Interaction of Short Laser Pulses with Model Contamination Microparticles on a High Reflector

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Contamination in the optical components of large-aperture laser systems is a well-known problem originating from the handling, installation, and operational environment of these large components. The main problems associated with contamination particles are that they can facilitate laser-induced damage (LID) during operation of the system by creating (a) localized absorption and damage of the host optic and (b) intensification (hot spots) of the propagating beam, giving rise to damage in downstream optical components. Previous studies on this issue have focused on identifying the origin of contamination[1] and understanding the interaction of nanosecond laser pulses with the contamination particles.[2,3] These studies have highlighted that contamination can originate from various sources (including ejected debris from LID of adjacent parts, target materials, and the optics themselves) and therefore can involve various types of materials. Depending on the type of contamination particle (metal, transparent, etc.), its interaction with the laser pulse varies and can be characterized by three main effects: (1) particle removal, (2) secondary contamination of the host surface by fragments of the original contamination particle, and (3) LID of the host surface. Particle removal or ejection is often desirable (frequently referred to as "laser cleaning"[4]), but LID and secondary contamination degrade the performance of the optic.

The effectiveness of contamination particles to accelerate LID in optical components in the short-pulse (picosecond to femtosecond) regime has so far remained uninvestigated. Furthermore, direct translation of the knowledge attained for nanosecond-pulse systems is not warranted since short-pulse systems typically employ reflective optical elements and operate at higher laser peak intensities by many orders of magnitude. This work investigates the interaction of 10-ps and 0.6-ps laser pulses with microparticles located on the surface of a multilayer dielectric mirror in order to understand and assess the risk of contamination-induced damage in short-pulse laser systems. Irradiation with one laser pulse caused particles to eject from the surface with an onset fluence in the range 5× to 100× below the particle-free, laser-induced damage threshold (LIDT) of the mirror. Morphological analysis showed, however, that the ejection process always generated ablation craters and/or secondary contamination, both of which can degrade the performance of the optic during subsequent pulses. Ejection and damage mechanisms are discussed for each particle type.

Four different particle materials (one metal, one glass, and two polymers) were used as representative contaminants in this experiment. All four species have similar ≈40-μm diameters, while three are spherical in shape. Although contaminant particles in an actual laser system would have a broad distribution of sizes and irregular shapes, these controlled variables of size and shape enable one to more directly compare and contrast the mechanisms and resulting surface modifications. The particles were used to intentionally contaminate 2-in.-diam commercially available multilayer dielectric mirrors that exhibit high reflection at our 1053-nm laser wavelength at angles of incidence from 0° to 45°.

A dry powder of particles was dispersed onto the mirror sample. The sample was then placed in an experimental setup for short-pulse laser irradiation of individual particles. Laser pulse durations of 0.6 or 10 ps were selected for this work. Beam profile and energy were recorded for each pulse to measure the beam-normal peak fluence of the 300-μm-diam (e^{-2}) Gaussian beam. Isolated contaminant particles were positioned to within 20 μm of the laser peak location and then irradiated by a single pulse. Subsequently, the morphologies of the irradiated sites were analyzed.

The fluences of median (50% probability) ejection (F_E) and median LID (F_{th}), displayed in Fig. 1, are organized by contaminant particle type. Noting the logarithmic scale, these data show that the onset of particle ejection always occurs at fluences significantly lower (in the range 1% to 20%) than F_0, the LIDT of the pristine (noncontaminated) mirror. The ejection fluence of the glass and steel did not vary significantly with pulse duration, whereas each of the two polymers showed a factor of 3 between F_E at the two pulse durations.

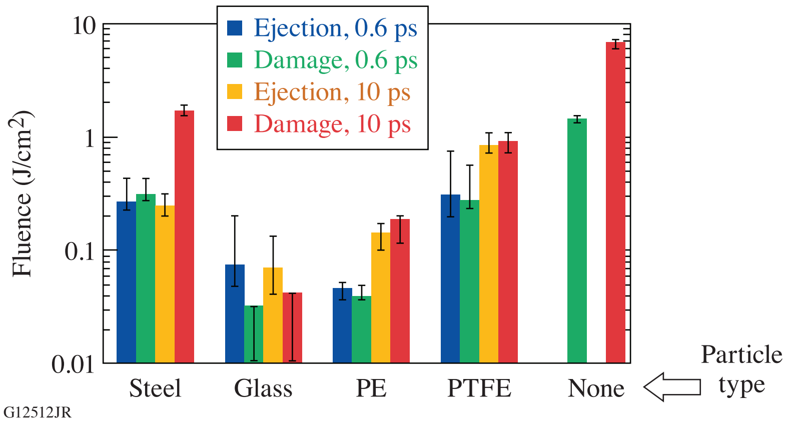

Figure 1
Median ejection and LID fluences. Error bars show the observed range from 0% to 100% probability, except for glass, where all tested fluences caused LID and a large lower bound was artificially added.

The morphological data and analysis for each of the eight tests (two pulse durations, four materials) were subsequently analyzed. Figure 2 displays the subset of this data set that shows the morphologies generated with stainless steel particles. These images show three representative laser fluences: (1) below, (2) just above, and (3) well above the particle ejection fluence. Slightly below the F_E of steel [Figs. 2(a) and 2(d)], a large number of submicrometer particles are observed on the mirror without ejection of the main particle. As fluence is increased to F_E [Figs. 2(b) and 2(e)], the main particle is ejected. This ejection was measured to occur at the same fluence for both pulse durations, consistent with the linear absorption (not dependent on intensity) of metals such as steel. At higher fluences [Figs. 2(c) and 2(f)], in addition to surface contamination by microparticles, LID is observed in sickle shapes on the laser-incident side. This suggests the formation of an interference pattern (from the directly incident beam and the beam reflected from the particle) exceeding the onset of damage initiation, especially exemplified in the 0.6-ps interaction. Under exposure to 10-ps pulses, a film of secondary contamination is observed to form [in Fig. 2(c)]. These observations together may suggest that 0.6-ps interactions bring a greater risk of LID, but 10-ps interactions bring a greater risk of secondary contamination.

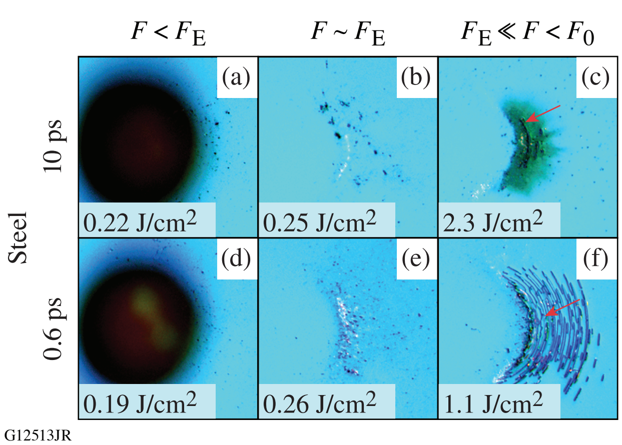

Figure 2
Optical microscopy of one-pulse–irradiated steel particle sites, organized by row (pulse duration) and column (relative fluence). Red arrows indicate ablation of the mirror. The laser is incident from the right at a 45° angle of incidence and *s* polarization.

Although all particle ejections left a residue of particles, films, and/or coating ablation at fluences far below the pristine LIDT, future work seeks to employ this knowledge to develop protocols of laser cleaning for optics in short-pulse, high-powered laser systems and could help devise self-cleaning protocols using the laser itself at lower operating fluences.

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