

Stronger materials could bloom with new images of plastic flow

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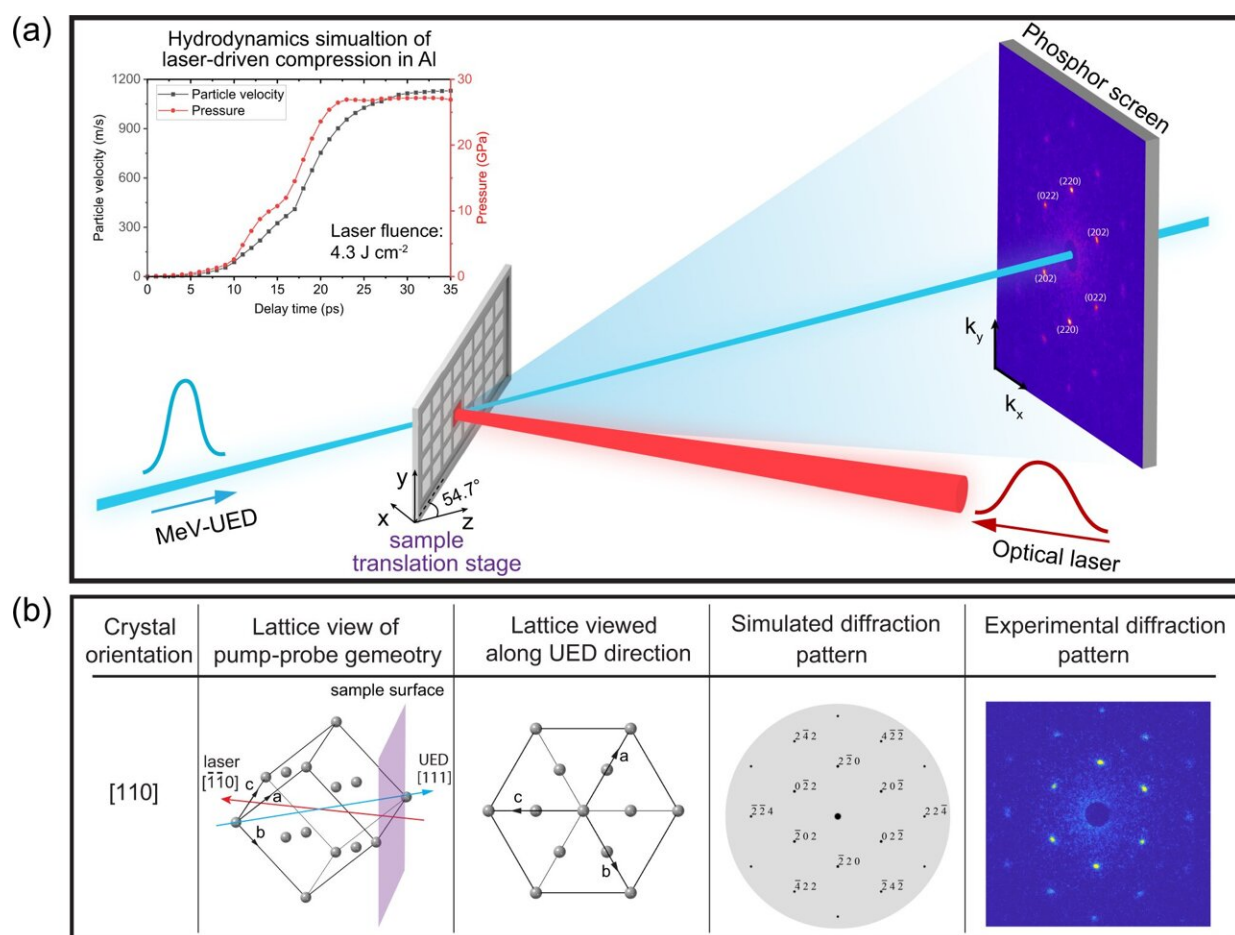


Fig. 1: Configuration for laser pump–electron probe experiments and diffraction patterns of Al single crystals at ambient (uncompressed) conditions. a Experimental setup for in situ UED under dynamic compression. The 3.7-MeV electrons generated by a radio-frequency (RF) gun are focused by two separate solenoids onto the sample; the electron beam spot size at the sample location is $\sim 184 \mu\text{m} \times 250 \mu\text{m}$ ($x \times y$), the electron bunch charge is ~ 90 fC and the pulse

duration is ~ 0.6 ps. The sample is rotated around the y-axis by a certain angle to probe lattice planes with a desired orientation (see bottom panel). The sample is ablated by counter-propagating laser pulses (800 nm, 20 ps FWHM, ≤ 10 mJ) with a Gaussian-like intensity profile (~ 360 μm FWHM). The laser incident angle is close to normal incidence. The inset shows the time history of peak particle velocity and peak pressure in 200-nm-thick Al irradiated with a laser fluence of 4.3 J cm^{-2} , which are obtained by hydrodynamics simulation (see the “Methods” section). b The pump-probe spatial overlap viewed from the crystal lattice perspective, and the comparison of the ambient diffraction patterns between simulations and experiments. The simulated diffraction pattern is used to identify the detected lattice planes. Credit: DOI: 10.1038/s41467-022-28684-z

Imagine dropping a tennis ball onto a bedroom mattress. The tennis ball will bend the mattress a bit, but not permanently—pick the ball back up, and the mattress returns to its original position and strength. Scientists call this an elastic state.

