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Material characterization and development of a constitutive relationship for hypervelocity impact of 1080 Steel and VascoMax 300 ☆

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Abstract

The area of hypervelocity impact and associated high energy is one of extreme interest in the research community. A specific example of this emphasis is the US Air Force test facility at Holloman Air Force Base which specializes in the field of hypervelocity impact testing. This Holloman AFB High Speed Test Track (HHSTT) is currently working to increase the speed of their test vehicle to above Mach 10. As the test sled's speed has increased into the Mach 8.5 range, a material interaction has developed which causes "gouging" in the rails or the sled's "shoes" and this starts a process that can result in catastrophic failure. In the tests that do not structurally fail, the rails and shoes are damaged. Previous efforts in investigating this event have resulted in a choice of the most suitable computer code (CTH), and a model of the shoe/rail interaction. However, the specific materials present in this impact problem were not available in CTH. In this work, the specific materials present at the HHSTT (VascoMax 300 and 1080 Steel) will be characterized using the Split Hopkinson Bar Test and a Johnson–Cook constitutive model will be developed. The model will then be validated by comparison to a series of Taylor impact tests. The coating materials utilized on the rails at the HHSTT will also be evaluated using a Taylor impact test.
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Keywords: 1080 steel; VascoMax 300; Hopkinson bar; Taylor test; Constitutive

1. Introduction

Investigation into the phenomenon of hypervelocity gouging has revolved around attempting to characterize the event within the context of a numerical simulation. Eulerian shock wave codes, such as CTH [1,2], have been successful in modeling some of the key aspects of this type of hypervelocity impact [3–7]. However, CTH does not possess material constitutive models (only equation-of-state models) for the material of the rail (1080 Steel) and of the sled's shoe (VascoMax 300—a maraging steel). Materials such as iron and

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VascoMax 250 were utilized instead by previous efforts. In those previous works, the effect of the constitutive model to the hypervelocity gouging scenario was demonstrated.

Therefore, the specific materials were tested using a tension Split Hopkinson Bar apparatus to determine material constants for the well-known Johnson–Cook constitutive model. These constants were validated by comparing predicted deformations (in a Lagrangian finite element code and CTH) to a series of Taylor impact tests. Finally, Taylor impact specimens coated with the materials used at the HHSTT to mitigate hypervelocity gouging were also compared to numerical simulations to validate the modeling of impact with coatings.

2. Split Hopkinson bar tests

Specimens of 1080 Steel and VascoMax 300 were prepared for the standard tension split Hopkinson bar test by the HHSTT facilities. The specimens for the 1080 Steel were machined from existing rail stock and the VascoMax 300 specimens were manufactured and then heat treated exactly in the same manner as the sled shoes. Therefore, the test specimens were identical to the materials in the sled test.

The Hopkinson bar tests were conducted in the standard manner [8–11]. Fig. 1 depicts the test set-up, where ε_i is the incident wave, ε_r is the reflected wave, ε_t is the transmitted wave, E is the modulus of elasticity, L is the specimen test section length, A_s is the specimen cross-sectional area, and A is the bar cross-sectional area. Applying the Hopkinson bar relationships, we note that

$$\left\{\begin{array}{l} \varepsilon_s = \dfrac{c_0}{L}\int_0^t(\varepsilon_t - \varepsilon_r - \varepsilon_r - \varepsilon_t)\,dt = -\dfrac{2c_0}{L}\int_0^t \varepsilon_r\,dt, \\ \sigma_s = E\dfrac{A}{A_s}\varepsilon_t, \\ \dot{\varepsilon}_s = -\dfrac{2c_0}{L}\varepsilon_r, \end{array}\right\}, \tag{1}$$

where ε_s is the specimen strain, c_0 is the material wave speed, σ_s is the specimen stress, and $\dot{\varepsilon}_s$ is the specimen strain-rate.

A series of Hopkinson bar tests were conducted at various strain rates and temperatures to characterize the behavior of both of these materials. The 1080 Steel behaved in an expected manner, with a stress–strain curve showing strain-hardening characteristics during all the tests. Additionally, examination of the post-test specimens revealed very little necking. VascoMax 300, conversely, exhibited behavior that indicated the material could not strain harden and was brittle (albeit very high strength). Fig. 2 contrasts the quasi-static curves of these materials. The same form of curve was present over all the strain rates and temperatures. Also, the post-test specimens of the VascoMax 300 showed necking.

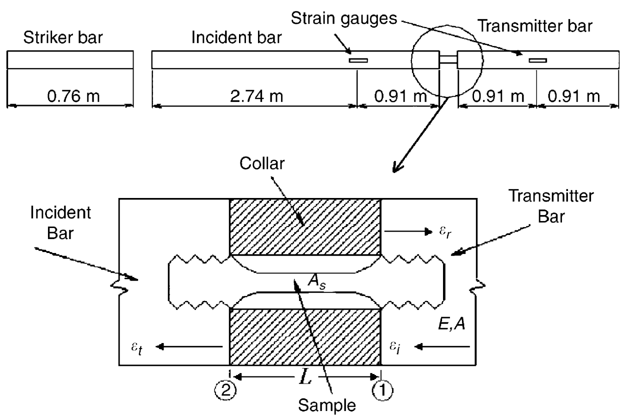

Fig. 1. Split Hopkinson bar diagram.