Laser Micromachining: Shaped femtosecond laser pulses improve ultrafast-micromachining quality

The technique improves fabrication precision, quality, throughput, and repeatability, and effectively controls micro/nanoscale structures.

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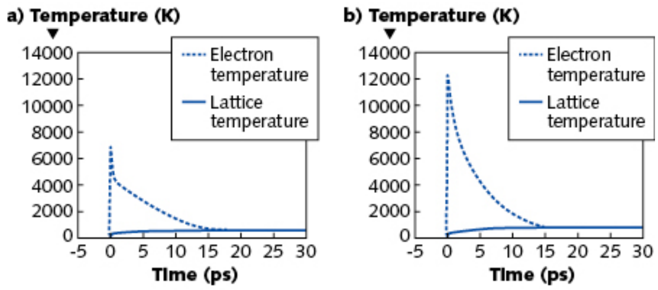
In an open paper whose free distribution may help many ultrafast-laser machining outfit to improve its manufacturing process, scientists from Beijing Institute of Technology (Beijing, China), the University of Minnesota (Minneapolis, MN), and the University of Nebraska-Lincoln have summarized their research showing how shaping femtosecond laser pulses can improve the quality of the microfabrication process (see figure).1 Specifically, they show that the technique improves "fabrication precision, quality, throughput, and repeatability and effectively control micro/nanoscale structures."



Improved models of electron dynamics helped researchers determine the best way to shape femtosecond pulses to improve micromachining; shown are calculated electron and phonon temperatures of 200 nm gold film irradiated by a 140 fs, 1053 nm laser pulse at a 0.2 J/cm2 intensity via the classical model (a) and the improved model (b). (Adapted from L. Jiang et al.1)

This is not just theory; the group also provides an extensive list of experimental examples. The technique was also used to fabricate microstructures in a Chinese project. The researchers' results, and their list of accomplishments, are the culmination of a 10-year project..

Electron dynamics control

Because the interaction of a femtosecond laser with a material is so short timewise, it is dominated by the photon-electron iterations, rather than any resulting lattice motion, which happens on a longer picosecond time scale. Thus, shaping the pulses to alter these electron dynamics can alter the fabrication process. The hard part is determining what pulse shape for what process.

To simulate electron dynamics control (EDC), the researchers used four different theoretical models: calculations for electron dynamics, a molecular dynamics simulation for phase change, a plasma model for ionization processes, and a two-temperature model for energy transport.

Based on the simulation results, the researchers experimented with temporally and spatially shaping femtosecond pulses, creating subpulses that have a pulse delay shorter than the characteristic time scale of electron-lattice coupling. With an amplified laser as a light source, the pulses in the experimental setup were shaped using a commercial 4f-configuration-based pulse shaper by Biophotonic Solutions (East Lansing, MI). The sample was mounted on a stage with a 1 μm accuracy.

Results could be of wide use

Using the processes they developed, the researchers achieved some stunning results through their project, including:

1) *increasing the processing efficiency of microchannel fabrication by 56X and the maximum aspect ratio of the microchannels by 3X;*
2) *boosting a laser-assisted chemical etching rate by 37X;*
3) *adjusting the periods, orientations, and structures of surface ripples by adjusting electron generation on fabricated material surfaces;*
4) *creating surface-enhanced Raman spectroscopy (SERS) surfaces with enhancement factors up to 1.1 × 109; and 5) fabricating deep-subwavelength (~1/14 of laser wavelength) and high conductivity (~1/4 of bulk gold) nanowires in open air.*

In just one specific, the sensitivity of SERS substrates, which is because of an enhancement of the electromagnetic field in the vicinity of the surface microstructures by surface plasmon resonance, was boosted because the EDC process allowed tailoring of the surface structures into ordered nanopillar arrays rather than the conventional subwavelength ripples.

The researchers also experimented with spatial pulse shaping, changing the beam's Gaussian profile to other shapes using a phase-based spatial light modulator. A dual-peak-shaped beam spot was one result, which allowed the high-precision formation of nanowires in a gold film. Using spatial pulse shaping to create Bessel beams (so-called "nondiffracting" beams), EDC was also used to fabricate structures such as taper-free microholes with a diameter of 1.6 µm and an aspect ratio of 330:1.

The group has developed techniques to measure EDC fundamentals that includes a pump-probe shadow-graph imaging technique, time-resolved plasma photography, laser-induced breakdown spectroscopy, and a commercial fast-imaging CCD.