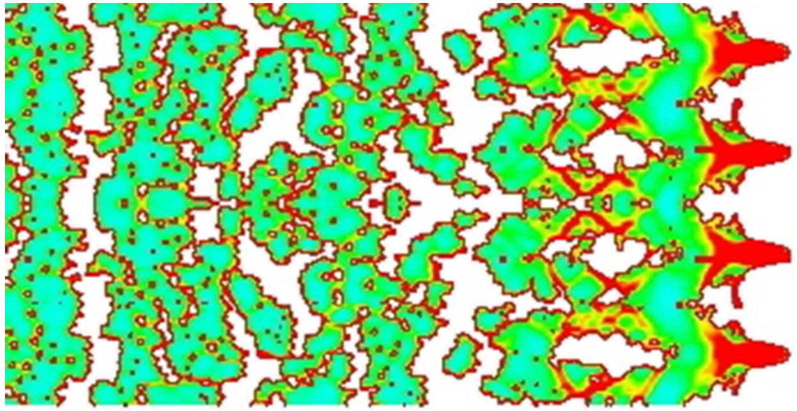
SAND2017-3828C



4/25/17

Eulerian Hydrocode Predictions of Richtmyer-Meshkov Instability and Growth

S.P. Rojas and E.N. Harstad

2017 Hypervelocity Impact Symposium

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2017-XXXXP

Motivation

- Hypervelocity impact phenomena
  - Strain rates exceeding 10^{11} s^{-1}
  - Pressures exceeding 10 GPa
- Strength models rely on experimental data within a relatively narrow span of strain rates
  - Lower rate regimes; mechanical testing machines; 10^{-4} – 10^{-1} s^{-1}
  - Higher rate regimes; split hopkinson bar; 10^{4} – 10^{5} s^{-1}
- Above thermal activation regime of 10^{4} s^{-1} , experimental data for strength models: relatively sparse
- Work presented here focuses on the intermediate strain rate regime of 10^{4} – 10^{9} s^{-1}
  - Johnson-Cook; High Rate Johnson-Cook
  - Preston-Tonks-Wallace (PTW)
  - Mechanical Threshold Stress (MTS)

Methods For Studying Strength at High Pressures

- Comparison to hydrostatic response
- Lateral stress gauges
- Pressure-Shear Loading
- X-Ray Diffraction
- Growth of instabilities
  - Rayleigh-Taylor
  - Richtmyer-Meshkov
- Diamond Anvil Cells
- Shock Recovery Experiments

COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIII, 297–319 (1960)

Taylor Instability in Shock Acceleration of Compressible Fluids*

ROBERT D. RICHTMYER

1. Introduction

G. I. Taylor developed a theory of the growth of irregularities on the interface between two fluids of different densities when they are in accelerated motion. The fluids are assumed incompressible and the interface to have sinusoidal corrugations, so that the position of the interface in a suitably oriented cartesian coordinate system is given by

$$z = a \cos kx \quad (1)$$

at some instant, where a and k are constants and where

$$ka \ll 1. \quad (2)$$

Then, if there is an acceleration of the system as a whole and if $g(t)$ represents the z-component of acceleration, the growth or decay of the amplitude $a = a(t)$ of the corrugations satisfies the equation

$$\frac{d^2}{dt^2} a(t) = kg(t)a(t) \frac{\rho_{(+)} - \rho_{(-)}}{\rho_{(+)} + \rho_{(-)}}, \quad (3)$$

where $\rho_{(+)}$ and $\rho_{(-)}$ are the densities of the fluids on the $+z$ and $-z$ sides of the interface, respectively.

If viscosity, surface tension, compressibility are absent, (3) remains rigorous so long as (2) continues to hold. If the irregularity consists of a superposition of sinusoidal corrugations, each satisfying (2), then each of them also satisfies (3) with its appropriate value of k. For constant acceleration directed toward the denser fluid, (3) gives an exponential growth of $a(t)$. It is also known that after ka has reached about 1, the increase of a is more leisurely, at about a constant rate (the shape is no longer sinusoidal). It is therefore generally assumed that (3) describes fairly well the growth of long-wavelength irregularities of small amplitude ($ka \ll 1$), even though irregularities of very short-wavelength have gone out of the linear range near the beginning of the acceleration, since the fuzziness of the interface caused

*This paper was originally published while the author was at the Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico, as Report LA-1914, July, 1954, under the auspices of the Atomic Energy Commission. Reproduction in whole or in part permitted for any purpose of the United States Government.

