Advances in Ceramic Armor, Bioceramics, and Porous Materials

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A Collection of Papers Presented at the 40th International Conference on Advanced Ceramics and Composites January 24–29, 2016 Daytona Beach, Florida

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Preface

I had the pleasure of being the lead organizer for the 14th Armor Ceramics Symposium in 2016 at the 40th International Conference on Advanced Ceramics and Composites. I am very grateful for the guidance and support that was provided by Jeff Swab, Andy Wereszczak, and the organizing committee in putting this symposium together. Consistent with the history of this symposium, we strived to create a program that would foster discussion and collaboration between researchers from around the world in academia, government, and industry on various scientific issues associated with the topic of armor ceramics.

The 2016 symposium consisted of approximately 50 invited, contributing, and poster presentations from the international scientific community in the areas of synthesis & processing, manufacturing, materials characterization, testing & evaluation, quasi-static & dynamic behavior, modeling, and application. In addition, because of their importance for the foreseeable future, this symposium also had special focused topic sessions on Glass, Additive Manufacturing, and Ballistic Behavior. Based on feedback from attendees, the 2016 symposium was a success, and the manuscripts contained in these proceedings are from some of the presentations that comprised the 14th edition of the Armor Ceramics Symposium.

On behalf of Jeff Swab and the organizing committee, I would like to thank all of the presenters, authors, session chairs, and manuscript reviewers for their efforts in making this symposium and the associated proceedings a success. I would also especially like to thank Andy Wereszczak, Tim Holmquist, Mike Golt, Steve Kilczewski, Kris Behler, Victoria Blair, and Nitin Daphalapurkar for hosting and chairing the symposium when we were unable to due to remnant effects of Sequestration.

This issue contains the proceedings of the “Next Generation Bioceramics” and “Porous Ceramics: Novel Developments and Applications” symposia of the 40th International Conference and Exposition on Advanced Ceramics and Composites (ICACC’15), which was held from between January 24th and January 29th, 2016 in Daytona Beach, Florida, USA.

A rapidly growing area of ceramic science & engineering involves the development of novel ceramic materials that facilitate the diagnosis and/or treatment of medical conditions. Researchers have recently developed several types of bioinspired and biomimetic ceramics, which imitate many of the attributes of materials that are found in nature. The "Next Generation Bioceramics" symposium addressed many topics associated with processing, characterization, modeling, and applications of ceramics for medical applications. Topics covered by the symposium included processing of advanced bioceramics; bioinspired and biomimetic ceramics; biomineralization; self-assembly of bioceramics; inorganic-organic composite materials; nanostructured bioceramics; mechanical properties of bioceramics; in vitro and in vivo characterization of bioceramics; bioceramics for drug delivery; bioceramics for gene delivery; bioceramics for sensing; and bioceramics for dental applications. This symposium facilitated productive discussions among various groups in the global bioceramics community, including academic researchers, industrial researchers, governmental researchers, and graduate students.

The symposium on Porous Ceramics dealt with innovations in processing methods and synthesis, membranes and high specific surface area ceramics, filters, innovative characterization methods and properties, especially mechanical ones, of porous ceramics. The presenters came from all over the world and the symposium was well attended by members of academia and industry.

Fabrication methods presented included direct foaming, freeze casting, replica and the use of sacrificial fillers, and great attention was devoted to the characterization of porosity and modeling of properties by using advanced Computed Tomography analysis. The experimental reliability of bending tests as well as the statistical analysis of strength data was discussed and examples of important technological applications such as advanced thermal insulation components, filters, membranes and parts for ultrasonic transducers. We are looking forward to the next symposium, in which the new innovations in this exciting field will be presented.

We would like to acknowledge the efforts of the authors and reviewers, without whom this volume would have not been possible. We thank the leadership of the Engineering Ceramics Division of The American Ceramic Society for their tireless efforts. We would also like to recognize Marilyn Stoltz and Greg Geiger of The American Ceramic Society, for their support and tireless efforts without which the success of these symposia would not be possible. We hope that this volume becomes a useful resource for academic and industrial efforts involving armor ceramics, porous ceramics and bioceramic materials. Finally, we hope that this volume facilitates advances in ceramic science & technology and contributes to the leadership of The American Ceramic Society in these emerging areas.

