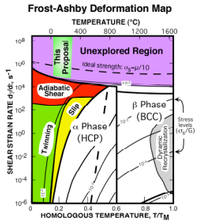
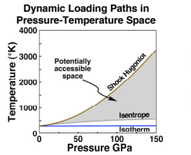
# Deformation of Single Crystal Copper Under Extreme Conditions – Effect of Loading Path

J. M. McNaney[1], B. Torralva[1], E. M. Bringa[1], M. S. Schneider[2], J. S. Harper[1], K. T. Lorenz[1], B. A. Remington[1], M. A. Meyers[2]
[1]Lawrence Livermore National Laboratory, [2]University of California, San Diego

## Material behavior at high pressure and strain rate is not well understood and is programmatically significant



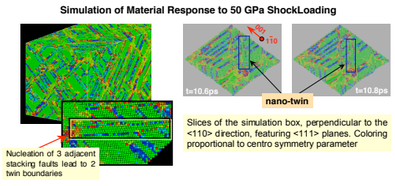

The deformation mechanisms are the scientific underpinning of the constitutive models used to describe material deformation behavior




Loading along the shock Hugoniot constrains the pressure, temperature, strain, and strain rate. Accessing a loading path on or near the isentrope allows independent control of the pressure, temperature and strain rate.

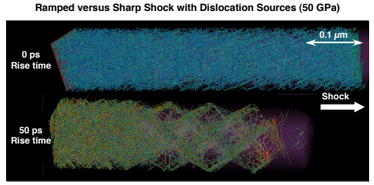
**Knowledge of material behavior along loading paths off of the shock Hugoniot is needed to understand the physical processes involved as well as constrain the form of the models used to describe them.**

## Molecular dynamics provides insight into the deformation mechanisms




Slices of the simulation box, perpendicular to the <110> direction, featuring <111> planes. Coloring proportional to centro symmetry parameter

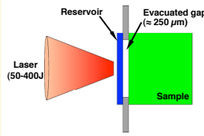
**Twin formation in shock driven molecular dynamics simulations has been observed. The mechanism is one of stacking fault coalescence, as proposed by Zaretsky [*Appl. Phys.* 78, 3740 (1995)].**



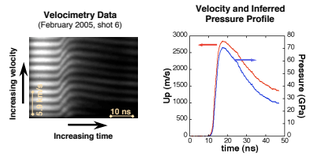

**During ramped loading, source activiation leads to lower dislocation density. Based on the mechanism above, this reduction is expected to lead to an increase in the pressure required for twin formation.**

**Limits on length and time scales constrain MD simulations to loading paths along the the shock Hugoniot**

## A laser based platform is used to access shockless loading paths



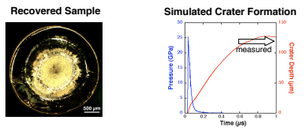

**The drive is generated by illuminating a reservoir material using the Omega laser (Rochester, NY). Subsequently the reservoir material creates a smooth, short pressure pulse in the sample to be studied.**



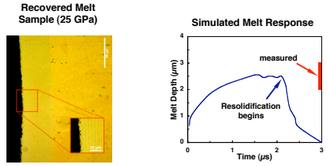

**Velocimetry measurements performed on thin foils yield information on the pressure versus time profile and provide benchmarking for hydrodynamic simulations**


**The experimental package is contained in a tube, facilitating material recovery. The sample size, large compared to the loading pulse width, ensures wave reflections are negligible.**

## Comparing calculations with experimental results confirms the validity of the simulations

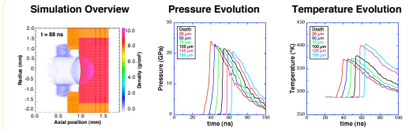



**A comparison of predicted versus measured crater depth ensures that the constitutive models used are appropriate.**

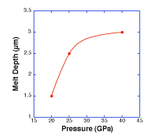



**A novel geometry has been developed to assess the amount of melting due to the drive plasma-solid interaction. Comparison with simulation yields confidence in the conductivity models employed. This capability has already been fielded elsewhere for programmatic efforts.**

## Hydrodynamic simulations identify material locations to be examined

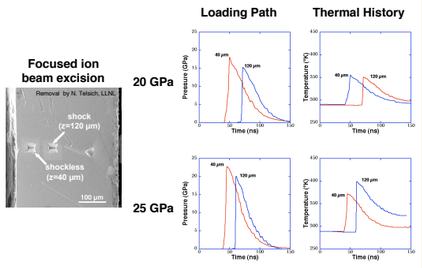



**The transition from a shockless to shock loading path, which occurs at constant pressure, is most easily seen in the accompanying temperature rise. The transition takes place over a distance of about 50 μm**



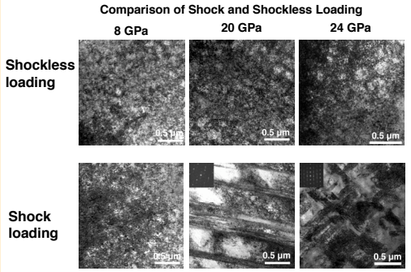

**Calculations indicate the amount of material that melts over the pressure range of interest. This allows us to avoid regions affected by thermal transients.**

## Localized sample excision provides material for comparing along different loading paths

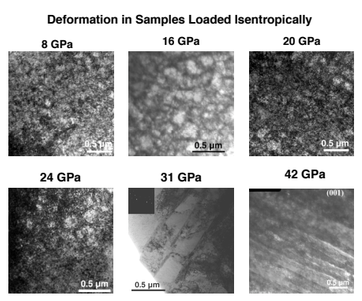



**Transmission electron microscopy samples are removed from the recovered material using a focused ion beam method. This method allows us to precisely match the location of the sample to the desired loading conditions.**

## Significant changes in deformation between loading paths is observed




**Under shock loading, the transition from dislocation cells to stacking faults occurs over the range 8-24 GPa. The incomplete stacking fault formation at 20 GPa indicates it is very near the threshold. Under shockless loading no transition is seen over the same pressure range.**




**Samples deformed under shockless loading display a gradual transition over the 8-42 GPa pressure range. This result, the first of its kind, is generally supportive of the MD simulations.**

## Summary

- This work represents the first study looking at high pressure, high strain rate deformation mechanisms occurring near the isentrope
- Our observations confirm that significant differences in behavior exist along different loading paths
- The methodology is now being implemented in two programmatic efforts: Multiscale Modeling and High Pressure Strength

## Future Work

- Based on this work a new technique has been proposed to investigate deformation properties under high strain rate, low pressure loading conditions. If successful, the method could provide highly sought after data to constrain material constitutive models.

## Publications

"Shock-induced void collapse in fcc metals", E.M. Bringa, et. al., *Applied Physics Letters*, *In Press.*

"High pressure, laser driven deformation of an aluminum alloy," J. M. McNaney, et. al., *Met. Trans A*, 35A, pp 2625-2631 (2004).

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