E. E. Meshkov

Izv. AN SSSR. Mekhanika Zhidkosti i Gaza, Vol. 4, No. 5, pp. 151–157, 1969

ABSTRACT: Results are presented of an experimental study of the stability of the interface of two gases traversed by a shock wave. It is found that the interface is unstable both in the case of shock wave passage from the lighter to the heavier gas and for passage in the opposite direction. The interface disturbance grows linearly with time in the first approximation.

1. The instability of the interface of two fluids of different density which are accelerated, with the acceleration normal to the interface and directed from the lighter fluid toward the heavier, is termed gravitational instability and was first examined by Taylor [1]. Richtmyer [2] considered the case in which the acceleration is impulsive and, in particular, the case in which the interface is accelerated by a shock wave. He examined this problem under the assumption that the interface of the compressible fluids has the form

$$y = a_0 \cos kx \qquad (a_0 k \ll 1). \quad (1.1)$$

The case is examined in which plane shock wave 1 traverses interface 2 from the lighter fluid toward the heavier (Fig. 1a). At the interface the shock wave is refracted, forming the reflected shock 3 and the transmitted shock 4, which will also be weakly disturbed (Fig. 1b). In the interface disturbance trough the transmitted wave diverges weakly, while the reflected wave converges weakly. This creates some pressure increase in the light fluid and decrease in the heavy fluid, i.e., a pressure gradient normal to the interface develops. A similar situation develops in the interface disturbance crest region, but with a pressure gradient of opposite sign. Thus, forces arise which lead to growth of the interface disturbance.

Richtmyer [2] obtained the equations and the initial and boundary conditions for the numerical solution of the problem. He presents several results of a computer calculation of individual cases for ideal gases $\gamma = 3/2$ and $\gamma = 9/7$ and density ratios 1/8 and 1/16. His calculations indicate, that da/dt first increases and then, after several oscillations with decreasing amplitude, approaches a limiting value.

This paper contains the results of an experimental study of the stability of the interface of two ideal gases which are accelerated by a shock wave.

2. The study was made using a shock tube (Fig. 2). The shock tube construction is similar to that described in [3]. A schematic of the shock tube and recording equipment is shown in Fig. 2, where 1 is the shock tube chamber; 2 is the diaphragm, 3 is the channel, 4 is the test section, 5 is the transparent portion of the test section, 6 is the IAB-451 schlieren setup, 7 is the SFR-3M high-speed camera, 8 is the IFK-120 light source.

The shock tube channel and chamber are cylindrical, with internal diameter 208 mm. The chamber was separated from the channel by a diaphragm consisting of four layers of cellulose acetate film, each 0.2 mm thick. The intial pressure in the chamber was 6.5 gauge atm, that in the channel was 1 atm abs. Diaphragm bursting was initiated by an exploding electric wire bonded to the center of the diaphragm. This made it possible to synchronize the operation of the shock tube and the SFR recording camera.

The parameters of the resulting shock wave in air were: pressure $\Delta p = 1.53$ gauge atm, wave velocity $D = 520$ m/sec, mass velocity $u = 247$ m/sec.

The 120 × 40 mm rectangular test section 4 (Fig. 2) was installed a the end of the channel, with the test section extending 0.7 meters into the cylindrical channel.

Figure 3 shows a fragment of the test section with the interface being studied: in the figure 1 and 2 are thin films, 2 is the interface being studied; 3 is the shock wave front, 4 is air, 5 is gas 1, 6 is gas 2, 7 is the edge of the SFR camera frame. Thus, the shock wave has been split into two parts, one of which travels in the test section while the other enters the closed portion of the channel and has no effect on the flow in the test section. The end portion of the test section consisted of individual plexiglass blocks which were fitted tightly against one another. The blocks were assembled on two guide rods and clamped together by a steel plate. This portion of the test section served as a viewing window. The individual blocks were separated from one another with the aid of the thin films 1 and 2

