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ScienceDirect

Procedia Engineering 204 (2017) 247–254

Procedia Engineering

www.elsevier.com/locate/procedia

14th Hypervelocity Impact Symposium 2017, HVIS2017, 24-28 April 2017, Canterbury, Kent, UK

Towards predictive transferable simulations of ceramic failure in ballistic events

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Abstract

This work discusses the calibration of an advanced material model for boron carbide and then compares simulations of a ballistic impact event to highly instrumented experiments. The experiments are instrumented using flash x-ray, high-speed video, and photon Doppler velocimetry (PDV). Possible sources for the differences between the simulations and experiments are discussed.

Peer-review under responsibility of the scientific committee of the 14th Hypervelocity Impact Symposium 2017.

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1. Introduction

Predictive simulation capabilities for brittle materials undergoing failure due to high velocity impact have been a research goal for a long time. Predictive models will enable both greater understanding of the experimental conditions leading to the failure of a complex structure during an impact event and simplified testing and evaluation procedures that maximize the information gained from each test. Prior work has established ceramic material models that are suitable for simulations of impact events [1-4]. In this work we focus on a single impact experiment which was designed to be easily instrumented with high speed video, flash X-ray, and photon Doppler velocimetry (PDV) to record as much information as possible during the impact event. These time resolved experimental measurements are sensitive to the failure process within the material. To reflect the series of events observed using these methods, the models must not only capture the final failure pattern of the material, but also its spatio-temperoal evolution.

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1877-7058
Peer-review under responsibility of the scientific committee of the 14th Hypervelocity Impact Symposium 2017.
10.1016/j.proeng.2017.09.732

In addition to looking at the results of a specific simulation with a fixed set of input parameters, we look at the range of responses that are possible given the range of input parameters that fit the experimental data. Understanding the range of responses is important for assessing how robust a particular result is given the uncertainty in the input data.

2. Method

To model boron carbide we use a modified version of the micromechanics based damage model developed by Tonge and Ramesh [2]. In the model three mechanisms are tracked. First there is subscale crack growth based on a wing cracking model. Once damage reaches a critical value, a granular flow model is enabled where inelastic deformation is permitted based on a pressure and Lode angle dependent yield surface with both pore compaction and dilatation. The third mechanism is volume preserving inelastic deformation similar to traditional J_2 or Von-Mises plasticity. This third mechanism is independent of the other two. The model has been discussed in detail in other publications [1-3].

2.1. Model calibration

The material model is calibrated based on fundamental material tests. These tests include planar shockwave experiments to determine the Mie-Gruneisen equation of state parameters, compression tests on dog bone shaped specimens to generate uniaxial stress conditions at failure [5], and tests on the material after various levels of damage [6]. Based on these tests there is a range of parameters that are consistent with the experimental data.

To match the plate impact data from Vogler et al. [7] we start by using the Mie-Gruneisen parameters in [8] then adjust the J_2 yield strength to capture the material Hugoniot Elastic Limit (HEL). Vogler et al. reported HEL values between 13.4 GPa and 18.0 GPa. We estimate the magnitude of the deviatoric stress at yield from the HEL based on the reference bulk and shear moduli using:

$$\tau_0 = \sigma_{HEL}\left(\frac{2\left(\sqrt{\frac{2}{3}}\right)G}{K+\frac{4}{3}G}\right) \tag{1}$$

Here the longitudinal stress at the HEL is σ_{HEL}, and the bulk and shear moduli are K and G respectively. The shear stress measure (τ_0) is the magnitude of the deviatoric stress tensor. This quantity is proportional to the more commonly used Von-Mises effective stress, where the relationship between the two is $\tau_0 = \sqrt{2/3}\sigma_{VM}$. Values of is τ_0 between 8.7 GPa and 11.7 GPa are consistent with the range of HEL values reported in [7]. Figure 1 shows simulated plate impact experiments with varying yield strengths. The simulated HEL is sensitive to this parameter and particle velocity in the shocked state is slightly sensitive to this parameter.

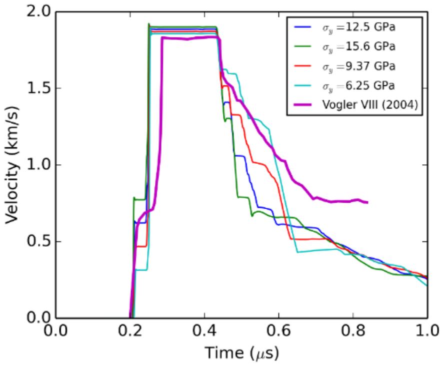

Figure 1: Effect of yield parameter on plate impact velocity profile.