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Author(s): Prime, Michael Bruce

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Strain Rate Sensitivity of Richtmyer-Meshkov Instability Experiments for Metal Strength

Michael B. Prime
MS A142, Los Alamos National Laboratory, Los Alamos, NM 87545 USA.

ABSTRACT

Recently, Richtmyer-Meshkov instabilities (RMI) have been used for studying strength at strain rates up to at least 10^7/s. RMI experiments involve shocking a metal interface with sinusoidal perturbations that invert and grow subsequent to shock and may arrest because of strength effects. To use RMI strength estimates as calibration data for rate-dependent constitutive models, one must understand the strain rates that apply to the strength estimate, but the strain rate varies spatially and temporally during the instability. In this study, we use a series of numerical simulations to establish the strain rate(s) to which the instability is most sensitive.

Keywords: Richtmyer-Meshkov Instability, high-rate strength

INTRODUCTION

Recently, researchers have shown that Richtmyer-Meshkov Instabilities (RMI) are sensitive to strength at strain rates up to at least 10^7/s [1-12]. Fig. 1 illustrates an RMI experiment in the configuration fielded for recent experiments [3,4]. As shown in Fig. 1, in an RMI experiment the initial perturbations invert after shock, and the subsequent peaks are called spikes and the valleys are called bubbles. Recent work has shown that the peak spike velocity, as shown in Fig. 2, is quite sensitive to the deviatoric strength of the sample and offers advantages over using total spike growth as the measure of strength [13]. As with the previous work using total spike growth [4,3], the peak spike velocity is used to estimate an average strength that best matches the data.

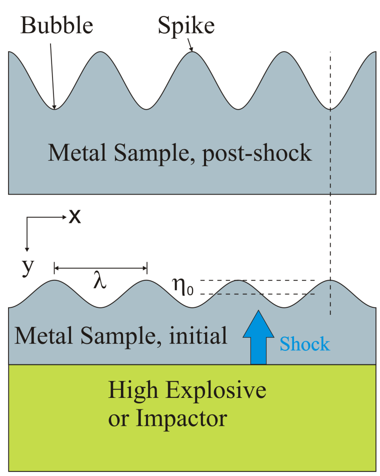

Fig. 1 A Richtmyer-Meshkov instability experiment. The perturbed surface of the sample is accelerated by a shock. At later time, the perturbations have inverted

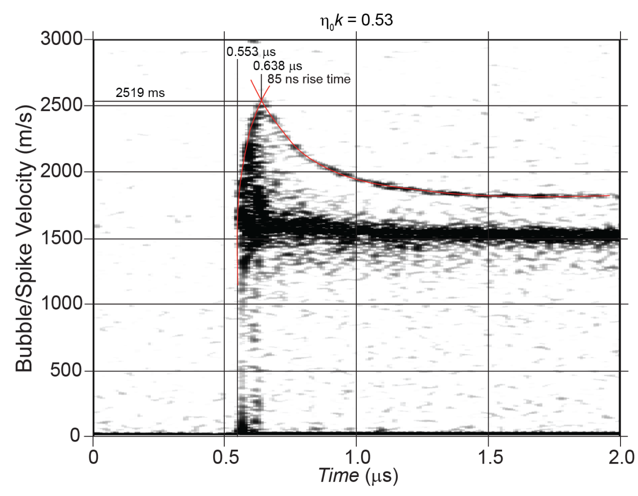

Fig. 2 An experimental PDV velocity spectrogram for $\eta_0 k$ = 0.52 in copper shows a distinct velocity trace for the spike growth peaking at 2519 m/s

Since strength is generally a function of strain, strain, temperature and pressure, e.g., [14], and those properties vary spatially and temporally during RMI growth and arrest, how useful is an average strength? We begin to explore this question by examining the sensitivity to the strain rate-dependent portion of a constitutive model.

