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13. ABSTRACT (Maximum 200 words)

The objectives of this project were to quantify the strength of shocked ceramics during uniaxial strain and to understand the mechanisms that govern shock wave induced inelastic deformation. Dense, polycrystalline silicon carbide (SiC) was selected for this study and two independent measurement techniques (lateral and longitudinal stress determination using in-material piezoresistance gauges; and combined compression and shear wave propagation) were used to examine the shocked state. Nonlinear elastic response below the Hugoniot Elastic Limit (11.5 GPa) was quantified. In the shocked state, the maximum shear stress increases from 4.5 GPa at the HEL to 7.0 GPa at twice the HEL. The inelastic deformation was interpreted as a combination of in-grain micro-plasticity and highly confined micro-fissures. The results suggest that confinement stress, inherent in shock wave loading, plays a dominant role. To reconcile the high strength in compression and very low strength in tension, unloading wave profiles were obtained using in-situ gauges. These data provided a determination of the Unloading Elastic Limit (UEL) and demonstrated that UEL decreases with increasing peak stress. The shocked SiC despite apparent strengthening undergoes damage, at least partially. Material models were developed to incorporate pressure dependent strength and damage in shocked SiC.

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A. PROBLEM STATEMENT AND APPROACH

A good understanding of the response of ceramics under shock wave uniaxial strain compression is important for the use of these materials in armor applications involving rapid impulsive loading. Because of the potential as an armor material (due to their lightweight and high strength), many engineering ceramics have been characterized in shock wave experiments. Ceramic response is significantly different from that of a metal under shock loading because ceramics display considerably higher Hugoniot Elastic Limit (HEL), but their spall strength is lowered when shocked beyond the HEL. This behavior leads to a number of scientific questions that also have a bearing on armor penetration: What material mechanisms govern inelastic deformation in shocked ceramics? What is the primary reason (high strain rate or inertial confinement) that ceramics have high HEL values? What is the nature of the material state in a ceramic shocked beyond its HEL? These questions are relevant to penetration in ceramics because the penetrator is moving into a material that has been subjected to a large amplitude shock wave.

An important first step in addressing the issues above involves a quantitative determination of the material strength (the ability to support stress deviators) in the shocked state. However, the usual longitudinal, shock wave measurements by themselves are insufficient to determine the strength properties in the shocked state. Determination of stress deviators or mean stress in shocked ceramics is important to fully characterize their mechanical state and to gain insight into the nature of inelastic deformation under shock loading.

In this ARO project, we carried out an in-depth investigation on a selected ceramic: a dense, polycrystalline silicon carbide (SiC) manufactured by Cercom. This material was selected in consultation with Dr. D. P. Dandekar of the Army Research Laboratory, who provided all of the samples examined in this study. Two completely different types of experimental measurements were used in our work: lateral and longitudinal stress determination using in-material, piezoresistance gauges; and combined compression and shear wave measurements using in-situ electromagnetic velocity gauges. By using two independent methods, the shocked state can be characterized accurately.

Our experimental studies were a good complement to other plate impact studies on SiC carried out at ARL (Dr. D. P. Dandekar) and Sandia National Laboratories (Drs. D. E. Grady and D. Crawford).

B. SUMMARY OF IMPORTANT RESULTS

1. Shock response of polycrystalline SiC was examined experimentally using two independent methods and the results were consistent.

2. Compression and shear wave data showed that Poisson's ratio increased from an ambient value of 0.16 to 0.19 at the Hugoniot Elastic Limit (11.5 $\pm$ 0.4 GPa).

3. In SiC, the elastic-inelastic transition is not distinctive. Using independent methods, the mechanical state was fully characterized under shock wave uniaxial strain. In the shocked state, the material supports a maximum shear stress that increases from 4.5 GPa at the HEL to 7.0 GPa at twice the HEL.

4. The post-HEL behavior, as inferred from the shock wave data, resembles neither massive cracking or classical plasticity response. Confined stress, inherent in shock wave experiments, plays a dominant role in such behavior. We interpret the observed inelastic deformation qualitatively using a combination of in-grain micro-plasticity and highly confined micro-fissures. Our results suggest that confinement will play an important role in the use of SiC (and similar ceramics) in armor applications.

5. As a part of this work, a comprehensive effort was completed to develop an in-depth analysis of lateral stress gauges in shocked solids. This development permits a reliable approach to specifying the full stress state in a shocked solid and is expected to be applicable for a broad range of materials.

6. Unloading response of the SiC was examined, using in-situ particle velocity gauges, to reconcile the following material behavior: SiC has a large strength in the shock compressed state but is very weak in tension. Through careful unloading experiments and their analysis, we determined the Unloading Elastic Limit (UEL), which is a measure of the elastic jump (from the peak state) during unloading. The maximum shear stress associated with the UEL decreases with increasing peak stress. Our results suggest that despite the apparent strengthening in the shocked state due to inertial confinement (item 3), the material is damaged (at least partially) due to shock wave compression. To the best of our knowledge, results in item 3 and the unloading results have provided unique information and constitute a major contribution from this work.

7. In addition to the pressure-dependent strength model used successfully for modeling compression wave data, we have also carried out work on the development of a continuum model to incorporate damage in shocked SiC.

In conclusion, the work carried out under this ARO project has provided novel experimental results that, in turn, have provided new and interesting insight into shock wave induced inelastic deformation in a dense, polycrystalline ceramic.

Dr. D. P. Dandekar, of the Army Research Laboratory, is sincerely thanked for his considerable help throughout the course of this project.

C. PUBLICATIONS

Manuscripts Published

"Shock response of polycrystalline silicon carbide undergoing inelastic deformation," R. Feng, G. F. Raiser, and Y. M. Gupta, J. Appl. Phys., 79(3), 1378 (1996).

"Dynamic strength and inelastic deformation of shocked polycrystalline silicon carbide," R. Feng, G. Yuan, G. F. Raiser, and Y. M. Gupta, Proceedings of the 14th US Army Symposium on Solid Mechanics, October 16-18. 1996, Myrtle Beach, South Carolina, p. 39.

"Dynamic analysis of the response of lateral piezoresistance gauges in shocked ceramics", R. Feng, Y. M. Gupta, and M. K. Wong, J. Appl. Phys., 82(6), 2845 (1997).

"Dynamic strength and inelastic deformation of ceramics under shock wave loading" R. Feng, Y. M. Gupta, and G. Yuan, Shock Compression of Condensed Matter – 1997, 483 (AIP Publication 1998).

"Material strength and inelastic deformation of silicon carbide under shock wave compression," R. Feng, G. F. Raiser, and Y. M. Gupta, J. Appl. Phys., 83(1), 79 (1998).

"Determination of lateral stresses in shocked solids: Simplified analysis of piezoresistance gauge data," R. Feng and Y. M. Gupta, J. Appl. Phys., 83(2), 747 (1998)

"Continuum measurements and modeling of strength degradation in shocked silicon carbide," J. L. Ding and Y. M. Gupta, Proceedings of the 14th Ceramic Modeling Working Group Meeting, February 8-10, 1999, University of Texas, Austin, p. 329.

"Compression and shear wave measurements to characterize the shocked state in silicon carbide," G. Yuan, R. Feng, and Y.M. Gupta (submitted to J. Appl. Phys.)

Manuscripts In Preparation

"Continuum modeling of strength degradation in shocked silicon carbide."

"Unloading response of shocked silicon carbide."

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