describe inelastic processes that occur when the material is loaded beyond its elastic limit. As a result, there is no direct correlation between model parameters and the microstructural properties of the material. For this reason, phenomenological constitutive models tend to produce good results within the calibrated range, but they often lack the predictive capability required to extrapolate beyond this range. The predictive capability of phenomenological models can be improved by directly linking the macroscopic material response predicted by the models to the underlying microstructural deformation mechanisms. Recent advances in modeling capabilities coupled with modern high performance computing platforms enable physics-based simulations of heterogeneous media with unprecedented details, offering a prospect for significant advances in the state of the art. This paper provides an overview of some of these modern computational approaches, discusses their advantages and limitations, offers suggestions for post failure material properties that could improve predictability, and presents simulation results that elucidate several aspects of the complex behavior of armor ceramics and similar heterogeneous materials in extreme dynamic loading environments.

INTRODUCTION

Predictive capabilities for synthesis, processing, characterization, and performance of ceramic armor remain a modern day scientific frontier. In part this is due to a lack of comprehensive understanding of the complex physical processes associated with the transient response of armor materials—particularly in the post-failure regime, and in part it is due to numerical challenges that prohibit accurate representation of the heterogeneities that influence the material response. Numerous models attempting to describe the mechanical response and damage evolution in ceramic armor have been developed [e.g., Fahrenthold (1991), Rajendran et al. (2006), Holmquist and Johnson (2008), Bar-on *et al.* (2003)]. Under certain circumstances, these have proven useful. But there are many phenomena that these models cannot predict, because the underlying physics remains speculative. For example, comminuted material is known to form in front of penetrators (i.e. the Mescall zone) in glass/ceramic targets, but the relationship between target confinement and the creation and subsequent flow of comminuted material is not well understood (see Staudhammer et al. (2001) and Nemat-Nasser et al. (2002)). Regardless, most continuum models are empirically based, and strive to describe the structural damage evolution using bulk, heuristic parameters. In order for damage models to be more predictive and enjoy wider applicability, the macroscopic descriptions used should be based upon the underlying microstructural phenomena that inherently control nonlinear deformation and damage evolution in the material during loading. During armor penetration, penetrators advance into the target by expelling material from the Mescall zone. The large deformation associated with this displacement is accommodated through several non-linear, dissipative deformation mechanisms that include fracture and fragmentation, intergranular friction, granular flow with compaction or dilation of the comminuted material (see Fig. 1). These processes occur under conditions of extremely high pressure and strain rates, and collectively, they comprise the dynamic forces exerted by the armor on the penetrator. We aim to develop the modeling capabilities needed to provide a quantitative description of these dynamic forces in terms of the physical parameters that influence them. In turn, this will provide a transition from the current empirically based design methodology which relies heavily on testing to make incremental design improvements, to a rational approach which relies on predictive modeling capabilities to make revolutionary advances in the design of future advanced armor.

The macroscale behavior of ceramic armor during and after failure are emergent from the interactions at much smaller scales. At the grain-scale, granular materials exhibit highly non-linear, history-dependent, and discontinuous behavior. This occurs, as interfaces multiply, shift, and deform with the rough, plastically deformable and frictional contact areas at the inter-grain contacts. Experiments have shown that this results in variable spatially correlated (non-local) behavior emerging at scales greater than two orders of magnitude of the grain size for even loosely consolidated material [Thoroddsen, 2001]. The theoretical effect of this for traditional penetration modeling approaches with finite elements is grim, since they rely on the assumption of local material behavior for the continuum modeled bulk material (i.e., there exists a characteristic length scale) but also on constitutive models themselves that are narrowly calibrated and designed based on experimentally accessible material states. The calibrated range, therefore, represents a subset of the material states that exist during a penetration event. This phenomenology explains some of the failures of current methods to adequately predict material behavior during penetration and armor system performance.

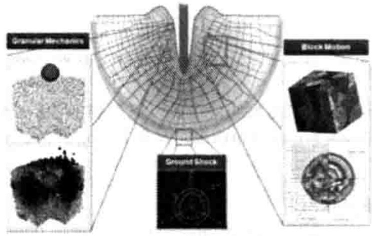

Figure 1. A schematic showing the various phases of dissipative non-linear deformation processes in the target during penetration.

