Iron Response in Extreme Compression and Tension Regimes:
Complementary NIF and Janus Experiments

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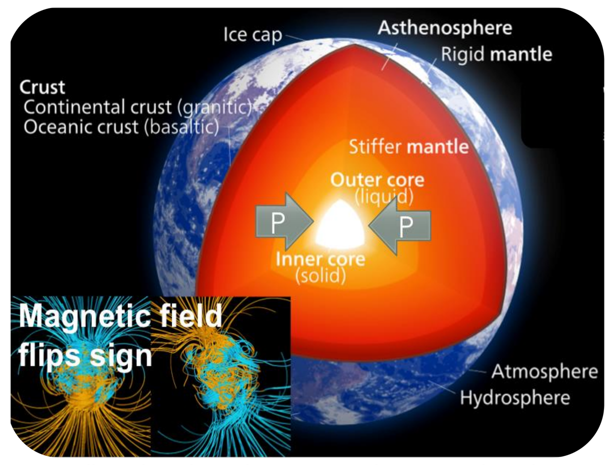
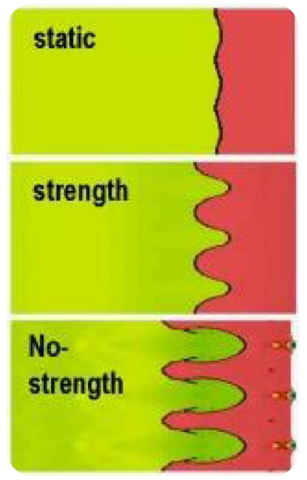
Motivation and Objectives

Iron is the major component of the Earth's core. Determining its strength at extreme conditions is crucial to understanding core rheology, geophysical observations, and the origin of the geodynamo.
Objectives of this study are:

- Advance fundamental knowledge of the strength and constitutive behavior of iron at extreme pressure, temperature, and strain rate conditions.
- Investigate the role of material strength on Rayleigh-Taylor (RT) stabilization.
- Reconcile discrepancies in the literature around the strength of iron at extreme conditions.

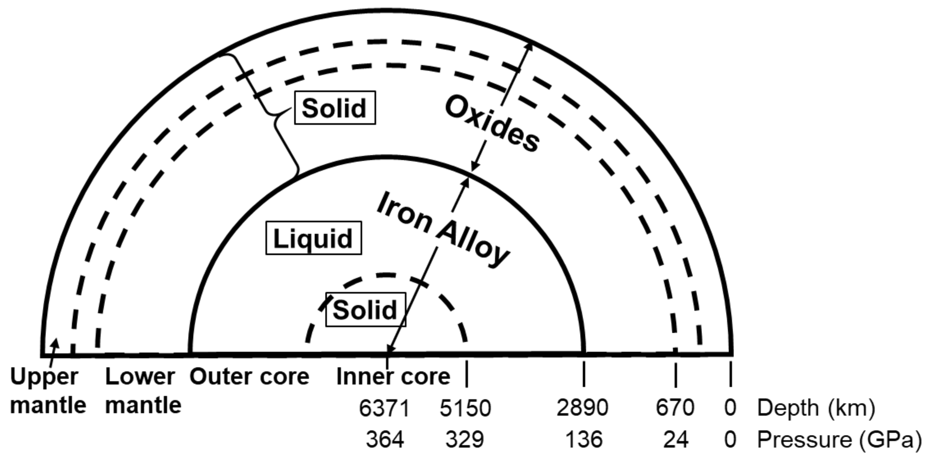


Matija Cuk and Sarah Stewart, *Science*, 338 (2012).



