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Form 836 (7/06)

Copper strength at high strains and strain-rates

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Abstract

Material strength models, such as Preston-Tonks-Wallace (PTW) and Steinberg-Guinan, are constitutive models with parameters derived from data sets obtained primarily from quasi-static and Hopkinson-bar experiments. Consequently, the major predictive uncertainty of the models lies in the range of strain and strain-rate conditions where these experimental techniques are not well suited to yield data. These conditions, with strains up to several hundred percent at strain-rates between 10^5 and 10^8 s^{-1}, are precisely where explosive loading or high-velocity impact simulations utilize the models to predict the ensuing plastic deformation of metals. Therefore, experiments are needed to validate the predictive accuracy of strength models throughout an extended range of strains and strain-rates. A series of such high-strain rate strength model validation experiments have recently been conducted using copper samples. The experimental technique utilizes a flat metal plate with perturbations of known wavelength and amplitude machined into one surface. A high-explosive (HE) plane-wave lens is used to generate shock-free, planar loading on the perturbed side of the plate and the amplitude of the Rayleigh-Taylor unstable perturbations are measured via a sequence of radiographs acquired as a function of time. The perturbation growth rate is inhibited by the dynamic strength of the metal and is compared directly to that predicted by various strength models via hydrodynamic simulations. These simulations show a tendency of the strength models to overestimate the dynamic strength of the copper at strain-rates between 10^5 s^{-1} and 10^6 s^{-1}.

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Copper Strength at High Strains and Strain-Rates

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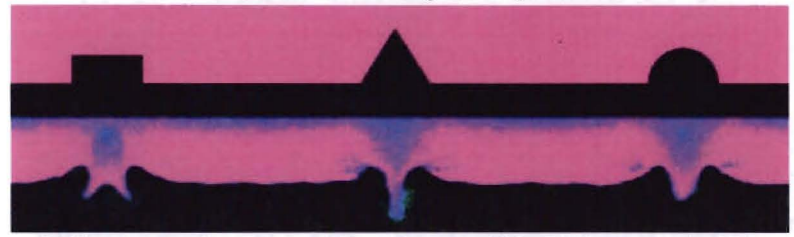
Material strength models are required to simulate the deformation of metals under extreme loading conditions.

- **Hydrodynamic simulations, and the material strength models invoked in the codes, are increasingly used to predict the plastic response of metals at high strains and strain-rates.**
  - Explosively driven deformation/welding.
  - Implosion dynamics.
  - High velocity impacts.

Simulation of Cu Jetting and Ejection

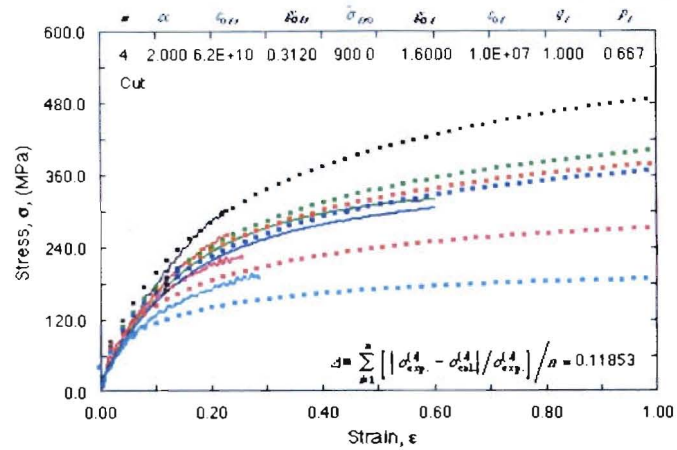


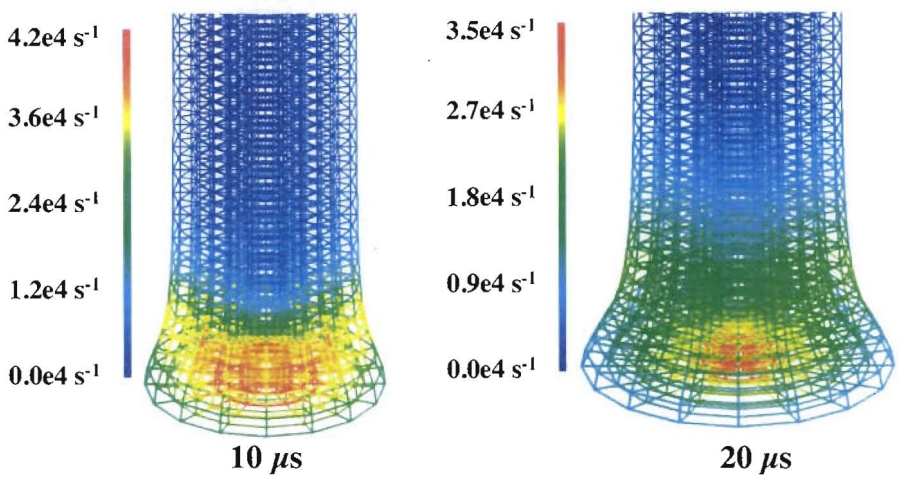
LANL Roadrunner Simulation: S. Swaminarayan, Timothy Germann *et al.*

- **Strength models implemented in hydrocodes are either largely empirical (Steinberg-Guinan, Johnson-Cooke) or more physics based (Preston-Tonks-Wallace, Mechanical Threshold Stress, etc.) in nature.**
  - Models must capture effects of thermal softening, work hardening, strain-rate hardening, etc.
  - Empirical strength models compute the flow stress using a functional form where the parameters are used to fit the available experimental data.
  - Physically based strength models are constructed on the premise that plastic deformation can be described via the motion of dislocations.
    - » **Example:** PTW invokes a thermally assisted dislocation glide mechanism at low strain-rates with a discontinuous transition to dislocation drag at high strain-rates.

Strength model parameters are determined using data obtained at low to moderate strain rates (<10^4 s^{-1}).

- **Both empirical and physically based strength models require experimental data to set the parameters.**
  - Typically quasi-static (<10^1 s^{-1}), Hopkinson-bar (<10^4 s^{-1}), and shock driven experiments (>10^9 s^{-1}) are used.