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Introduction

This collected proceedings consists of 104 papers that were submitted and approved for the proceedings of the 40th International Conference on Advanced Ceramics and Composites (ICACC), held January 24–29, 2016 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 Engineering Ceramics Division (ECD) of The American Ceramic Society (ACerS) since 1977. This year's meeting continued the tradition and added a few grand celebrations to mark its 40th year.

The 40th ICACC hosted more than 1,100 attendees from 42 countries that gave over 900 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 2016 conference was organized into the following 17 symposia and 5 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	13th International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology
Symposium 4	Armor Ceramics: Challenges and New Developments
Symposium 5	Next Generation Bioceramics and Biocomposites
Symposium 6	Advanced Materials and Technologies for Direct Thermal Energy Conversion and Rechargeable Energy Storage
Symposium 7	10th International Symposium on Nanostructured Materials: Functional Nanomaterials and Thin Films for Sustainable Energy Harvesting, Environmental and Health Applications

Symposium 8	10th International Symposium on Advanced Processing & Manufacturing Technologies for Structural & Multifunctional Materials and Systems
Symposium 9	Porous Ceramics: Novel Developments and Applications
Symposium 10	Virtual Materials (Computational) Design and Ceramic Genome
Symposium 11	Advanced Materials and Innovative Processing ideas for the Production Root Technology
Symposium 12	Materials for Extreme Environments: Ultrahigh Temperature Ceramics (UHTCs) and Nano-laminated Ternary Carbides and Nitrides (MAX Phases)
Symposium 13	Advanced Materials for Sustainable Nuclear Fission and Fusion Energy
Symposium 14	Crystalline Materials for Electrical, Optical and Medical Applications
Focused Session 1	Geopolymers, Chemically Bonded Ceramics, Eco-friendly and Sustainable Materials
Focused Session 2	Advanced Ceramic Materials and Processing for Photonics and Energy
Focused Session 3	Materials Diagnostics and Structural Health Monitoring of Ceramic Components and Systems
Focused Session 4	Additive Manufacturing and 3D Printing Technologies
Focused Session 5	Field Assisted Sintering and Related Phenomena at High Temperatures
Focused Session 6	Hybrid Materials and Processing Technologies
Special Symposium	40th Jubilee Symposium: Engineered Ceramics—Current Status and Future Prospects
Special Symposium	5th Global Young Investigators Forum
Special Symposium	Emerging Technologies Symposium: Carbon Nanostructures and 2D Materials and Composites

The proceedings papers from this conference are published in the below seven issues of the 2016 CESP; Volume 37, Issues 2–7, as listed below.

- Mechanical Properties and Performance of Engineering Ceramics and Composites XI, CESP Volume 37, Issue 2 (includes papers from Symposium 1)
- Advances in Solid Oxide Fuel Cells and Electronic Ceramics II, CESP Volume 37, Issue 3 (includes papers from Symposia 3 and 14)
- Advances in Ceramic Armor, Bioceramics, and Porous Materials, CESP Volume 37, Issue 4 (includes papers from Symposia 4, 5, and 9)
- Advanced Processing and Manufacturing Technologies for Nanostructured and Multifunctional Materials III, CESP Volume 37, Issue 5 (includes papers from Symposia 8 and 11 and Focused Sessions 4 and 5)
- Ceramic Materials for Energy Applications VI, CESP Volume 37, Issue 6 (includes papers from Symposia 6 and 13 and Focused Session 2)
- Developments in Strategic Materials II, CESP Volume 37, Issue 7 (includes

papers from Symposia 2, 10, 12, Focused Sessions 1, and the Special Symposia on Carbon).

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 41st International Conference on Advanced Ceramics and Composites (http://www.ceramics.org/icacc2017) January 23-28, 2017 in Daytona Beach, Florida.

