Mitigation of laser damage growth in fused silica by using a non-evaporative technique*

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A non-evaporative technique is used to mitigate damage sites with lateral sizes in a range from 50 μm to 400 μm and depths smaller than 100 μm. The influence of the pulse frequency of a CO_2 laser on the mitigation effect is studied. It is found that a more symmetrical and smooth mitigation crater can be obtained by increasing the laser pulse frequency form 0.1 to 20 kHz. Furthermore, the sizes of laser-affected and distorted zones decrease with the increase of the laser pulse frequency, leading to less degradation of the wave-front quality of the conditioned sample. The energy density of the CO_2 laser beam is introduced for selecting the mitigation parameters. The damage sites can be successfully mitigated by increasing the energy density in a ramped way. Finally, the laser-induced damage threshold (LIDT) of the mitigated site is tested using 355 nm laser beam with a small spot (0.23 mm^2) and a large spot (3.14 mm^2), separately. It is shown that the non-evaporative mitigation technique is a successful method to stop damage re-initiation since the average LIDTs of mitigated sites tested with small or large laser spots are higher than that of pristine material.

Keywords: fused silica, CO_2 laser, non-evaporative technique, energy density

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1. Introduction

Fused silica is the most developed substrate material used in high power laser systems for large aperture components. Defect and damage are the major factors related to the durability of the optical components. Once the defects are damaged under high fluence 3ω laser illumination, the damage will grow exponentially under subsequent laser shots.[1,2] Thus, mitigating damage growth on fused silica is important for extending the usable optical lifetime of fused silica.[3–5] The most effective technique is to utilize a tightly focused 10.6 μm CO_2 laser beam to remove the damaged material by a combination of melting and ablation.[6–9]

At present, two CO_2 laser-based mitigation approaches, i.e., non-evaporation and evaporation approaches, have been investigated.[3] In the non-evaporative approach, the laser is operated at a moderate power with a beam spot larger than the damage and an exposure time longer than thermal diffusion time. The temperature should be well below the evaporative threshold. In the evaporative approach, a CO_2 laser with a spot size much smaller than the damage is scanned over the damage site using a galvanometer to evaporate and ablate the damaged material.[3,10] A critical difference between the two mitigation methods is the surface temperature at the heated region when using the evaporation technique, which is estimated to be between 4000 K and 5000 K, while it is 3000 K when using a non-evaporative technique.[10] For the non-evaporative technique, the biggest difficulty is selecting an appropriate laser power and irradiation time in order to strike a balance between low re-initiation damage and problematic downstream intensification.[10]

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In this study, damage sites with values of lateral size (L) in a range of about 50–400 μm and depth values smaller than 100 μm are conditioned by using the non-evaporative mitigation technique. Energy density (ED) is introduced to select mitigation parameters, and the damage site is mitigated with multi-shots by increasing the ED in a ramped way. The occurrance of bubbles and re-deposited debris can be avoided to a maximal extent. In Section 3, the influence of the pulse frequency of the CO_2 laser on the mitigation effect is studied. Then the method of selecting the ED is presented. In Section 4, the laser-induced damage threshold (LIDT) of mitigated sites is tested using a 355 nm laser with different beam spot sizes to verify the mitigation efficiency of the non-evaporative technique.

2. Experimental details

Polished fused silica (Corning HPFS 7980) samples with a nominal size of 40 mm×60 mm×5 mm were firstly etched in buffered hydrofluoric acid (BHF) (1 wt.% HF+15 wt.% NH_4F, PH=5) for 10 min to remove the re-deposited layer and reveal the defects. Secondly, at least 80 damage sites with lateral sizes from 50 to 400 μm were produced on the exit surface by using a Gaussian-shaped pulse from frequency tripled Saga Nd:YAG laser at 355 nm, with 6.4 ns pulse length and 0.23 mm^2 beam size. Then the damage sites were mitigated using a radio frequency power excited Coherence GEM-100L CO_2 laser. The diameter of the CO_2 laser beam spot used for mitigation was adjusted by passing the beam through a 10 cm focal length ZnSe lens. The transmission rate is about 85%. The ZnSe lenses were mounted on a two-dimensional translation stage, which could be moved along the laser propagation axis to adjust the lens-to-sample separation. After mitigation, the samples were annealed at 850 °C for 10 h in a clean furnace to eliminate the residual stress. Finally, the annealed samples were etched for 15 min in BHF to remove any possible re-deposited debris and contamination on the surface. The LIDT of the mitigated sites was measured by using an R-on-1 procedure using a Nd:YAG laser operated at 355 nm. The test beam was a Gaussian beam with an area at $1/e^2$, changing from a small spot (0.23 mm^2) to a large spot (3.14 mm^2). The beam size was characterized by using a Spiricon beam analyzer. Optical microscopy was used to measure the morphologies of the damaged and mitigated pits. Stylus profilometry was used to measure the profile trace of the mitigation sites, and the wave-front gradient root mean square (GRMS) of each conditioned sample was measured with an interferometer.