Background

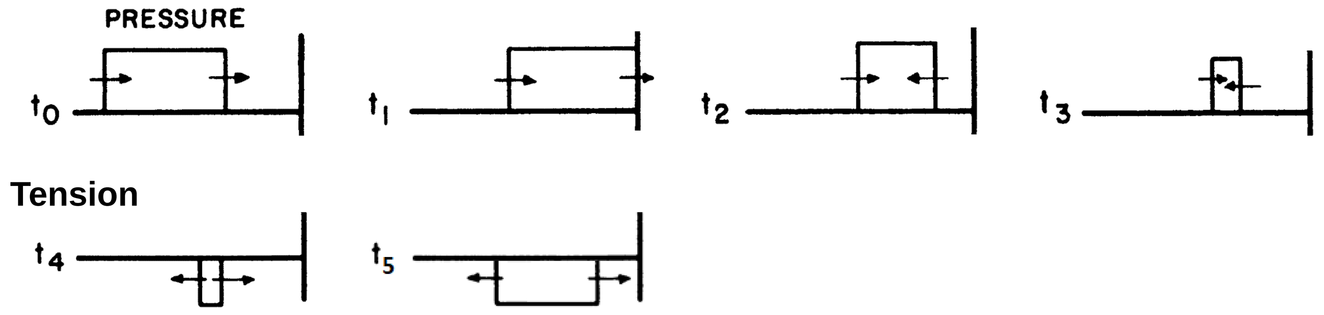
The Earth's core is an iron-nickel alloy containing roughly 4% Ni. Core pressures and temperatures range from 136 - 364 GPa and 4,000 K respectively.



Reproduced from R. Jeanloz, *Annu. Rev. Earth Planet. Sci.*, 18 (1990).

Existing data on iron strength and constitutive behavior is limited and inconsistent. Resolution of discrepancies will help calibrate existing theories on Earth core formation and geodynamo processes. A higher determined strength leads to slower core formation and geodynamo.

Spallation is dynamic material failure due to a tensile stress. When a compressive wave travels through a material and reaches the free surface, it gets reflected back as a tensile wave. If sample is thin enough, this will cause spall at the back surface.



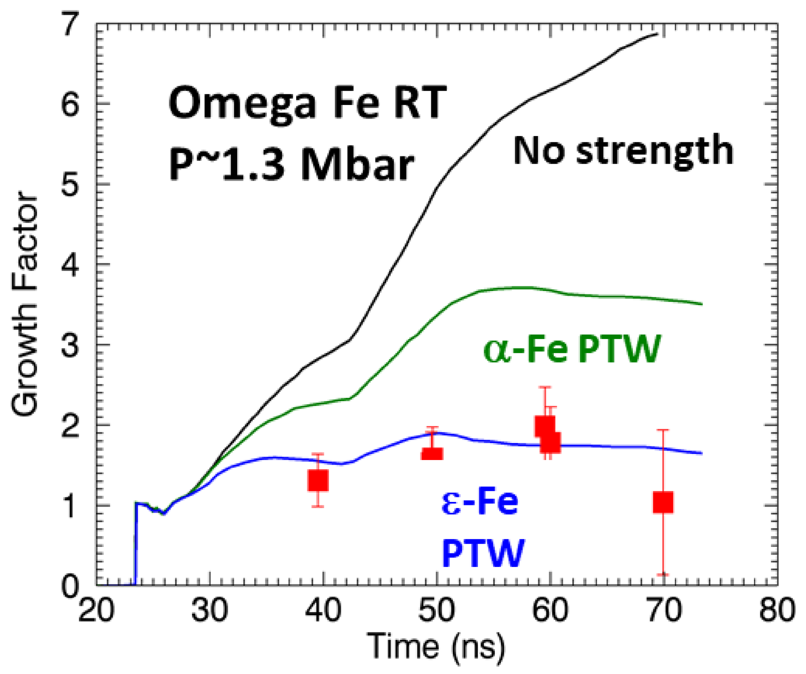
Meyers, M.A., 1994. Dynamic Behavior of Materials, J. Wiley.