To purchase additional CESP issues as well as other ceramic publications, visit the ACerS-Wiley Publications home page at www.wiley.com/go/ceramics.

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Volume Editors
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Armor Ceramics

A COMPARISON OF DAMAGE IN GLASS AND CERAMIC TARGETS

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Keywords: Cone Crack, Impact, Indentation, Ceramic, Damage

Abstract

The high strength and low density of many ceramics and the transparency and low cost of glasses make them potentially useful candidates for many applications, including armor. Both ceramics and glasses are very brittle and they can go through a complex fracture process when impacted. Ballistic impacts on ceramics produce different types of damage including varying levels of comminution, cone cracking, and radial cracking. Sphere impacts on brittle targets are a useful way to study the evolution of ceramic damage. We performed sphere impact experiments on fused silica glass targets. This work is compared with X-ray computed tomography scans of recovered samples generated from previous work on boron carbide [B. Aydelotte and B. Schuster, in Dynamic Behavior of Materials, Volume 1, Springer International Publishing, 2016, pp. 19-23.]. The damage morphologies of the sphere impacted fused silica and boron carbide targets are compared. We found that cone cracks in boron carbide and fused silica have the same general shape in response to temporally and spatially changing loads and appear to exhibit cone rotation that is related to the component of the velocity tangential to the target surface. Cone angles in boron carbide were larger when measured in a plane which contains the shot-line vector and intersects the apex of the fracture conoid. Measurements of the fracture cone angle on a plane perpendicular to the plane containing the shot-line vector were consistently smaller for the same velocity. Measurements of cone angles in fused silica exhibited no such trends.

Introduction

Damage due to normal impact on ceramics and glasses has received considerable attention (see for example [1, 2, 3, 4, 5, 6, 7]). Earlier research has demonstrated that the formation of cone cracks tends to happen at characteristic cone angles and that increasing impact velocity tends to lead to decreases in the cone angle (see for example [1]).

Relatively less published literature exists on the oblique impact of ceramics. Salman et al. [8] studied the effect of oblique impacts on alumina particles, finding that oblique impacts resulting in mostly similar forms of damage with lower probability of failure, likely due to the reduced normal velocity component.. Much of the oblique impact literature is similar to that published by Sandanandan and Hethrington [9] and Hohler et al. [10]. Sadanandan and Hethrington[9] and

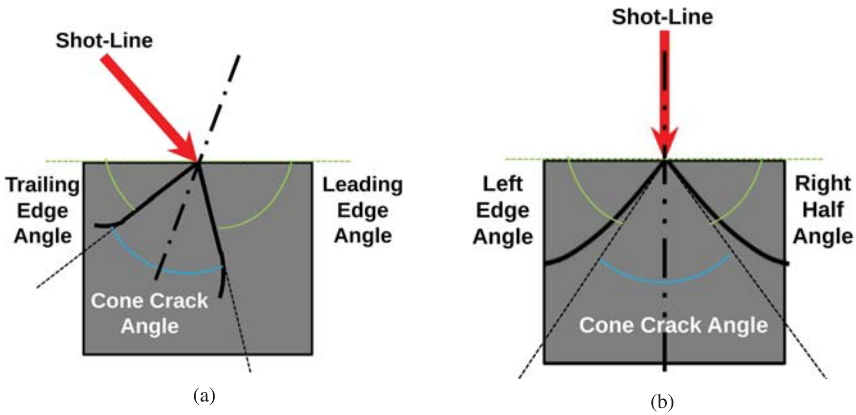

Figure 1: Diagrams of our terminology for the various angles associated with cone cracking in normal and oblique impacts and how they are measured. (a) Schematic of a cone crack resulting from an oblique impact and the leading and trailing edge angles as viewed in a plane which contains the shot-line and intersects the apex of the cone crack. The terms leading and trailing edge angles are used when referring to a cone crack, resulting from an oblique impact, as viewed in the plane containing the shot-line as shown here. (b) Schematic of symmetric cone crack with left and right edge angles indicated. This schematic also represents a cone crack resulting from an oblique impact as viewed from a plane perpendicular to the one defined in (a).