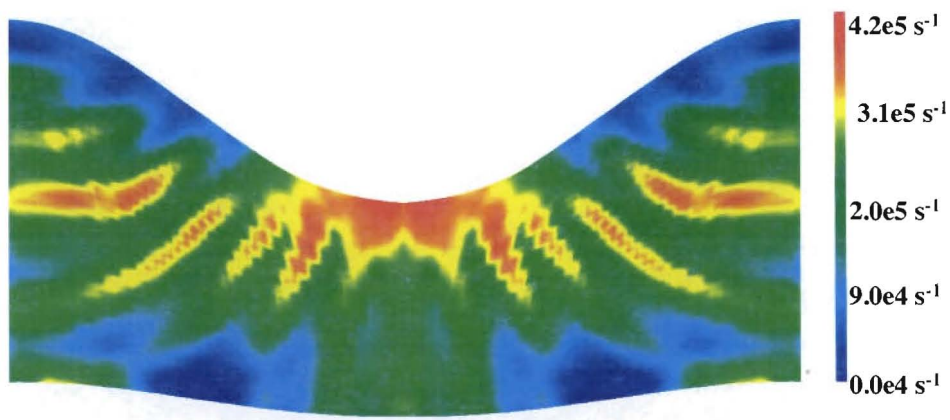


- **Strength models are typically validated against experiments such as Taylor cylinder tests.**
  - Typically subject the sample to strain rates of ~10^4 s^{-1}, moderate strain <100%, and low pressure.

- **Traditional experimental techniques not well suited to provide validation data for ε >100% at $d\varepsilon/dt$ ~ 10^5-10^7 s^{-1} ...the strength models are often extrapolating in hydrodynamic simulations.**

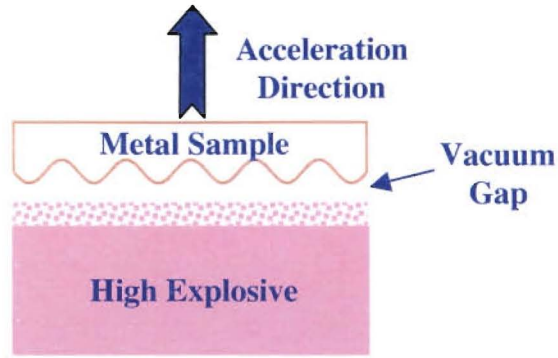
Strength inhibited R-T growth experiments can be used to validate models at higher strains and strain-rates.

- **Accelerate a sinusoidally perturbed, solid metal surface and radiographally measure the Rayleigh-Taylor unstable perturbation amplitude, *A(t)*, as a function of time.**
  - The simplest case is to shocklessly accelerate a sample to avoid shock hardening the material into a undefined initial state.
  - Experimentally controlled variables are initial perturbation amplitude, wavelength, plate acceleration, and sample material.
  - Unstable amplitude growth is inhibited by dynamic material strength.
  - Strain rates of 10^4-10^7 s^{-1} can be achieved.

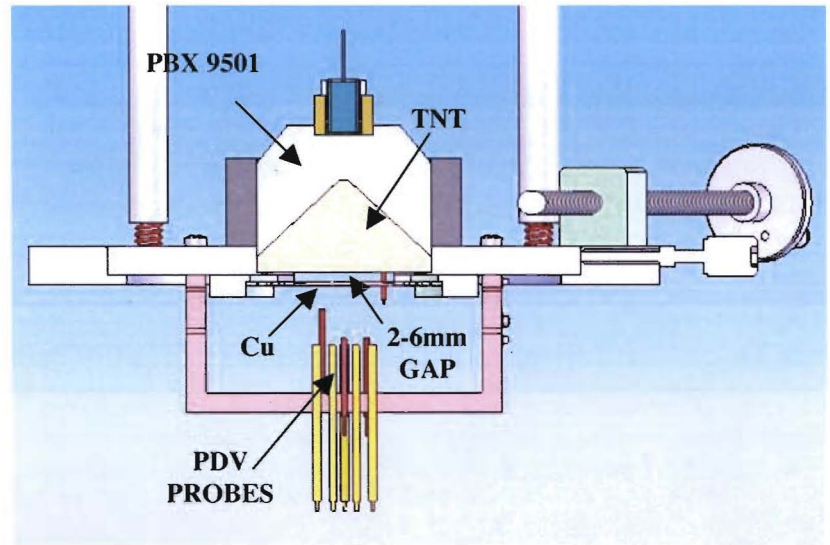


The experimental technique utilizes explosive by-products to shocklessly accelerate a perturbed metal sample.

- **A high-explosive lens is located a few millimeters from the sample.**
  - HE by-products move across a small vacuum gap and stagnate on the perturbed sample surface.
  - Sample acceleration and large density difference at the perturbed surface causes unstable R-T growth.
  - Technique initiated by Barnes[1], *et al.* and further developed by Raevsky[2], *et al.*

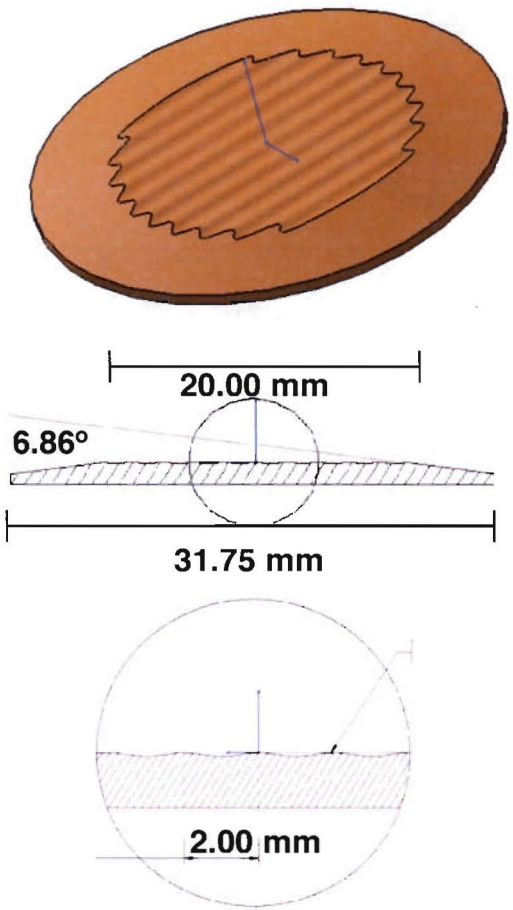


- **Experimental setup:**
  - Sample located 2.0-6.0 mm from output face of 56 mm diameter, solid explosive plane wave HE lens.
  - Precise tip, tilt, altitude, and rotational adjustments to align with proton radiographic (pRad) beam axis.
  - Photon Doppler Velocimetry (PDV) measures acceleration at the back surface of the sample.

