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Observation of ultrafast dynamic compression at the lattice-level; experimental capabilities and early science at the Linac Coherent Light Source

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An in-depth understanding of the stress-strain behavior of materials during ultrafast dynamic compression requires experiments that offer in-situ observation of the lattice at the pertinent temporal and spatial scales. To date, the lattice response under extreme strain-rate conditions ($>10^8$ s^{-1}) has been inferred predominantly from continuum-level measurements and multi-million atom molecular dynamics simulations. Several time-resolved x-ray diffraction experiments have captured important information on plasticity kinetics, while limited to nanosecond timescales due to the lack of high brilliance ultrafast x-ray sources. Here we present new experimental capabilities at the Linac Coherent Light Source (LCLS) combining ultrafast laser-shocks and serial femtosecond x-ray diffraction. The high spectral brightness ($\sim 10^{12}$ photons per pulse, ΔE/E=0.2%) and subpicosecond temporal resolution (<100 fs pulsewidth) of the LCLS x-ray free electron laser allow investigations that link simulations and experiments at the fundamental temporal and spatial scales for the first time, thus enabling validation of plasticity models at these extreme strain rates. We describe early pump-probe experiments at LCLS that offer insights to the transient lattice states and compare with predictions from large-scale molecular dynamics simulations. A movie of the lattice undergoing rapid shock-compression, composed by a series of single femtosecond x-ray snapshots, demonstrates the transient behavior while successfully decoupling the elastic and plastic response in a polycrystalline material. We discuss future directions that LCLS can offer to the materials science community, ultimately leading to a predictive understanding and control of the material response during ultrafast dynamic compression.