LA-UR- 08-4209

Approved for public release; distribution is unlimited.

Title: Dynamics of the Onset of Damage in Copper under Shock Loading

Author(s): Aaron KoskeloScott Greenfield, ShengNian Luo, Kenneth McClellan, Darrin Byler, Robert Dickerson, ShengNian Luo, Dennis Paisley, Damian Swift, Davis Tonks (LANL)
Pedro Peralta, (Arizona State University)

Submitted to: 8th World Congress on Computational Mechanics (WCCM8)
July 1, 2008
Venice, Italy

Los Alamos
NATIONAL LABORATORY

Dynamics of the Onset of Damage in Copper under Shock Loading

Aaron Koskelo

Los Alamos National Laboratory

Scott Greenfield, ShengNian Luo, Darrin Byler, Kenneth McClellan, Robert Dickerson, Dennis Paisley, Damian Swift, Davis Tonks (LANL)

Pedro Peralta, (Arizona State University)

8th WCCM

Thermodynamics Aspects of Metal Behavior at Extreme Loading Rates.

Joint International Association for Computational Mechanics (IACM) and International Union of Theoretical and Applied Mechanics (IUTAM) Mini-symposium

July 1, 2008

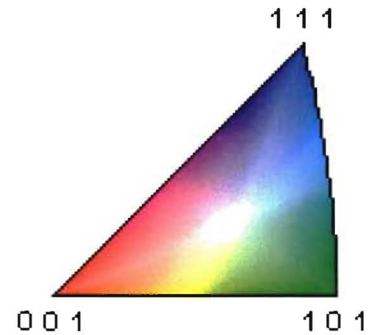
Other contributors

- **Los Alamos National Laboratory and Arizona State University**
  - Technical Staff Members
    - John Bingert, MST-8
    - Elshan A. Akhadov, MPA-CINT
    - Carl Necker, MST-6
    - Pat Dickerson, MST-6
  - Post-doc
    - Eric Loomis, P-24
    - Heber D'Armas, ASU
  - Graduate Students
    - Stephan DiGiacomo, ASU
    - Shima Hashemian, ASU
  - Undergraduate Students
    - Travis Schmidt, South Dakota School of Mines
    - Stephen Daugherty, Vanderbilt
    - Beau Turner, ASU
  - High School Student
    - Samantha Rich, Los Alamos High School
- **External Collaborators**
  - Eduardo Bringa, Lawrence Livermore National Laboratory
  - Ron Armstrong, U of Maryland

Outline

- Project description
- Experiment configuration
- Incipient spall shot, TIDI at breakout and early release
  - An example of richness of data exhibiting different dynamic length scales
- Dimple formation
- TIDI sensitivity to dynamics of embedded objects
- Near-surface spall dynamics movie
- Conclusion

Spall damage in copper under shock loading



Koskelo et al, 2007 APS SCCM

- **Focus: role of material microstructure in dynamics of damage.**
  - Time and length scales where damage develops
  - Bridge between atomic scale/ps phenomena and bulk/µs phenomena
- **Project goals**
  - Physics of damage development
  - Statistical basis for spall
  - Develop material damage model suitable for predictive capability and uncertainty quantification

Project overview

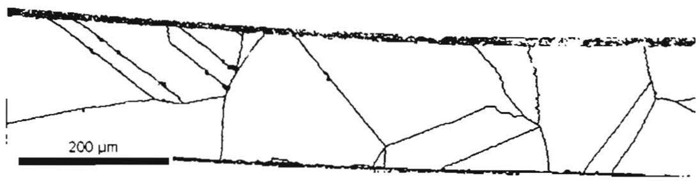
- **Primarily focused on details of spall development in copper**
- **Couple well-characterized material specimens with laser-launched flyer/target shock experiments**
  - Shots conducted at LANL Trident Laser Facility
- **Connect pre- and post- shot material and damage characterization with dynamics of microstructure measured at the breakout surface during shock loading experiments**
- **Use a unique diagnostic suite to probe the dynamic inhomogeneity at the breakout surface**
  - Transient Imaging Displacement Interferometry (TIDI, formerly TIM)
  - Line VISAR and Point VISAR
- **Specimens with engineered voids or embedded wires**
  - Defines diagnostic signatures
  - Study local void/inclusion dynamics to aid in model development

Thin-to-thick buildup of material spall models

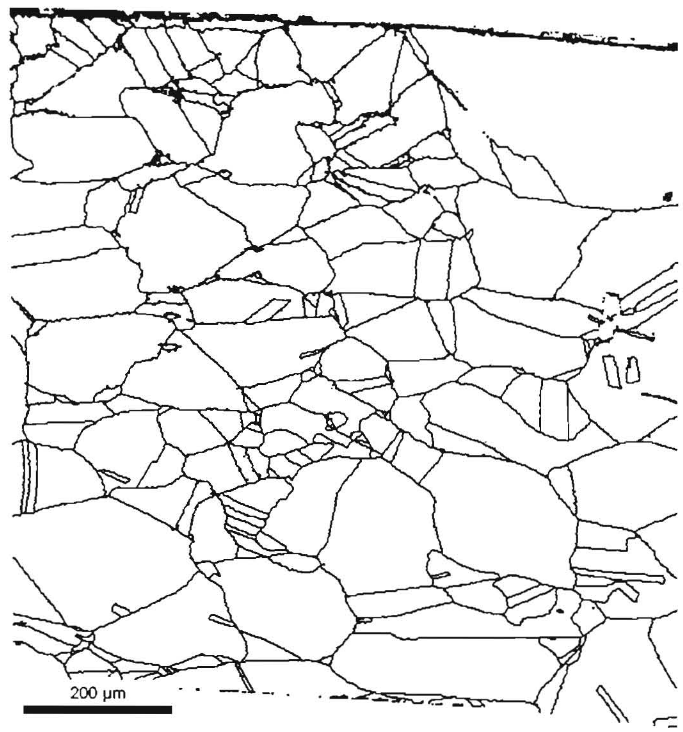
- **Quasi-columnar-grained specimens**
  - Simplicity of modeling
    - At most, 1 or 2 grain boundaries for shock to propagate through before reaching diagnostic surface
  - Examine effects of orientation mismatches between individual grain pairs
  - Discern damage origination within individual grains vs. at grain boundaries
- **Multicrystalline specimens**
  - Next stage in developing model
    - Enough grains to develop a statistical distribution
- **Polycrystalline specimens**
  - Results on multicrystalline specimens will indicate whether they are sufficient for polycrystalline models
  - Link to historical gas gun results