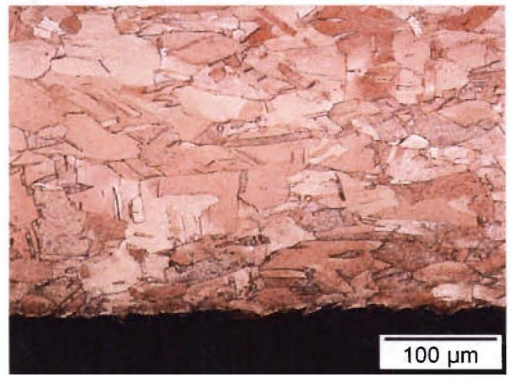


[1]J.F. Barnes, *et al.*, J. Appl. Phys. **45**, 727 (1974).
[2]V.A. Raevsky, All-Russian Institute of Experimental Physics (VNIIEF) Technical Report to LANL under Agreement B70040006-35, TA 051, Mod. 12. 2002.

The geometry, material processing, manufacturing, and metallurgy of the sample are all carefully controlled.

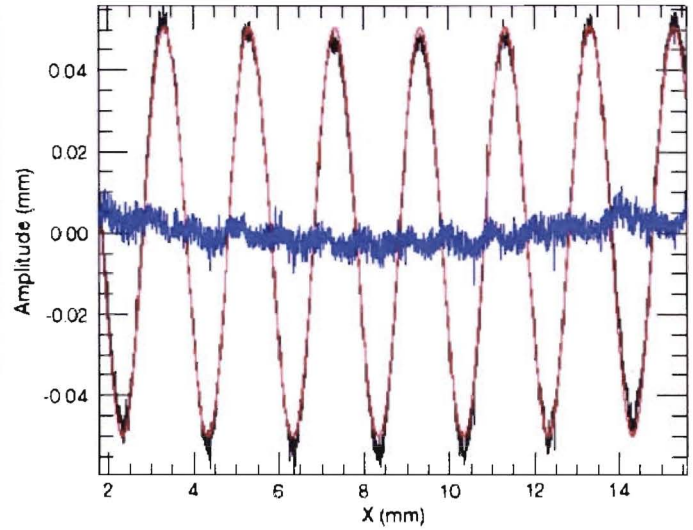


Pre-strained Cu sample with EDM surface



$$A(x) = A_0 \sin\left(\frac{2\pi x}{\lambda}\right)$$

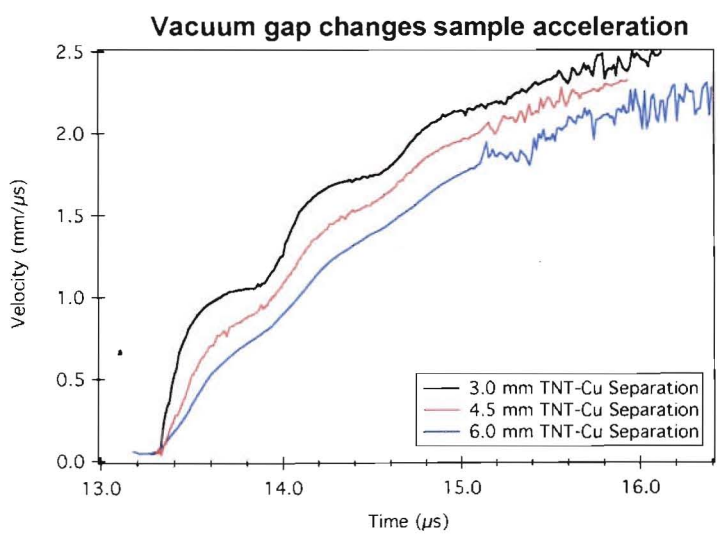
Sinusoidal Perturbation with Fit and Residual

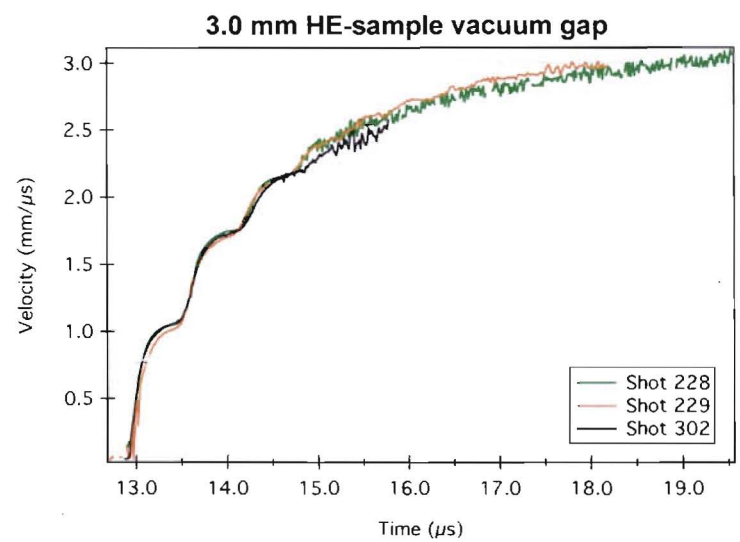


- **λ_0 and A_0 of sinusoidal perturbation chosen to create unstable growth that remains strength-inhibited.**
  - Typical values: λ_0 = 2.00 mm, A_0 = 55 μm
- **~7° bevel necessary to minimize dynamic 'cupping' of the sample.**
- **Sample grain size, microstructure (twinning, grain elongation, etc.), and machining effects characterized.**
  - Annealed Cu (600 °C for 1 hour): 60 μm average grain size

Sample acceleration measurements provide a constraint on the drive in hydrodynamic simulations.