On the other hand, if you drop something heavy—like a refrigerator—the force pushes the mattress into what scientists call a plastic state. The plastic state, in this sense, is not the same as the plastic milk jug in your refrigerator, but rather a permanent rearrangement of the atomic structure of a material. When you remove the refrigerator, the mattress will be compressed and, well, uncomfortable, to say the least.

But a material's elastic-plastic shift concerns more than mattress comfort. Understanding what happens to a material at the atomic level when it transitions from elastic to plastic under high pressures could allow scientists to design stronger materials for spacecraft and nuclear fusion experiments.

Up to now, scientists have struggled to capture clear images of a

material's transformation into plasticity, leaving them in the dark about what exactly tiny atoms are doing when they decide to leave their cozy elastic state and venture into the plastic world.

Now for the first time, scientists from the Department of Energy's SLAC National Accelerator Laboratory have captured high-resolution images of a tiny aluminum single-crystal sample as it transitioned from elastic to plastic state. The images will allow scientists to predict how a material behaves as it undergoes plastic transformation within five trillionths of a second of the phenomena occurring. The team published their results today in *Nature Communications*.

A crystal's last gasp

To capture images of the aluminum crystal sample, scientists needed to apply a force, and a refrigerator was obviously too large. So instead, they used a high-energy laser, which hammered the crystal hard enough to push it from elastic to plastic.

As the laser generated shockwaves that compressed the crystal, scientists sent a high-energy electron beam through it with SLAC's speedy "electron camera," or Megaelectronvolt Ultrafast Electron Diffraction (MeV-UED) instrument. This [electron beam](#) scattered off aluminum nuclei and electrons in the crystal, allowing scientists to precisely measure its atomic structure. Scientists took multiple snapshots of the sample as the laser continued to compress it, and this string of images resulted in a sort of flip-book video—a stop-motion movie of the crystal's dance into the plasticity.

More specifically, the high-resolution snapshots showed scientists when and how line defects appeared in the sample—the first sign that a material has been hit with a force too great to recover from.

Line defects are like broken strings on a tennis racket. For example, if you use your tennis racket to lightly hit a tennis ball, your racket's strings will vibrate a bit, but return to their original position. However, if you hit a bowling ball with your racket, the strings will morph out of place, unable to bounce back. Similarly, as the [high-energy laser](#) struck the aluminum crystal sample, some rows of atoms in the crystal shifted out of place. Tracking these shifts—the line defects—using MeV-UED's electron camera showed the crystal's elastic-to-plastic journey.

Scientists now have high-resolution images of these line defects, revealing how fast defects grow and how they move once they appear, SLAC scientist Mianzhen Mo said.

"Understanding the dynamics of [plastic](#) deformation will allow scientists to add artificial defects to a material's lattice structure," Mo said. "These artificial defects can provide a protective barrier to keep materials from deforming at high pressures in extreme environments."

UED's moment to shine

Key to the experimenters' rapid, clear images was MeV-UED's high-energy electrons, which allowed the team to take sample images every half second.

"Most people are using relatively small electron energies in UED experiments, but we are using 100 times more energetic electrons in our experiment," Xijie Wang, a scientist at SLAC, said. "At high energy, you get more particles in a shorter pulse, which provides 3-dimensional images of excellent quality and a more complete picture of the process."

Researchers hope to apply their new understanding of plasticity to diverse scientific applications, such as strengthening materials that are used in high-temperature [nuclear fusion](#) experiments. A better

understanding of material responses in extreme environments is urgently needed to predict their performance in a future fusion reactor, Siegfried Glenzer, the director for high energy density science, said.

"The success of this study will hopefully motivate implementing higher laser powers to test a larger variety of important materials," Glenzer said.

The team is interested in testing materials for experiments that will be performed at the ITER Tokamak, a facility that hopes to be the first to produce sustained fusion energy.

More information: Mianzhen Mo et al, Ultrafast visualization of incipient plasticity in dynamically compressed matter, *Nature Communications* (2022). [DOI: 10.1038/s41467-022-28684-z](https://doi.org/10.1038/s41467-022-28684-z)

Provided by SLAC National Accelerator Laboratory

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