Through thickness cross-sections

Quasi-columnar

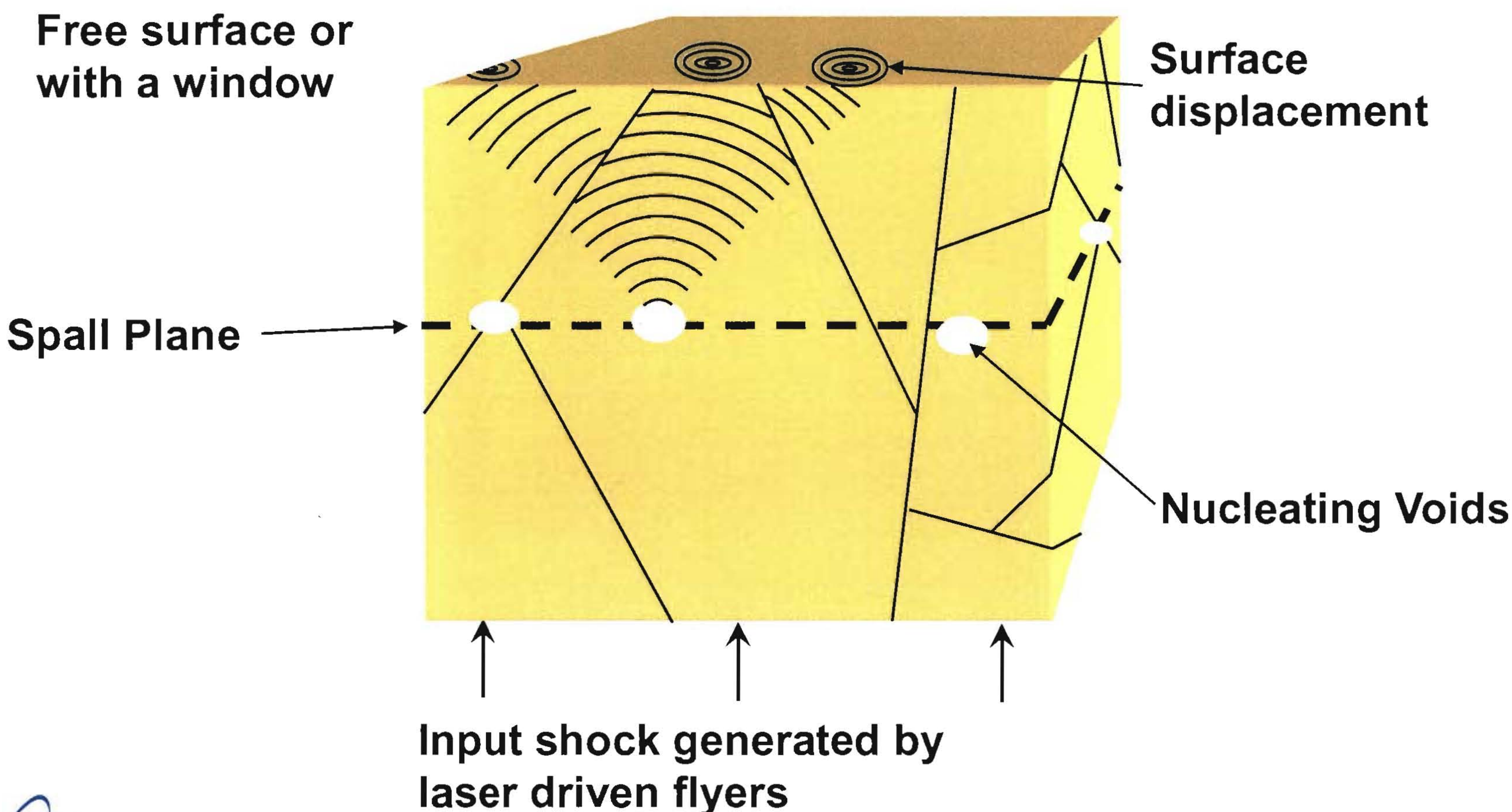


Polycrystalline



Experiment Configuration

Incipient spall development dependent on microstructure and shock conditions

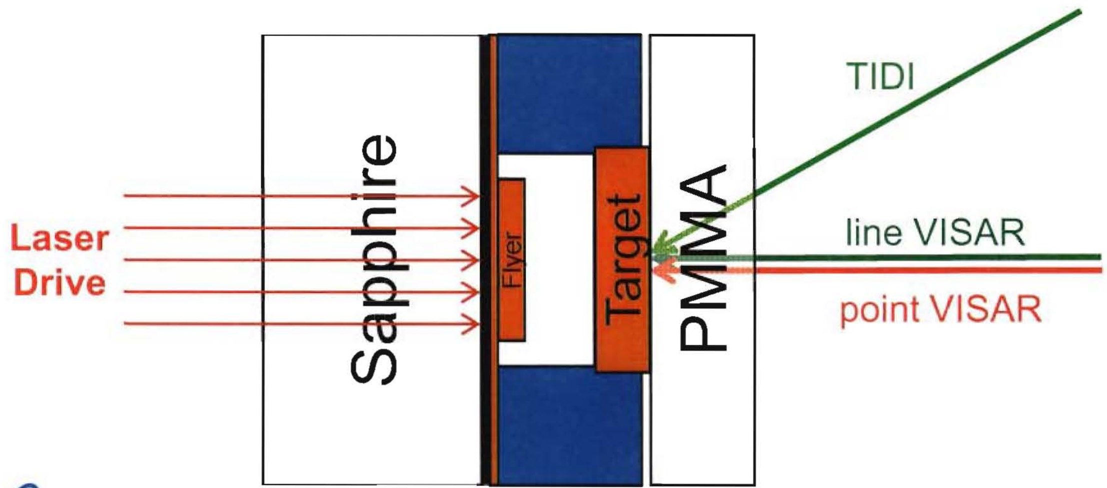


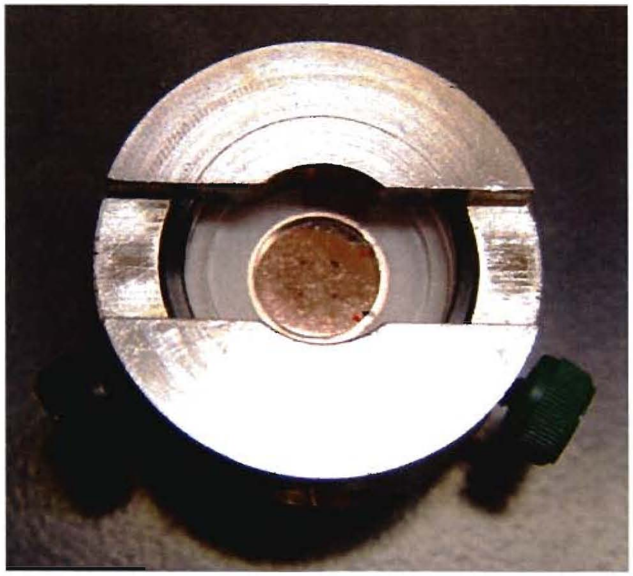
Materials

- **Targets and Flyers**
  - Polycrystalline targets and flyers
    - Half hard C10100 copper manufactured by Hitachi Cable Ltd was used as received or heat-treated
  - Multicrystalline targets
    - Half hard C10100 copper manufactured by Hitachi Cable Ltd was annealed
  - Single crystal targets and flyers
    - Half hard C10100 copper manufactured by Hitachi Cable Ltd was used to provide rods for unseeded Bridgman growth
    - Rods removed from mold and measured for orientation
    - Seeds were harvested from the heat-treated rod to provide for seeded crystal growth using the Bridgman method.
    - Grown crystal measured using Laue and specimens of known orientation harvested and remeasured

Target Assembly

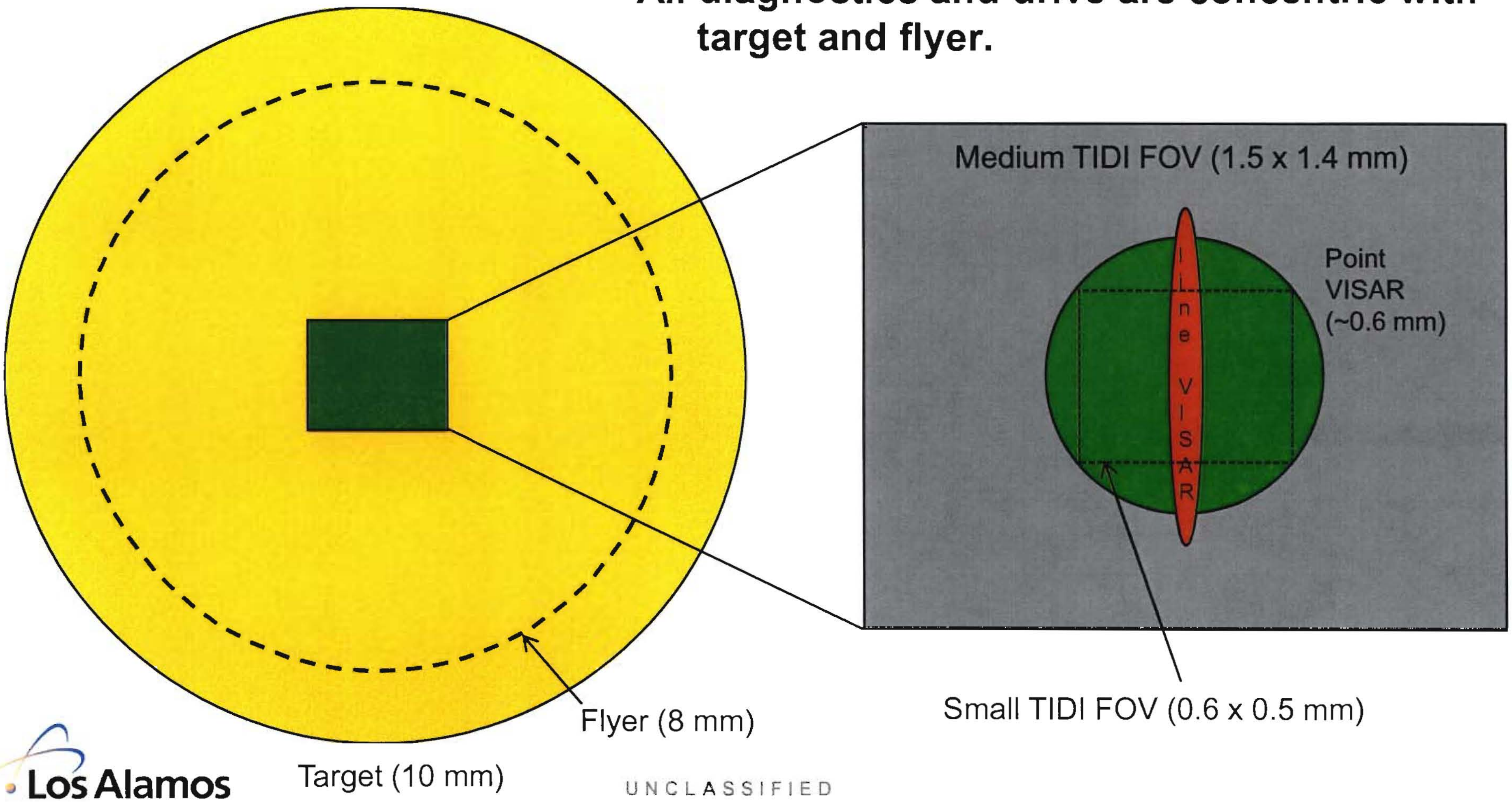
- **Sample system assembly needs to be done very precisely, so have (1) flat impact, (2) repeatable flight distance and hence timing, and (3) concentric flyer, target and diagnostic FOV.**
- **System held together with pressure.**
  - No glue.
  - Optical contact between target and window.



