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Multi-scale defect interactions in high-rate failure of brittle materials, Part II: Application to design of protection materials

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ABSTRACT

Micromechanics based damage models, such as the model presented in Part I of this 2 part series (Tonge and Ramesh, 2015), have the potential to suggest promising directions for materials design. However, to reach their full potential these models must demonstrate that they capture the relevant physical processes. In this work, we apply the multiscale material model described in Tonge and Ramesh (2015) to ballistic impacts on the advanced ceramic boron carbide and suggest possible directions for improving the performance of boron carbide under impact conditions. We simulate both dynamic uniaxial compression and simplified ballistic loading geometries to demonstrate that the material model captures the relevant physics in these problems and to interrogate the sensitivity of the simulation results to some of the model input parameters. Under dynamic compression, we show that the simulated peak strength is sensitive to the maximum crack growth velocity and the flaw distribution, while the stress collapse portion of the test is partially influenced by the granular flow behavior of the fully damaged material. From simulations of simplified ballistic impact, we suggest that the total amount of granular flow (a possible performance metric) can be reduced by either a larger granular flow slope (more angular fragments) or a larger granular flow timescale (larger fragments). We then discuss the implications for materials design.

1. Introduction

Computational models of failure during impact events are important for a variety of impact applications including personnel and vehicle protection. In order to design new materials for improved protective systems, it is important to capture the competing mechanisms that control the performance of a given material under impact loading conditions. Our interest here is the design of improved armor ceramic materials. In Part I of this work we presented a micromechanics-based model (Tonge and Ramesh, 2015) that accounted for variability in ceramics and provided a connection between the material microstructure and the input parameters for application scale models. As these models are developed, one must ensure that they accurately reproduce the observed behaviors of the materials in the application environment. In Part II of this work, we show that this can enable targeted material development. We apply the model (Tonge and Ramesh, 2015) to an advanced ceramic (boron carbide) and simulate two experimental loading geometries to investigate the model under two additional confinement conditions. Based on these simulations, we suggest an approach to designing the material for

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improved performance under complex (ballistic) loading conditions.

First we discuss the important physical processes that occur during a high velocity impact event, and then provide a brief discussion of possible performance metrics for ballistic loading problems.

1.1. Energy pathways in impact events

During high velocity impact events, there is a large amount of energy deposited in the target in a short amount of time. Since the energy travels at a finite speed, the rapid nature of impact events leads to very high local energy densities. These high local energy densities activate a number of energy dissipation pathways. It is the nature of these pathways, the timescales over which they operate, and their effect on the structural integrity of the material that determine how a given material performs in a particular impact scenario. The model presented in Tonge and Ramesh (2015) provides the following dissipation mechanisms:

- shock heating,
- microcracking, and
- granular flow of the highly damaged material.

In addition to these energy dissipation pathways, brittle materials exhibit a distribution of strengths, which is important for controlling the onset and degree of localization leading to fragmentation.

When modeling impact events, the goal is typically to predict the outcome of a given impact scenario for a particular material (although quantitative measures of the outcome are often poorly defined). As industry moves towards leveraging computational power to reduce the number of costly design-build-test iterations required to bring a new product to market, there is increased reliance on the ability of computer models to predict the outcome of an impact scenario. For robust predictions of impact outcome, one first needs to capture the dissipation processes that occur during an impact event and the timescales associated with those processes.

1.2. Possible performance metrics in protection applications

When considering material design problems, one must identify some metric that can measure the performance of the material. One of the difficulties in the design of ceramic materials for protection applications is that there is not a single figure of merit that can rank materials based on easily measured properties such as stiffness, hardness, density, fracture toughness etc. At the other extreme, one could perform simulations of standard test geometries such as depth of penetration (MIL-STD-376A, 1998) or V_{50} (Grubinskas, 1998) measurements; however, these are specialized tests that were designed for batch screening in a quality control setting and may not provide the scientific insight that can be gained from a more fundamental performance metric, which to our knowledge has yet to be satisfactorily defined for general impact problems.

From the discussion in the previous section, during an impact event there is a fixed amount of kinetic energy available at the beginning of the event and this energy is partitioned between deformation of the projectile, the various deformation mechanisms in the target, and residual kinetic energy. The energy dissipated through plastic deformation of the projectile leads to thermal energy rise in the projectile material. We use the ratio of the initial kinetic energy to the increase in thermal energy in the projectile as one performance metric. To compliment the measurement of energy dissipated in the projectile, we also look at the volume of material that has reached the threshold for granular flow. Within the model discussed in Part I (Tonge and Ramesh, 2015), this material is highly damaged and no longer contributes to the structural stability of the piece. It has been converted from the initial monolithic ceramic to a granular material like sand.

In Part I of this 2 part series (Tonge and Ramesh, 2015), we presented a mechanism based material model that captures these dissipation processes and captures the effect of material variability. In this part, we use that material model to simulate simplified ballistic experiments in which a tungsten carbide cobalt sphere impacts a boron carbide cylinder at velocities between 100 and 400 m/s and use these simulations to suggest future directions to improve material performance under ballistic impact conditions. We assume that the reader is familiar with the notation and terminology developed in Tonge and Ramesh (2015) when presenting the model. We begin by parameterizing the Tonge–Ramesh model for boron carbide using available literature data. In the next section we simulate dynamic uniaxial compression loading to understand the effects of the model input parameters before continuing on to more complex loading conditions. In Section 5 we simulate simplified ballistic experiments similar to the ones conducted by Lasalvia et al. (2005) to provide additional qualitative validation of the material model, and suggest future directions both to improve the performance of the material and to improve the predictive capabilities of the material model.

2. Model parameters for boron carbide

The parameters for the micromechanics based damage model (Tonge and Ramesh, 2015) describe the behavior of an individual microcrack and the distribution of microcracks in the system. Based on Paliwal and Ramesh (2007) we assume that the fracture toughness of boron carbide is 2.5 MPa $\sqrt{\mathrm{m}}$. As in Tonge and Ramesh (2015), we assume a bounded Pareto