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ABSTRACT

We present results from a study to determine an acceptable CO_2 laser-based non-evaporative mitigation protocol for use on surface damage sites in fused-silica optics. A promising protocol is identified and evaluated on a set of surface damage sites created under ICF-type laser conditions. Mitigation protocol acceptability criteria for damage re-initiation and growth, downstream intensification, and residual stress are discussed. In previous work [1], we found that a power ramp at the end of the protocol effectively minimizes the residual stress (<25 MPa) left in the substrate. However, the biggest difficulty in determining an acceptable protocol was balancing between low re-initiation and problematic downstream intensification. Typical growing surface damage sites mitigated with a candidate CO_2 laser-based mitigation protocol all survived 351 nm, 5 ns damage testing to fluences >12.5 J/cm^2. The downstream intensification arising from the mitigated sites is evaluated, and all but one of the sites has 100% passing downstream damage expectation values. We demonstrate, for the first time, a successful non-evaporative 10.6 μm CO_2 laser mitigation protocol applicable to fused-silica optics used on fusion-class lasers like the National Ignition Facility (NIF).

Keywords: Fused-silica, SiO_2, surface damage, damage mitigation, CO_2 laser mitigation, CO_2 lasers, downstream intensification, residual stress

1. INTRODUCTION

Efficient operation of large aperture, multi-kilo-joule UV laser systems involves management of damage on the surfaces of the UV optics [2]. Management of this surface damage primarily involves controlling the exponential growth these sites will exhibit upon continued illumination [3]. One attractive technique to control or mitigate exponential growth of surface damage sites is via treatment with a CO_2 laser [4-8]. LLNL is currently pursuing two CO_2 laser-based mitigation approaches, evaporative and non-evaporative. Figure 1 illustrates the basic setup and effect on a damage site of the two approaches. The non-evaporative approach has the advantage of minimal surface perturbation or material removal, no re-deposited debris in or around the damage site, and lends itself to a simple system setup. The evaporative approach, on the other hand, offers control of the final shape of the mitigated site and it can be applied to typically larger sites with deeper cracks. In this report we discuss and demonstrate a successful non-evaporative technique (protocol).

For a mitigation protocol to be acceptable, it must satisfy three basic acceptability requirements. First, the protocol must prevent the re-initiation and/or growth of a damage site upon subsequent exposure to UV laser pulses. We require that mitigated damage sites survive testing at 3ω, 5 ns to >12.5 J/cm^2 with a <3% re-initiation rate. Second, the level of residual stress in the substrate left by the protocol must be low enough that nearby features (i.e. flaws and/or cracks) in the surface will not subsequently induce fracture. Third, the mitigated site must exhibit a final physical shape that will not cause unacceptable downstream intensification when a UV laser beam passes through it.

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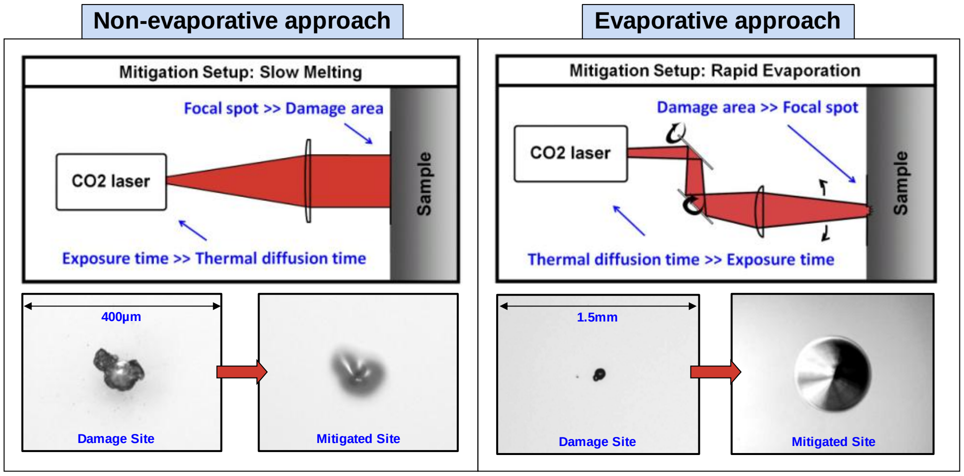


Figure 1: Illustrative comparison between evaporative and non-evaporative CO_2 laser-based mitigation techniques. Note the melted appearance of mitigated site in the non-evaporative case as compared to the complete removal of the site in the evaporative case.

2. RESULTS AND DISCUSSION

2.1 CO_2 Laser Mitigation Setup

A simple setup utilizing a CO_2 laser was used to perform the mitigation. A schematic of the mitigation setup is shown in Figure 2. The laser utilized is a quasi-CW Synrad Firestar v20 operating at a wavelength of 10.6 µm. The beam was allowed to free propagate to a ZnSe aspherical lens where it was weakly focused through the sample plane. The spatial profile of the beam at the sample plane was Gaussian. A computer system interfaced with the CO_2 laser controlled the exposure parameters during the mitigation.

