Temporal Pulse Shaping and Optimization in Ultrafast Laser Ablation of Materials

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The necessity to modify materials on and below the scale of optical wavelengths and the need for enhanced controllability have promoted ultrafast laser technology to the forefront of material processing. In this respect femtosecond lasers offer unrivaled capabilities for reduced-scale processing, taking advantage of the nonlinear and selective, non-thermally driven interactions, reduced heat effects, and the unique possibility of pulse adaptive manipulation.

Dielectric materials (1) show specific ways to respond to the sudden laser energy input, depending on the efficiency of the free electron generation and on the ability to release the electronic energy into the lattice. Electronic loss mechanisms, the efficiency of surface charging, as well as the strength of the electron-phonon interaction control the effectiveness of the energy deposition into the lattice.

Photoionization and electrostatic energy accumulation on the surface lead to a primarily impulsive ion ejection, followed by lattice heating and subsequent thermal expulsion of particles in both neutral and ionized state. The coulombian disintegration is significant only in dielectrics while in semiconductors and metals efficient neutralization occurs. Defect accumulation processes at repetitive irradiation change the dynamics of the material removal, leading to increased ablation rates with low ionization degree, thus shifting the balance towards thermal mechanisms. Time-resolved measurements on both ions and photo-ejected electrons have shown that the electrostatic surface break-up is a fast, sub-ps process, while thermal mechanisms start to dominate on a longer, picosecond time scale given by the electron-lattice equilibration and phase transformation time.

The developments in the field of dynamic pulse temporal tailoring and adaptive optimization (2) introduce the possibility to regulate and manipulate excitation and energy transfer, to exploit dynamic processes and optimize structuring, unfolding new perspectives for “intelligent”, feedback-assisted processing of materials. Knowledge of the specific response times of materials establishes a guideline for using temporally shaped pulses or pulse trains in order to optimize the machining process with respect to the efficiency of material removal and reduction of the residual damage (3). Effects of a modulated excitation on materials with different electronic relaxation times irradiated with temporally tailored pulses derived from time-resolved measurements of the ablation products and surface topology investigations will be presented. Smaller and controllable structures were achieved for materials with fast carrier trapping by applying pulses modulated on the time scale of the electronic decay.

As a consequence of the accumulated mechanical stress, femtosecond laser micromachining of brittle dielectrics often results in specific collateral damage in forms of fracture and exfoliation. However, improvements can be made when temporally modulated pulses are used on materials exhibiting strong electron-lattice interactions. Carrier self-trapping induces local lattice deformations, softening the interaction region, and the use of modulated pulses determines an optimum energy deposition rate. It will be shown that the use of sub-picosecond modulated pulses enlarges the processing window and allows the application of higher fluences and number of sequences per site while keeping fracturing at a reduced level.

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