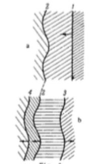


Fig. 1

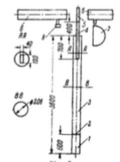


Fig. 2

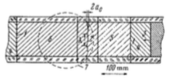
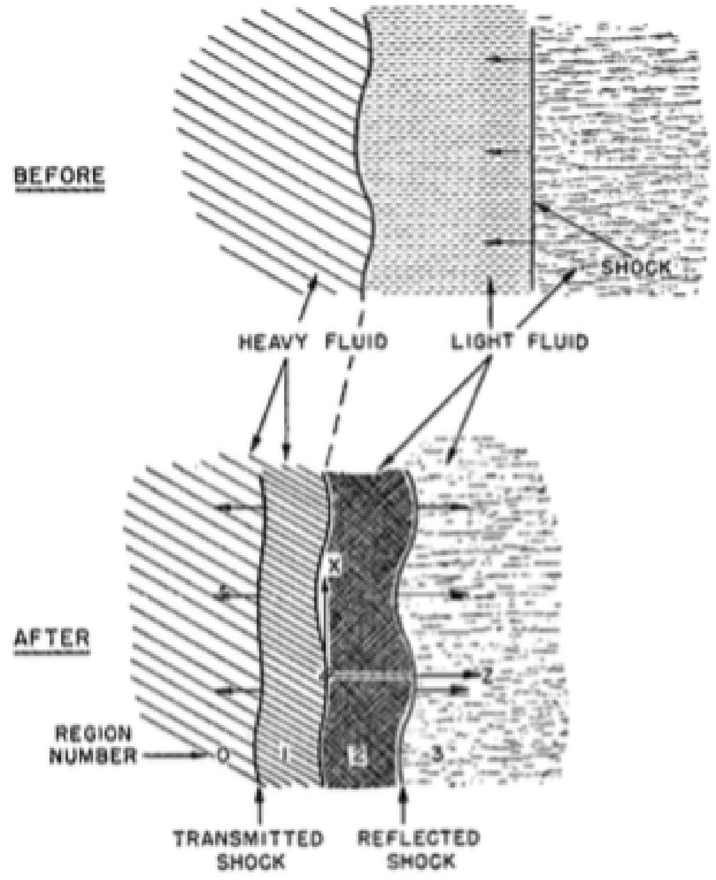


Fig. 3

Richtmyer-Meshkov Instabilities for Studying Strength

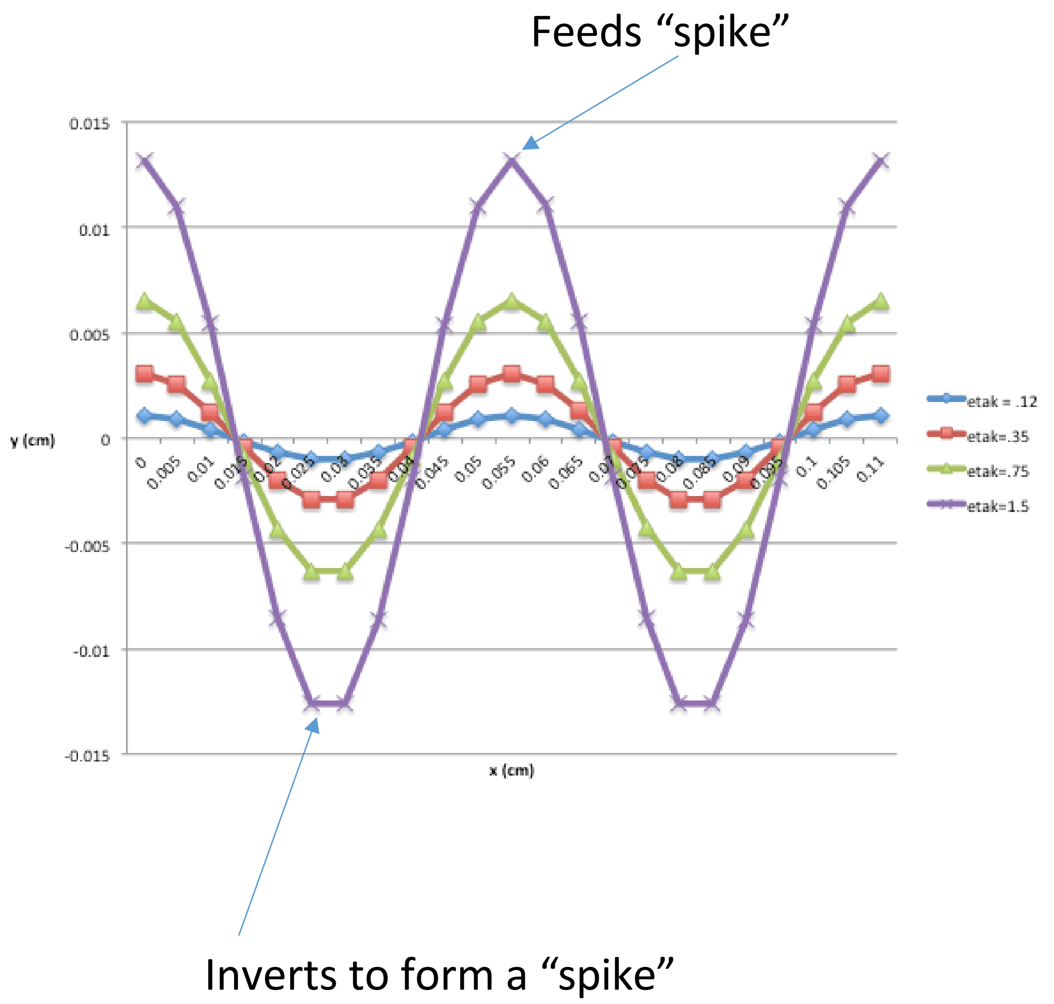
- RMI: shock amplifies perturbations at material interfaces a rate that depends on material properties
- Alternative to Rayleigh-Taylor experiments for studying strength at high pressure
  - Relatively easy to field and diagnose
- Interface oscillates harmonically at a rate that depends on solid shear modulus



