Lateral stress evolution in Chromium Sulfide

O E Petel\textsuperscript{1}, G J Appleby-Thomas\textsuperscript{2}, A Hameed\textsuperscript{2}, A Capozzi\textsuperscript{3}, S Goroshin\textsuperscript{3}, D L Frost\textsuperscript{3} and P J Hazell\textsuperscript{4}

\textsuperscript{1} Carleton University, Mechanical and Aerospace Engineering, Ottawa, ON, K1S 5B6, Canada
\textsuperscript{2} Cranfield Defence and Security, Cranfield University, Shrivenham, Swindon, SN6 8LA, United Kingdom
\textsuperscript{3} McGill University, Department of Mechanical Engineering, Montréal, QC, H3A 0C3, Canada
\textsuperscript{4} School of Engineering and Information Technology, University of New South Wales, Canberra, Northcott Drive, Canberra, ACT 2600, Australia

E-mail: oren.petel@carleton.ca

Abstract. In this paper the shock response of CrS, a cermet of potential interest as a matrix material for ballistic applications, has been investigated. Compacts with a Chromium:Sulfur ratio of 1.15:1 were investigated via the plate-impact technique. These experiments allowed the material to be loaded under a one-dimensional state of strain. Embedded manganin stress gauges were employed to monitor the temporal evolution of longitudinal and lateral components of stress. Comparison of these two components has allowed assessment of the variation of material shear strength both with impact pressure/strain-rate and time.

1. Introduction

Metal matrix composites (MMCs) have been investigated extensively for their ballistic and high strain rate response. MMC systems involving ceramic inclusions integrated within an aluminum or titanium matrix have been of particular interest [1-3]. In the present study we investigate the dynamic material strength of CrS, which could be a candidate MMC matrix material, under plate impact loading conditions instrumented with manganin gauges.

Chromium Sulfide (CrS) can be produced using a flame synthesis technique known as Self-propagating High-temperature Synthesis (SHS) [4,5], which involves a gasless reaction between sulfur and chromium. The product of this reaction is a cermet, with varying amounts of metal integrated into its microstructure, depending on the stoichiometry of the green mixture. Using flame synthesized CrS could provide several advantages over other matrix materials. The ductility of the CrS can be controlled through the variation of the stoichiometry of the green mixture, enabling the CrS to contain excess chromium for increased ductility. Sulfur has a low melting point, meaning that the green mixture can be prepared as a slurry, enabling low cost near net shape synthesis of complex forms. Further, the high-temperatures involved in the synthesis could result in favorable adhesive properties to other materials.

The dynamic response of CrS was investigated using a plate impact experimental technique, involving embedded manganin gauges to determine the temporal evolution of the principal stresses within the specimens. Manganin gauges have been used extensively to measure the principal stress histories with a variety of materials [6-9]. The investigation of the dynamic response of CrS involved measurements of the lateral and longitudinal stress histories within a sample of CrS from which the dynamic strength of the material can be calculated.
2. Material preparation and experimental configuration

The synthesis of the CrS samples involved a multi-stage process involving chromium (Atlantic Equipment Engineers) and sulfur (American Chemicals Ltd.) powders mixed with a molar ratio of 1.15:1 (excess chromium). The chromium powder that was used in these studies had a mean particle size of 5 microns. The powders were premixed on a roller mill for an hour prior to melting the sulfur in a heating sleeve, which resulted in a thick slurry of liquid sulfur and chromium powder, the green mixture. This slurry was then placed under vacuum while being agitated on a vortex mixer to remove any trapped gases. The green mixture was then cast into a preheated mould and placed in a reaction chamber with a nichrome wire embedded in it. The chamber was pressurized to 275 bar at which point the nichrome wire was used to ignite the mixture.

The initiated reaction was highly exothermic and was almost completely gasless, whereby the combustion reaction resulted in a solid final product. Due to the high temperature of the synthesis process, the development of thermal stresses can lead to internal cracking of the final product, CrS. In order to reduce the occurrence of these thermal cracks, a technique was used to directionally cool (solidify) the final material. A more thorough discussion of the synthesis process is found in [10]. The CrS that was used in the present study had a density of approximately 3.68 g/cc, which represents 92% of the theoretical maximum density. A photograph of the bulk CrS samples and an optical microscope image of one of the samples are shown in figure 1.

The experiments were carried out with a 50-mm internal bore single-stage gas gun, which provided flyer plate velocities in the range of 316 to 877 m/s for the present study. Three flyer plate types were used in the present study, a 10 mm thick aluminum plate, a 10 mm thick copper plate, and a 5 mm copper plate. Using the three different impactor configurations allowed for a broader range of stress states to be investigated given the velocity constraints of the gas gun. The gas gun muzzle and relative diagnostic configuration can be seen from the two schematics in figure 2.