3. Parameter study

3.1. Influence of frequency on the mitigation effect

Besides laser power, spot size and irradiation time, frequency is also an important factor in determining the mitigation effect. In order to study the influence of frequency on the mitigation effect, a number of CO_2 laser irradiation sites were produced on the surface of a blank fused silica sample with various frequencies. The CO_2 laser beam diameter and irradiation time were fixed at 2 mm and 4 s, respectively. Figures 1(a) and 1(b) present microscopic images of typical sites produced with pulse frequencies of 0.1 and 15 kHz, respectively. The laser power for each site is also shown in the corresponding image. The corresponding profiles of the typical craters are shown in Fig. 2. The irradiation power for both profiles is 13 W. Some evident results can be observed from the images.

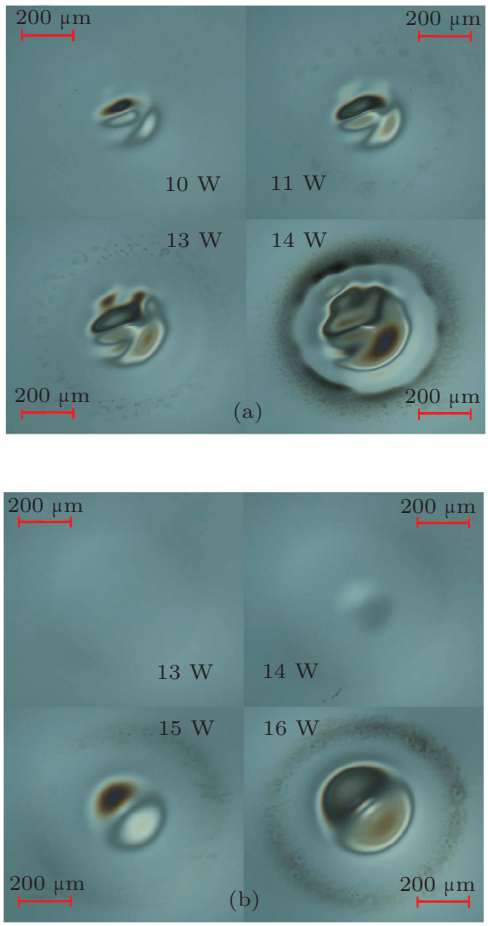


Fig. 1. (colour online) Microscopic images of typical sites irradiated by a CO_2 laser at frequencies of 0.1 kHz (a) and 15 kHz (b). The laser power is shown in the corresponding image.

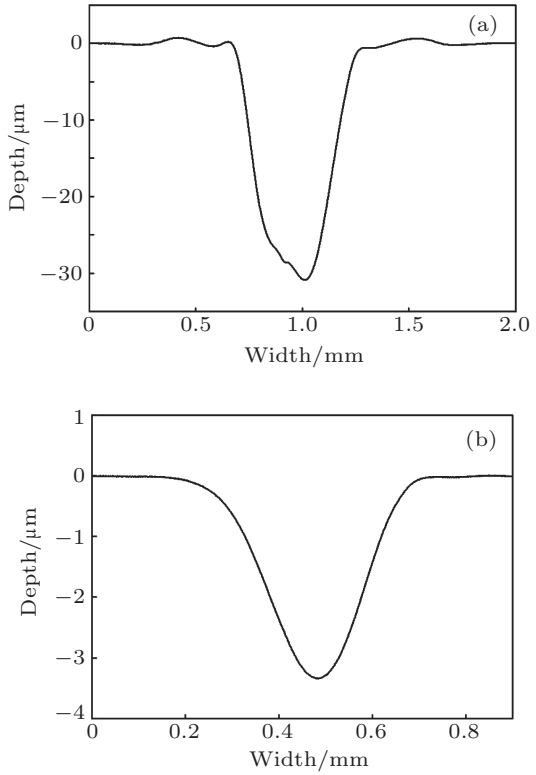


Fig. 2. Stylus profile of the crater produced by a CO_2 laser beam at 0.1 kHz (a) and 15 kHz (b).