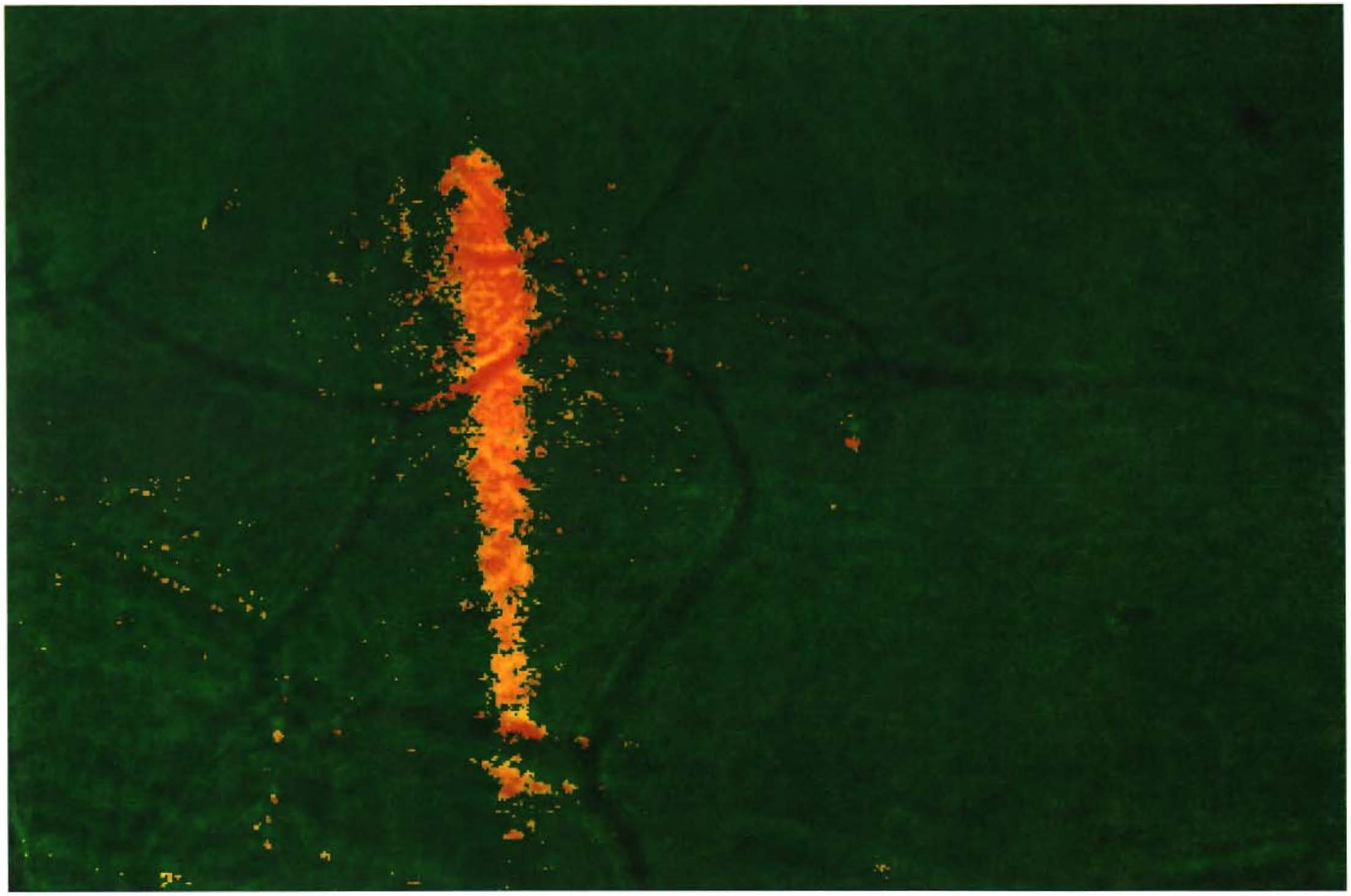


Diagnostics Fields of View (FOVs)

All diagnostics and drive are concentric with target and flyer.