From: Richtmyer, R.D., 1960. “Taylor Instability in Shock Acceleration of Compressible Fluids”, Communications on Pure and Applied Mathematics, Vol. XIII, 297-319 (1960)

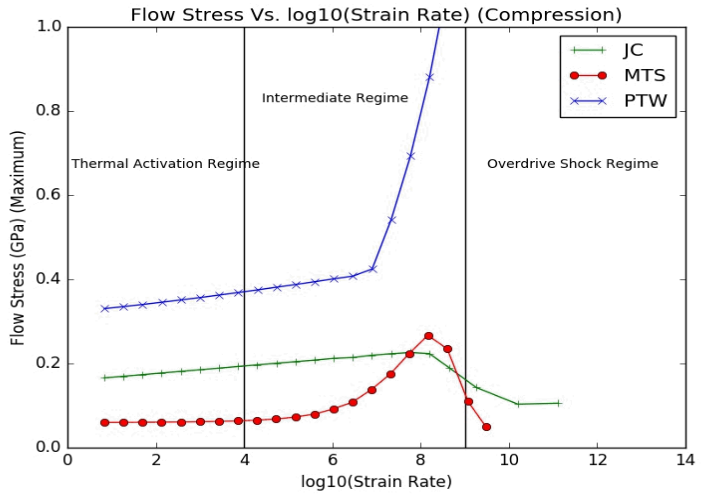
Studying Strength by Varying RMI Target "Corrugation"

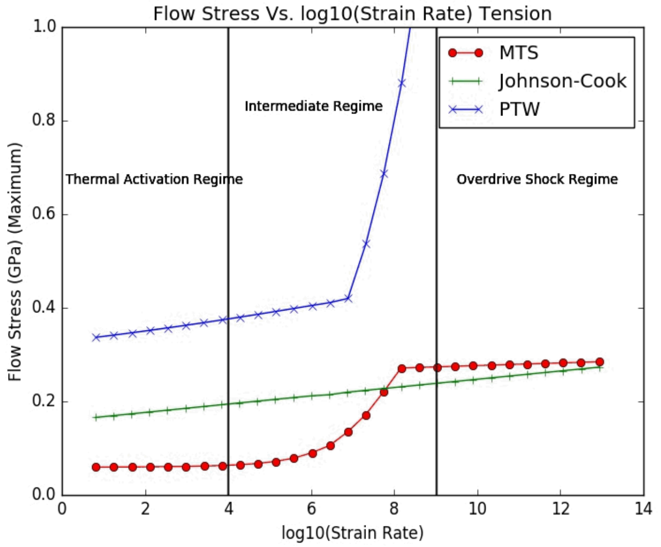
- Modify target "corrugation" to study strength
  - η_0 = initial perturbation amplitude
  - λ = wavelength
  - $k = 2\pi/\lambda$
- Larger $\eta_0 k$, more deformation
- Aim for arrest and growth to study strength effects
- For $\eta_0 k = .35$, Buttler observed RMI strain rates ~10^7
  - In the intermediate strain rate regime of interest
  - Arrest and growth observed for this configuration



