Dislocations faster than transverse speed of sound

Dislocation motions in crystals cause ductile materials to deform or fail in response to their surroundings. As such, dislocation dynamics are essential to understand the mechanical properties of materials. The maximum speed at which dislocations can travel has long been thought to be limited by the transverse sound speed of the crystal, because their self-energy and stress diverge as the dislocations approach those velocities [1]. However, recent theories and molecular dynamics simulations suggest that dislocations can move faster than these limiting velocities if they are created at such high speeds [1,2]. Experimental observations of dislocations moving faster than the sound speed would deepen the knowledge of how crystals deform under extreme conditions, as high-speed deformation mechanisms differ from conventional plasticity.

In this study, we coupled the XFEL and the high-energy laser available at SACLA **BL3 EH5** [3]. We irradiated the high-energy laser onto our single-crystal diamond samples to drive strong shock-waves. We cut the diamonds along two different orientations to enable our shocks to propagate along the [100] and [110] directions to examine the orientational dependence of the shock response. We estimate the peak shock stresses in diamond to be 184 ± 16 GPa and 92 ± 15 GPa for the [100] and [110] shock directions, respectively. The unfocused XFEL beam generated at SACLA probed the diamond samples during shock compression, visualizing the dynamics of the shock-induced deformations as they occurred. We placed a lithium fluoride (LiF) crystal at ~11 cm downstream from the diamond sample to collect the transmitted X-rays as color centers in the LiF. The distribution of the color centers can be read by using a confocal laser microscope, allowing us to observe the X-ray intensity map [4]. While our X-ray images exhibit some phase-contrast effects because of the small characteristic sizes of the features formed in the diamonds under shock-deformations, we call our measurements as X-ray radiography because of the short distance between the sample and LiF detector, and to distinguish from phase-contrast imaging set-ups used for laser-shock experiments at XFELs.

A representative X-ray radiograph image of diamond shocked along [110] orientation is shown in Fig. 1(b) [5]. Our X-ray radiography visualized the elastic and plastic shock wavefronts traversing the sample from the bottom to the top of the image. Behind the plastic shock wavefront, we observed phase contrast caused by stacking faults traversing the diamond along the {111} slip planes of diamond.

When an edge of a stacking fault is within a crystal (i.e., not at a grain boundary or crystal surface), the edge is a partial dislocation. Thus, the observed stacking faults reaching to the plastic wavefront indicate that partial dislocations are present at the plastic wavefront, though the dislocations themselves are too small to be resolved by our measurements with ~1 μm spatial resolution [4]. The observed

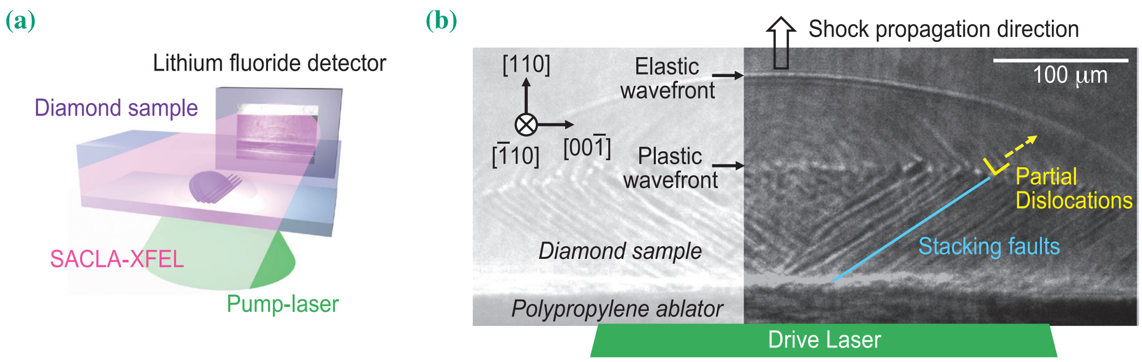

Fig. 1. **(a)** The dynamic X-ray radiography for laser-shock experiments at SACLA BL3 EH5. **(b)** An X-ray radiograph image of single-crystal diamond shocked along [110] orientation taken at 12 ns after the pump-laser irradiation. The two shock wavefronts corresponding to the elastic and plastic wavefronts and the shock induced stacking faults diagonally propagating the diamond behind the plastic wavefront are visualized. The stacking faults (eye guided by the light blue line) appear along the {111} slip planes of diamond.

stacking faults appear as continuous lines with no significant kinks, indicating these partial dislocations are traveling with the plastic wavefront from the diamond surface. By changing the time difference between the laser-pump and XFEL-probe, we took snapshots of the deformation dynamics to determine the velocities of the propagating partial dislocations (i.e., the velocities of the stacking fault extension). The observed dislocation velocities are shown in Fig. 2 along with the three sound wave velocities of diamond. Because of its structural anisotropy, diamond has two transverse sound wave speeds (c_2 and c_3) in addition to a longitudinal sound speed (c_1). These sound speeds define a supersonic regime, two transonic regimes, and a subsonic regime, as indicated in Fig. 2. Our measurements show that the velocities of the partial dislocations for the [100]-shock and [110]-shock both fall in the 1st transonic regime, which is the first experimental evidence of dislocations propagating faster than a transverse sound speed in a real-crystal.

To summarize, we used the XFEL-based dynamic X-ray radiography technique to indirectly observe transonic partial dislocation propagations in diamond under a high-strain rate shock deformation. As most current models for high-strain rate deformations assume transonic or supersonic dislocations to be prohibited, our results provide new insights to refine these models. This will now open a new field of crystal plasticity – experimentally exploring the physics that describes dislocation motion at these ultrafast velocities. The findings from this work will help to refine and validate models that are essential to understand the behavior of ultrafast materials science, of planetary impact and geology, and of high-energy density physics, among others.

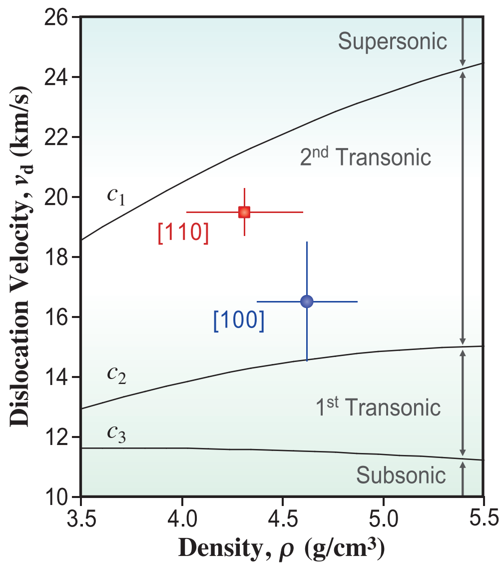

Fig. 2. Measured dislocation velocities as a function of the diamond's material density. The blue circle and red square represent the results for the [100] and [110] shock directions, respectively. The black curves are the longitudinal sound velocity (c_1) and two transverse sound velocities (c_2 and c_3) of diamond propagating along [110] direction.

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