- **It is a pre-requisite to accurately simulate the sample acceleration before the data can be used for strength model validation.**
  - Initial acceleration, sample 'ringing', and asymptotic velocity must be matched. This is a complex F=ma problem because it requires accurately modeling the HE by-product expansion into vacuum.
  - 'Ringing' frequency defined by sample thickness and longitudinal bulk sound speed.
- **Measured sample accelerations are shockless, controllable, and repeatable.**
  - Shockless acceleration is important to avoid shock hardening the sample into an unknown initial state.

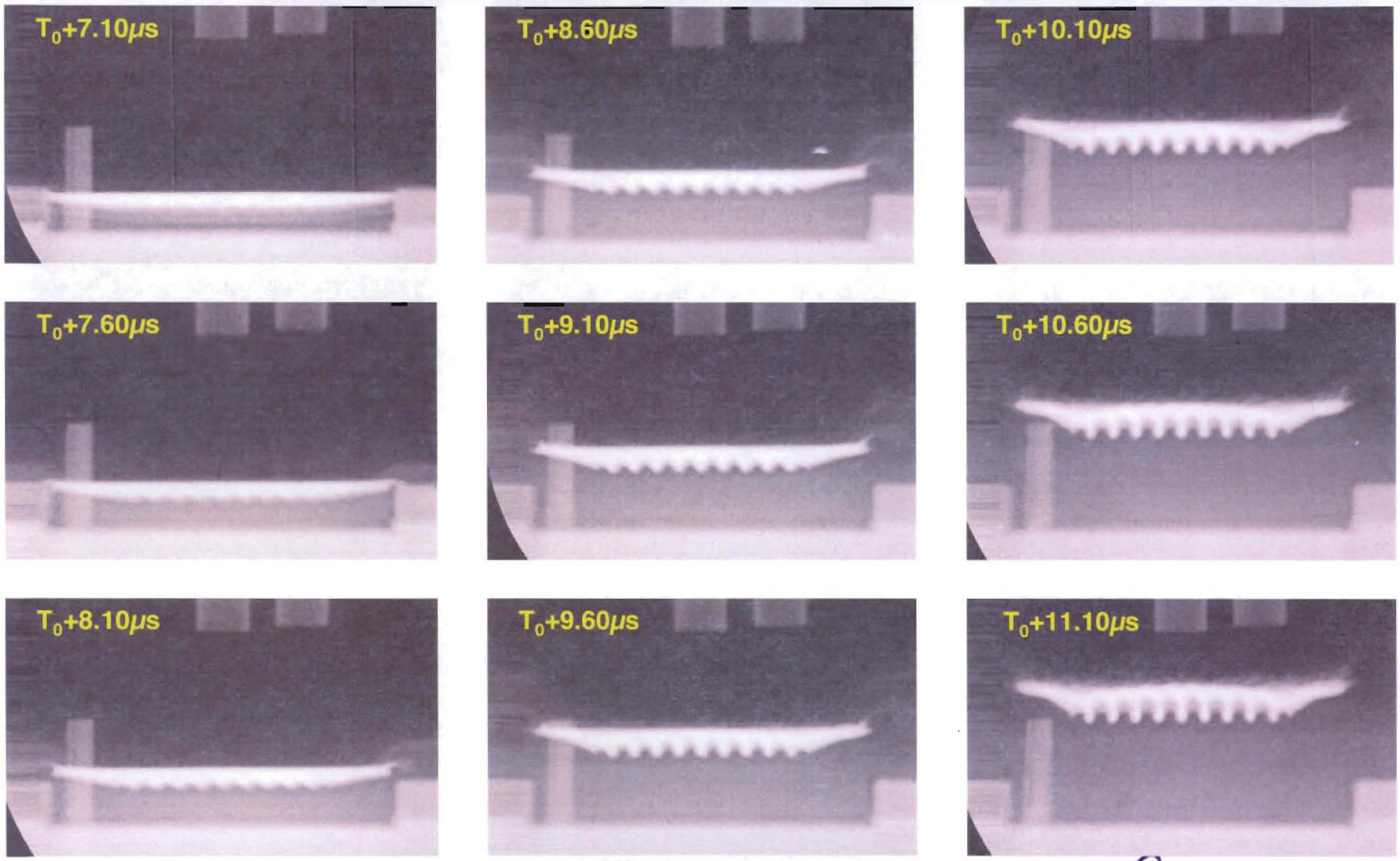




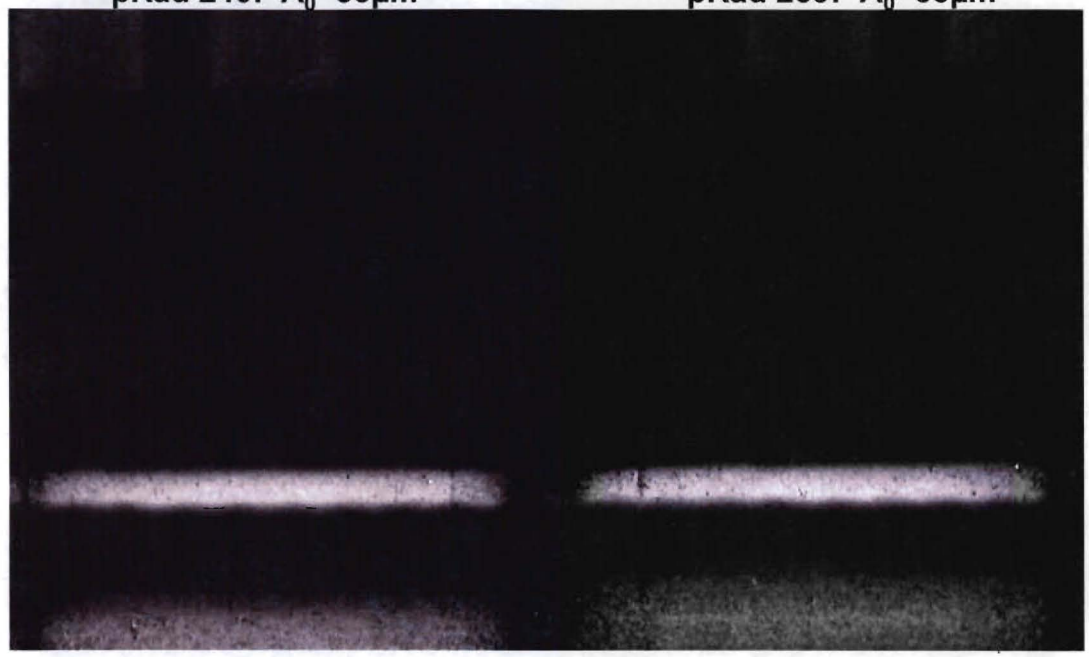
Proton Radiography (pRad) at is used to measure the perturbation growth rate as a function of time.

