Morphologies and Underlying Mechanisms of Laser-Induced Damage by Model Contamination Particles on a High Reflector

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Due to the significant cost to replace optics that have sustained laser-induced damage in large-aperture laser systems, management strategies aim to maintain laser-damage performance over long time durations by (a) preventing the generation of new damage sites and (b) arresting the growth of existing damage sites. Contamination of optical elements during installation and from the operational environment has been recognized for nanosecond-class lasers as an important contributor toward these problems.[1–6] Specifically, contamination particles can become the source of damage initiation via a number of mechanisms, depending on the contamination material (such as metal or dielectric) and optical substrate properties (such as reflective or transmissive). Furthermore, the laser-induced–damage process with nanosecond pulses has been shown to eject particles from the affected optics that can transport onto adjacent optics and become the source of additional damage initiation.[7]

The potential for analogous processes occurring in short-pulse laser systems has received much less attention, although there have been reports of degradation of laser-induced–damage thresholds (LIDT's). The LIDT-degradation of the LFEX (laser for fast ignition experiment) laser pulse compressor was attributed to organic contamination,[8] and the cause of degradation of OMEGA EP compression gratings is not yet resolved.[9] We recently demonstrated, using model contamination particles (including metal, glass, and plastic spherical particles) dispersed on the surface of a multilayer dielectric mirror, that exposure to 0.6-ps and 10-ps pulses at 1053 nm can introduce damage and spread secondary contamination at fluences that are significantly lower than that of the pristine surface.[10] Here we expand on that work, with a primary objective to investigate the laser–particle interactions that lead to these damage initiations and/or secondary contamination depositions. Several interaction mechanisms leading to material modification and damage are identified, including localized field intensification by multibeam interference and particle-induced microlensing, plasma-induced scalding, and secondary contamination via nanoparticle generation and particle melting. The secondary objective of this work is to investigate the impact of additional pulses irradiating these sites. A second pulse irradiating damaged sites caused damage growth at fluences significantly below the initiation threshold, and a second pulse irradiating secondarily contaminated sites could not significantly remove that contamination without initiating additional damage.

The reduction of LIDT in the presence of the particles was caused by intensification of the electric field locally, as shown in Fig. 1. For reflective particles (steel in this work), a multibeam interference pattern between the particle and mirror is generated, leading to sickle-shaped ripples of intensification on the laser-incident side of the microsphere. The peak value of intensity or fluence enhancement ($4.3 \times$ the incident value) calculated by coherent ray-tracing simulation is consistent with the LIDT reduction factor measured in experiments (4.6 and 4.0 for 0.6-ps and 10-ps pulses, respectively). On the other hand, transparent particles act as a microlens, focusing the laser onto the optic surface and leading to an ablation crater of a few-μm diameter. Due to the symmetry of the microspheres, a strong local fluence enhancement factor of approximately 200 was observed for glass microspheres. This damage can occur even without removal of the particle, as demonstrated by Fig. 1(e).

These intensification mechanisms were also responsible for energy deposition and ablation from the surface of the particle itself, leading to dispersal of secondary contamination onto the optic. The multibeam interference mechanism occurring for the steel particles produced fringes of similar amplitude on the particle as well and generated nanoparticles that could be deposited over a large area of the optic [Fig. 2(a)]. Although the peak intensification of the microlensing mechanism occurs outside the particle,

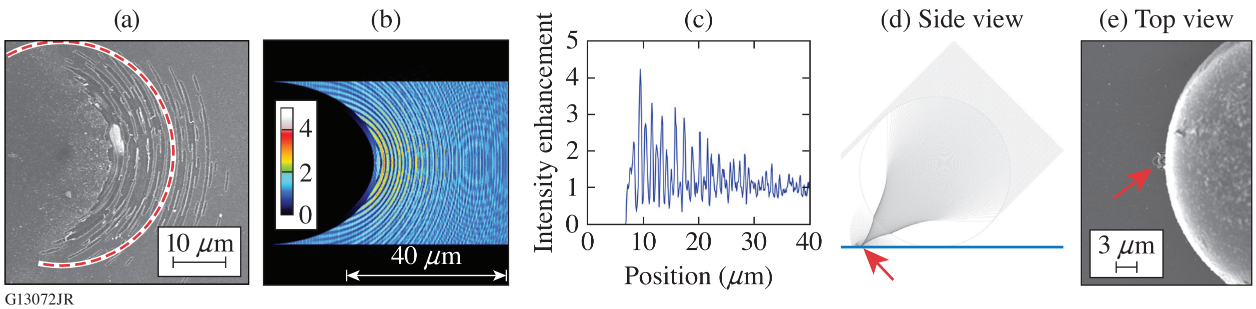

Figure 1
Mechanisms of laser intensification that lead to damage initiation. Optical interference from a steel microsphere: (a) damage morphology for 0.6 ps, 1.1 J/cm^2, with initial particle location shown (dashed line), (b) corresponding calculated intensity pattern with (c) central horizontal lineout. Microlensing by a glass microsphere: (d) ray-tracing diagram and (e) damage morphology for 0.6 ps, 32 mJ/cm^2, with damage indicated by an arrow. Laser is incident at 45° incidence from the right.