19069 Pre-shot line VISAR location within TIDI Frame

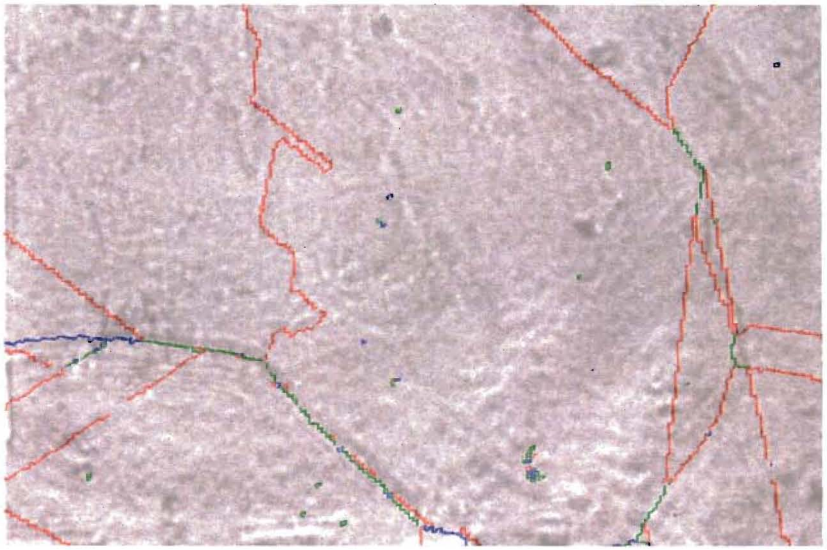


Incipient spall shot, TIDI at breakout and early release

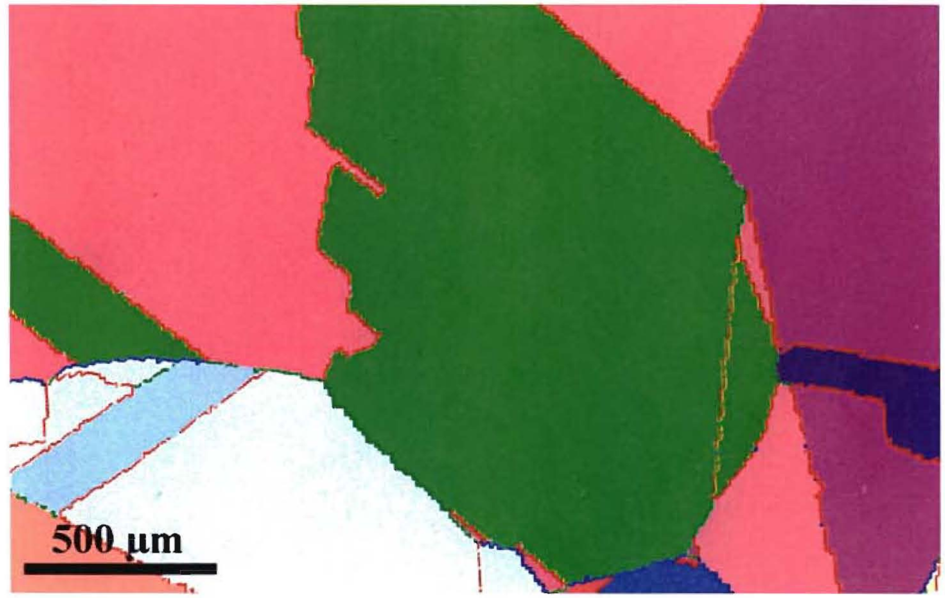
Shot 19071
300μm Polycrystalline Copper Flyer

1mm Quasi-Columnar Copper Target

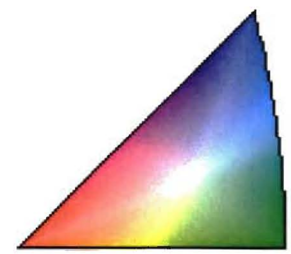
Shot 19071: Pre-shot TIDI Image/ overlaid EBSD GB Map