Alleviating the shortcomings of existing methods requires the development of modeling capabilities that correlate observed macroscopic response to underlying physical mechanisms. This requires the development of integrated multiphysics code capabilities that capture the phenomenology of complex physical processes occurring across a wide range of time- ($\sim 10^{-6}$ to $\sim 10^{-2}$ s) and length- ($\sim 10^{-5}$ to $\sim 10^{0}$ m) scales. The large scale disparity necessitates the use of a multi-scale modeling approach wherein mesoscale simulations are utilized to correlate deformation mechanisms to underlying physical processes like fracture, comminution, and granular flow. The results of the mesoscale simulations are then used to develop a continuum model suitable for analyzing the response of a ceramic armor target during penetration. Of particular interest is the development of a predictive, robust and mesh-insensitive continuum model for the post-failure response of the material under high intensity dynamic loading conditions. This requires an integrated approach, which includes several regularization approaches for softening and damage such as flaw seeding, rate dependence and automatic identification and handling of localization bands. Fracture and comminution will lead to fragment size distributions that may include fragments that are larger than the cell size as well as fragments that are much smaller than the cell size. The larger fragments will be represented discretely, but the smaller fragments will require the development of an equivalent continuum model based on the meso-scale simulations.

In this paper we review existing experimental and numerical methods used to investigate the response of ceramic materials under dynamic loadings and propose an adaptive discrete-continuum numerical approach to model these materials. Specifically, we propose to evaluate the characteristic Representative Volume Element (RVE) size using meso-scale simulations and apply loading conditions recorded at the macro-scale. Thus, we will focus on using mesoscale modeling to fine tune a macro-scale continuum model for specific loading conditions relevant to the problems of interest.

REVIEW OF EXPERIMENTAL STUDIES AND MODELING APPROACHES

Experimental Studies

There has long been an interest in the protective strength of ceramic armor, and numerous experimental investigations have been performed to better understand the ballistic performance and penetration resistance of these materials under dynamic loading conditions [e.g., Klement et al. (2008), Strassburger (2009); Steinhauser et al. (2009), Grujicic et al. (2009), Behner et al. (2008)]. Anderson et al. (2009), and Orphal et al. (2009) studied failure in ceramics under conditions of long rod penetration. Anderson et al. (2009) investigated failure front propagation in borosilicate glass impacted by short gold cylindrical rods at impact velocities in the range 1-2 km/s. The failure front was observed to propagate in a wave-like fashion ahead of the penetrating rod, but propagation was arrested shortly after the rod was completely eroded. The time delay between complete erosion and the failure cessation was consistent with the release wave traveling from the tip of the penetrating rod to the location of the failure front.

Orphal et al. (2009) continued the work of Anderson et al. (2009) by studying failure in borosilicate glass during multiple short-rod impacts. The motion of the failure front was monitored using X-ray diagnostic techniques. The failure front velocity was found to increase with impact velocity, with the ratio of the failure front velocity to the penetration velocity decreasing with increased impact velocity, asymptotically approaching unity. The failure front was also limited to a propagation velocity lower than that of the shear wave velocity in the material. When the first and second rods were made of significantly different materials (Au or Cu), experimental results showed that the failure front velocity is a function of the driving stress rather than the impact velocity. Based on these results, the authors concluded that the failure wave is not a wave phenomenon but rather a result of nucleation and growth of cracks and, possible densification taking place during the impact.

Anderson et al. (2008) conducted a series of experiments to study projectile penetration into pre-damaged hot-pressed silicon carbide cylindrical targets at impact velocities ranging between 1 and 3 km/s. The targets ranged from thermally shocked but seemingly intact SiC to compacted SiC powder. The results of this study showed a linear dependence of penetration velocity on impact velocity with the slope remaining practically constant regardless of whether the target was intact or damaged.

Lynch et al. (2006) studied the influence of radial confinement on the resistance of Al_2O_3 ceramic tiles impacted by 1.8 and 2.6 km/s tungsten projectiles, and showed a slight increase in target performance under confinement. Iyer (2007) analyzed the fracture patterns in silicon carbide targets caused by an impact of tungsten carbide sphere with 500 m/s velocity. The author noted "the grain-scale microcracking directly underneath the impact region is three-dimensional, whereas macro-scale cracking in other regions are largely axisymmetric". The Hertz solution for a flat elastic half-space deformed by a spherical body was used to analyze the stress distribution compared to the crack pattern observed in experiments. Based on that comparison the author concluded that the majority of the observed cracking occurs during the loading phase and can be described using linear elasticity.

There exists a significant body of experimental investigations focused on the response of ceramic armor under a wide range of loading conditions. The vast majority of these experimental investigations addresses material behavior at the macro scale, and typically involves investigations of the response of ceramics during and after penetration, or measurements of static (e.g., toughness, hardness, yield strength) and dynamic (e.g., Hugoniot elastic limit, rate effects on yield strength) properties in strength-dominated regimes. Data obtained from these types of experiments are often used to calibrate phenomenologically based constitutive models that are used in hydrodynamic simulations of the response of ceramic armor during penetration. Relatively little attention is paid to the post-failure material response, and even less to the behavior of the failed material at the mesoscale,