Chapter 16
Improved Richtmyer-Meshkov Instability Experiments for Very-High-Rate Strength and Application to Tantalum

Michael B. Prime, William T. Buttler, Saryu J. Fensin, David R. Jones, Ruben Manzanares, Daniel T. Martinez, John I. Martinez, Derek W. Schmidt, and Carl P. Trujillo

Abstract Recently, Richtmyer-Meshkov instabilities (RMI) have been used for studying metal strength at strain rates up to at least 10ˆ7/s. RMI experiments involve shocking a metal interface with geometrical perturbations that invert, grow, and possibly arrest subsequent to the shock. In experiments one measures the growth and arrest velocities to study the specimen's flow (deviatoric) strength. In this paper, we describe experiments on tantalum at three shock pressure from 20 to 34 GPa, with six different perturbation sizes at each pressure, making this the most comprehensive set of RMI experiments on any material. In addition, these experiments were fielded using impact loading, as compared to high explosive loading in previous experiments, allowing for more precise modeling and more extensive interpretation of the data. Preliminary results are presented.

Keywords Dynamic strength · Richtmyer-Meshkov instability · High-rate strength · Shock physics · Hydrocode

16.1 Introduction

Recently, researchers have shown that Richtmyer-Meshkov Instabilities (RMI) are sensitive to strength at strain rates up to at least 10^7/s [1–18]. Figure 16.1 illustrates a nominal RMI experiment for strength. The initial perturbations invert after shock, and the subsequent peaks are called spikes and the valleys are called bubbles. The initial perturbation size is characterized by the non-dimensional number $\eta_0 k$ (where $k = 2\pi/\lambda$).

Previous RMI experiments to interrogate strength used high explosive loading to generate the shock [4, 19]. This work reports the first such measurements using impact loading as an improvement. Interpreting the data requires modeling the experiments in a hydrocodes or something similar [19]. Impact loading can be modelled both more simply and more accurately than high explosive, as illustrated by the significant previous effort to model explosive loading [19]. More accurate modeling should make for easier and more accurate strength estimation. Furthermore, impact loading makes it simpler to adjust impact pressure and interrogate strength over a wider range of conditions.

16.2 Experiments

The experiment used the same batch of "Starck" tantalum that has been well characterized and used in other work [20–22]. The three tantalum targets were 40 mm diameter and 1.45 mm thick. On one face, diamond turning techniques were used to machine six regions containing multiple wavelengths of a sinusoidal surface perturbation, with $\eta_0 k$ ranging from 0.3 to 0.9 with a constant wavelength of 0.25 mm except for the $\eta_0 k = 0.9$ region which had a wavelength of 0.3 mm. These targets were then pressed into a tantalum momentum ring, 55 mm diameter, 1.45 mm thick, the purpose of which was to avoid edge release waves reaching the central region where diagnostics were placed, ensuring a simple one-dimensional loading. Finally, a 0.25 mm thick tantalum foil was glued to the impact face, covering both the sample and the momentum ring, resulting in a final target thickness of 1.7 mm.

Each target was bonded to the front of a Lexan plate. This plate served to both mount the target in the gas gun and position the PDV probes. A 50 mm hole in the Lexan plate allowed the probes to directly image the rear of the target. A total of 24

M. B. Prime (✉) · W. T. Buttler · S. J. Fensin · D. R. Jones · R. Manzanares · D. T. Martinez · J. I. Martinez · D. W. Schmidt · C. P. Trujillo
Los Alamos National Laboratory, Los Alamos, NM, USA
e-mail: prime@lanl.gov

J. Kimberley et al. (eds.), *Dynamic Behavior of Materials, Volume 1*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-319-95089-1_16

