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MATERIAL DYNAMICS AT EXTREME PRESSURES AND STRAIN RATES*

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Solid state experiments at extreme pressures (10-100 GPa) and strain rates ($\sim 10^6$–$10^8 s^{-1}$) are being developed on high-energy laser facilities, and offer the possibility for exploring new regimes of materials science. [Re 2004] These extreme solid-state conditions can be accessed with either shock loading or with quasi-isentropic ramped pressure pulses being developed on the Omega laser. [Ed 2004] Velocity interferometer measurements establish the high strain rates. Constitutive models for solid-state strength under these conditions are tested by comparing 2D continuum simulations with experiments measuring perturbation growth due to the Rayleigh-Taylor instability in solid-state samples. Lattice compression, phase, and temperature are deduced from extended x-ray absorption fine structure (EXAFS) measurements, from which the shock-induced a-w phase transition in Ti is inferred to occur on sub-nanosec time scales. [Ya 2004] Time resolved lattice response and phase can be inferred from dynamic x-ray diffraction measurements, where the elastic-plastic (1D-3D) lattice relaxation in shocked Cu is shown to occur promptly (< 1 ns). [Lo 2003] Subsequent large-scale MD simulations have elucidated the microscopic dynamics that underlie the 3D lattice relaxation. Deformation mechanisms are identified by examining the residual microstructure in recovered samples. [Re 2004] For example, the slip-twinning threshold in single-crystal Cu shocked along the [001] direction is shown to occur at shock strengths of 20-40 GPa, whereas the corresponding transition for Cu shocked along the [134] direction occurs at shock strengths of 40-60 GPa. We present highlights from our group's research in laser-based material science including our newest approach for achieving much higher pressures, P > 1000 GPa, in the solid state on the National Ignition Facility (NIF) laser.

One of our long-range goal is to develop an experimental capability to test constitutive models of solid-state plastic flow at extreme pressures and strain rates. Two relevant examples of widely used constitutive models are the Preston-Tonks-Wallace (PTW) [Pr 2003] and the Steinberg-Lund models [St 1989] for high pressure, high strain rate material strength. Both of these methods assume thermal activation processes for the strain rate, $\dot{\varepsilon}$, functionally depicted below for $\dot{\varepsilon} < \dot{\varepsilon}_c$:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_0 \mathbf{e}^{-\Phi/kT}, \tag{1}$$

where $\dot{\varepsilon}_0$ is an attempt frequency, Φ a barrier energy, k the Boltzmann constant, $\dot{\varepsilon}_c$ a strain rate threshold, and T the lattice temperature. Above the threshold, $\dot{\varepsilon} > \dot{\varepsilon}_c$, the PTW model transitions to a power law dependence on strain rate,

$$\boldsymbol{\sigma \propto (\dot{\varepsilon} / \gamma \dot{\varepsilon}_0)^{\beta}} \tag{2}$$

that has been fit to reproduce shock wave rise times for overdriven shock data, giving $\beta \approx 1/4$. For contrast, the Steinberg-Lund model assumes for $\dot{\varepsilon} > \dot{\varepsilon}_c$ that all strain rate effects have saturated, and that deformation and flow stress (material strength) are independent of strain rate. Using the nominal parameters for Ta suggested in [Pr 2003] and [St 1989], the critical threshold, $\dot{\varepsilon}_c$, for the Steinberg-Lund model for Ta is three orders of magnitude lower than for the PTW model.

It is model differences such as described above that we aim to distinguish in our current and future experiments. The implementation of this experimental program requires the utilization of unique and world-class laser facilities such as the Omega laser at the Laboratory for Laser Energetics (LLE) at the Univ. of Rochester, and the National Ignition Facility (NIF) laser, under construction at Lawrence Livermore National Laboratory (LLNL). On Omega, we have developed a technique that generates a ramped (shockless) pressure pulse. The laser is focused onto a ~0.2 mm thick, low-Z reservoir, launching a strong shock through it. When the shock breaks out of the back side, the reservoir expands across a ~0.3 mm vacuum gap, and stagnates against the 10-40 μm thick sample of interest. The increasing ram pressure with time from this stagnating reservoir plasma produces an increasing (ramped) pressure pulse in the sample. By varying the target conditions and laser intensity, we can access at Omega ramped pressures that are shockless from 0.1 – 2 Mbar (10 – 200 GPa), at strain rates in the range of 10^6-10^8 s^{-1}, and rise times ranging from 2-20 ns. [Ed 2004] We are designing an experiment for the NIF laser that will extend this ramped drive and potentially permit us to study the properties of solids to pressures > 10 Mbar (10^3 GPa). We have parallel efforts to develop the time resolved diagnostic techniques to be able to infer sample compression, strain, temperature, and phase, using time-resolved diffraction [Lo 2003], EXAFS [Ya 2004], and radiography [Re 2004]. The goal is to be able to experimentally test and discriminate between the PTW and Steinberg-Lund models, for example, in the 10^6-10^8 s^{-1} strain rate regime at pressures ranging from 0.1 – 10 Mbar (10 – 1000 GPa).

As discussed at length in ref. [Re 2004], pressure scaling should allow details about the Peierls barrier to be probed. Strain rate scaling will be a good method for probing deformation mechanisms. Velocity interferometer measurements allow the time-dependent drive (applied pressure versus time) on the sample to be well characterized spatially and temporally. [Ed 2004] Timed resolved radiography, used in hydrodynamic, Rayleigh-Taylor instability experiments, will allow high pressure strength to be studied, and sample recovery should allow deformation mechanisms to be inferred. [Re 2004] Time-resolved x-ray diffraction probes long-range lattice response to compression, allowing strain rate and phase to be directly measured. [Lo 2003] Diffraction is also sensitive to Peierls stress, through the time scale for the transition from 1D-to-3D compression, and may allow a lattice level measure of strength, by the degree to which the lattice deviates from hydrostatic conditions. EXAFS probes short-range lattice response, and offers a good measure of volume-average temperature in the ~100 meV range, relevant to this high pressure materials science work. [Ya 2004] Both diffraction and EXAFS allow phase to be determined on a sub-nanosecond time scale. At the ultrahigh pressures (P >> 100 GPa) and strain rates ($\dot{\varepsilon} >> 10^5$ s^{-1}) accessible, models, codes, and mechanisms can be tested in their "asymptotic limits". Finally, the short time scales and small spatial scales may make it possible to allow direct comparisons between our experiments and results from large-scale molecular dynamics (MD) as well as with continuum and mesoscale simulations. [Re 2004] This will offer a challenging test of constitutive models and interatomic potentials at the very highest strain rates and pressures, with experiments, continuum code simulations, and MD simulations all being compared on equal footing.

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