1) A more symmetrical and smooth crater can be obtained by increasing the pulse frequency.

2) For the same laser power with higher frequency, less re-deposited debris is found around the crater, i.e., with the increase of the pulse frequency, a higher power is required to produce re-deposited debris around the crater. Figure 3(a) shows the frequency dependence of the laser power at which the re-deposited debris is observed.

3) Smaller sizes of laser affected zone (formed by the melting and probably a little evaporation of the substrates) and laser distorted zone (formed by the mass loss of fused silica material) are obtained by using high-frequency CO_2 laser irradiation. Taking the site of the first appearance of re-deposited debris as an example, the relationships between the sizes of the affected zone and distorted zone of sites and the frequency are shown in Fig. 3(b). The sizes of the two zones decrease with the increase of the frequency. However, there is no distinct change when the frequency is larger than 15 kHz. Considering the characteristic of the CO_2 laser equipment, 15 kHz is used in the following experiment.

Based on the results mentioned above, the difference between craters irradiated with different frequencies may be attributed to the effective irradiation time of a pulsed CO_2 laser. As shown in Fig. 4, setting the laser power to be at a fixed value, the duty ratio of a 0.1 kHz laser is larger than that of 15 kHz laser. This makes the effective heating time of a 0.1 kHz laser larger than that of a 15 kHz laser when the total irradiation time is larger than the plus width (the total irradiation time in our experiments is 4 s), leading to a higher maximum temperature of the irradiated material and easier formation of re-deposited debris.

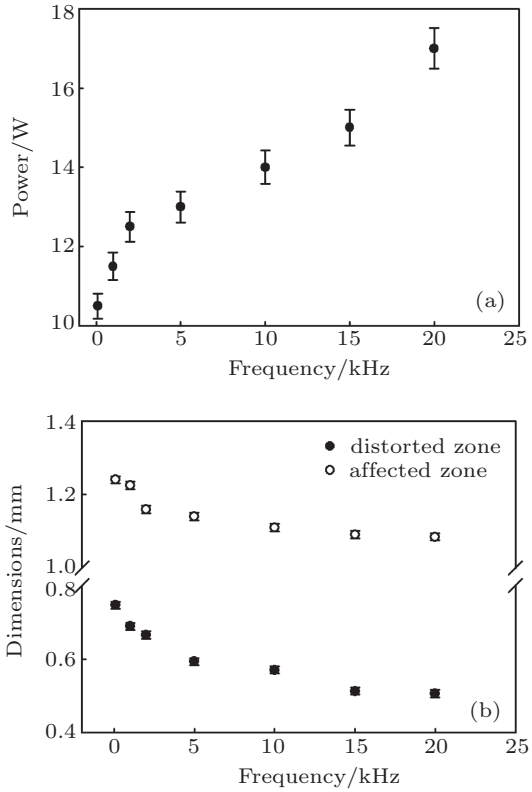


Fig. 3. Frequency dependences of the (a) laser power and (b) the laser affected and distorted zones when the re-deposited debris is firstly observed. The power deviation and the size deviation are about ±3% and ±10 μm, respectively.

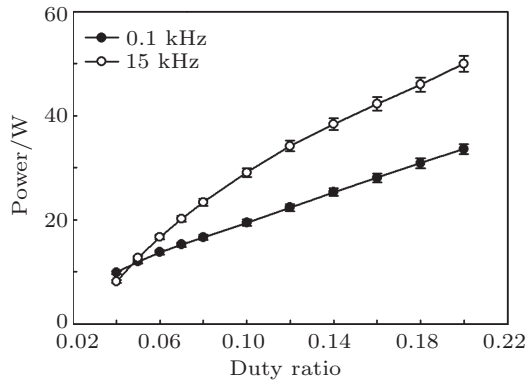


Fig. 4. Measured laser powers each as a function of the duty cycle of the CO_2 laser used for experiments. The power deviation is ±3%.

For example, to obtain a power of 20 W, the duty ratio (DR) and the interval time between two square pulses (ITP) of a 0.1 kHz laser are 10.5% and 895 μs, respectively. The DR and ITP of a 15 kHz laser with the same power are 7.2% and 62 μs, respectively. This makes the temperature fluctuation of irradiated material caused by pulse on and pulse off of a 0.1 kHz laser larger than that of a 15 kHz laser. The smaller temperature fluctuation caused by the 15 kHz laser may be a reason for the smoother carter.