Intermediate Strain Rate Regime of Interest for Hypervelocity Phenomena

- CTH PRDEF (PRescribed DEFormation) capability: initial scoping studies across strain rate regimes
  - 1D uniaxial tension, compression
  - Test strength models in simple, controlled conditions (homogeneous deformation)
- MTS deformation history not accounted for in PRDEF simulations
  - RMI problem: several compression, release cycles
  - MTS expected to under-predict strength for PRDEF simulations

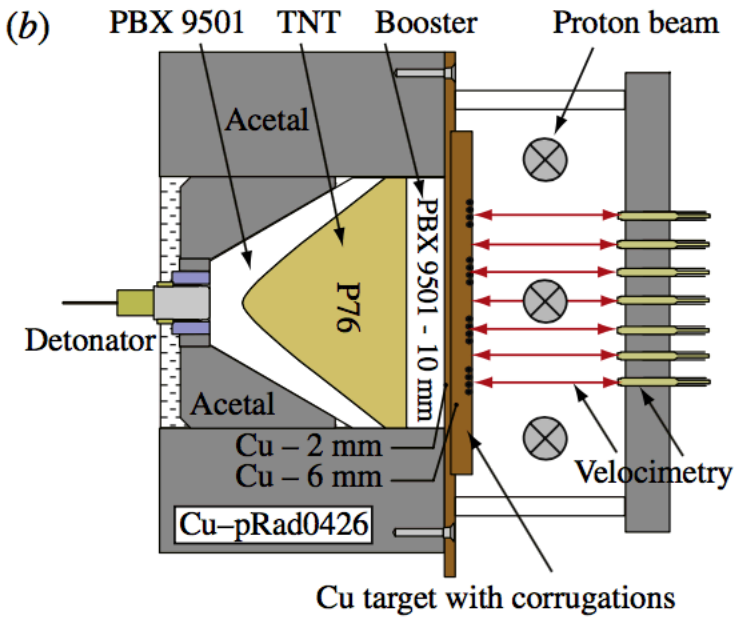


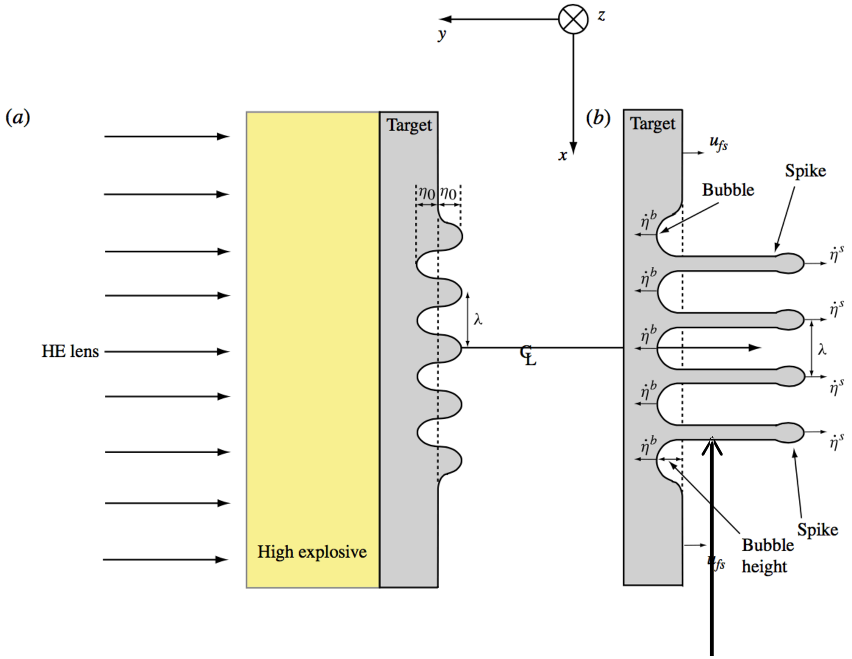


CTH PRDEF Simulations Showing Strain Rate Regimes

RMI Experiments -- Buttler

From: "Unstable Richtmyer-Meshkov growth of solid and liquid metals in vacuum"; J. Fluid Mech (2012), vol. 703 Buttler et al.