MODELING APPROACH

An RMI experiment was modelled using the Abaqus Explicit commercial finite element code [15] based on extensive previous finite element modeling of RMI experiments [13]. A 2-D, plane strain model was used with the model domain including two full wavelengths of the perturbation and 3 mm thickness of copper. Fig. 3 is zoomed in on the right end of the domain to show the 10 μm zoning and the perturbations with an amplitude $\eta_0 k$ = 0.5. The top and bottom surfaces are constrained in the vertical direction to simulate periodic behavior. For simplicity in the sensitivity study, a shock pressure of 30 GPa was applied at t = 0 to the left end of the domain. To minimize noise in the predicted velocities, the default linear and quadratic coefficients for bulk viscosity were increased from 0.06 and 1.2 to 0.20 and 1.7. To sufficiently resolve the velocity peak, the SCALE FACTOR parameter was used to reduce Abaqus' default time increment by a factor of five.

The constitutive behavior was modeled using a the Zerilli-Armstrong model with parameters for copper [16]. To allow for model variations for the sensitivity study, the model was tabularized for use in Abaqus. For strain rate, Abaqus suggest tabular data be given at regular logarithmic intervals, so we used strain rates of 10^n/sec with n = 4.0,4.25,4.5, … 7,75, 8.0. The "parametric studies" capability in Abaqus was used to sequentially scale the magnitude of the stress-strain curve for a given strain rate to 0.95 of its original value and repeat the simulation. The peak speak velocity for each simulation was extracted and compare to the baseline simulation to estimate the sensitivity of the experiment to a given strain rate.

RESULTS AND DISCUSSION

Fig. 4 shows the encouraging results of the sensitivity study. This particular case is sensitive to a tight range of strain rates, peaking at 10^7/sec. Based on the standard logarithmic dependence of strength on strain rate [14], the result indicates that the average strength could be characterized as effectively probing this single strain rate ± a small band and used as a single point to calibrate a constitutive model.

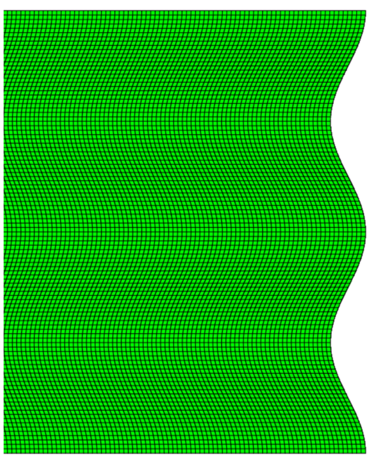

Fig. 3 The Abaqus model simulated two full periods of the sine wave perturbation using Cartesian 2D plane strain elements. The figure here shows only perturbation region

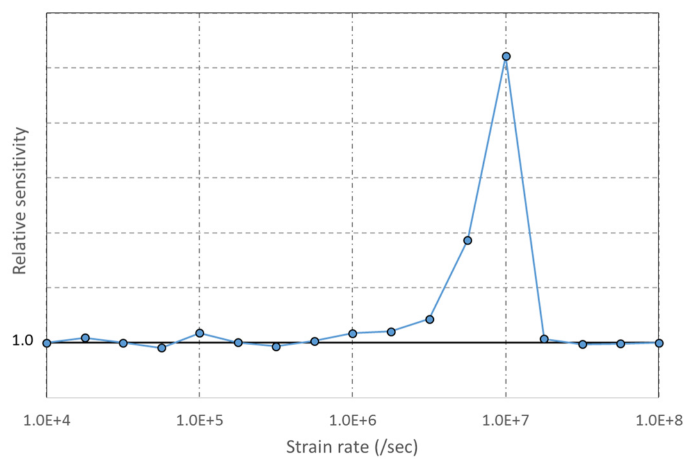

Fig. 4 For the simulation with η_0k = 0.5 and a 30 GPa shock, the peak spike velocity is sensitive to the strength model over a quite narrow band of strain rates, peaking at 10^7/sec

Further work is needed. Similar sensitivity studies should be performed for strain, temperature, and pressure. As appropriate based on those results, the average strength could be assigned to a point in (strain, strain rate, temperature, pressure) space and used for calibrating a constitutive model that is dependent on all of the variables. Using a number of RMI experiments with different shock loading, perturbation sizes, and initial temperatures, a reasonable span of conditions could be evaluated and extend the usefulness for constitutive model calibration. The ability of the calibrated model to reproduce the full range of experimental data would be the first check on the suitability of such a calibration scheme.

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