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Femtosecond Laser Heat Affected Zones in Aluminum

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The emergence of ultrashort pulsed laser (UPL) ablation has allowed for large area and volume materials analysis typically not accessible through focused ion beam techniques. Material damage and damage mitigation strategies from focused ion beams have been widely studied, therefore it is of interest to perform similar studies for UPL ablation performed in systems such as the Helios Laser PFIB™. Thermal effects from pulsed laser ablation can lead to a heat affected zone (HAZ) in materials. The femtosecond pulse regime is often considered to be HAZ free since the pulse duration is shorter than the characteristic relaxation times, while HAZ in the nanosecond regime can be 10 – 1000 µm [1].

Typically, laser HAZ is studied via single pulses or drilled holes. However, it is necessary to understand the HAZ in materials prepared with realistic conditions used for preparing large area cross-sections with ultrashort pulsed lasers. For example, spot overlap and/or multiple pulses per pixel in a pattern are generally necessary to achieve a high-quality planar cut-faces in short times on the Helios Laser PFIB™. Since many factors such as pulse duration, pulse energy, and incident angle impact HAZ thickness, it is necessary to further study HAZ from laser cut-faces on instruments used for emerging UPL workflows.

A previous study found the damage layer in commercial grade 6061-T6 aluminum for 30 kV Ga^+ FIB and Xe^+ PFIB to be ~6 nm and 4 nm, respectively. A 1.8 nm damage layer was observed from 2 kV Ga^+ FIB and no damage layer was measured for 2kV Xe^+ PFIB. [2] To investigate femtosecond laser HAZ in 6061-T6 aluminum, cross-sections were prepared on a Helios Laser PFIB™ with an in-situ femtosecond pulsed laser using parameters which could prepare large area cross-sections. Femtosecond laser ablation can produce ripples on the cut-face, often referred to as laser induced periodic surface structures (LIPSS). However, non-periodic surface texture and recast were present after UPL ablation with 515 nm and 1030 nm, which is shown in Figure 1. The laser cut-face was protected with 2 kV electron beam-induced deposition (EBID) W and 8 kV ion beam induced-deposition (IBID) W prior to using standard in-situ lift-out techniques to prepare transmission electron microscopy (TEM) specimen on a Helios G4 PFIB™ equipped with an EasyLift™ nanomanipulator with final PFIB polishing done at 2 kV. TEM specimens were analyzed by Scanning Transmission Electron Microscopy (STEM) / Energy Dispersive X-ray Spectroscopy (EDS) on a Metrios™ S/TEM at 200 kV. Figure 2 contains STEM/EDS from a 515 nm cut-face with 5 uJ (30 mW average power), 1 pulse per pixel (100 x 10 pixels), ~20 µm spot size, and 220 fs pulse duration. Based on STEM, the measured HAZ is ~2.5 nm, which agrees with prior results from Si had a HAZ < 5 nm. [3] No overlap or mixing was seen between the EBID W protective cap and Al laser cut-face from EDS. While this HAZ is small, it is possible to remove the HAZ with a low kV PFIB polish to produce a damage-free cut-face.

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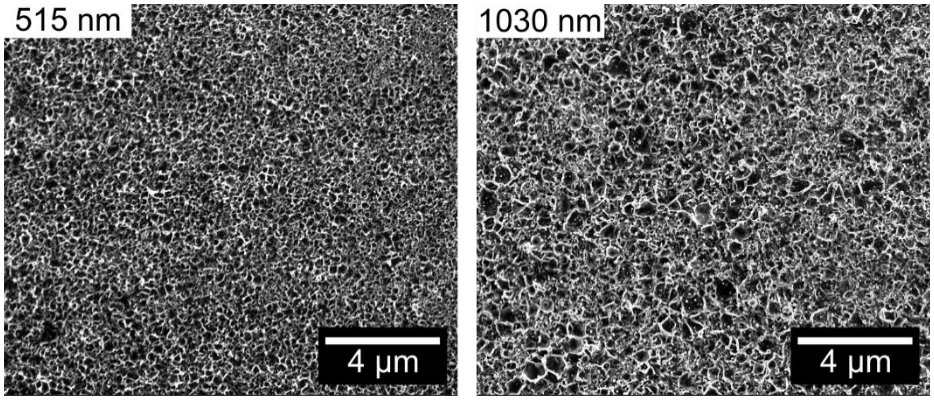

Figure 1. Secondary electron images of femtosecond laser ablation prepared cut-faces on 6061-T6 aluminum using 515 nm (left) and 1030 nm (right).

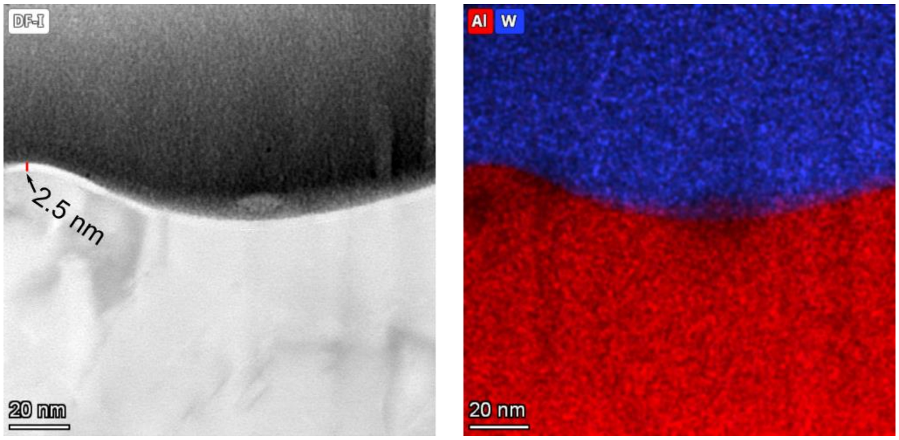

Figure 2. DF-STEM (left) with ~2.5 nm HAZ (red line) in 6061-T6 aluminum from a cross-section of a 515 nm laser cut-face. Corresponding STEM-EDS (right) map with Al and W, showing no overlap/mixing between the W protective cap and Al laser cut-face where HAZ was measured.

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