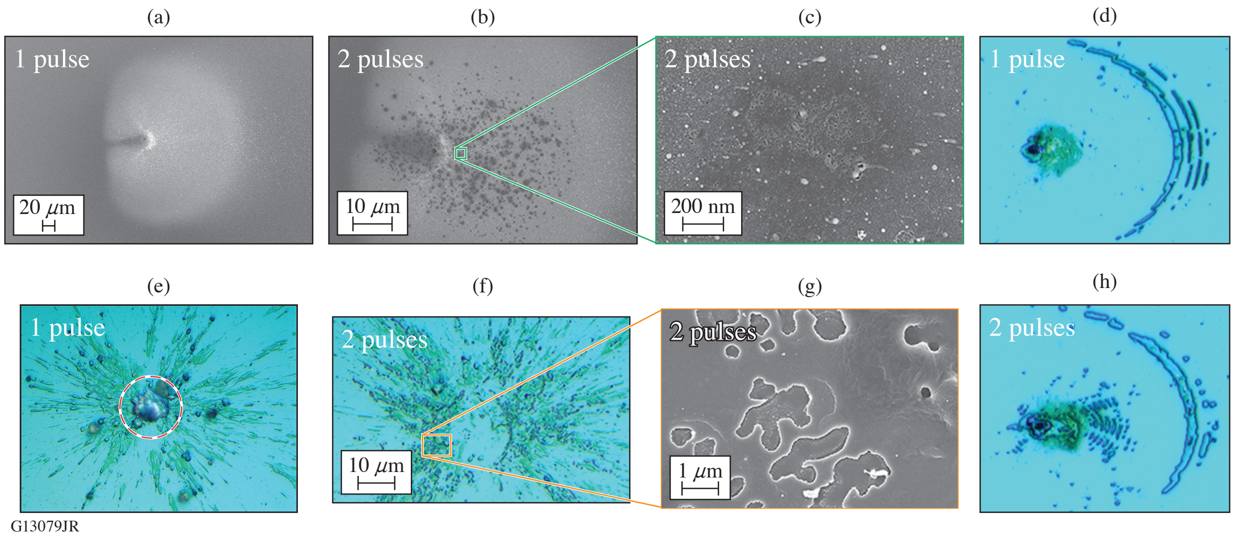

Figure 2
Morphological effects compared between one and two laser pulses incident on a microparticle. Parameters: [(a)–(c)] steel microsphere, 10 ps, 1.4 J/cm^2; [(e)–(g)] polyethylene microsphere, 0.6 ps, 0.8 J/cm^2; [(d),(h)] glass microsphere, 0.6 ps, 0.9 J/cm^2. For comparison, pristine LIDT was 1.4 J/cm^2 and 6.7 J/cm^2 for 0.6-ps and 10-ps pulses, respectively.

the partial beam convergence inside the bulk of the particle leads to intensification of up to one order of magnitude. This causes absorption in the bulk, leading to localized ablation accompanied by secondary contamination by liquefied jets and fragments [shown for polyethylene in Fig. 2(e)].

An additional pulse irradiating these sites did not cause favorable results. For steel particles [Figs. 2(b) and 2(c)], the nanoparticle contamination was partially removed ("laser cleaning"), but that process created plasma scalds (permanently modifying the surface). For polyethylene particles [Figs. 2(f) and 2(g)], the contamination removal process generated ablation sites in the coating. For all particle types, the second pulse could also cause the growth of any existing damage, as shown in Figs. 2(d) and 2(h) with glass particle morphology as an example. In this case, the fluence was high enough with the first pulse to generate damage by both interference and microlensing mechanisms. The second laser pulse caused all craters to grow in area and additionally generated new ripples of damage.

This work demonstrates that the contamination microparticles can be a potent precursor for optical damage with short pulses, causing damage initiation far below the pristine LIDT, and thereby exposing optics to the potential for damage growth. It is therefore important to better understand the role of such mechanisms in the operation of laser systems such as OMEGA EP and to devise proper management or mitigation strategies.

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