Pre-shot TIDI Image/
overlaid EBSD GB Map

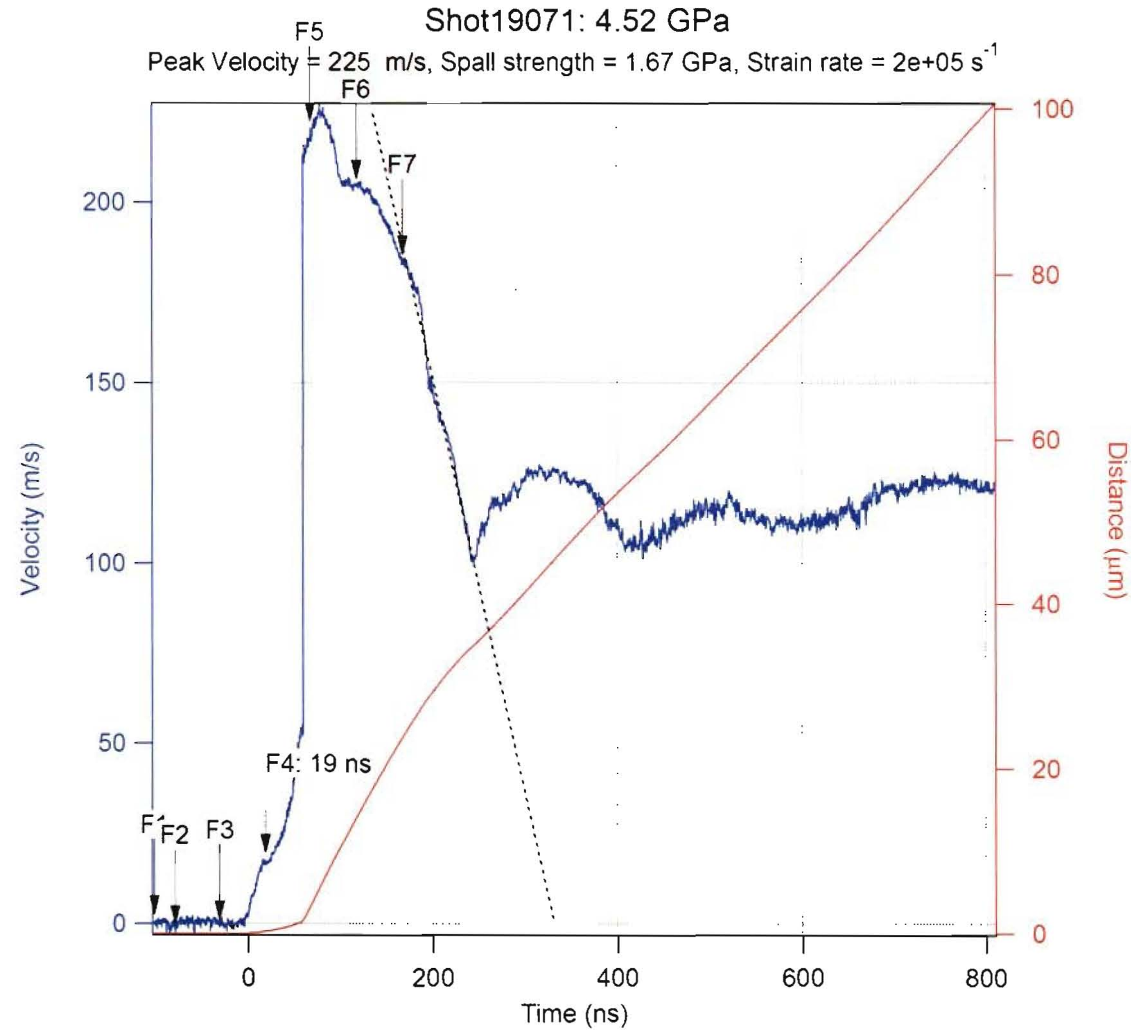


EBSD GB Map

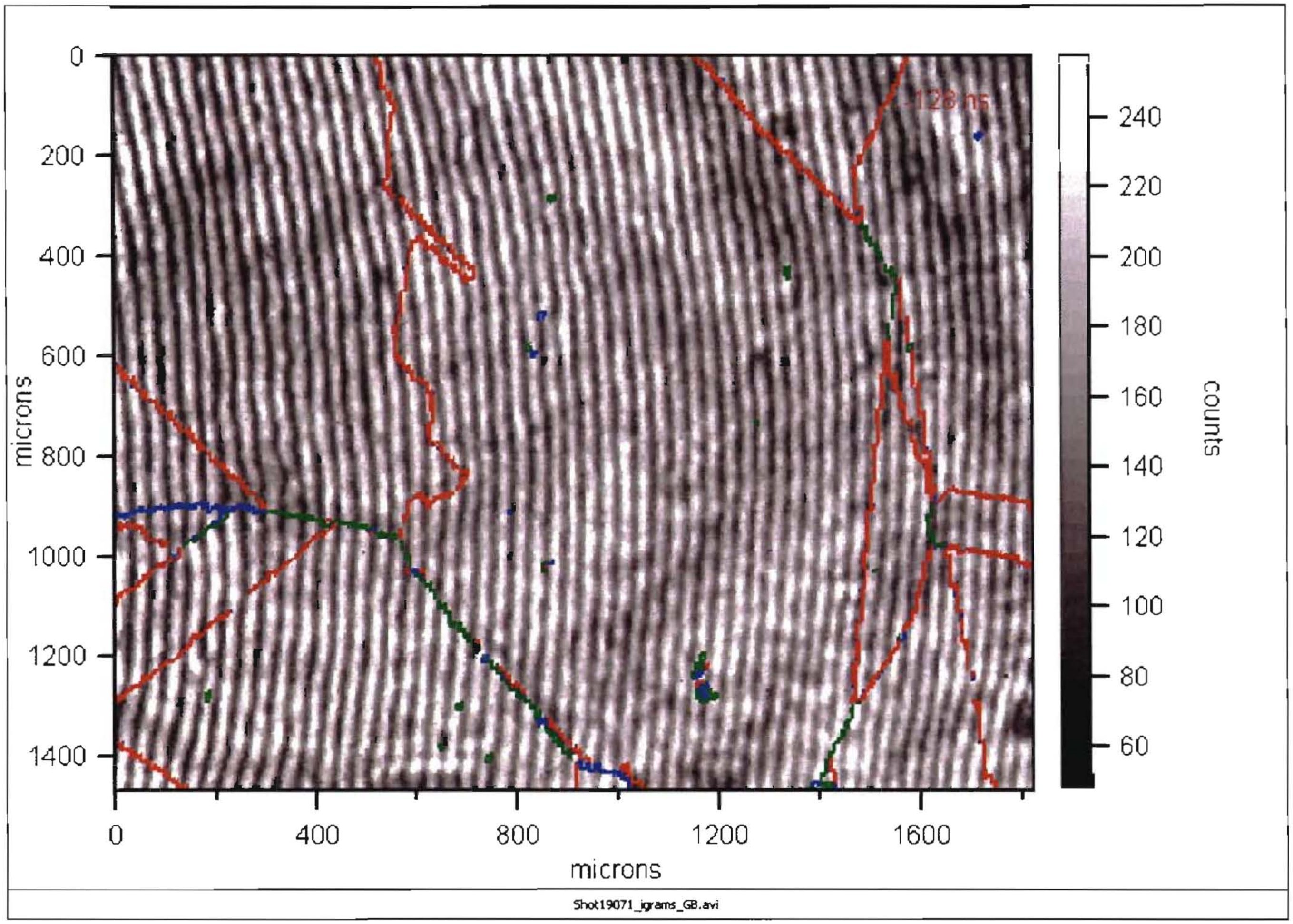


BLACK: low angle boundaries
GREEN: <39° boundaries
BLUE: 40-60° boundaries
RED: 60° twin boundaries

Shot 19071: Point VISAR indicating TIDI frame timing

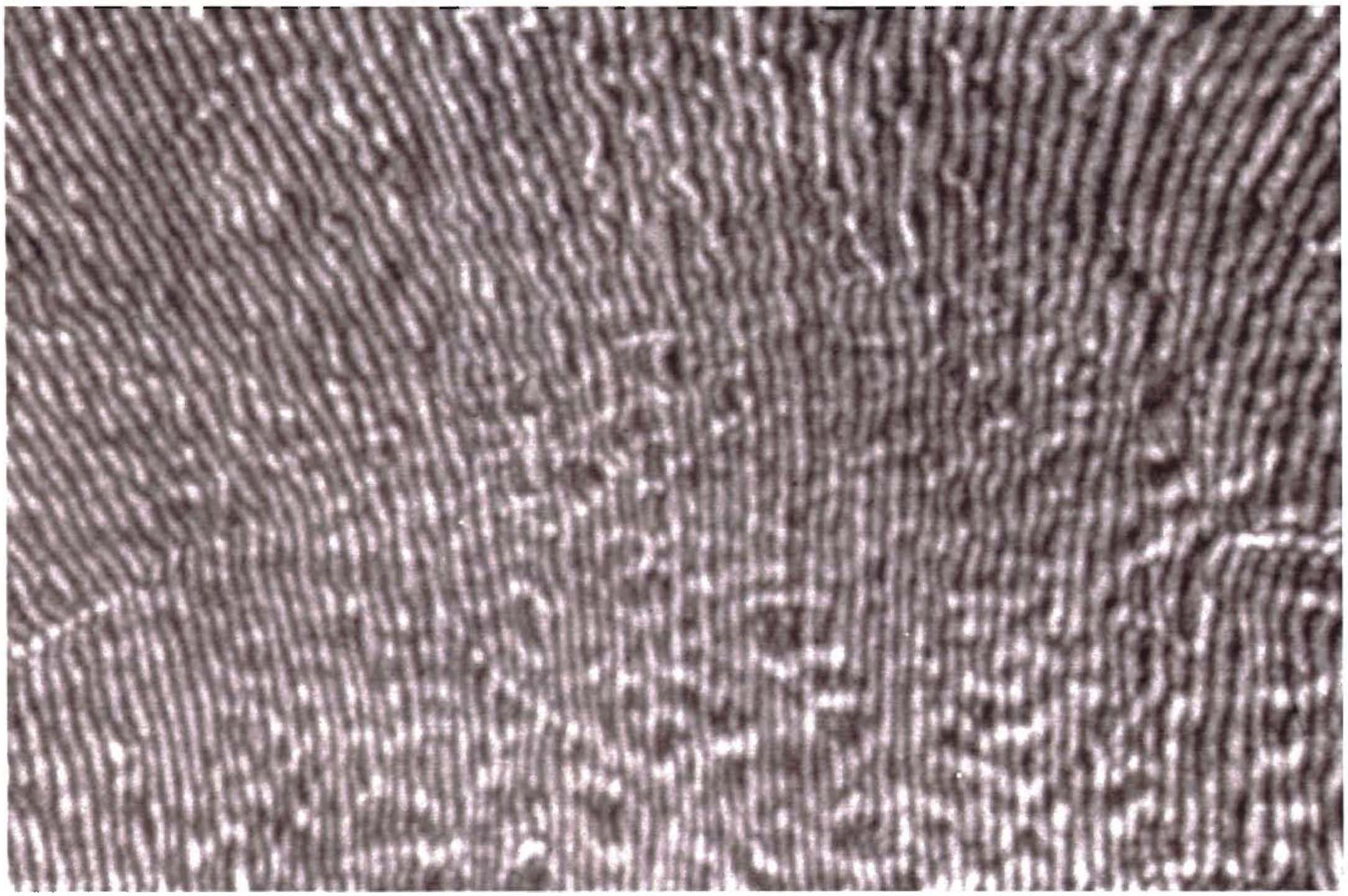


Shot 19071: TIDI Raw Interferogram Movie



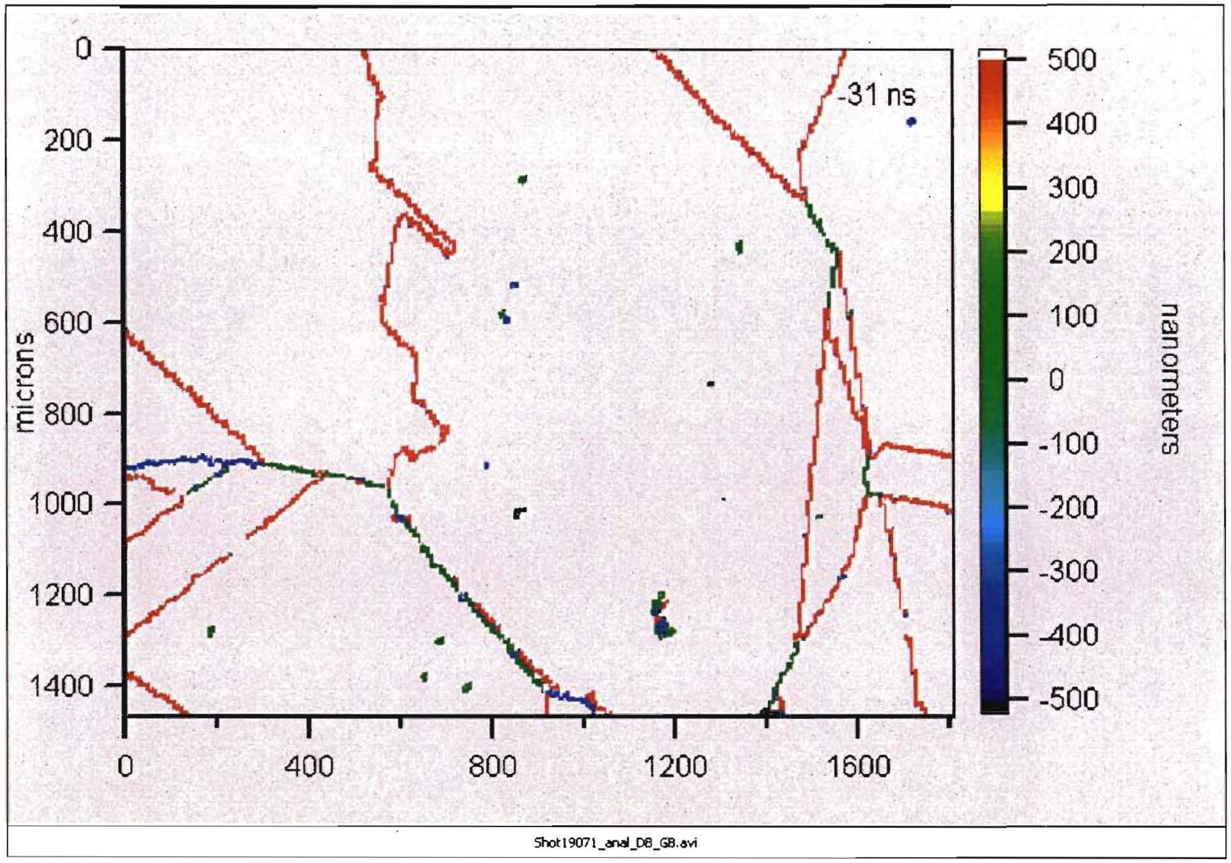
UNCLASSIFIED

Shot 19071: Frame 5 at 69 ns (raw interferogram)



