Materials Science Under Extreme Conditions of Pressure and Strain Rate

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Solid-state dynamics experiments at very high pressures and strain rates are becoming possible with high-power laser facilities, albeit over brief intervals of time and spatially small scales. To achieve extreme pressures in the solid state requires that the sample be kept cool, with $T_{\mathrm{sample}} < T_{\mathrm{melt}}$. To this end, a shockless, plasma-piston "drive" has been developed on the Omega laser, and a staged shock drive was demonstrated on the Nova laser. To characterize the drive, velocity interferometer measurements allow the high pressures of 10 to 200 GPa (0.1 to 2 Mbar) and strain rates of 10^6 to $10^8\ \mathrm{s}^{-1}$ to be determined. Solid-state strength in the sample is inferred at these high pressures using the Rayleigh-Taylor (RT) instability as a "diagnostic." Lattice response and phase can be inferred for single-crystal samples from time-resolved X-ray diffraction. Temperature and compression in polycrystalline samples can be deduced from extended X-ray absorption fine-structure (EXAFS) measurements. Deformation mechanisms and residual melt depth can be identified by examining recovered samples. We will briefly review this new area of laser-based materials-dynamics research, then present a path forward for carrying these solid-state experiments to much higher pressures, $P > 10^3$ GPa (10 Mbar), on the National Ignition Facility (NIF) laser at Lawrence Livermore National Laboratory.

I. INTRODUCTION

HIGH-STRAIN-RATE materials dynamics and solid-state deformation mechanisms have been a topic of great interest for decades.[1–8] Materials response to shocks and other high-strain-rate deformation has led to a number of theories, both empirical and, more recently, physically based. There is a particular interest in developing and testing constitutive models that allow continuum hydrodynamic computer codes to simulate plastic flow in the solid state. Models such as the Johnson–Cook,[9] Zerilli–Armstrong,[10,11] mechanical threshold stress (MTS),[12] thermal-activation–phonon-drag,[13,14] Steinberg–Lund,[15] and Steinberg–Guinan[16] models are widely used in the materials-dynamics community. These models have typically been tested and "calibrated" with experiments on Hopkinson bars, Taylor cylinders, and with high-explosive (HE)–driven shock or compression waves at pressures up to a few tens of gigapascals and strain rates of 10^3 to $10^5\ \mathrm{s}^{-1}$. We describe here our progress toward developing experiments in a new regime of materials science at much higher pressures ($P \gg 10$ GPa) and strain rates ($d\varepsilon/dt \gg 10^5\ \mathrm{s}^{-1}$), where we anticipate new dynamics and, possibly, new mechanisms of solid-state deformation. To reach these very-high-pressure conditions in solids, we use large laser facilities to focus macroscopic quantities of energy into microscopic volumes, generating very-high-energy densities ($E_{\mathrm{Laser}}/\mathrm{Volume} \sim P$). The time sequence of the ensuring dynamics in the samples under study is characterized with a variety of time-resolved and time-integrated diagnostics.

To illustrate the potential for exploring new regimes of extreme materials science, we present a list of ten fundamental questions that may be addressed with experiments at ultrahigh pressures and strain rates.

1. Are there upper limits on the dislocation density (ρ_{disloc}) and dislocation multiplication rate ($d\rho_{\mathrm{disloc}}/dt$) as strain rates are increased to extremely high values, where $d\varepsilon/dt \gg 10^5\ \mathrm{s}^{-1}$?
2. Is there a "relativistic" regime at the highest $d\varepsilon/dt$ value (*i.e.*, is there an absolute limit on dislocation velocity (u_{disloc})?
3. How much do initial conditions matter at ultrahigh shear stresses and compressions?
4. Is Schmid's law universally obeyed at extreme applied shear stresses and $d\varepsilon/dt$ in single crystals?
5. What is the dominant deformation mechanism at ultrahigh strain rates?
6. How does the Peierls–Nabarro stress scale to ultrahigh pressures?
7. Does material strength continue to scale with shear modulus as P and d´/dt increase to extreme values (i.e., is

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