NIF – National Ignition Facility

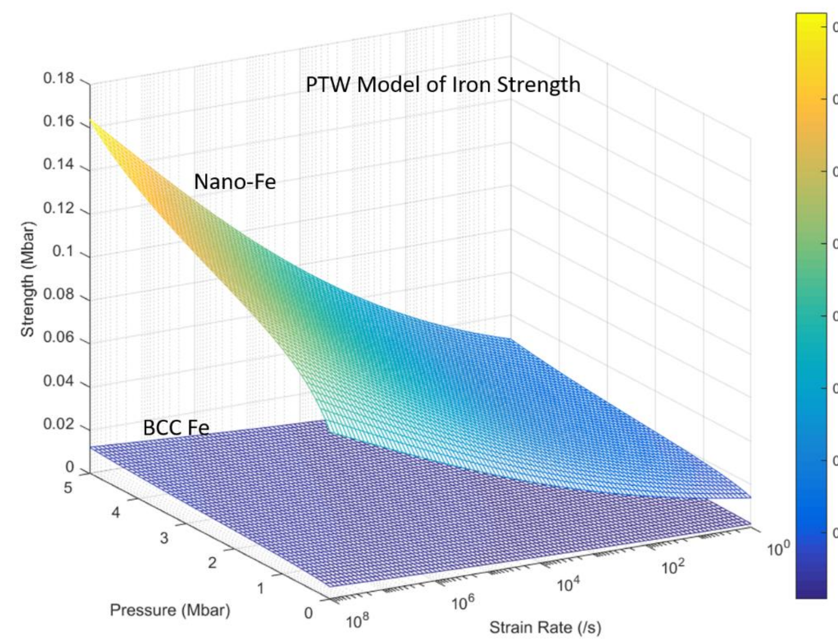
Background

Previous ramp compression experiments at Omega and shock-recovery experiments at Janus, both at a lower pressure, suggest that iron shows a very low growth factor. This provides evidence that iron is much stronger at elevated pressures than previously thought.

Constitutive modeling predicts strength of nanocrystalline iron more than one order of magnitude larger than coarse-grained iron.

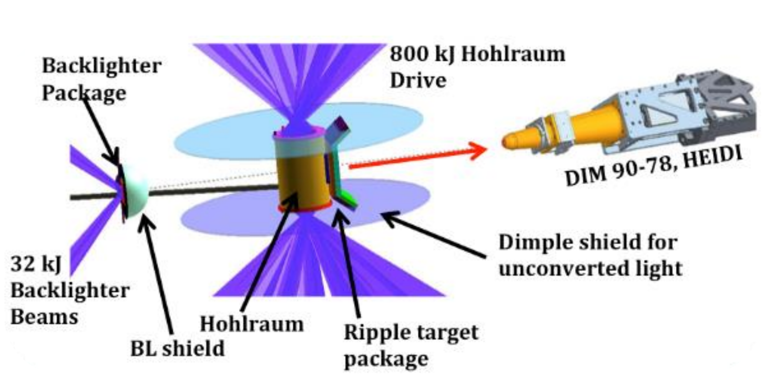


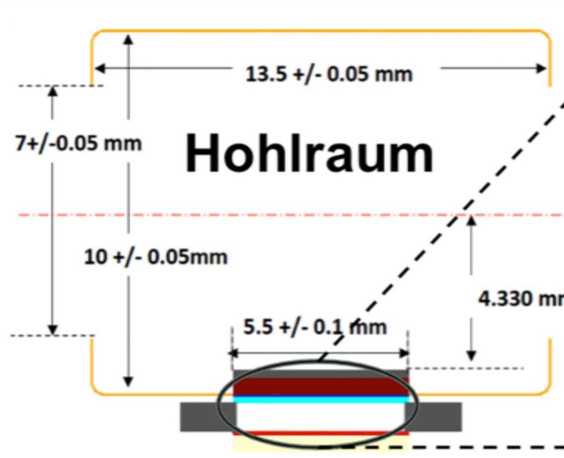
C. Hungtington et al., SCCM, 2010

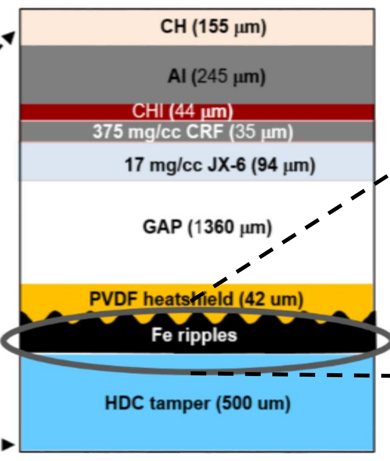


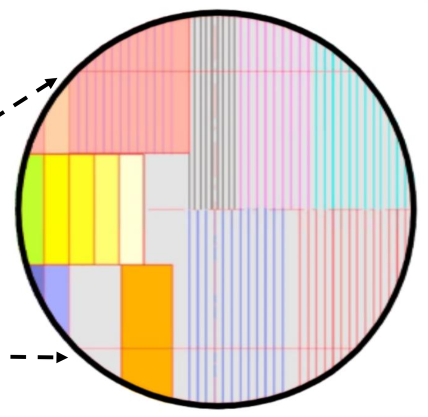
Experimental Setup

Indirect-drive Hohlraum to launch stress pulse. Calibrated ablator reservoir to obtain the desired ramp pulse shape. Precise diamond turning to fabricate rippled targets through General Atomics. Slit-point backlighter package currently used for the NIF-RT platform.