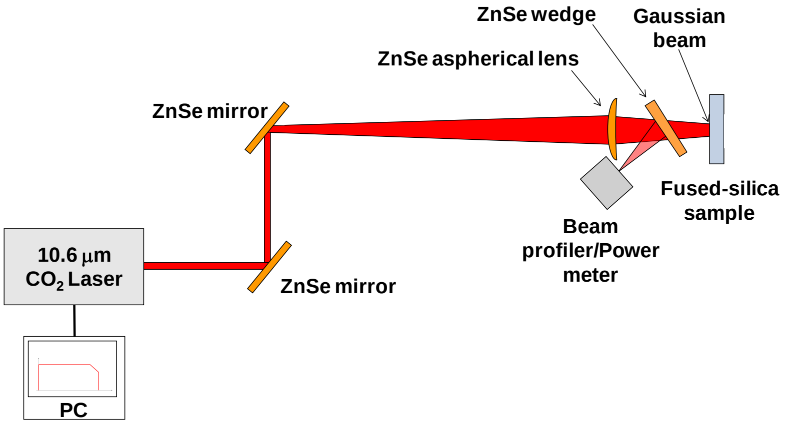
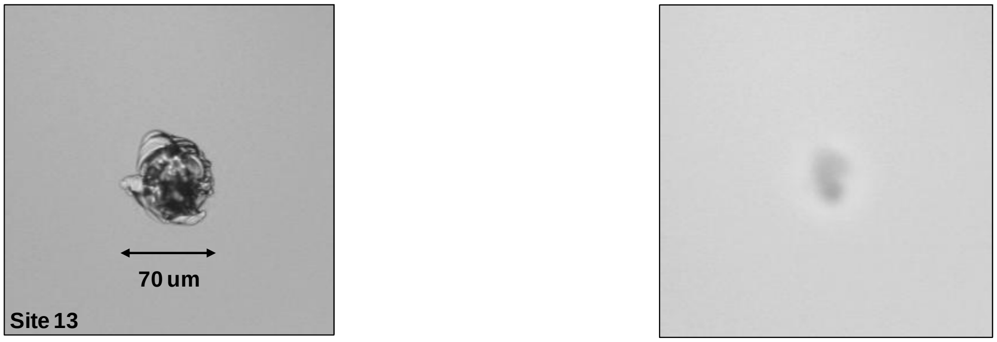


Figure 2: Schematic of the CO_2 laser mitigation setup.

Growing surface damage sites were prepared on the output surface of an uncoated 50.8 mm diameter, 10 mm thick Corning 7980 fused-silica round. The sample was etched and cleaned prior to initiation. A 58 site pattern was initiated on the output surface of the sample using single pulses from a Nd:YAG laser operating at 355 nm, 7 ns with a $1/e^2$ beam diameter of ~500 um. This created sites with an average site diameter of D_{avg} = 70 µm and a maximum site diameter of

D_{max} = 110 µm. The initiated sites were then subjected to "growth" shots at 351 nm (3ω), 5 ns in LLNL's Optical Sciences Laser facility (OSL) [9] to ensure that every site was actually exhibiting growth. Only 33 out of the 58 sites initiated on the sample were single, isolated sites. Figure 3 shows an example of one of the growing sites on the sample before and after mitigation.



a.) b.)

Figure 3: Micrographs of one of the growing sites on the sample: a.) Before CO_2 laser mitigation and b.) After CO_2 laser mitigation.

2.2 Power and Exposure Time

In general, the protocol consists of a constant CO_2 laser exposure followed by a ramp down. Figure 4 shows the general power-time profile used in this study. We found that as P1 and/or t1 are increased, the re-initiation rate goes to zero; however, the downstream intensification quickly becomes problematic. Therefore, the biggest difficulty we faced in determining an acceptable protocol was balancing between low re-initiation and problematic downstream intensification. We succeeded in identifying a particular power and exposure time (P1 and t1) combination that balances these two effects.

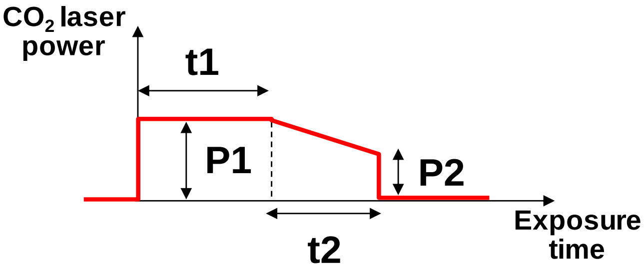


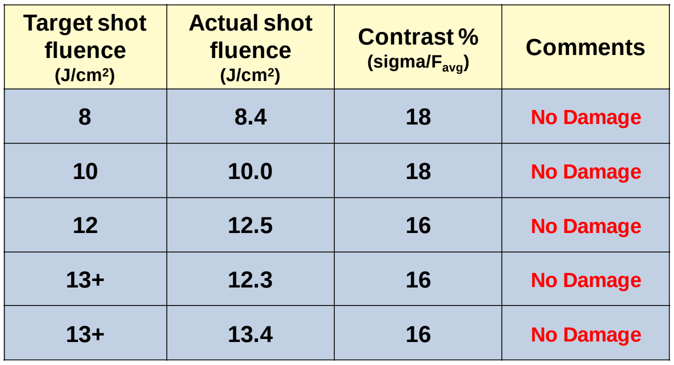
Figure 4: General CO_2 laser power-exposure time profile used to mitigate the surface damage sites.

