Comparative Analysis of Microstructural Defects in Monocrystalline Copper: Shock Compression Versus Quasi-isentropic Compression

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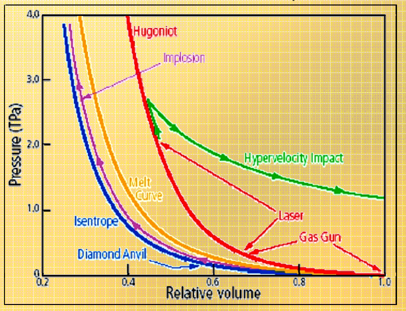
OBJECTIVES:

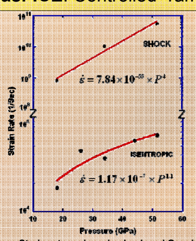
- Understanding deformation mechanisms of [001] Cu under various high-pressure and high-strain rate loading conditions.
- Microstructural characterization.
- Develop constitutive models to determine slip-twinning transition in Quasi-ICE and shock compression.



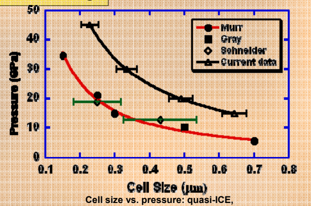
Source: M.Pullington et al., Discovery.

QUASI-ICE VS. SHOCK

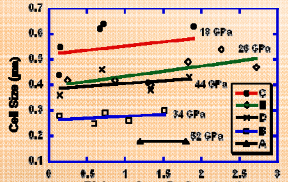
Shock: Instantaneous loading.
Quasi-ICE: Controlled "ramped" loading.



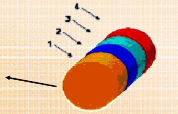
Strain-rate regimes in shock and Quasi ICE-Gas-Gun



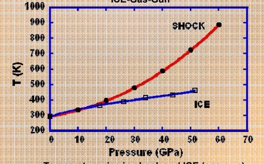
Cell size vs. pressure: quasi-ICE, laser shock and flyer-plate



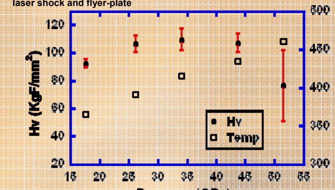
Dislocation cell size vs. distance from sample free surface: Gas-gun ICE



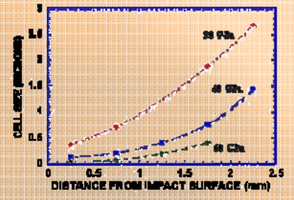
Slices cut from cylindrical samples



Temperature rise in shock and ICE (gas-gun)



Hardness, Temp. vs. Peak Pressure: Gas-gun quasi-ice



Dislocation sell size vs. distance from sample free surface: Laser shock

TWINNING THRESHOLD MODELING

- The Preston-Tonks-Wallace (PTW) constitutive description is used to determine critical twinning pressure in both shock and quasi-isentropic conditions.
- PTW equation takes into account both thermal activation regime and dislocation drag regimes.
- The instantaneous flow stress is given by:

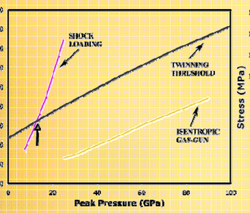
$$\tau=\hat{\tau}_s+\frac{1}{p}(s_0-\hat{\tau}_y)\ln\left\{1-\left[1-\exp\left(-p\frac{\hat{\tau}_s-\hat{\tau}_y}{s_0-\hat{\tau}_y}\right)\right]\exp\left[\frac{-p\theta\psi}{(s_0-\hat{\tau}_y)\left[\exp\left(p\frac{\hat{\tau}_s-\hat{\tau}_y}{s_0-\hat{\tau}_y}\right)-1\right]}\right]\right\}$$

Where $\hat{\tau}_s$ and $\hat{\tau}_y$ are work hardening saturation stress and yield stress, respectively. S_0 is the value of taken at zero temperature, ψ, θ are the strain and work hardening rate, respectively, and p is a dimensionless material parameter.

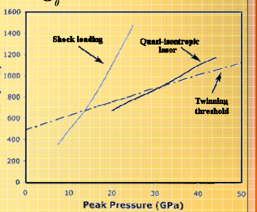
Thermal Activation Regime	Strong Shock Regime
$\hat{\tau}_s=s_0-(s_0-s_\infty)erf\left[\kappa\hat{T}\ln(\gamma\dot{\xi}/\dot{\psi})\right]$	$\hat{\tau}_s=s_0\left(\frac{\dot{\psi}}{\gamma\dot{\xi}}\right)^\beta$
$\hat{\tau}_y=y_0-(y_0-y_\infty)erf\left[\kappa\hat{T}\ln(\gamma\dot{\xi}/\dot{\psi})\right]$	$\hat{\tau}_y=s_0\left(\frac{\dot{\psi}}{\gamma\dot{\xi}}\right)^\beta$