- **The pRad facility is located at LANSCE at Los Alamos National Laboratory.**
  - LANSCE is an 800 MeV linear proton accelerator.
- **The X3 pRad magnifier is used to obtain a temporally resolved sequence of radiographs (actually proton shadowgraphs) as a function of time.**
  - 23 high resolution (70μm) and 18 lower resolution (120μm) images per experiment.
  - 40mm X 40mm field-of view.
  - 50 ns long exposures spaced 300-500 ns apart.
  - Magnets tuned for low energy loss (~5 MeV) so essentially acquiring proton shadowgraphs.

The sequence of pRad images provides a measurement of the perturbation amplitude at many different times.



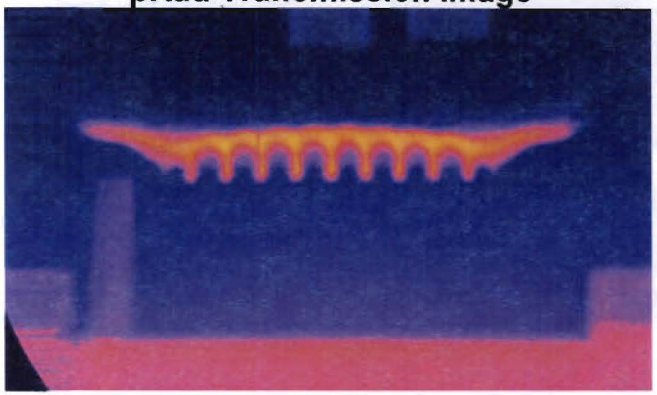
A movie of the perturbation growth can be constructed using the sequence of pRad images.



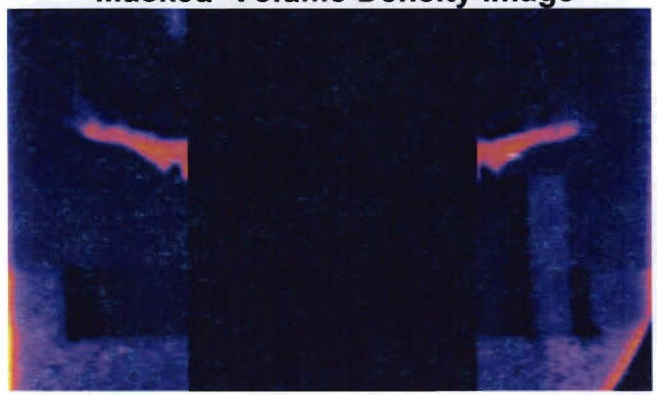
- **A direct comparison of two Cu experiments: pRad 239 and pRad 240.**
  - » Experiments identical (λ_0 =2.00mm, 3.0mm vacuum gap, fully annealed Cu samples, pRad timing, etc.) EXCEPT for initial perturbation amplitude (pRad 239: A_0=55μm, pRad 240: A_0=35μm).
  - » NOTE: Images processed to remove effect of beveled target edge.

Each pRad radiograph must go through a series of image processing steps to allow accurate *A(t)* extraction.

