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Behaviour of rippled shocks from ablatively-driven Richtmyer-Meshkov in metals accounting for strength

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Abstract. While numerous continuum material strength and phase transformation models have been proposed to capture their complex dependences on intensive properties and deformation history, few experimental methods are available to validate these models particularly in the large pressure and strain rate regime typical of strong shock and ramp dynamic loading. In the experiments and simulations we present, a rippled shock is created by laser-ablation of a periodic surface perturbation on a metal target. The strength of the shock can be tuned to access phase transitions in metals such as iron or simply to study high-pressure strength in isomorphic materials such as copper. Simulations, with models calibrated and validated to the experiments, show that the evolution of the amplitude of imprinted perturbations on the back surface by the rippled shock is strongly affected by strength and phase transformation kinetics. Increased strength has a smoothing effect on the perturbed shock front profile resulting in smaller perturbations on the free surface. In iron, faster phase transformations kinetics had a similar effect as increased strength, leading to smoother pressure contours inside the samples and smaller amplitudes of free surface perturbations in our simulations.

1. Introduction

Hydrodynamic instabilities are a dominant feature of many High-Energy-Density (HED) systems [1]. The growth of these instabilities depends on material phase and intrinsic fields that perturb the hydrodynamics away from an ideal fluid flow [2-4]. Many materials can retain significant resistance to shear deformation at the large strain rates developed under large transient pressure conditions [5]. This strength is known to decrease Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instability growth rates relative to those under ideal hydrodynamic conditions [3-5]. Little is known, however, about the effects of material strength on these instabilities as phase boundaries (solid-solid, solid-liquid, etc.) are approached. Specifically, the behaviour of shock and release waves undergo sharp changes near these boundaries [6], suggesting that significant changes to the growth rate of instabilities may occur at perturbed solid-state interfaces. It is also likely that material strength could mitigate instability growth in inertial confinement fusion (ICF) capsules using metal ablators [7]. Here we describe a novel experimental setup for validating and calibrating material models in loading regimes typical of hydrodynamic instabilities in solids. We study two materials, copper to explore material strength sensitivity, while iron is used to study phase transformation effects from the α to ε transition [6].

2. Experimental Details

Shock experiments were conducted via laser ablation of a sample's free surface as shown in Figure 1a. Pressure was controlled by varying the laser intensity, which determined material strength/phase regimes the sample experienced during loading. Laser pulses lasted for about ~ 7 ns and produced pressures from 10 to 30 GPa. Two sample geometries were used. Flat samples with an approximate 100 μm thickness were tested first and used to correlate a known laser intensity pulse and resulting velocity history at the opposite free surface, to a pressure boundary condition (BC) via simulation. The laser BC to pressure BC calibration was performed with a range of laser energies. All free surface velocities were recorded with a Line VISAR (Velocity Interferometer System for Any Reflector).

Another set of samples had the ablated surface perturbed with a square wave, as shown in Figure 1a, by a photolithography process [8]. Samples had wavelength (λ), amplitude (η), and thickness (t), of approximately 150 μm, 20 μm, and 100 μm, respectively. The perturbations produced a rippled shock front that imprinted the initially flat free surface with a perturbation at breakout. This, in turn, resulted in an RM instability. Out-of-plane displacement measurements were recorded at the free surface with Transient Imaging Displacement Interferometry (TIDI) [9], as seen in Figure 1b. Only two framing cameras were used to obtain two dynamic images per sample. Free surface velocity was monitored with Line VISAR (Figure 2a). The use of TIDI was of interest in this experiment because it provided an alternative for capturing the RM instability evolution. Other instability studies [3] have used radiography, which is not as sensitive to the small displacements seen here. All experiments were carried out at the TRIDENT Laser Facility at Los Alamos National Laboratory (LANL).