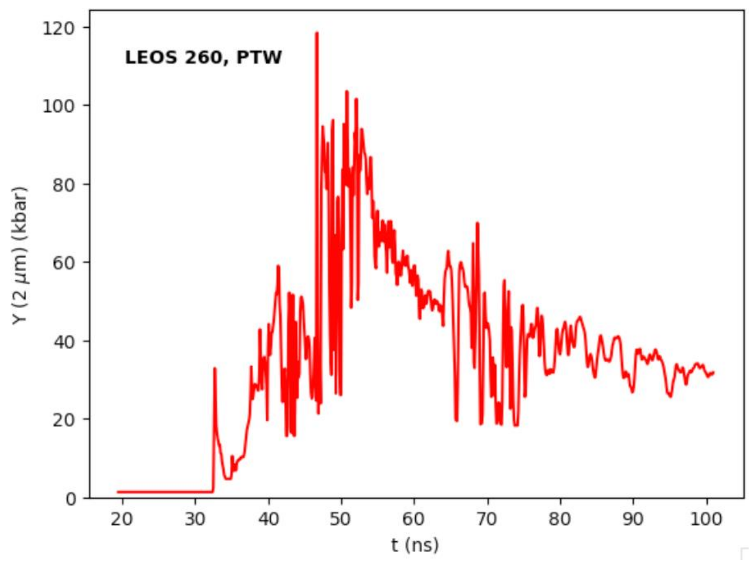




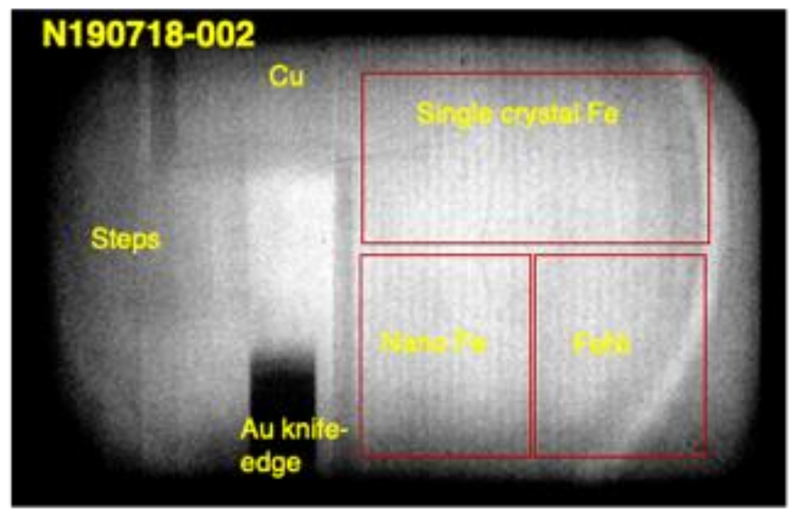
Results

Experimental results for RT stabilization in 2D (NIF shot N190718-002) resulted in low growth factor, indicating Fe is stronger than existing models. Growth factor prediction of ~4 corresponds to strength ~6 GPa while measured growth factor of ~2 corresponds to strength ~12 GPa