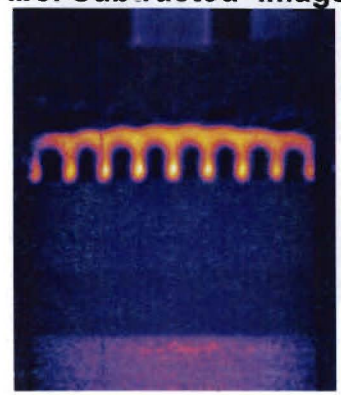
pRad Transmission Image



'Masked' Volume Density Image



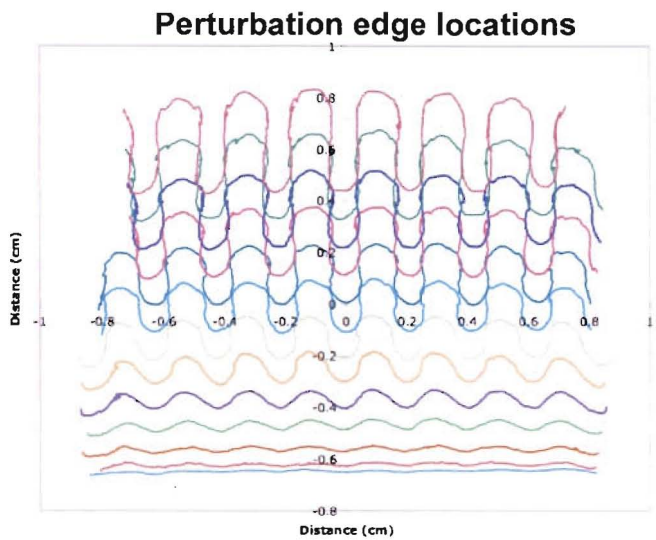
'Abel Subtracted' Image

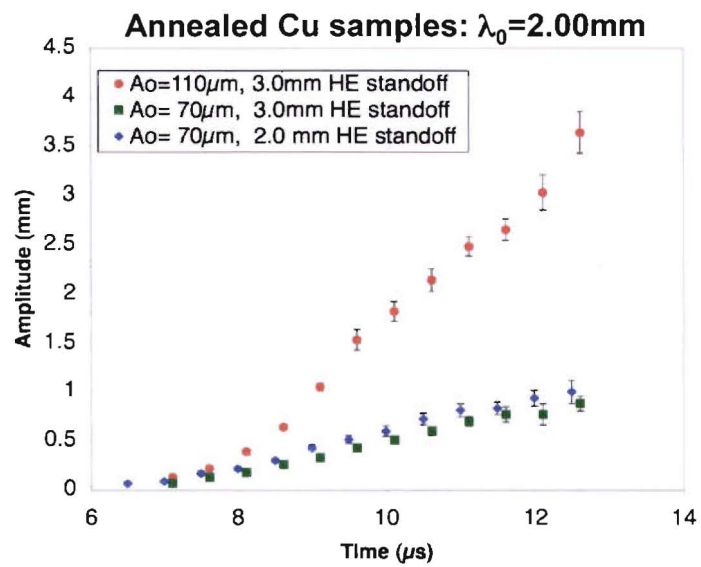


- **Small, axially symmetric perturbation partially obscures sinusoid troughs in the transmission images.**
  - Occurs at location where beveled edge intersects the sample surface.
  - Abel-inverted volume density image created from a masked areal density image.
  - Calculated transmission image subtracted from actual pRad image to create an 'Abel subtracted' image for edge analysis.

- **Image processing checked for accuracy by fitting a sinusoid to the early time perturbations.**
  - Theoretically expect single mode sinusoidal growth for $A(t) << \lambda_0$.

Extracted perturbation edge locations are extracted from each radiograph to obtain *A(t)*.

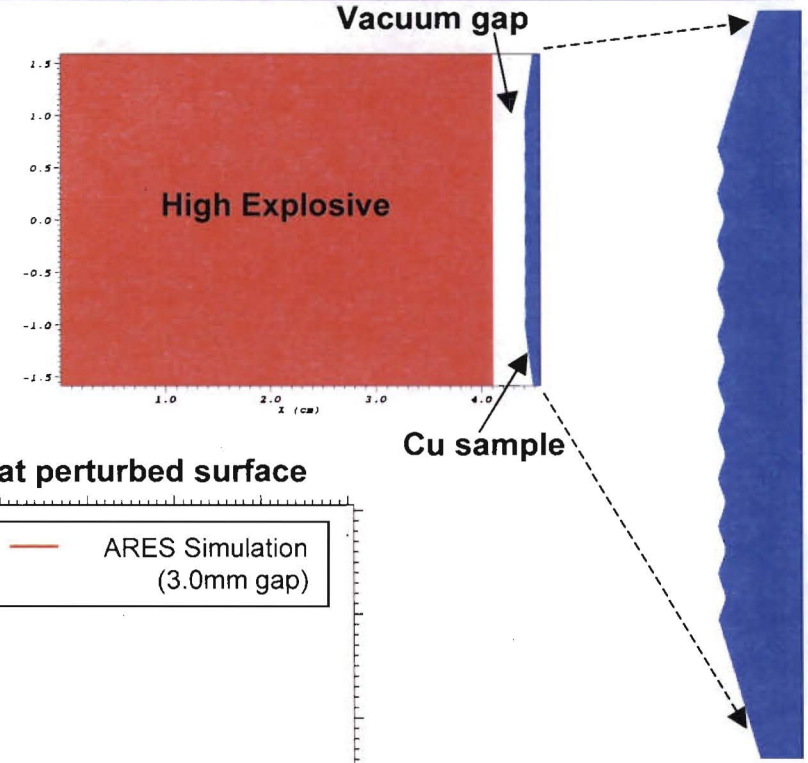




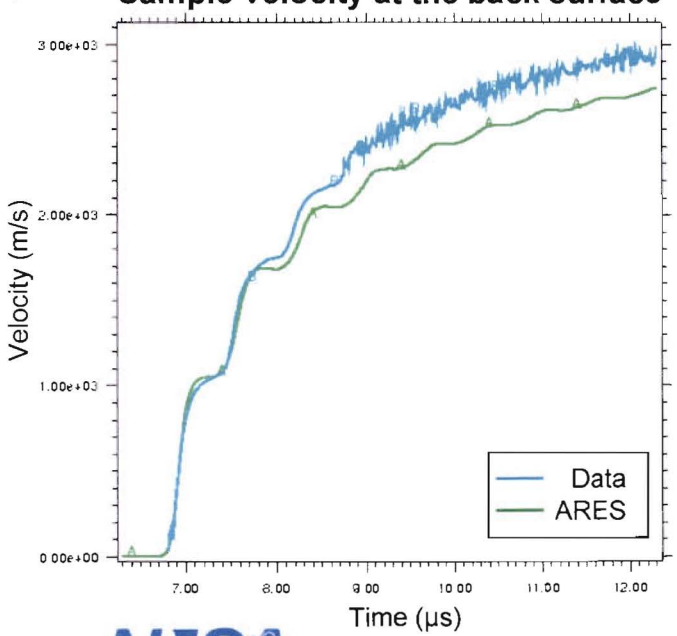
- **Optimal strength model validation experiments using an R-T growth technique require that the perturbation growth be unstable, but strongly inhibited by the material strength.**
  - Must avoid experimental conditions (A_0 to large, acceleration to high, etc.) that create fluid-like behavior.
  - A strength stabilized perturbation growth result is not useful for validation purposes either.

R-T growth simulations have been conducted using the ARES hydrodynamic code.