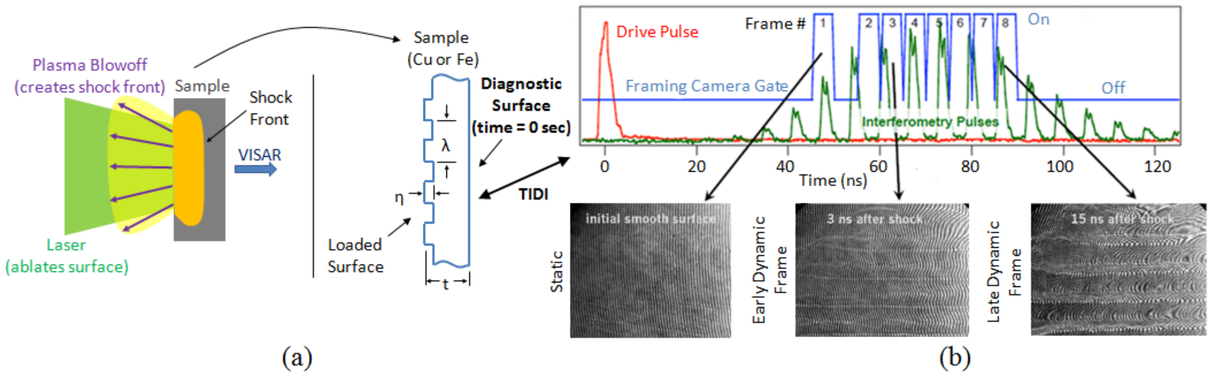

Figure 1. Schematic of experimental setup and diagnostics. (a) Laser ablation and sample configuration. (b) Pulse train of laser illumination to capture raw TIDI data with framing cameras.

3. Experimental Results

Figure 2 shows typical experimental results obtained with the VISAR and TIDI diagnostics. Figures 2a and 2b (raw VISAR images) are interferograms of a line on the diagnostic surface (x-axis) with time (y-axis). A vertical line out of post-processed Line VISAR interferograms produces a velocity history (Figure 2c) of a particular point on the diagnostic surface. The velocity histories of flat samples (Figures 2b and 2c) have the usual form seen in laser ablation or plate impact experiments, i.e., the surface accelerates and decelerates as a whole with the shock front and release wave respectively. The free surface of the perturbed samples, however, evolves from an initially flat surface (Figure 2d) to a perturbed surface (Figures 2e and 2f) with a wavelength equal to the etched perturbations that were laser loaded. The perturbations evolve higher harmonics with time due to interactions with the release wave. Note that Figures 2d and 2e are post-processed displacement plots from raw static and dynamic images (interferograms) similar to those in Figure 1b.

4. Simulation Results and Discussion

Two dimensional, plane strain simulations were performed to assess sensitivity of the behavior to strength and phase transformation properties. Calculations were carried out in ABAQUS/Explicit^{TM},

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via a user material subroutine (VUMAT) with a model similar to that used in [10]. An equation of state (EOS) [11] was used for the volumetric response and a Preston-Tonks-Wallace (PTW) model for the deviatoric response [12]. In iron, the phase transformation kinetics followed the phenomenological model shown in [13]. Separate EOS and strength parameters were used for each phase.

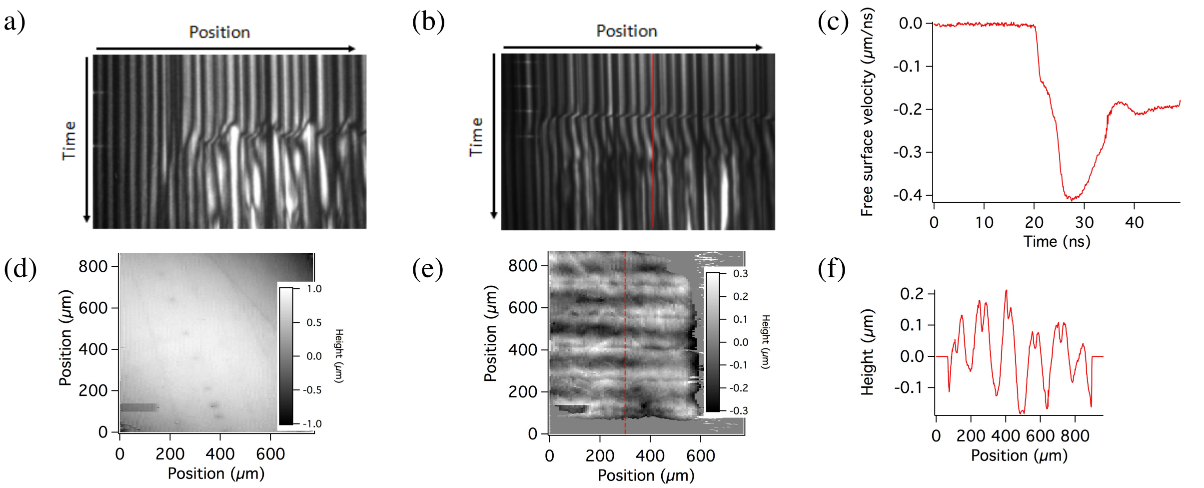

Figure 2. Typical experimental data. (a) and (b) raw Line VISAR of perturbed and flat Cu samples respectively. (c) Line out of flat sample Line VISAR data. (d) Pre-shot TIDI data of perturbed sample. (e) Dynamic TIDI data of perturbed sample. (f) Line out of dynamic TIDI data.