- Flow stress is normalized to shear modulus and twinning threshold assumed to vary with pressure:

$$\sigma_T(P)=\sigma_T^0\frac{G(T,P)}{G_0}$$

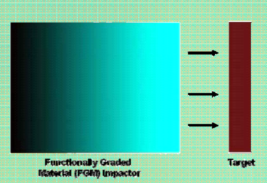
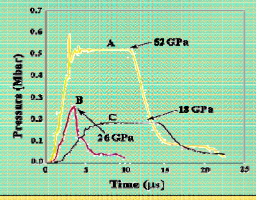
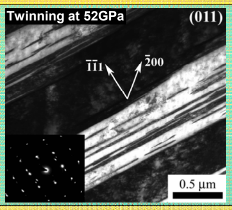
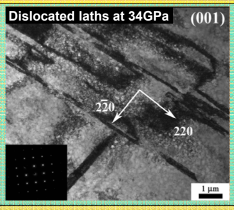
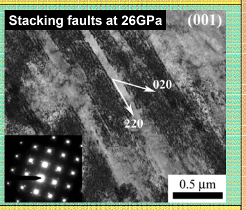
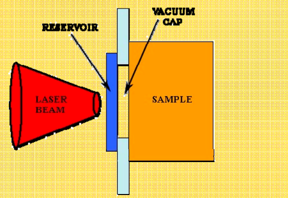
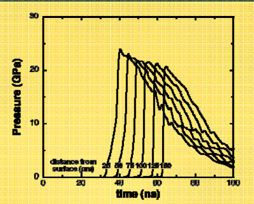
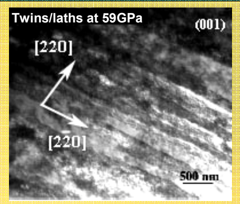
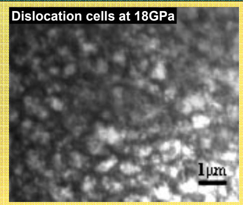
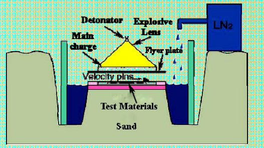
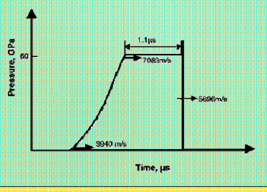
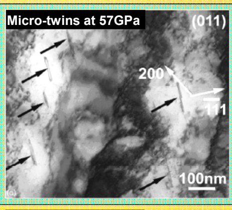
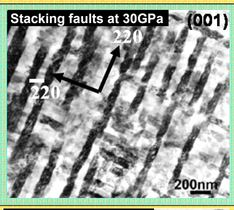
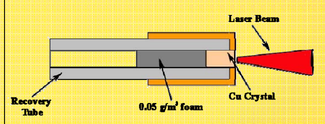
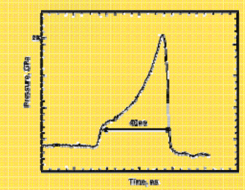
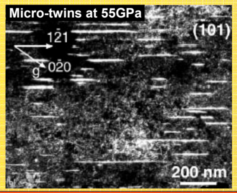
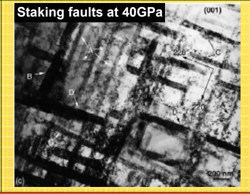
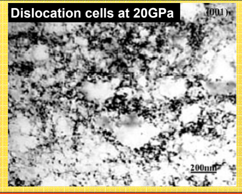


Flow stress vs. peak pressure: gas-gun modeling



Flow stress vs. peak pressure: laser modeling

TRANSMISSION ELECTRON MICROSCOPY (TEM) OF KEY FEARURES AT:

DYNAMIC COMPRESSION METHOD	EXPERIMENTAL SETUP	PRESSURE PROFILES	50-60 GPA	30-40 GPA	15-30 GPA
GAS-GUN QUASI-ICE &~10^4 s^{-1}	 Functionally Graded Material (FGM) Impactor; Target		 Twinning at 52GPa (011)	 Dislocated laths at 34GPa (001)	 Stacking faults at 26GPa (001)
LASER QUASI-ICE &~10^7 s^{-1}	 RESERVOIR; VACUUM GAP; LASER BEAM; SAMPLE		 Twins/laths at 59GPa (001)	 Dislocation cells and stacking faults at 24GPa (001)	 Dislocation cells at 18GPa
FLYER PLATE IMPACT &~10^4 s^{-1}	 Detonator; Explosive Lens; Main charge; Flyer plate; Velocity pins; Test Materials; Sand; LN2		 Micro-twins at 57GPa (011)	 Stacking faults at 30GPa (001)	(Experimental data unavailable)
LASER SHOCK &~10^9 s^{-1}	 Laser Beam; Recovery Tube; 0.05 g/m³ foam; Cu Crystal		 Micro-twins at 55GPa (101)	 Staking faults at 40GPa	 Dislocation cells at 20GPa

CONCLUSIONS AND FUTURE WORK

- Dislocation activity decreased away from impact surface in all cases.
- TEM revealed twinning at higher pressures, stacking faults and dislocated laths at intermediate pressures and mostly dislocation cells at relatively lower pressures.
- Modeling revealed twinning threshold lower for higher-strain rate compression experiments and reasonable agreement with experimental data.
- Future work will incorporate nanocrystalline materials (e.g. nc Ni and nc Ni%Fe).
- Understanding deformation mechanisms in nc materials:
  - Dislocation interactions with grain boundaries.
  - Grain boundary sliding.
  - Pressure effects on hardness.
  - Twinning thresholds modeling.
- Molecular dynamics (MD), specifically LAMMPS, will be used to simulate and study shock and high-strain-rate phenomena in nc materials and compare with experiments.
- High strain rate phenomena in bulk metallic glasses (BMGs) will also be integrated into study.

ACKNOWLEDGEMENT:

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