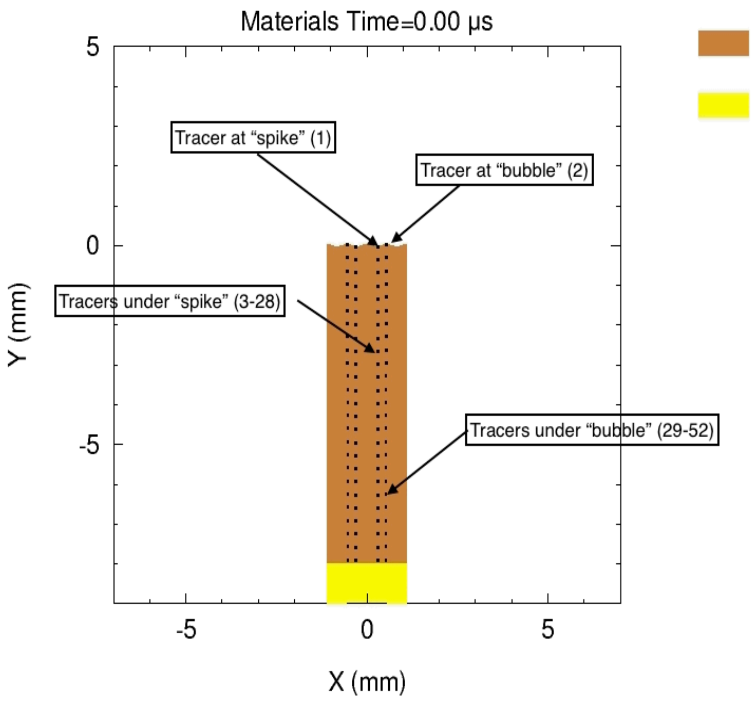


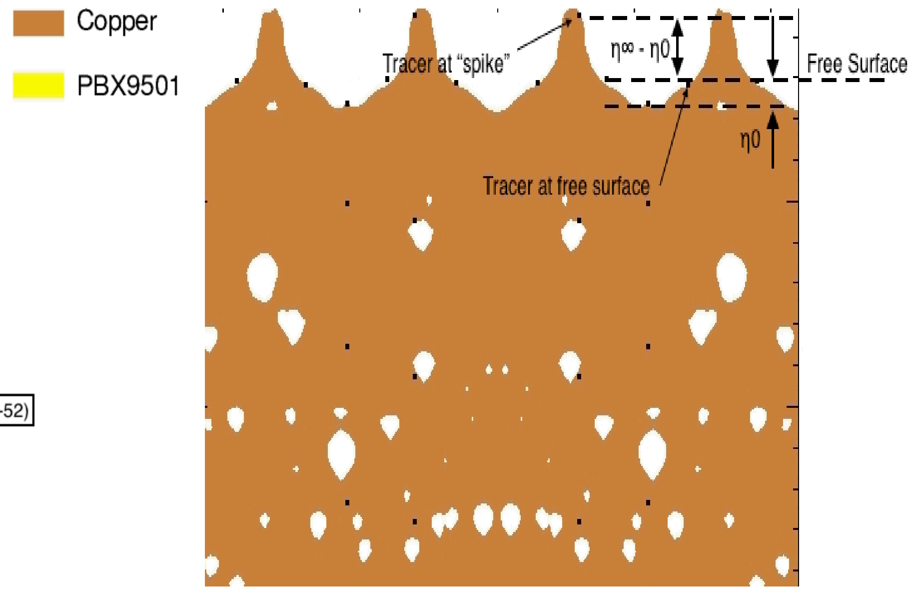


Plasticity determines maximum perturbation amplitude

RMI CTH Simulations

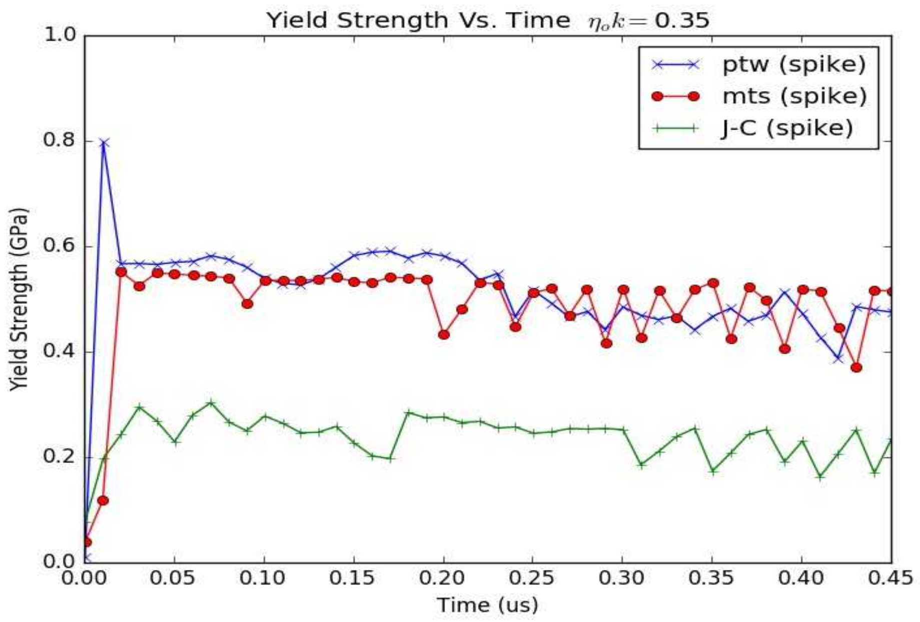
- 2D, 5 μm / cell
- Periodic BC's
- 9501: JWL
- Cu: MG, PTW/MTS/JC
  - PFRAC damage
- $\eta_0 k = .35$
  - Arrest and growth observed experimentally





Baseline Results

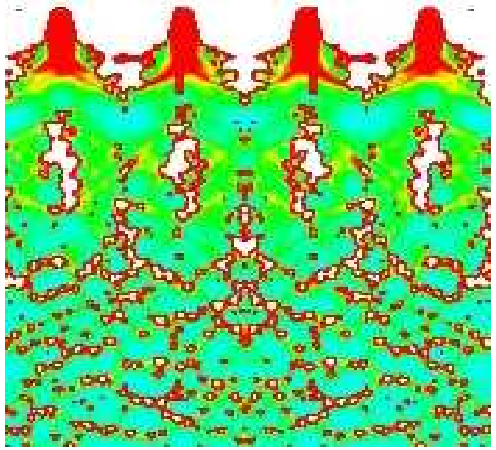
- MTS
  - 30 input parameters
  - intermediate regime: deformation history effects
- PTW