Shot 19071: Movie of analyzed TIDI frames

- Detail along some grain boundaries
- Localized detail within grains also visible

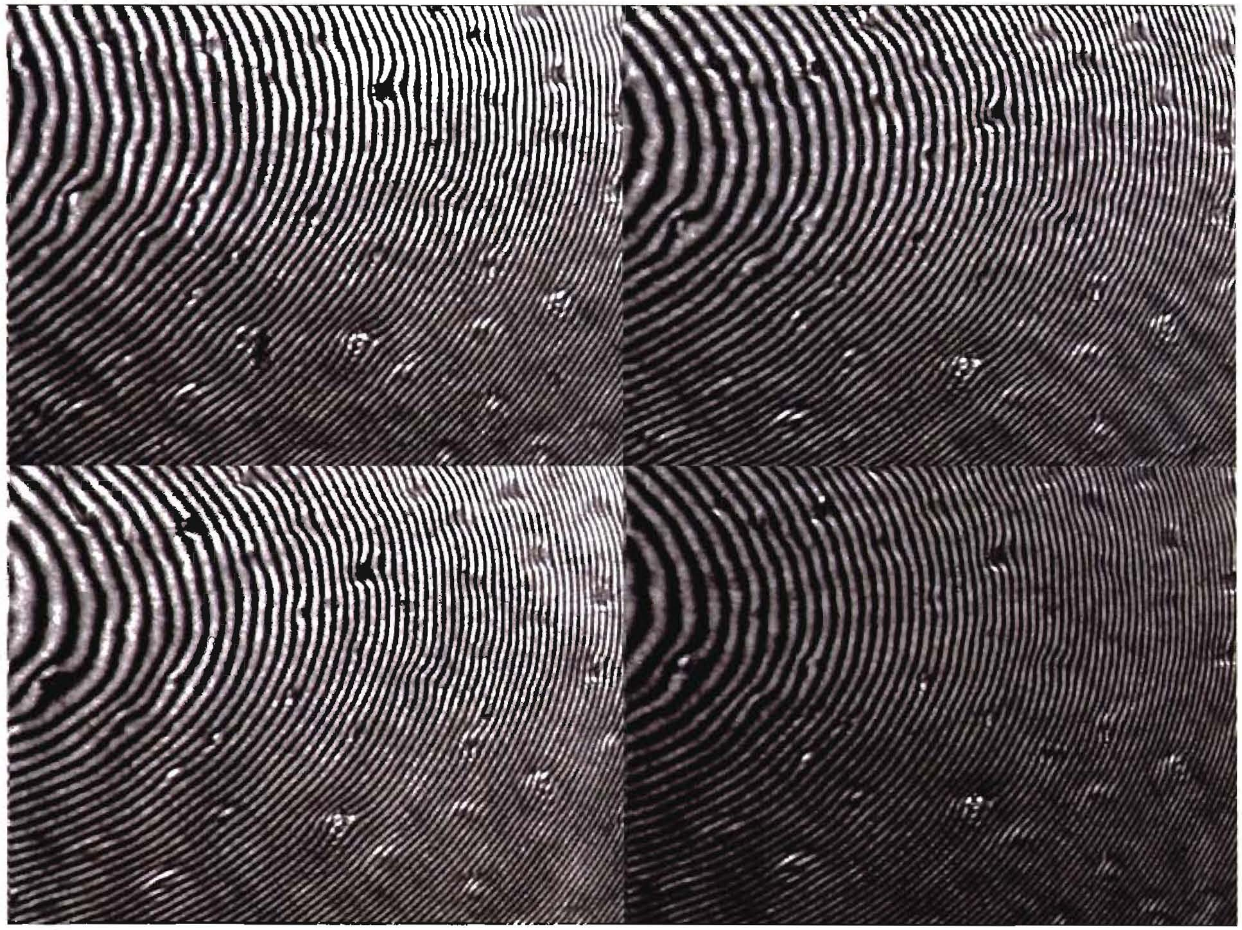


BLACK: low angle boundaries
GREEN: <39° boundaries
BLUE: 40-60° boundaries
RED: 60° twin boundaries

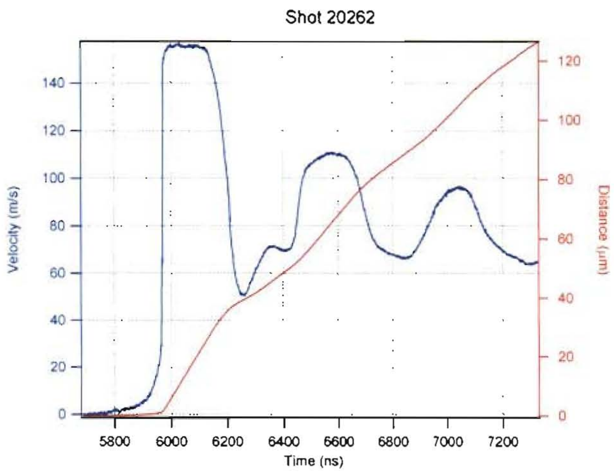
Dimple Formation

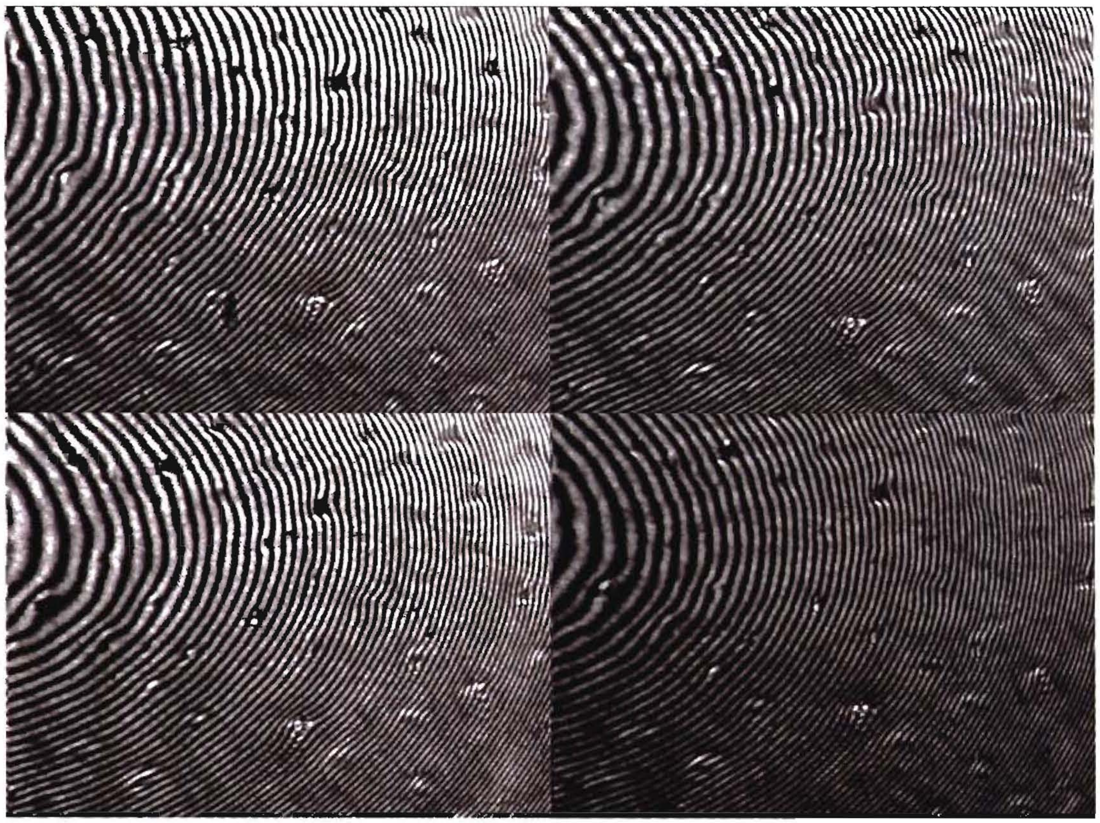
Single crystal Cu target (<114> in shock direction)