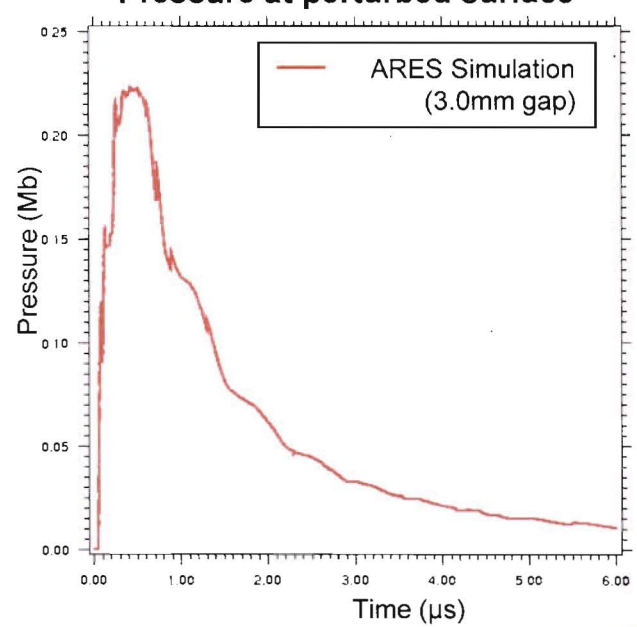
- **ARES is a Lawrence Livermore National Laboratory hydrodynamics code.**
  - High explosive plane wave lens is approximated as a single piece of explosive.
  - Square zoning in Cu.
  - 120 zones per wavelength.



Sample velocity at the back surface



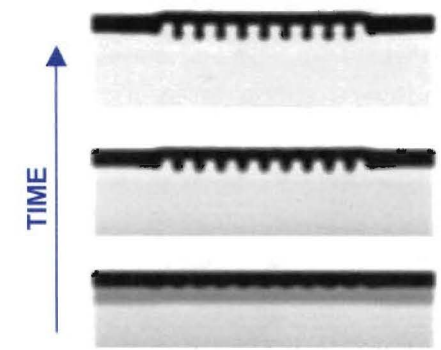
Pressure at perturbed surface



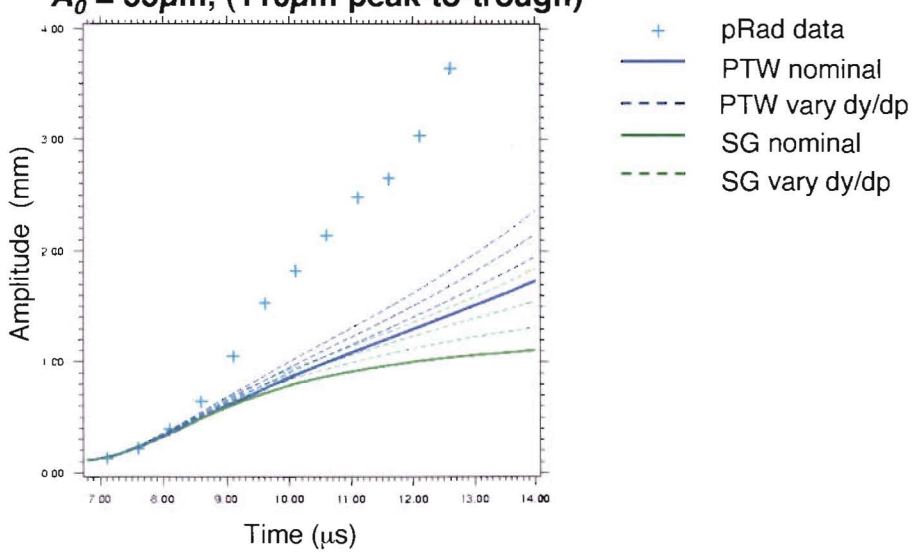
Simulations using multiple different strength models consistently over estimate the strength of annealed Cu.

- **Observed RT growth rates for several different copper experiments are larger those predicted by the strength models.**
  - Fully-annealed Cu.
  - 60 µm average grain size.
  - Identical sample acceleration.
  - A_0 = 35µm and 55µm sinusoidal perturbation.
  - 3.0 mm vacuum gap.

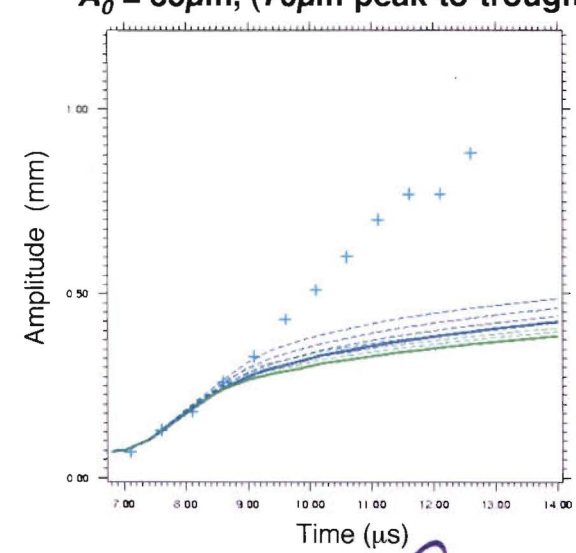
Simulated pRad Radiographs



A_0 = 55μm, (110μm peak-to-trough)