2.3 Residual Stress

Residual stress in and around the mitigated damage site can cause catastrophic fracture of nearby surface flaws or initiations. In previous work [1], we identified a power ramp that suitably minimizes the residual stress (<25 MPa) left in the substrate. The "ramp" (P2 and t2 in Figure 4) chosen efficiently minimizes the residual stress through a linear decrease in power to a temperature just below the glass transition temperature, maximizing the relaxation of the glass, followed by an immediate turn-off.

2.4 Damage Testing at 3ω, 5 ns

Damage tests of the mitigated sites (58) were conducted in OSL to evaluate their re-initiation probability. The damage testing was performed at 3ω with 5 ns flat-in-time temporal pulses. The samples were held at vacuum and subjected to 3ω shots at a rate of about one per hour. The sample was tested with the mitigated sites on the output surface. Figure 5 summarizes the results of the 3ω damage tests. As can be seen, no damage was observed up to an average fluence of 13.4 J/cm^2.



Target shot fluence (J/cm²)	Actual shot fluence (J/cm²)	Contrast % (sigma/F_{avg})	Comments
8	8.4	18	No Damage
10	10.0	18	No Damage
12	12.5	16	No Damage
13+	12.3	16	No Damage
13+	13.4	16	No Damage

Figure 5: Results of the 3ω damage testing of the mitigated sites. No damage of the mitigated sites was observed.

2.5 Downstream Intensification

The downstream intensification from the mitigated sites was evaluated using a LLNL built modulation measurement system. Diffraction patterns at discrete distances downstream from each of the mitigated sites were measured and the total expected number of initiations were calculated for each diffraction image [10]. The total expected number of initiations, <N>, per image, assuming a background fluence of 8 J/cm^2, was found by

$$\langle N\rangle = \sum \rho(\phi = \textbf{pixel fluence})(\textbf{pixel area})$$

where ρ(ϕ) is the surface initiation number density probability as a function of fluence evaluated at a given pixel and the sum is over all the pixels in the image. The calculated total expected number of damage sites at each downstream distance (each image) were compared to a requirement of <0.1 initiations as shown in Figure 6.

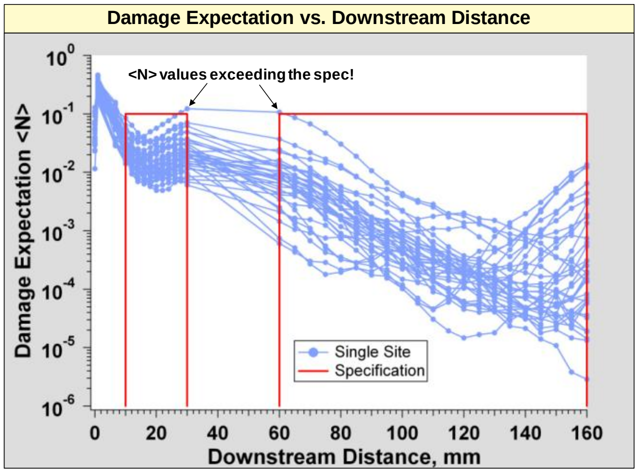


Figure 6: Calculated damage expectation values vs. downstream distance for the 33 single, isolated sites on the sample. Only one site has values that exceed the specification.

All but one of the mitigated single, isolated sites has 100% passing damage expectation values. The one failure in this set of sites implies a <0.3% downstream initiation probability. Subsequently, we have mitigated and damage tested 125 more sites and observed no damage re-initiation or downstream damage expectation values >0.1.

3. SUMMARY

A promising non-evaporative CO_2 laser mitigation protocol was identified and evaluated on a set of NIF-like prepared surface damage sites. In general, the protocol consists of a constant CO_2 laser exposure followed by a ramp down. The "ramp" profile chosen efficiently minimizes the residual stress. The mitigated surface damage sites were tested at 3ω to fluences >12.5 J/cm^2, 5 ns with no damage or re-initiation observed. The mitigated sites' downstream intensification was evaluated using a LLNL built modulation measurement system. Diffraction patterns at discrete distances downstream from the mitigated sites were measured, and the total expected number of initiations were calculated using the relation between surface damage initiation number density and fluence ($\rho(\phi)$). All but one of the mitigated sites passed the downstream damage expectation specification. The one failure implies a <0.3% initiation probability. We have demonstrated, for the first time, a successful non-evaporative 10.6 μm CO_2 laser mitigation protocol for use on fused-silica optics, such as those used in the National Ignition Facility, with surface damage sites ≤ 110μm in diameter.

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