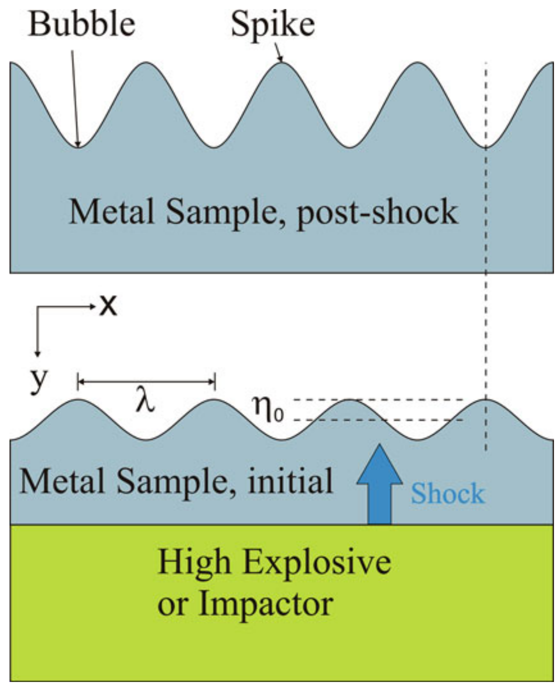

Fig. 16.1 A Richtmyer-Meshkov instability experiment. The perturbed surface of the sample is accelerated by a shock. At later time (upper figure), the perturbations have inverted

PDV probes were used, measuring the response of both the perturbed regions and flat regions, see Fig. 16.2. One probe was mounted in the Lexan plate, collimated down the gas-gun barrel, to measure the impact velocity. A single piezo-electric pin was also mounted in the Lexan plate to provide a trigger signal for the diagnostics at impact. A series of irises, mirrors, and a HeNe laser was used to align the Lexan plate normal to the end of the gas-gun barrel to provide a planar impact. Typical impact-tilts achieved with this technique are sub milli-radian.

For all three experiments, the flyer plate was a 38 mm diameter, 2.5 mm thick, tantalum disc. This was mounted to the front of the projectile, supported by a glass micro-bead material to avoid bowing of the flyer plate during the launch. The 80 mm diameter gas-gun in MST-8 at LANL was used to accelerate the projectile to velocities from ~630 m/s to ~1000 m/s, generating stresses on the order of 20 GPa, 30 GPa and 34 GPa.

16.3 Results

Figure 16.3 shows an exemplar PDV velocity spectrogram. For the 34 GPa experiment, velocity results for the largest initial perturbation size are shown. The highest velocities in the spectrogram come from the spike. In this case, the peak spike velocity is about 1900 m/s, which is well above the rest of the velocities thus indicating spike growth. Over about 1 μs, the velocity decays to the background level of about 1000 m/s indicating arrest: the spike growth has ceased. The lowest velocities after shock breakout are around 600 m/s, which come from the bubble region during the perturbation inversion process. As with the spike, those velocities return to the background level indicating cessation of the instability growth.

16.4 Discussion

The experiments provided good velocity data for all perturbation sizes at all three shot pressures. Work is underway to estimate the strength for each shot following a previously reported procedure [19]. Following that, the strength will be calculationally assigned to the appropriate strain, strain, rate and temperature [14] so that the strength values can be used to help calibrate a constitutive (strength) model valid for wide ranges of conditions [23].

Acknowledgements Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By

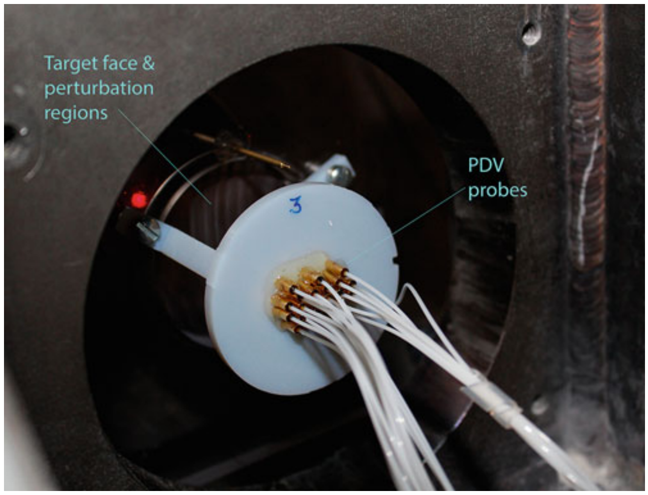

Fig. 16.2 A view of the target free surface and the PDV probes prior to execution