Copper and iron unitless PTW parameters were initially taken from literature [12,14] and adjusted to match the shock front profiles from the flat sample VISAR records. For both phases of iron the s_0, s_{inf}, y_0, y_{inf}, and y_1 parameters [12] were multiplied by 1.75 relative to [14]. This translated the thermal activation region up along the vertical flow stress axis to better match the elastic precursor seen here. In copper, y_0, y_{inf}, and y_2 were changed from 1e-4, 1e-4, and 0.575 to 1e-3, 1e-5, and 0.250, respectively, which increased the initial yield stress and kept the saturation stress unchanged. Strain rate sensitivity and phonon drag characteristics were the same for both materials as in [12] and [14].

Phase kinetic parameters for iron were initially set at ν = 1e5 s^{-1} and B = 3375 J/kg, where ν represents a reference transformation rate and B is akin to an energy barrier [13]. These values reproduced the data in [6] and references therein well. However, for our relatively thin samples changing B to 688 J/kg (or ν to ~1e7 s^{-1}) reproduced velocimetry data better, suggesting a very fast transformation (~1 ns), defined as a 95% transformation at the large driving forces used here [15]. More work is needed to understand the discrepancy in B, i.e., a better kinetics model may be needed.

Tables 1 and 2 show peak-to-peak (P-P) amplitudes obtained from perturbed sample TIDI data and from simulations using the parameters calibrated to flat sample VISAR data. These baseline parameters were used to look at the perturbation growth sensitivity to in material parameters. For copper, the strain rate sensitivity was increased (~2x) and decreased (~0.5x) by likewise changes in the $\varkappa$ and β PTW values [12] relative to the baseline, while other PTW values were changed to retain similar quasistatic strength across all simulations. As shown elsewhere [3] strength parameters were found to have a significant effect, simulations showed that the perturbed shock front profile traveling through the sample was less perturbed in samples with increased strength. In iron simulations parameters controlling phase kinetics were varied. Faster kinetics led to more uniform pressure contours, having a similar result on transient free surface ripple formation as increasing the strength of the material. All simulations showed smaller permanent deformations, relative to the transient deformations, after the shock release wave reached the free surface. Simulations showed that with a longer pressure (laser) pulse the transient perturbations at the free surface would have grown at a quasi-linear rate typical of small amplitude RM instabilities [2]. Figures 3 and 4 illustrate the simulation results, in Figure 4 the 'slow' kinetics had ν = 1.00e5 s^{-1} and B = 3375 J/kg.

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Table 1. Cu (s25288, 19J) amplitudes, experimental and baseline simulation results.

Time[a] (ns)	Experimental Amplitude P-P (microns)	Simulation Amplitude P-P (microns)
6.2	0.20 +/- 0.05	0.18
12.7	0.65 +/- 0.05	0.62

a. Time since shock breakout.

Table 2. Fe (s25293, 55J) amplitudes, experimental and baseline simulation results.

Time[a] (ns)	Experimental Amplitude P-P (microns)	Simulation Amplitude P-P (microns)
9.1	0.48 +/- 0.07	0.50
28.2	0.15 +/- 0.05	0.17

a. Time since elastic wave breakout.

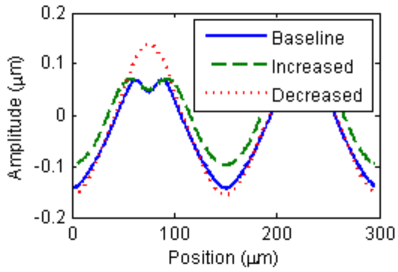

Figure 3. Copper free surface simulations results at 6.2 ns since shock breakout.

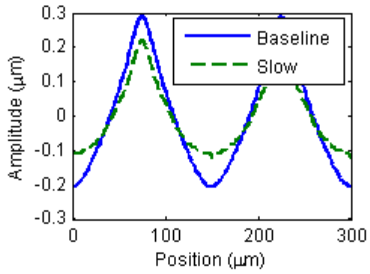

Figure 4. Iron free surface amplitude simulation results at 9.1 ns since elastic wave breakout.

5. Conclusions

Anticipation and control of hydrodynamic instabilities is critical in many applications, particularly ICF design. To accurately predict instability evolution a comprehensive material model is needed that accounts for the wide variation in strength and phases that evolve with the loading conditions. We have described a novel experimental setup that provides data to validate material models/parameters in high strain rate and pressure regimes typical of hydrodynamic instabilities in solids. Preliminary experiments and simulations show that experimental results of this setup are sensitive to material properties controlling strength and phase kinetics, and are useful for supplying additional experimental data for model validation in addition to typical velocity measurements, e.g., Line and Point VISAR.

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