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Effect of residual stress on laser-induced damage characterization of mitigated damage sites in fused silica

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ABSTRACT

The influences of residual stress on damage morphology and laser-induced damage threshold (LIDT) of mitigated sites in fused silica optical components before and after annealing are investigated. The results indicate that the cracks occur either at the inner location or at the maximum retardation location of mitigated sites once the residual stress (retardation) exceeds 26.49 ± 1.79 MPa (22.25 ± 1.5 nm). Meanwhile, the discrepancy of stress at different locations results in the fluctuation of LIDTs. The results of isochronal and isothermal annealing indicate that annealing temperature is the most important influence factor and the residual stress can be effectively controlled if the residual stress induced by the maximum CO_2 laser beam is eliminated. Furthermore, the LIDT of mitigated sites can be enhanced without dramatical fluctuation and the damage growth coefficient that is sharply increasing can be avoided if the retardation of mitigated site is equal to or less than 5 nm. The study demonstrates that annealing significantly improves the resistance of fused silica optics.

1. Introduction

Laser induced damage of fused silica optical components is still a hot topic at present [1,2]. The primary reason for these issues is that the fused silica is widely applied in high power laser systems. To avoid the damage and/or even enhance the damage resistance of optics, CO_2 laser has been demonstrated as one of the most promising methods to achieve this purpose. The treatment generally requires depositing sufficient laser energy to heat the damaged materials [3–5], it can locally melt and evaporate the damage site by producing a typically smooth and Gaussian shaped mitigated sites [5,6]. However, it is well known that this treatment will result in birefringence/residual stress around the mitigated sites [7,8].

Moreover, there are clear correlations between the initial damage location and the maximum retardation around the mitigated site [9,10]. The experimental results show that the damage initiation occurs on the peripheral area of mitigation sites [8,11]. Cormont et al. considered the damage mainly resulting from the debris and residual stress [9]. They utilized the second heating process to treat the mitigated sites, i.e. CO_2 laser annealing to eliminate the debris and reduce residual stress [10]. It is shown that CO_2 laser annealing significantly improves the resistance of fused silica optics. Unexpectedly, the damage still occurs on the peripheral area of mitigated sites except that the damage size is decreased [10]. Gallais et al. demonstrated that the damage still occurs on the peripheral area free from any visible defects or re-deposited debris [11]. The present investigations do not give exact explanations on this phenomenon or its correlations.

In this paper, the influence of residual stress on damage morphology and how small stress can be accepted and enhance the damage resistance ability of fused silica optics without any negative factors are investigated. To address this issue, the experimental details of stress measurements and damage testing schemes are firstly given. Secondly, the damage features of annealed and without any treatment mitigated sites are discussed. Then, the annealing schemes and the features of residual stress after being treated by each scheme are studied. Finally, the R/1 (irradiating the same area with a number of pulses at a repetition rate) damage threshold and damage growth of mitigated sites with different residual stresses are investigated. Meanwhile, the optimized value of residual stress is obtained, which not only can avoid the appearance of crack, but also can enhance the damage resistance of mitigated sites.

2. Experimental details

Polished fused silica (Corning HPFS 7980) samples with a size of $40 \times 60 \times 5$ mm^3 are firstly etched in the buffered hydrofluoric acid (BHF) to remove the re-deposited layer and expose the sub-surface defects. Then, a matrix of damage sites with certain size is created on the

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sample by high-fluence nanosecond laser. The damage sites are repaired by far-infrared 10.6 μm CO_2 laser at last. The details of the mitigation parameters and process are described in Ref. [12].

The retardation of residual stress around the mitigated site is measured by a PTC-720 stress analyzer based on a photoelastic method. The measurement resolution is ±1.5 nm. A mono-longitudinal mode Nd:YAG (SAGA) pulse laser operated at 355 nm with a pulse length of 6.3 ns is used to create damage site, test R/1 laser-induced damage threshold (LIDT) and damage growth of mitigated sites. The profile and diameter of laser beam are measured by a Spiricon beam analyzer. An on-line detection system is utilized to observe and capture the morphology of damage growth.

A small Gaussian profile beam with a diameter of 0.6 mm ($1/e^2$) is used to investigate the correlations between residual stress and LIDT of mitigated site. Based on the actual distribution of residual stress shown in Fig. 1(a), the test schematic is shown in Fig. 1(b). A, B, C and D represent the main light pattern (or maximum retardation) associated to the distribution of residual stress in Fig. 1(a). N represents the number of test sites and black spot denotes the damage site. One of the most important decisive factors in damage test process is whether the damage occurs at the central location of light pattern, which can accurately reflect the character and influence of residual stress on damage resistance of mitigated site.