  - 17 input parameters
  - intermediate regime: “glide to drag” transition
  - overdriven shock theory
- Johnson Cook
  - 6 input parameters
  - empirical
  - intermediate regime: high rate Johnson-Cook extension

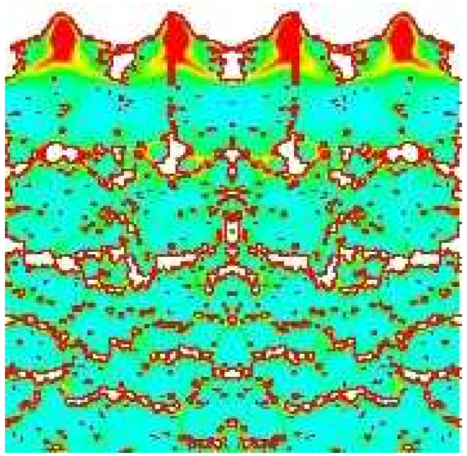


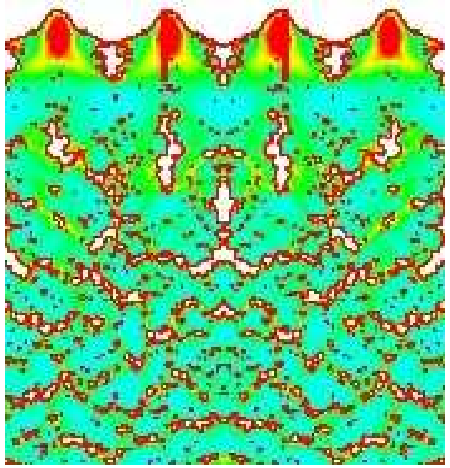
Baseline RMI CTH Results

Baseline Results

Strength Model	η_∞-η_0 (μm)	Peak Velocity (mm/μs)
Johnson-Cook (Cu)	245	2.17
PTW(Cu)	103	2.11
MTS (OFHC Cu)	127	2.10
Experiment (1/2 Cu)	**160**	**2.15**