3.2. Combination of laser parameters

The non-evaporative mitigation process requires melting a sufficient depth of fused silica material to ensure that the damaged material and fracture are melted and smoothed. In order to eliminate the damaged material and fracture without resulting in re-deposited debris and bubbles, it is very important to select proper mitigation parameters, which include laser power (P), beam diameter (D), irradiation time (T), and the number of shots (N). To avoid mass loss by evaporation during the CO_2 irradiation process, the surface temperature should be kept within a range of 2300–3000 K[11], which is a requirement of the non-evaporative technique.[10]

As mentioned in Subsection 3.1, the CO_2 laser frequency used for damage mitigation is fixed at 15 kHz and the beam diameter is changed from 2 to 7 mm according to the lateral size of damage site (L). Table 1 shows the mitigation parameters of these spot sizes. Considering the fluctuation of CO_2 laser power, the practical parameters may be adjusted according to the practical feature of the damage sites.

Table 1. CO_2 laser mitigation parameters for different sizes of damage site.

L/μm	D/mm	P/W	T/s	N
$50 < L < 150$	2	8.2	4	2
		9.5	4	2
		12.9	4	2
$150 < L < 250$	3	16.1	4	2
		19.2	4	2
		22.5	4	2
$250 < L < 400$	7	48.7	10	2
		50.0	10	2
		56.6	10	2

Although the damage site can be successfully mitigated using the parameters listed in Table 1, it is hard to find a proper combination because there are so many variable parameters. It is necessary to find a method for speculating the probable mitigation parameters. The ED is used to unify the parameters, including laser power, spot size, and irradiation time. The ED of etch shot is shown in Table 2. It is seen that the ED of each shot is in a range of 9–15 J/mm^2. Figure 5 shows the processes of mitigating a 220 μm damage site with 3 mm CO_2 laser spot. The damage site is first preheated with a lower ED, and then irradiated by increasing ED until the damaged material is completely melted. Although the damage sites can be repaired with one shot as long as a sufficient energy density is kept,[12] it is found that multi-shot irradiation can reduce the number of bubbles and the re-deposited

Table 2. Powers and energy densities of one-shot for each CO_2 laser beam.

D/mm	P/W	T/s	ED/J·mm^{-2}
2	8.2	4	10.44
	9.5	4	12.10
3	16.1	4	9.11
	19.2	4	10.86
	22.5	4	12.73
7	48.7	10	11.56
	50.0	10	12.99
	56.6	10	14.71

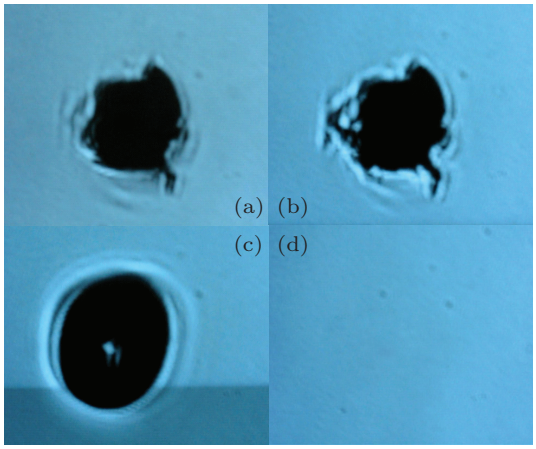


Fig. 5. (colour online) Mitigation process of the damage site. The images were measured on-line with a science CCD and the mitigation beam is 3 mm in diameter. (a) The original damage site with a lateral size of 220 μm. (b) The image of damage site after the first CO_2 laser exposure (with P = 16.1 W, T = 4 s, N = 2, ED=9.11 J/cm^2). The fracture around the damage site begins to melt. (c) The image of damage site after the second CO_2 laser exposure (with P = 19.2 W, T = 4s, N = 2, ED=10.86 J/cm^2). The fracture around the damage site is fully eliminated. (d) The image of damage site after the third CO_2 laser exposure (with P = 22.5 W, T = 4 s, N = 2, ED=12.73 J/cm^2). The crater is completely smooth, with no re-deposited debris and bubbles.

debris remains to a maximal extent. Furthermore, multi-shot irradiation can effectively reduce the depth of the crater and the value of light modulation resulting from the depth.[12]