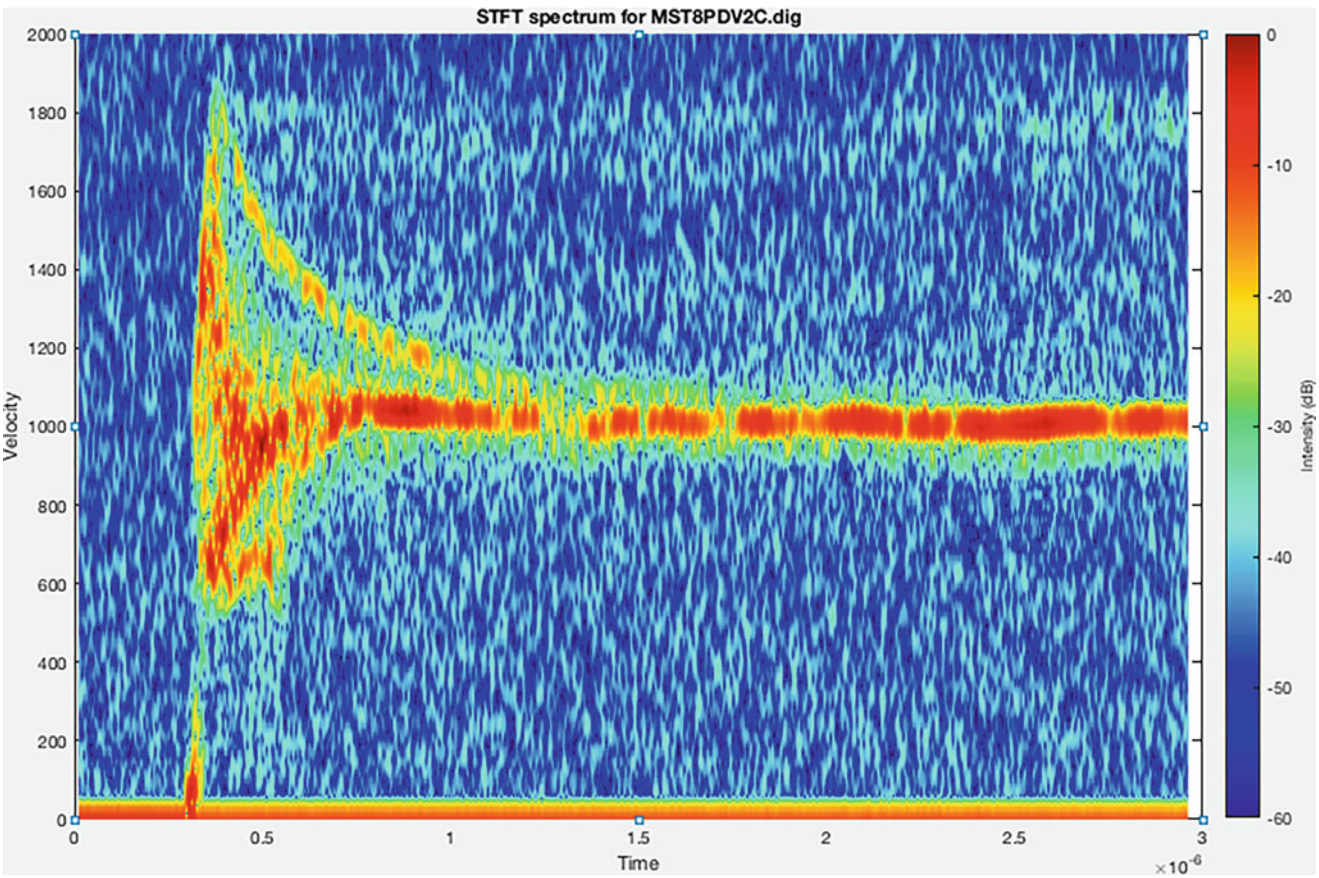

Fig. 16.3 The PDV velocity spectrogram for the region with $\eta_0 k = 0.9$ in the 34 GPa experiment shows a distinct signal for the spike with a maximum velocity near 1900 m/s during growth and a later return to the background velocity, indicating arrest