It has been demonstrated that different sizes of damage sites can be repaired with different sizes of CO_2 laser beams [13]. In order to investigate the correlations between the annealing effect and annealing parameters, the damage sites repaired by a certain size of CO_2 laser beam are mainly discussed in this paper. The sample is firstly divided into three areas with equal sizes, which can provide the same conditions used in annealing investigation. The matrix of damage sites ranging from 200 μm to 300 μm is created on each area with certain spacing. Those damage sites are repaired with 3 mm CO_2 laser. The details are described in Ref. [12]. Then the damage sites ranging from 50 μm to 400 μm are created on another sample and repaired with multiple beam sizes of CO_2 laser.

The residual stress of mitigated sites is annealed in a clean furnace in ambient atmosphere. The sample is placed in a silica protective box to avoid the surface contamination, and the sample is cooled to room temperature after the end of holding time. The annealing parameters are discussed in Section 3.2.

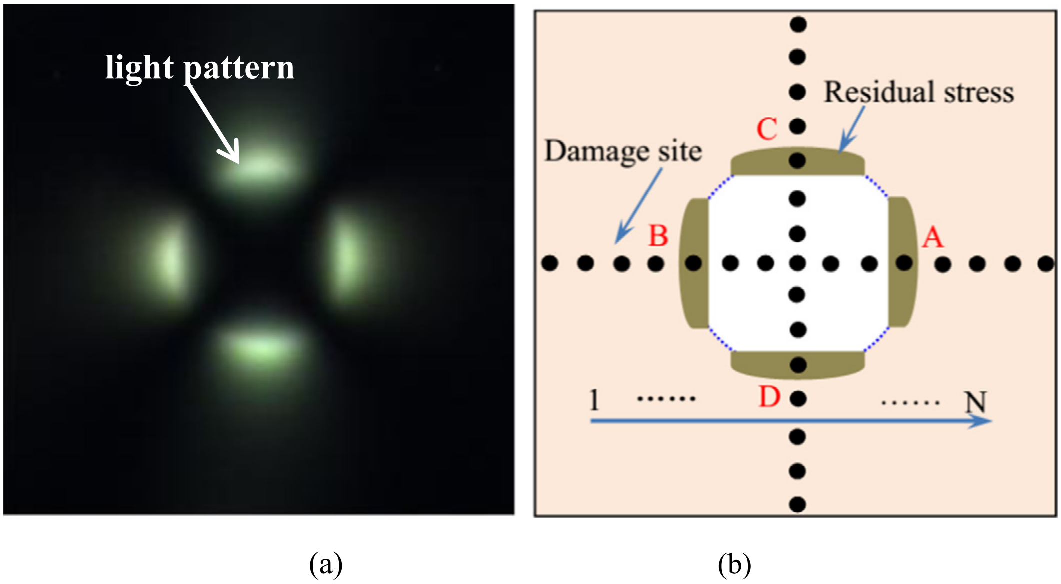
3. Results and discussion

3.1. Character of damage with and without annealing

Fig. 2 is the damage test results of mitigated sites without any treatment and observed at different times. The spacing between the two damage sites is 1 mm and the size of each site is about 50 μm. To conveniently study the feature of stress and damage types, a symbol is labeled on each mitigated site (1#–6#) and three representative damage sites (P1, P2 and P3) as shown in Fig. 2(a). A crack is firstly observed on 5#. Three new cracks appear on 2#, 3# and 4# after 24 h and no obvious changes after 72 h. However, the crack appears on all the tested sites after 120 h as shown in Fig. 2(d). Furthermore, another new crack appears in 4#. No apparent changes are observed after 120 h anymore.

An interesting phenomenon can be observed from Fig. 2(d) that the entire crack does not extend beyond the location of maximum retardation. The typical magnified birefringence and microscope image of tested site 4# are given in Fig. 3. The crack results from a bigger size (about 200 μm) of damage site. An angle is formed between the crack and the normal to the surface, which is similar as the Hertzian cone scratches [14]. Those cracks can be classified as two basic types based on the morphology. One type of crack occurs at the inner part of maximum retardation (Type I) shown as 4# and 5# in Fig. 2(d). The crack firstly extends along the radial direction, then along the shear direction at the location of maximum retardation. Another type is the crack that just occurs at the location of maximum retardation (Type II) shown as 1#, 2#, 3# and 6# in Fig. 2(d). The crack only extends along the shear direction, and a circular-arc is finally formed. Comparing Fig. 2(d) with Fig. 2(a), the intensity of light pattern obviously decreases. The appearance of crack effectively leads to the release of residual stress.

Besides the stress released by crack, it can be also partly eliminated by annealing treatment. As shown in the treatment mitigated sites given in Fig. 4, the maximum retardation before damage test is 22.25 ± 1.5 nm and 5.93 ± 1.5 nm after annealing at 650 °C and 750 °C for 10 h, respectively. The same test style as Fig. 1(b) is utilized to create a series of damage sites. The sizes of damage site for both samples have exceeded 200 μm, which is much larger than the size of damage site shown in Fig. 2. No crack is observed on



(a) (b)

Fig. 1. Distribution of birefringence (a) and schematic of damage test for mitigated site with residual stress (b).