Hohler et al. [10] focused primarily on studying various simplified armor packages impacted at different obliquities and their resistance to single impacts as measured by metrics like V_{50}. There was little information on characterizing impact-induced damage. Fawaz et al. [11] presented results of modeling oblique and normal impacts on ceramic targets. They reported the ability to accurately model conoid formation, though no simulation images of fracture conoids from normal and oblique impacts were presented. Some sliding indentation studies on polycrystalline ceramic materials have been published [12, 13, 14].

Some studies of damage in oblique glass targets have also been published [15, 16, 17]. For the purpose of studying the phenomenology of damage in the glass targets, the work published by Chaudhri and Liangyi [15] and Forde et al. [17] are the most useful. Forde et al. [17] reported a series of normal and oblique impacts on borosilicate glass targets by mild steel rods and published some high speed camera images of damage formation in the borosilicate glass targets. They were able to measure cone angles for some of the impacts at normal incidence, but provided little quantitative information about oblique impacts.

Chaudhri and Liangyi [15] conducted sphere impact studies on glass targets at various obliquities and filmed the damage evolution using a high speed camera. They observed that cone cracks, which form as a result of oblique impacts, form such that the leading edge of the cone crack tilts away from the impact surface toward the bottom surface and the trailing edge of the cone crack tilts toward the impact surface as a result of the changing position of the center of pressure as the projectile translates down the target. Chaudhri and Liangyi [15] deemed the effect of friction on the cone crack orientation insignificant by visualizing the stress field with circularly polarized light. The resulting fringes are symmetric about the surface normal suggesting that minimal shear

Table 1: Selected mechanical properties of hot-pressed B_4C and fused silica. The B_4C values are taken from from Vargas-Gonzalez et al. [19]. The fused silica properties are drawn from various sources.

Density	Elastic Modulus	Knoop Hardness	Fracture Toughness
2500 kg/m^3	445.5 GPa	2019±60 kg/mm^2 (HK2)	2.90±0.4 MPa$\sqrt{m}$
2200 kg/m^3 [20]	72.9 GPa [20]	540 kg/mm^2 [21]	–

stress is transmitted across the interface. However, this is early in the impact when surface damage is very minimal.

Aydelotte and Schuster [18] conducted normal and oblique impact experiments to study the damage morphology in polycrystalline ceramics. In this paper, they compared the cone cracking induced by normal and oblique impacts from tungsten carbide spheres on hot-pressed boron carbide (PAD B_4C) targets. They observed that cone cracks which form in ceramics as a result of oblique impacts have concave down curvature on the leading edge of the cone crack and concave up curvature on the trailing edge; the same mechanisms at work as with Chaudhri and Liangyi [15].

Experimental Setup

In this paper, the terminology for the various cone crack related angles and how the angles will be measured are shown in Fig. 1a and 1b. The rotation of the cone crack is equal to one half of the difference between the edge angles. Where the top surface is not sufficiently intact to provide a measurement, the appropriate angle with the bottom surface is measured.

The experimental setup for the ceramic cylinders is described in some detail in [18] and it will be repeated here briefly. B_4C cylinders 38.1 mm (1.5 in) diameter x 25.4 mm (1.0 in) in length were impacted with 6.35 mm diameter (0.25 in) tungsten carbide-6% cobalt (WC) spheres. Some selected properties of pressure assisted densification (PAD) formed boron carbide are shown in Table 1. Impact experiments were conducted at three different obliquities: 0°, 30°, and 60°. The spheres were fired out of a 0.30 caliber smooth-bore laboratory powder gun using discarding sabots at velocities between 200 and 500 m/s. The experimental setup is diagrammed in Fig.2.

In Aydelotte and Schuster [18], flash X-ray systems were used to view the cone cracks and make measurements. In some cases the flash X-rays were found to have some alignment issues so only measurements derived from XCT will be discussed here.