According to the ED range, we can speculate the mitigation parameter with a different size of beam and the corresponding power. The irradiation time and shot numbers are based on the features of the practical damage site. The irradiation time does not exceed 10 s for each shot and the shot number for each of ED/ power does not exceed 4. For example, for a 4 mm CO_2 laser beam for mitigating a large damage sites, as shown in Fig. 6(a) (the lateral size is 374 μm), based on the range of ED, 10.98 J/cm^2, 12.94 J/cm^2, and 14.56 J/cm^2 are chosen, the corresponding powers are 23 W, 27.1 W, and 30.5 W, and the irradiation time is 6 s and 2 shots for each ED/power. At the mitigation sites shown in Fig. 6(b), the damaged material is completely eliminated and a regular shape is obtained. Compared with the sites mitigated with a 7 mm CO_2 laser beam, as shown in Fig. 7, the laser-distorted zone of a 4 mm beam mitigated crater is smaller than that of 7 mm beam. As shown in Fig. 8, the wave-front quality of the mitigated sample decreases with the decreasing laser-distorted zone. The GRMSs of the sample conditioned with a 4 mm CO_2 laser beam are 2.52 λ/cm and 4.52 λ/cm for 7 mm beam, with $\lambda = 628$ nm. The changed wave-front gradient of the optical components will introduce phase that is in contrast to the beam in the laser system, causing an amount of downstream intensification tha may damage downstream optics.[13] It indicates the importance of selecting optimized mitigation parameters to reduce the distorted zone.

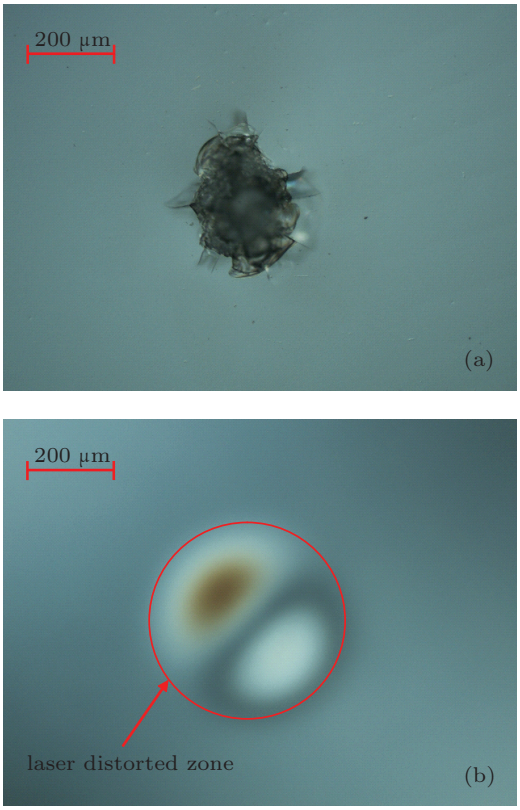


Fig. 6. (colour online) Microscopic images of (a) damage sites and (b) the corresponding mitigation sites.

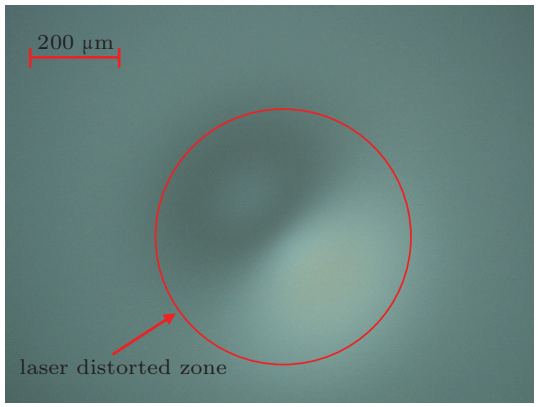


Fig. 7. (colour online) Microscopic image of a site mitigated with 7 mm CO_2 laser beam.

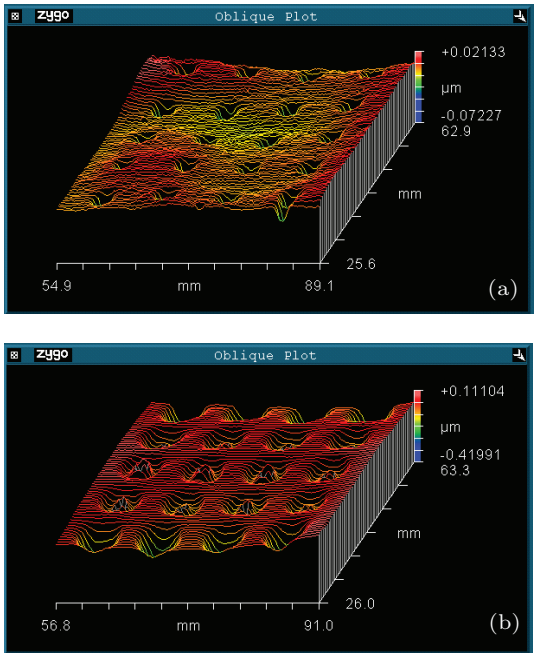


Fig. 8. (colour online) Wave-front images of a sample under the condition of (a) 4 mm and (b) 7 mm CO_2 laser beams.