The CrS samples were cut and polished to enable the manganin gauge placement, each piece measured 25 x 25 x 60 mm. The longitudinal manganin gauge was placed between the cover plate, which was matched to the flyer plate material, and the CrS in a Mylar encasement similar to the configuration described in [7]. The lateral manganin gauge was inserted 4 mm from the impact face of the CrS samples in the center of the impact plane. The manganin gauges that were used in the present study were sourced from Vishay Micro-Measurements and were of type LM-SS-125CH-048 and J2M-SS-580SF-025 for the longitudinal and lateral stress measurements respectively.
3. Results and discussion
A total of four experiments were conducted with the present configuration, measuring both the longitudinal and lateral stress histories in the same experiment. The longitudinal and lateral stress histories within CrS under the various impact conditions are shown in figures 3. The signals have had their time axis translated for comparison purposes, such that the stress histories all begin to rise at the same initial time. Several features of the stress histories should be noted, particularly in the lateral gauge signals (figure 3b). The lateral gauge signals possess a multi-stage rise, which might be indicative of an elastic precursor in the material under these impact conditions. It should be noted however, that the rate-dependency of the lateral stress history and the level of porosity in the CrS samples make it difficult to differentiate between the Hugoniot elastic limit and the effects of porosity. Further, it is worth emphasizing that the complexity of lateral gauge interpretation makes detection of such features difficult [6,12-14].

The density of the CrS samples was approximately 3.68 g/cc or 92% TMD, thus there was a significant amount of porosity within the samples (this is seen in figure 1). The relatively long
risetimes in the lateral stress signals is interpreted as being the result of pore collapse within the CrS. This material response was highly dependent on the impact velocity of the plate loading the sample, with a sharper risetime seen at higher impact pressures.

The shock Hugoniot of the CrS samples is shown in figure 4a. To aid in lateral gauge interpretation as well as for reference purposes, the longitudinal sound speed as well as the shear velocity was measured in the samples. While the Hugoniot data is sparse for this material, it is interesting to note that the general trend of the data illustrates a minimum in the wave speed that can be extrapolated back to the longitudinal wave speed. This type of wave propagation behaviour has been previously observed in another cermet, a cemented carbide (WC-Co), and has been attributed to the multi-phase response of the material [11]. However, a larger dataset would be necessary to make any conclusive remarks concerning the behaviour of CrS, particularly considering the effect that the porosity of the samples have demonstrated on the wave structure.

The primary interest of the present study was to determine the dynamic material strength of the CrS samples. The deviatoric component of stress within a material can be determined through the measurement of the principal stresses in a material using the expression,

\[ \tau = \frac{\sigma_{\text{long}} - \sigma_{\text{lat}}}{2} \]  

where \( \tau \) is the deviatoric stress in the material and \( \sigma_{\text{long}} \) and \( \sigma_{\text{lat}} \) are the longitudinal and lateral principal stresses in the material, respectively. The deviatoric stress histories within the CrS samples, shown in figure 4b, demonstrate an initial transient response that seems to scale with the impact velocity followed by a convergence to a common value for all impact conditions. It should be noted that this representation of the deviatoric component stress is biased toward higher values at early times due to the longer rise time of the stress in lateral gauge data. The result is an early transient portion of the signal that is likely a significant overestimate of the actual deviatoric stresses seen in the material. Despite these initial overestimates, it appears that the deviatoric stress histories converge quickly to a common value of approximately 1 GPa, independent of the impact conditions, a measure of the dynamic strength of the CrS material tested.

**4. Conclusions**

A material of possible interest as a matrix material in an MMC type armour configuration has been investigated using plate impact loading to determine its dynamic shear strength at
relevant loading conditions. The experimental results show that the wave propagation in the cermet is influenced by the collapse of the pores within its microstructure, an effect that is more pronounced at low impact velocities. Through measurement of the principal stresses within the CrS samples, the dynamic shear strength of the cermet was determined, showing that the CrS has a significant strength under dynamic loading.

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References
[1] Bless S J, Jurick D L, Timothy S P and Reynolds M A 1992 In Shock-Wave and High Strain Rate Phenomena in Materials 1051.
[2] Vaziri R, Delfosse D, Pageau G and Poursartip A 1993 Int. J. Impact Eng. 13 329.
[3] Gu Y and Nesterenko V F 2007 J. Compos. Mater. 41 2313.
[4] Merzhanov A G 1994 Combust. Sci. Technol. 98 307.
[5] Goroshin S, Miera A, Frost D L and Lee J H S 1996 Symp. Int. Combust. Proc. 26 1883.
[6] Rosenberg Z, Yaziv D and Partom Y 1980 J. Appl. Phys. 51 3702.
[7] Millett J C F, Bourne N K Rosenberg Z 1996 J. Phys. D: Appl. Phys. 29 2466.
[8] Appleby-Thomas G J and Hazell P J 2010 J. Appl. Phys. 107 123508.
[9] Petel O E and Higgins A J 2010 J. Appl. Phys. 108 114918.
[10] Capozzi A 2013 M. Eng. Thesis, McGill University.
[11] Appleby-Thomas G J, Hazell P J, Stennett C, Cooper G, Helaar K and Diederin A M 2009 J. Appl. Phys. 105 064916.
[12] Rosenberg Z and Brar N S 1995 J. Appl. Phys. 77 1443.
[13] Rosenberg Z and Partom Y 1985 J. Appl. Phys. 57 5084.
[14] Millett J C F, Bourne N K and Rosenberg Z 1996 J. Phys. D: Appl. Phys. 29 2466.