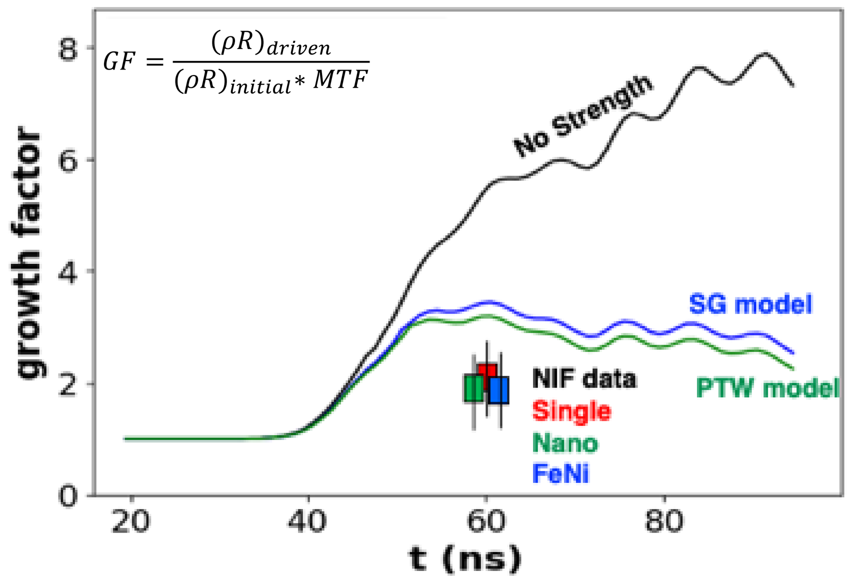
Yield strength prediction



Fe RT radiography



Predicted Fe growth factor vs NIF data

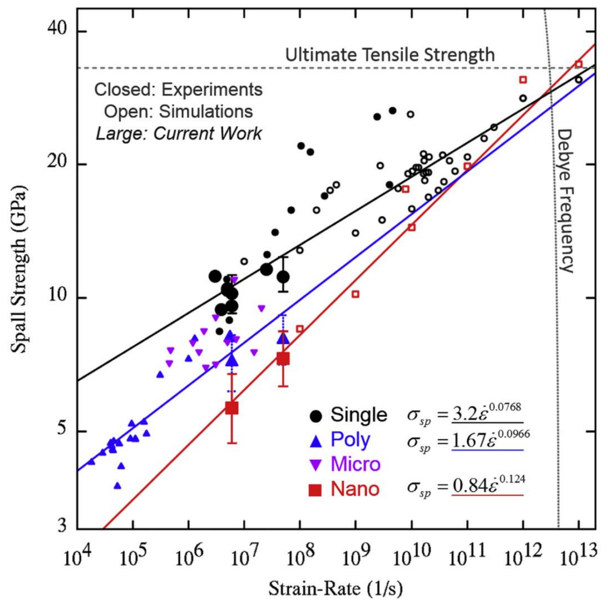


JLF – Jupiter Laser Facility, Janus

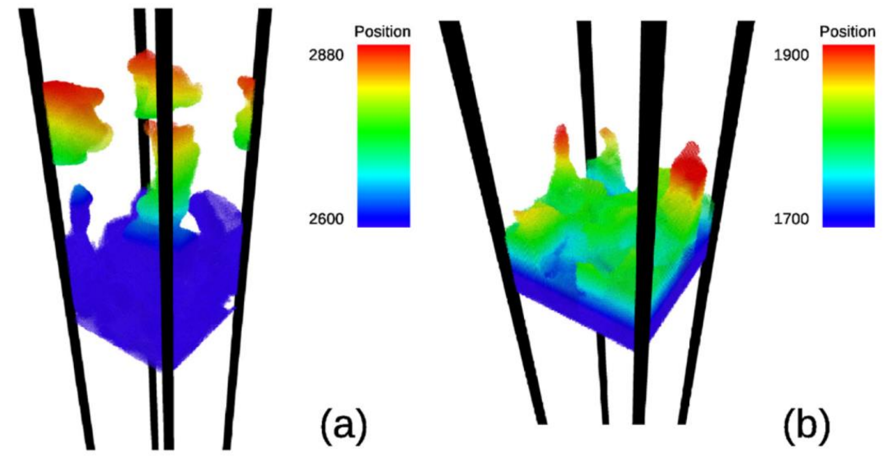
Background

Tantalum spall strength was found to decrease with decreasing grain size and strain rate. Since iron is also a BCC metal, spall strength should follow similar trend.

Spall surface morphology was found to differ because of phase transition. Smoother spall surface should be expected after α-ε phase transformation.