For the non-evaporative technique, ED increases in a ramped way and the value of each shot is kept in a range of from 9 to 15 J/mm^2. Experimental results indicate that about 99% of damage sites are completely repaired and free from re-deposited debris and bubbles. Unfortunately, re-deposited debris and bubbles appear in some mitigated site, which may be attributed to the fluctuation of CO_2 laser power.

4. Damage threshold test

To test the damage resistance of sites mitigated with the non-evaporative technique, the LIDT of mitigated pits was measured by using the R/1 procedure. All the damage sites are mitigated using the parameters listed in Table 1. The LIDTs of mitigated sites tested by small- and large- spot laser beams are 9.03 and 3.54 J/cm^2, and that for pristine material are 8.39 and 2.94 J/cm^2, respectively. Therefore, the average LIDT of mitigated sites tested by small and large spots is larger than that of pristine material.

However, about 10% of the mitigation sites are damaged at a fluence less than 95% LIDT (i.e., 7.97 J/cm^2 for large-spot and 2.79 J/cm^2 for small-spot) of pristine material as shown in Fig. 9, especially for the large sizes (L > 150 μm) damage site. From the images in Fig. 9(a) and 9(b), it follows that the resistance damage capability for small-sized mitigated damage sites is higher than those of large-sized sites for small-spot and large-spot testing beams. The damage re-initiation of mitigated sites may be attributed to several factors, such as the weakness located between laser-irradiated and non-irradiated regions,[1] bubbles,[6] and a non-healing crack under the crater. The crack depth of a large damage site is larger than that of a small damage site. It may be one of the reasons why the mitigation efficiency of small damage sites is higher than that of other damage site sizes. Detecting the mitigation sites using better apparatus and methods is required.

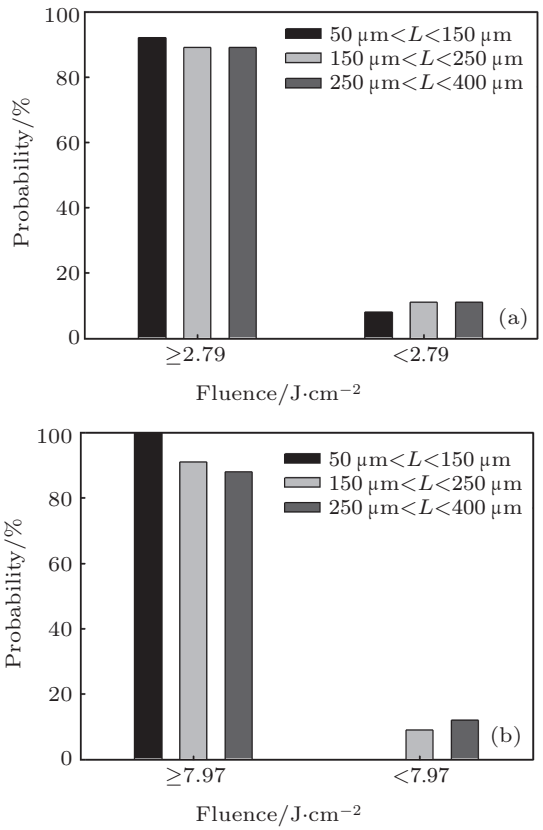


Fig. 9. Damage probabilities for different sizes of mitigated damage site tested by a (a) small-spot and (b) a large-spot laser beam.

5. Conclusion

A non-evaporative mitigation technique is studied in this paper. Our results indicate that the frequency of a pulsed CO_2 laser influences the mitigation effect of damage sites. Not only are the mitigation sites more symmetrical and smoother, but also a smaller size of laser-affected and distortion zone can be obtained by increasing the pulse frequency. The energy density is effective in selecting mitigation parameters, such as laser power, spot size and irradiation time. The damage site can be successfully mitigated without re-deposited debris and bubbles as long as the energy density is kept ramped from 9 to 15 J/mm^2. The LIDT indicates that the damage resistance of the mitigated damage sites can exceed that of the pristine material. The non-evaporative technique is a feasible method to arrest damage growth and prolong the lifetime of optical components.

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