Richtmyer-Meshkov Instability Experiments at Multiple Scales to Isolate Strain Rate Dependence of Copper Strength Near 10^7 /sec, and the Elusive Strength Upturn

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Abstract. A series of experiments to isolate strain rate effects on strength made use of an important observation about scaling Richtmyer-Meshkov Instability (RMI) perturbations to change the strain rate. In each experiment, a copper target was shocked to 25 GPa on a gas gun. Each individual target had three regions of sine wave perturbations with the same non-dimensional sine-wave amplitude $\eta_0 k$, but the dimensional scale spanned a factor of about five with wavelengths of 65, 130, and 320 μm. In such an experiment, all three regions see identical shock loading and very similar amounts of plastic deformation, but the strain rates in the instability scale with the inverse of the wavelength. The instability growth and arrest were measured with Photon Doppler Velocimetry and showed a clear trend of the maximum instability velocities increasing with increasing wavelength. The velocities were used to estimate strength. When plotted vs. strain rate along with strength data from the literature up to about 10^4/sec, the "upturn" in strength magnitude and the slope of the dependence are both striking. The location of the upturn does not quite agree with extrapolations from inconsistent literature observations at the lower rates.

Introduction

Richtmyer-Meshkov Instability (RMI) experiments for strength [1, 2] involve shocking a target with sinusoidal perturbations machined into a free surface, as shown in Figure 1. Depending on the size of the perturbations and the strength of the shock, the perturbations will tend to invert and then grow unstably, or arrest if the material is strong enough. Measurements of this behavior are very sensitive to strength and can be used to estimate strength at very high strain rates.

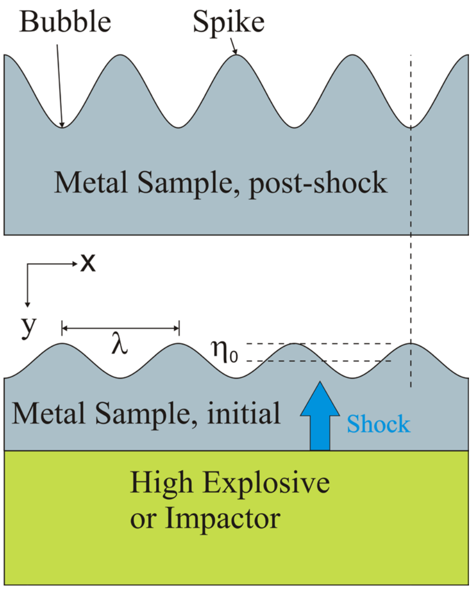

Figure 1. A Richtmyer-Meshkov Instability (RMI) experiment for strength. After the shock, the perturbations have inverted and may arrest if the sample is strong enough.

With their sensitivity to ultrahigh rate strength at low pressure, free-surface RMI experiments are well suited to contribute unique information to an open question in the literature. A very large increase in strength at strain rates of 10^3–10^5 /s for metals has been inconsistently observed in the literature. For copper, some have observed this upturn [3-5] and others found no significant upturn [6, 7]. Rosenberg [8] critically reviewed the discrepancy and identified possible explanations. Comparing different techniques, especially those that might include effects of higher pressures on strength, was a major concern. Lea and Jardine [16] have exploited this approach on copper to provide the highest signal-to-noise evidence of the upturn yet reported. They showed an upturn starting at 10^4 /s with a threefold increase in strength, the highest yet reported with SHPB testing. Their peak value came at 1.5×10^5 /s. The RMI experiments in this work will extend that maximum strain rate by more than two orders of magnitude.

To isolate strain rate effects on strength, we make use of an important observation about scaling RMI perturbations to change the strain rate. The strain rate in the perturbations scale inversely with the wavelength of the perturbations, i.e., the length scale.

Experiment

Three gas gun RMI experiments were carefully designed to isolate the effect of strain rate on strength by changing the length scale. The copper target for each individual experiment had three regions of sine wave perturbations machined in with the same $\eta_0 k$, the non-dimensional amplitude where $k = 2\pi/\lambda$, but the dimensional scale, i.e. λ, spanned a factor of about five with corresponding scaled amplitudes. Three experiments were fielded with different values for $\eta_0 k$ spanning a factor of three to explore different levels of instability growth and the resulting plastic strain. In each experiment, a copper target was shocked to 25 GPa on a gas gun.

Conclusion

The instability growth and arrest were measured with Photon Doppler Velocimetry and showed a clear trend of the maximum instability velocities increasing with increasing wavelength. The velocities were used to estimate strength. When plotted vs. strain rate along with strength data from the literature up to about 10^4/sec, the “upturn” in strength magnitude and the slope of the dependence are both striking. The location of the upturn does not quite agree with extrapolations from inconsistent literature observations at the lower rates.

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