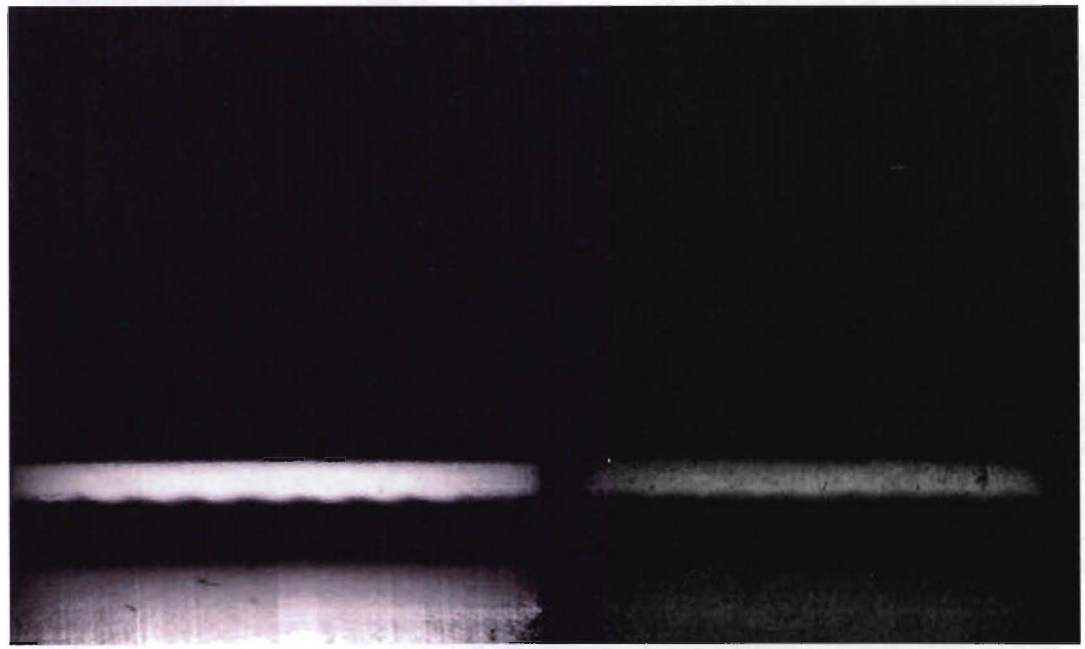
A_0 = 35μm, (70μm peak-to-trough)



R-T perturbation growth experiments have also been conducted to investigate the effect of material processing.

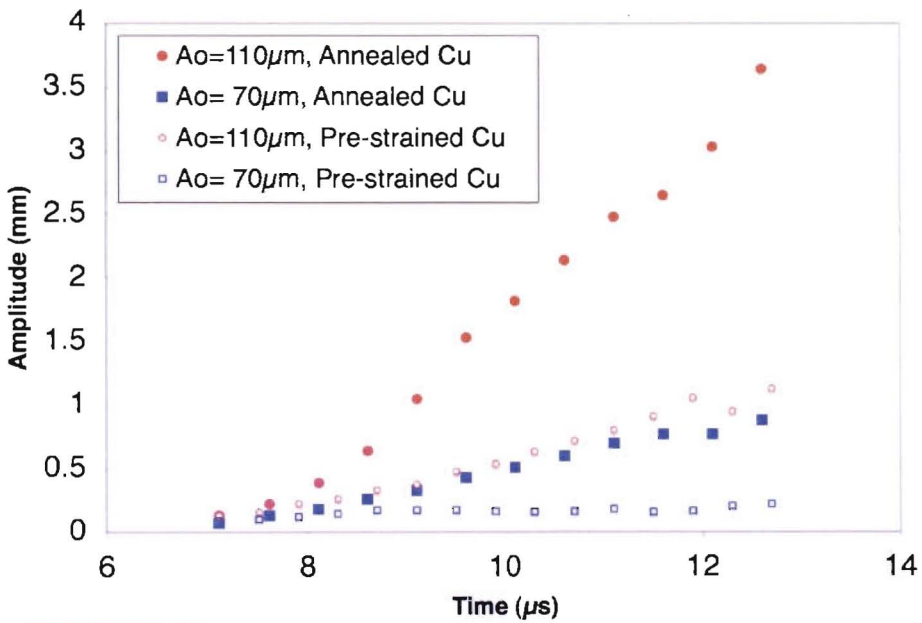
- **Comparison between fully annealed and cold worked copper samples.**
  - 55μm sinusoidal initial perturbation imposed on each sample.
  - Identical sample acceleration.
- **NOTE: Slightly different interframe time between radiographs (400ns versus 500ns).**

Pre-strained Cu sample **Annealed Cu sample**

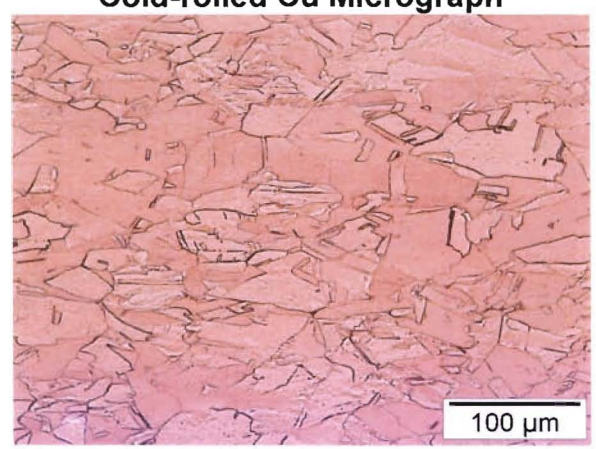


Observed perturbation growth rate is significantly reduced for pre-strained Cu samples.

- **Cold-work strengthens the Cu as expected.**
  - Cold rolling used to impose 30% strain on the Cu samples.
  - Grain elongation with annealing and deformation twins observed in sample metallurgy.
  - All other experimental variables, including sample acceleration, held constant.
- **Sample processing and resulting microstructure clearly affect the macroscopic R-T growth rate of the perturbations.**
  - Simulations using the Mechanical Threshold Stress strength model of the pre-strained Cu data are being conducted.



Cold-rolled Cu Micrograph



Conclusions and Future Directions

- **R-T perturbation growth technique is being used for validation of strength models at high strains and strain-rates.**
  - We cannot extract fundamental material parameters from these simple, integral experiments.
  - To be successful experiments, simulations, and modeling efforts must all be coordinated.

- **Dynamic yield strength of Cu is over estimated by the current strength models.**
  - Current speculation is that the macroscopic flow stress may be reduced as the temperature equilibrates around hot shear bands.

- **We are using different materials, materials processing, and experimental drive conditions to investigate high rate behavior.**
  - Fully-annealing, cold-work, shock hardening with Cu.
  - Crystalline structure (e.g. FCC vs. BCC) with Cu and Ta/V.
  - Grain size and inclusions with annealed and electroplated Cu.
  - Solid-solid phase transitions.
  - Strain localization, shear band formation, and dislocation density in recovered samples.
  - Other materials such as Depleted Uranium are also being tested.