The experiments conducted on glass cylinders here are very similar to those conducted previously. Fused silica cylinders were procured from McMaster-Carr (Princeton, NJ). The cylinders were 38.1 mm (1.5 in) diameter x 19.05 mm (0.75 in) in length; some selected properties of fused silica are shown in Table 1. The cylinders were transparent on the ends and had a ground finish on the cylinder sides. The fused silica cylinders were impacted using either steel or borosilicate glass spheres. The steel spheres generally did so much damage to the cylinders that it was difficult to recover the samples for further analysis. Both the steel and glass spheres were 6.35 mm diameter (0.25 in). The steel spheres were bearing balls made from hardened 52100 steel. The steel spheres had an average mass of 1.044 ± 0.001 g. The borosilicate glass spheres were purchased from Winsted Precision Ball. Their average mass was 0.328 ± 0.001 g. The spheres were fired out of a .30 caliber smooth-bore laboratory powder gun using full-caliber plastic obturators at velocities between 200 and 500 m/s. The obturators generally yielded better accuracy than discarding sabots, but at the cost of having the plastic obturators strike the targets.

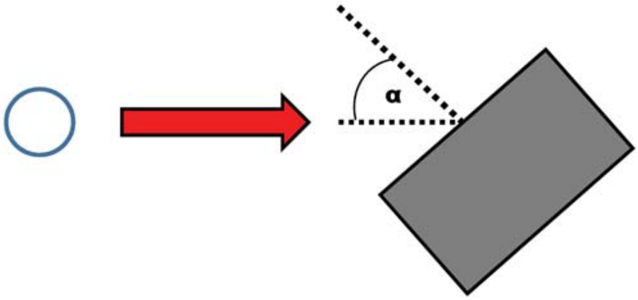

Figure 2: Schematic of the impact experiments showing the obliquity measurement.

XCT scans were performed on the recovered samples. The XCT machine used for scanning all of the samples was a Northstar Imaging X5000 with a Varian HPX-450 tube. The max potential is 450 kV with a spot size of 0.4 mm. The detector is a Perk and Elmer XRD 1621 AN3 ES with a pitch of 200 microns.

Experimental Results and Discussion

Cone cracks which form as a result of normal impacts are axisymmetric as shown in Fig. 1b unless the impact is off-center leading to non-uniform edge effects or the sample has material heterogeneities. Near the impact surface, the cone angle is relatively constant and the main axis of the cone is perpendicular to the surface and co-axial with the intact surface normal vector. When cone cracks are formed as a result of non-normal impacts, the cone angle is no longer axisymmetic. We have chosen to measure the cone angle in a plane containing the shot-line (shown schematically in Fig. 1a and in samples of boron carbide and fused silica in Fig. 3a and 3c) and in a plane perpendicular to plane containing the shot-line (shown schematically in Fig 1b and in samples of boron carbide and fused silica in Fig. 3b and 3d) with both planes intersecting the apex of the fracture conoid. When the cone angle is measured in each of these two views it is not necessarily the same for oblique impacts and indeed can be quite different as will be shown hereafter. The cone crack's main axis is also not necessarily perpendicular to the intact surface.

Cone cracks which form as a result of oblique impacts have concave down curvature on the leading edge and concave up curvature on the trailing edge. An example of this is shown in Fig. 3a for boron carbide and a partial cone crack in fused silica in Fig. 3c. Qualitatively, the shape and orientation of the cone cracks resulting from oblique impacts in fused silica look very similar. This same phenomena was observed by Chaudhri and Liangyi [15]. This was reported previously in boron carbide by Aydelotte and Schuster [18]. We believe this is a result of several factors. As the center of maximum applied pressure translates along the surface, the cone crack reorients itself due to the spatially and temporally varying stress field from the projectile and/or debris sliding along as reported by Chaudhri and Liangyi [15] also concluded that the movement of the point of contact was the cause of the curved cone cracks they observed in glass. There may also be some effect from applying a shear load to the surface through friction, though Chaudhri and Liangyi [15]