Johnson-Cook

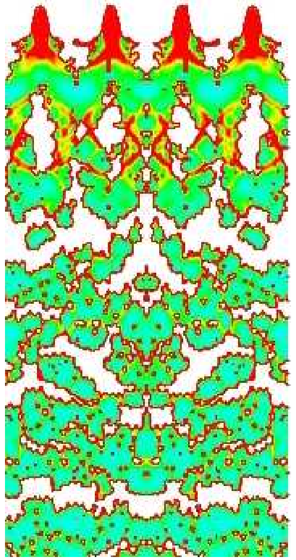

MTS


PTW

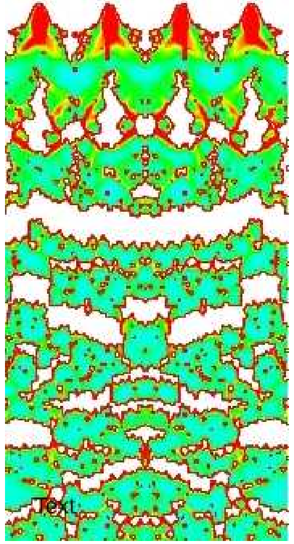
MTS, PTW overpredict strength; JC underpredicts. Can we increase strength in JC ? (or decrease strength in PTW, MTS ?)

Improved Results: High Rate Johnson-Cook

	Spike Growth (µm)	Peak Velocity (mm/µs)
Standard Johnson-Cook Model (Cu)	245	2.17
High Rate Johnson-Cook Model (Cu)	164	2.15
Experiment [9] (1/2 Cu)	160	2.15



Standard JC

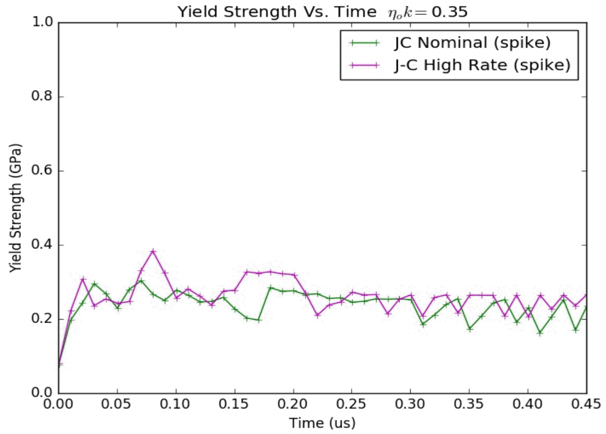


High Rate JC

$$Y = Y(\epsilon^p, \dot{\epsilon}^p, T)$$

$$= [A + B(\epsilon^p)^n]\left[1 + C ln(\dot{\epsilon^p}) + \underline{\boldsymbol{C_2 ln(\dot{\epsilon^p})^{C_3}}}\right][1 - \Theta_H^m]$$

added term



Conclusions

- PTW, MTS over-predicted flow stress
- Standard Johnson-Cook under predicted flow stress
- High Rate Johnson-Cook improved RMI predictions significantly
  - Two added parameters
- With additional Richtmyer-Meshkov experimental data, the accuracy of material strength models in the intermediate strain rate regime can be further improved

Possible Future Work

- Higher resolution simulations
- Parameter refinement using additional RMI data
  - limited data for current study
- Validation of high rate Johnson-Cook against additional experiments
  - Taylor Anvil
  - Flyer Plate
  - Shaped Charge
- Refinement of PTW, MTS parameters using RMI data
- Application towards RMI experiment design
- Fracture model studies using RMI data

Acknowledgements

The authors would like to acknowledge the Joint DOE/DoD Munitions Program and the Advanced Scientific Computing Physics and Engineering Program for supporting this work.

This work was performed under Contract 1635568 to Sandia National Laboratory. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

Questions ?