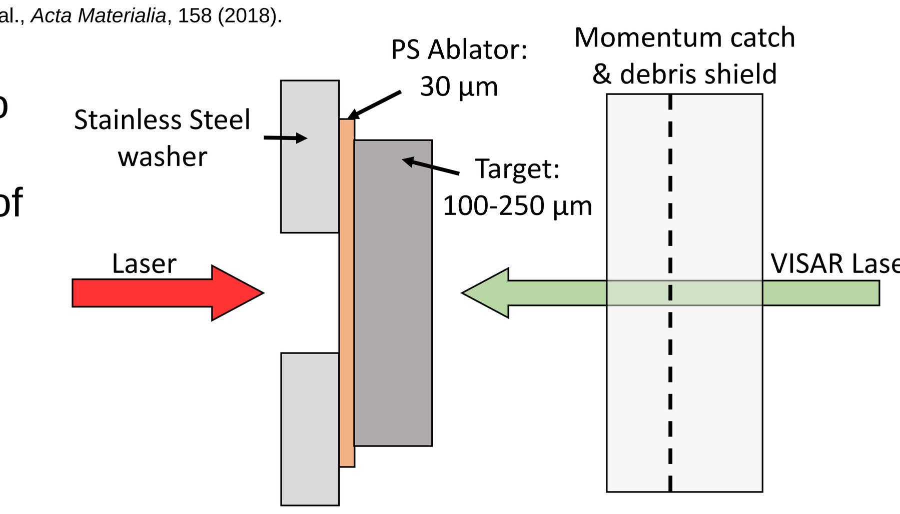
Remington, T.P., et al., *Acta Materialia*, 158 (2018).



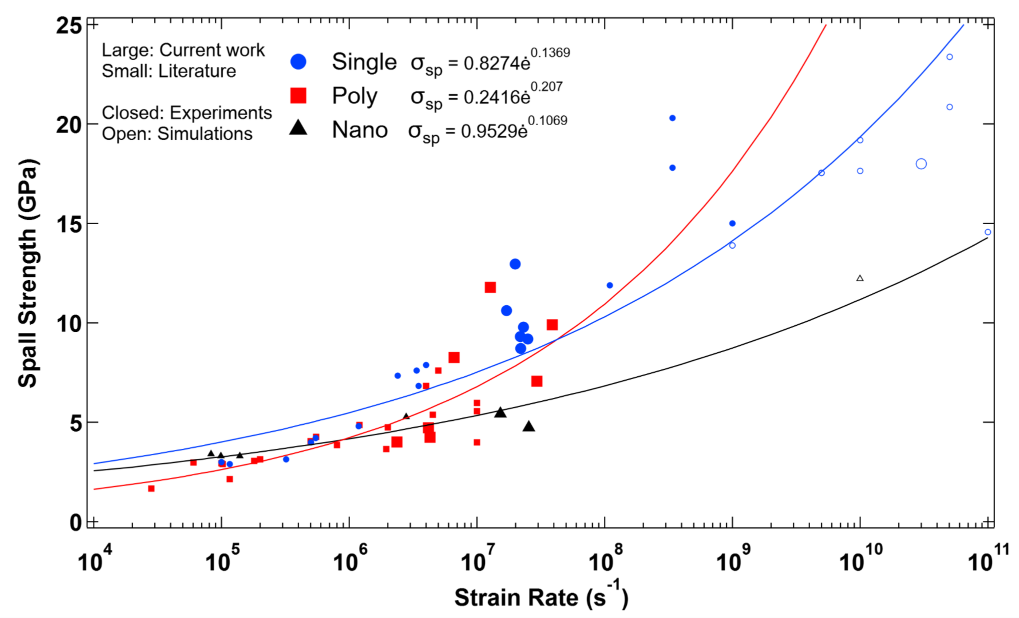
Gunkelmann, N., et al., *J. Appl. Phys.* 118 (2015).

Experimental Setup

Pulse laser impacts polystyrene ablator, turning polymer into plasma. Rapidly expanding plasma sends a planar shock wave through target. Debris shield/momentum catch made of transparent gel acts as recovery medium while still allowing VISAR laser to reach free surface. VISAR fringes measure free surface velocity from back surface.



Results



Using classical acoustic approximation, strain rate and spall strength are calculated using:

$$\dot{\varepsilon} = \frac{(u_{max} - u_{min})}{(\Delta t) * (2c)} \qquad P_{spall} = (1/2)\rho_0 c(u_{max} - u_{min})$$

Spall strength was found to decrease with decreasing grain size, consistent with other BCC metals. Spall strength-strain rate relationship follows power law of the form $\sigma = \sigma_0 \dot{\epsilon}^n$ where n is the strain rate dependence. Nanocrystalline iron, with the smallest n value, is the least sensitive to strain rate while single crystal iron is the most sensitive.

Summary

- Iron strength was studied in compression in tension regimes
- Strength at Earth core conditions was found to be ~12GPa
  - Second shot data will confirm this result
- Spall strength was found to decrease with decreasing grain size and follow power law that describes strain rate dependence.

Acknowledgements

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