References

1. Piriz, A.R., Cela, J.J.L., Tahir, N.A., Hoffmann, D.H.H.: Richtmyer-Meshkov instability in elastic-plastic media. Phys. Rev. E. **78**(5), 056401 (2008)
2. Piriz, A.R., Cela, J.J.L., Tahir, N.A.: Richtmyer–Meshkov instability as a tool for evaluating material strength under extreme conditions. Nucl Instrum Meth A. **606**(1), 139–141 (2009)
3. Dimonte, G., Terrones, G., Cherne, F.J., Germann, T.C., Dupont, V., Kadau, K., Buttler, W.T., Oro, D.M., Morris, C., Preston, D.L.: Use of the Richtmyer-Meshkov instability to infer yield stress at high-energy densities. Phys. Rev. Lett. **107**(26), 264502 (2011)
4. Buttler, W.T., Oró, D.M., Preston, D.L., Mikaelian, K.O., Cherne, F.J., Hixson, R.S., Mariam, F.G., Morris, C., Stone, J.B., Terrones, G., Tupa, D.: Unstable Richtmyer-Meshkov growth of solid and liquid metals in vacuum. J. Fluid Mech. **703**, 60–84 (2012)
5. López Ortega, A., Lombardini, M., Pullin, D.I., Meiron, D.I.: Numerical simulations of the Richtmyer-Meshkov instability in solid-vacuum interfaces using calibrated plasticity laws. Phys. Rev. E. **89**(3), 033018 (2014)
6. Mikaelian, K.O.: Shock-induced interface instability in viscous fluids and metals. Phys. Rev. E. **87**(3), 031003 (2013)
7. Plohr, J.N., Plohr, B.J.: Linearized analysis of Richtmyer-Meshkov flow for elastic materials. J. Fluid Mech. **537**, 55–89 (2005)
8. Prime, M.B., Vaughan, D.E., Preston, D.L., Buttler, W.T., Chen, S.R., Oró, D.M., Pack, C.: Using growth and arrest of Richtmyer-Meshkov instabilities and Lagrangian simulations to study high-rate material strength. J. Phys. Conf. Ser. **500**(11), 112051 (2014)
9. Opie, S., Gautam, S., Fortin, E., Lynch, J., Peralta, P., Loomis, E.: Behaviour of rippled shocks from ablatively-driven Richtmyer-Meshkov in metals accounting for strength. J. Phys. Conf. Ser. **717**(1), 012075 (2016)
10. John, K.K.: Strength of Tantalum at High Pressures through Richtmyer-Meshkov Laser Compression Experiments and Simulations. Ph.D. Dissertation, California Institute of Technology, Pasadena, CA (2014)
11. Buttler, W.T., GrayIII, G.T., Fensin, S.J., Grover, M., Prime, M.B., Stevens, G.D., Stone, J.B., Turley, W.D.: Yield strength of Cu and a CuPb alloy (1% Pb). AIP Conf. Proc. **1793**(1), 110005 (2017). https://doi.org/10.1063/1.4971668
12. Sternberger, Z., Maddox, B.R., Opachich, Y.P., Wehrenberg, C.E., Kraus, R.G., Remington, B.A., Randall, G.C., Farrell, M., Ravichandran, G.: A comparative study of Rayleigh-Taylor and Richtmyer-Meshkov instabilities in 2D and 3D in tantalum. AIP Conf. Proc. **1793**(1), 110006 (2017). https://doi.org/10.1063/1.4971669