- 0.491 mm polycrystalline flyer on 0.999 mm target
- Drive pulse = 73J

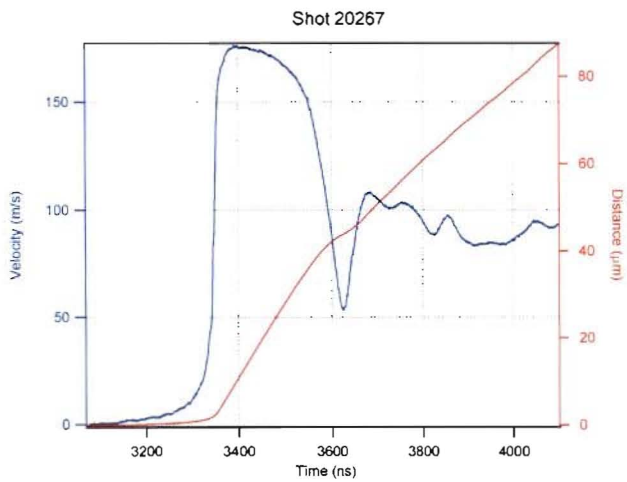


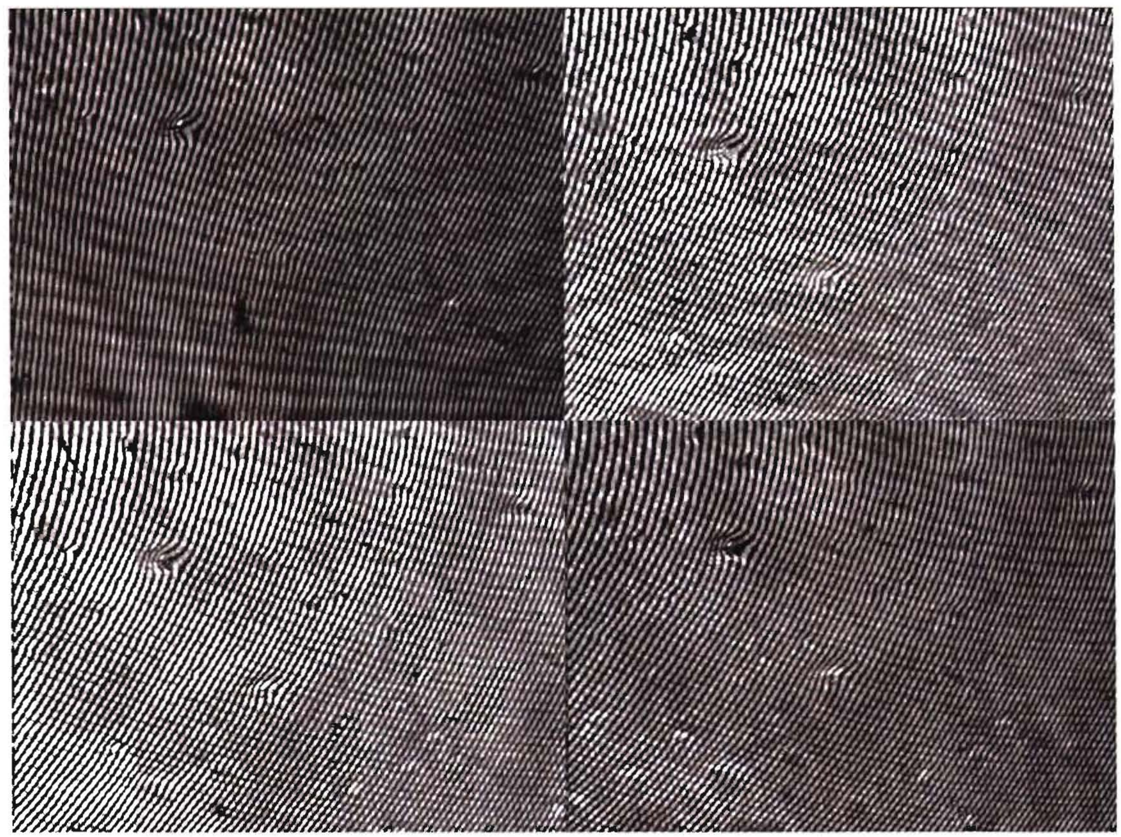
Single crystal Cu target (<114> in shock direction)—PMMA Window



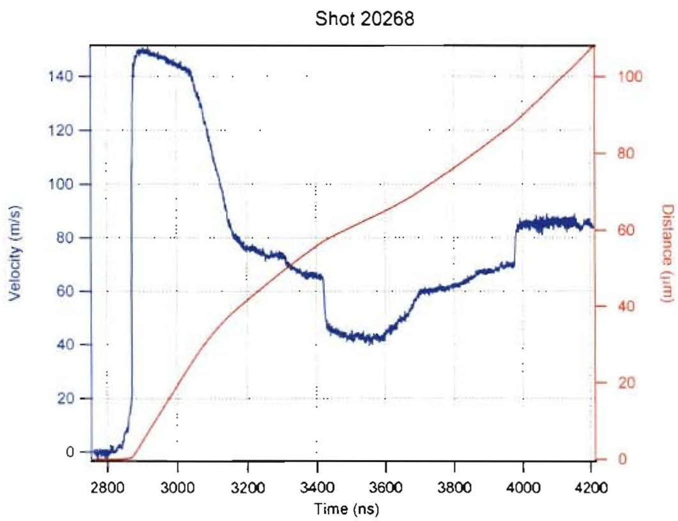


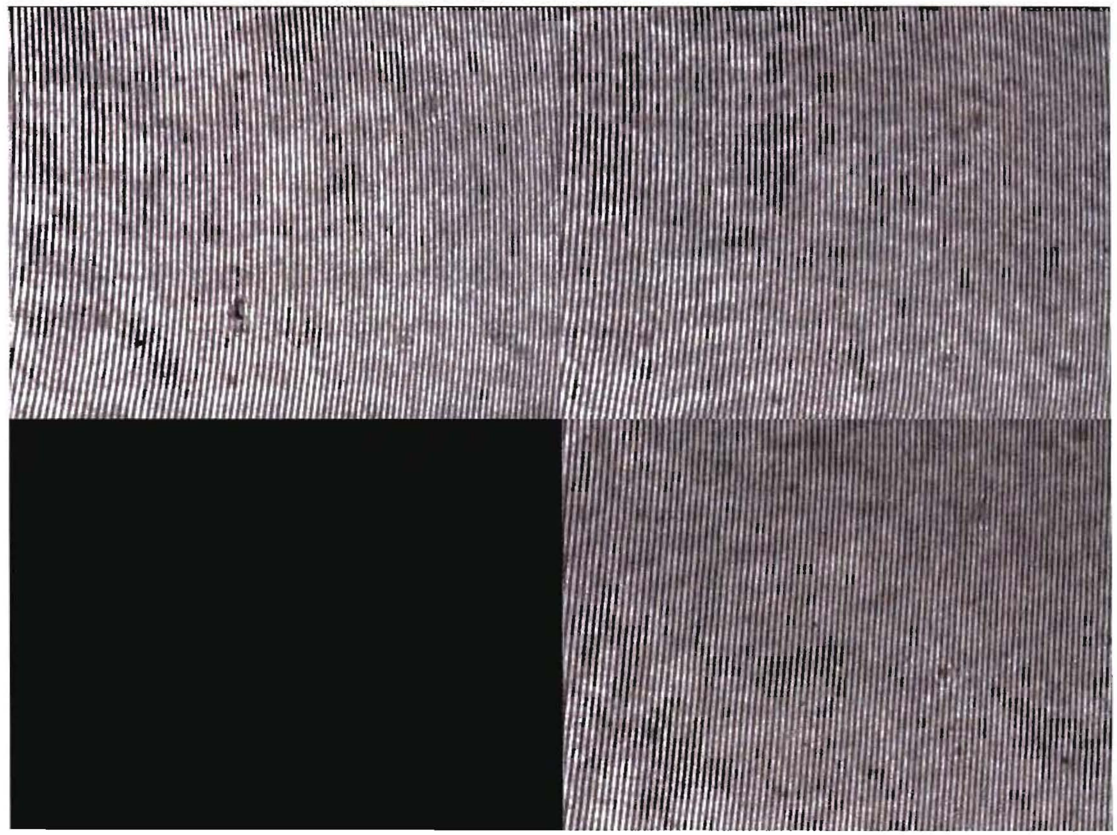
Single crystal Cu target (<114> in shock direction)— Free Surface