13. Prime, M.B., Buttler, W.T., Buechler, M.A., Denissen, N.A., Kenamond, M.A., Mariam, F.G., Martinez, J.I., Oró, D.M., Schmidt, D.W., Stone, J.B., Tupa, D., Vogan-McNeil, W.: Estimation of metal strength at very high rates using free-surface Richtmyer–Meshkov instabilities. J. Dyn. Behav. Mater. **3**(2), 189–202 (2017). https://doi.org/10.1007/s40870-017-0103-9
14. Prime, M.B.: Strain rate sensitivity of Richtmyer-Meshkov instability experiments for metal strength. In: Kimberley, J., Lamberson, L., Mates, S. (eds.) Dynamic Behavior of Materials, Volume 1: Proceedings of the 2017 Annual Conference on Experimental and Applied Mechanics, pp. 13–16. Springer International Publishing, Cham, Switzerland (2018). https://doi.org/10.1007/978-3-319-62956-8_3
15. Opie, S.: Effects of Phase Transformations and Dynamic Material Strength on Hydrodynamic Instability Evolution in Metals. Ph.D. thesis Arizona State University, Tempe. Arizona, USA (2017)
16. Sternberger, Z., Opachich, Y., Wehrenberg, C., Kraus, R., Remington, B., Alexander, N., Randall, G., Farrell, M., Ravichandran, G.: Investigation of hydrodynamic instability growth in copper. Int. J. Mech. Sci. (2017). in press, https://doi.org/10.1016/j.ijmecsci.2017.08.051
17. Zhou, Y.: Rayleigh–Taylor and Richtmyer–Meshkov instability induced flow, turbulence, and mixing. I. Phys. Rep. **720-722**, 1–136 (2017). https://doi.org/10.1016/j.physrep.2017.07.005
18. Zhou, Y.: Rayleigh–Taylor and Richtmyer–Meshkov instability induced flow, turbulence, and mixing. II. Phys. Rep. **723–725**, 1–160 (2017). https://doi.org/10.1016/j.physrep.2017.07.008
19. Prime, M.B., Buttler, W.T., Buechler, M.A., Denissen, N.A., Kenamond, M.A., Mariam, F.G., Martinez, J.I., Oró, D.M., Schmidt, D.W., Stone, J.B., Tupa, D., Vogan-McNeil, W.: Estimation of metal strength at very high rates using free-surface Richtmyer-Meshkov instabilities. J. Dyn. Behavior Mater. **3**(2), 189–202 (2017). https://doi.org/10.1007/s40870-017-0103-9
20. Vachhani, S.J., Trujillo, C., Mara, N., Livescu, V., Bronkhorst, C., Gray, G.T., Cerreta, E.: Local mechanical property evolution during high strain-rate deformation of tantalum. J. Dyn. Behav. Mater. **2**(4), 511–520 (2016). https://doi.org/10.1007/s40870-016-0085-z
21. Buchheit, T.E., Cerreta, E.K., Diebler, L., Chen, S.-R., Michael, J.R.: Characterization of Tri-lab Tantalum (Ta) Plate. Sandia National Laboratories Report SAND2014-17645 (2014)
22. Lim, H., Bong, H.J., Chen, S.-R., Rodgers, T.M., Battaile, C.C., Lane, J.M.D.: Developing anisotropic yield models of polycrystalline tantalum using crystal plasticity finite element simulations. Int. J Solids Struct. **730**(11), 50–56 (2018)
23. Preston, D.L., Tonks, D.L., Wallace, D.C.: Model of plastic deformation for extreme loading conditions. J. Appl. Phys. **93**(1), 211–220 (2003)