Single crystal Cu target (<114> in shock direction)—Sapphire Window





- NO DIMPLES

Dynamics of dimples

- **Dimples are depressions in the surface**
  - Displacements measured are not above the surface as would be expected--and observed--with compression waves
  - TIDI is calibrated for sign of displacement out of or into surface. Validated by specimens measured with optical microscopes and with a Wyko optical profiler (instrument used to measure optical flatness)
- **Dimples are 50 to 150 μm wide and 100 to 200 nm deep**
- **Dimples form "very quickly" at the rising edge of the plastic shock wave.**
  - Reduction of timing data to determine whether dimples form in the elastic precursor as well is underway.
- **Once formed, dimples do not evolve significantly in size and persist**
  - Dynamic sizes measured with TIDI agree well with post-shot Wyko optical profiler and optical microscope measurements

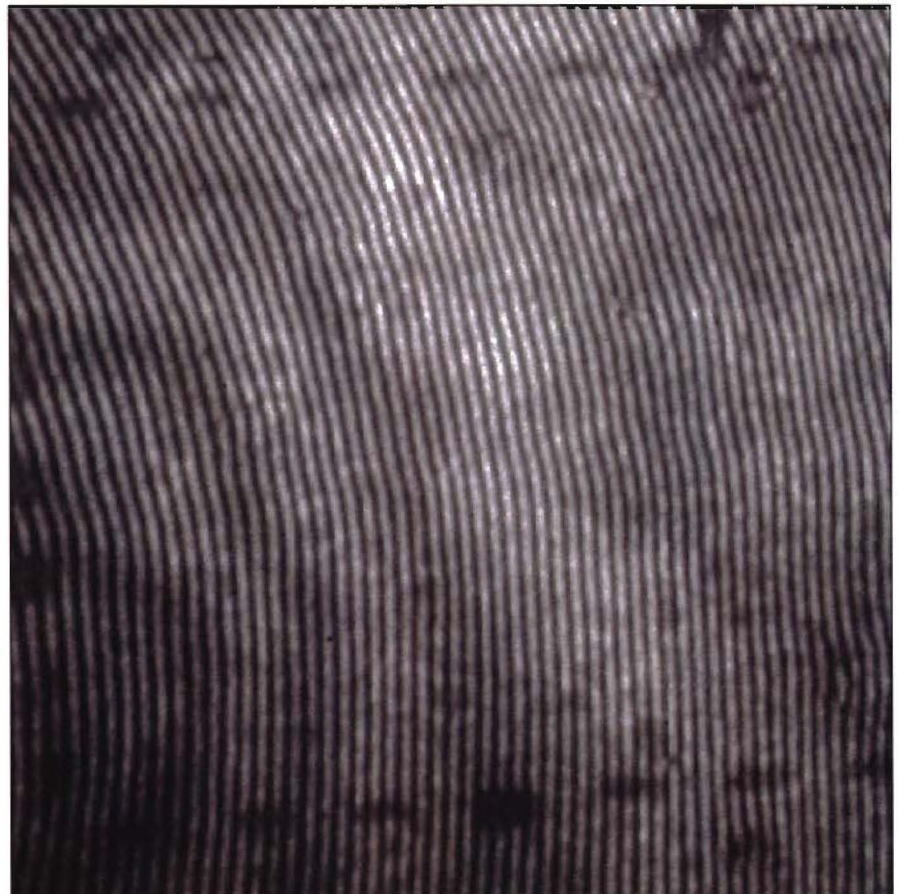
Dimples

- **Observations**
  - Dimples are not correlated with visible surface defects present in the sample
    - Pre-shot surface defects--such as embedded polishing grit, dirt and scratches--can also be seen in the TIDI images
    - Distribution of pre-shot defects much less than observed density of dimples
    - Dynamics arising from the pre-shot defects are very different than the dimples
  - Dimples do not appear to be correlated with any microscopically visible inclusions or voids in the sectioned material
    - Requires more sectioning to be completely confident
  - Dimples occur for all crystal orientations measured: <100>, <110>, <111>, <114> and <123>
  - Dimples occur for free surface and when PMMA window used
  - Dimples do not occur when sapphire window is used
- **Conclusions**
  - Dimples are the result of localized regions of tension that occur at the beginning of the plastic wave's arrival at the free surface
  - Experimental results appear compatible with non-uniform distribution of microscopic defects

TIDI sensitivity to dynamics of embedded objects

Embedded wire detected by TIDI

- Cu Polycrystal Target
- 100 micron diameter embedded tungsten wire
- Wire tilted from 120 to 180 microns below the surface in the dynamically observed region
- Flyer drive energy = 36J

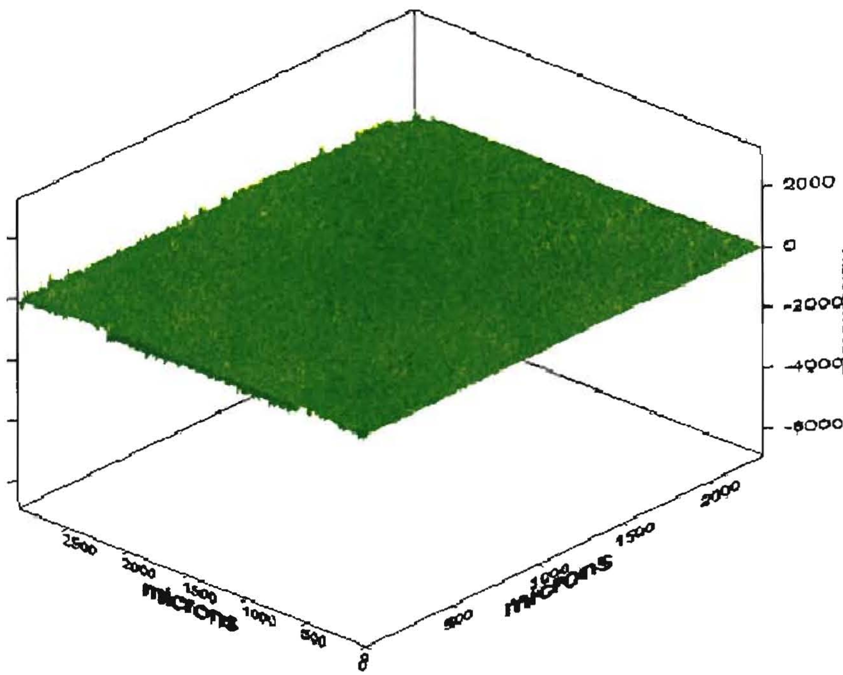


Shot20383_dyn.avi

Near surface spall

Near surface incipient spall movie

- **Drive pulse energy below that which results in a spall signature in Point VISAR**



Shot20393_anal_3D.avi

UNCLASSIFIED

Conclusion

- **TIDI Dynamic Images reveal immediate appearance of microscopic surface dimples during plastic deformation as free surface begins first release**
  - Observed localized deformations persist throughout at at least two cycles of compression
  - Deformations observed dynamically match post-shot dimples in size and location
- **TIDI easily observes dynamics of wave interacting with buried 100 micron wires in a polycrystalline target**
- **Signatures of incipient spall formation may have been observed**
  - Pending further analysis and post-shot metallographic investigation

Extra slides

Shot 20392 Movie

- **Conditions**
  - <100> Single Crystal
  - Polycrystalline flyer
  - 20J
- **Dimples**
- **Ridges—Near surface spall?**