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Influence of oil contamination on the optical performance and laser induced damage of fused silica

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ABSTRACT

The influence of oil contamination on the optical performance of fused silica and laser induced damage threshold (LIDT) at 355 nm is studied. The liquid vacuum oil is artificially spun on the fused silica surface. Optical microscopy and ultraviolet–visible (UV–vis) spectrophotometer are used to identify and understand the potential influence of oil contamination on the optical performance of fused silica. The results show that a large number of oil droplets are observed on the surface of fused silica after spin-coating, and the transmissivity of fused silica decreases with the increasing oil quantity. The LIDTs of fused silica decrease with the increasing oil mass for both on input and output surfaces at 355 nm, and the LIDT of fused silica with oil on input surface is lower than that on output surface at same contamination level. The damage mechanisms are also discussed by the photo-thermal measurement and three dimensional finite difference time domain (3D-FDTD) method. The experimental and simulated results show that the electric-field modulation by oil droplets, rather than its photo-thermal absorption, is mainly responsible for the oil contamination induced laser damage of fused silica.

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1. Introduction

High peak power laser systems such as National Ignition Facility (NIF) [1], Laser MegaJoule (LMJ) [2], and SG-III [3] are being developed for inertial confinement fusion (ICF) experiments and for the study of material property at extreme conditions. Thousands of optical components including fused silica glass are needed for these laser facilities, which are used for lenses, mirrors, debris shields etc. [4]. However, surface contamination of the optical components is inevitable during assembling and operating process. Furthermore, those contaminants are difficult to remove completely from optics surface [5]. Actually, contaminants maybe degrade the performance of optical systems because of obscuration, absorption, or damage. Since those potential effects will restrict the laser energy output and increase the running cost of laser system, it is necessary to establish a safe operational limit or tolerable contamination level for varieties of contaminants.

Contaminants are mainly classified as two groups: particles and organics. The influence of particulate contaminants such as dust, aerosol, metal flakes and cloth threads on the optical performance and LIDTs of optical components have been widely studied [6–9]. In most cases, the damage mechanism is usually attributed to thermo-mechanical rupture or laser intensity modulation [6,7]. For organic contaminant, it often exists as gaseous molecules or nonvolatile residues (NVRs). Gaseous organic contaminants involve airborne molecular contaminations (AMCs) [10] and outgassing from surrounding materials [11]. NVRs involve liquid and solid phase organic contaminants deposited on the surface of optical components [12]. Vacuum oil is a critical NVR contaminant for optical components due to wide usage in the laser facility to seal vacuum chamber. For instance, a heavy oil contamination was observed on the optical components in LFEX pulse compressor by Jitsuno et al. [13]. They reported the damage threshold of the contaminated mirror dropped to 1/2 or 1/3 of the original value. Therefore, the damage of optical components induced by oil contamination is a significant factor in decreasing laser reliability and lifetime. However, little work has contributed to the influence of oil contamination on the optical performance and UV laser induced damage of optics. Therefore, it is very important to systematically investigate the possible influences caused by vacuum oil from theoretical and experimental study, which is helpful for understanding the contamination behavior and damage mechanism.

In this work, the influence of oil contamination on the surface morphology, transmissivity and LIDT of pristine fused silica have been investigated. In addition, the photo-thermal absorption and light intensity modulation of the contaminated layer are also

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investigated to find out the reasons responsible for the decreased LIDT and the dominant damage mechanism. Photo-thermal absorption is measured by a photo-thermal microscopy and light intensity modulation is numerically calculated with three dimension finite difference time domain (3D-FDTD) method.

2. Experimental

2.1. Sample preparation

Optically polished fused silica samples (corning 7980) with 30 mm diameter and 3 mm thick were etched for 10 min in the buffered HF solution (1% HF+15% NH_4F+84% H_2O) and then cleaned with high pure water and alcohol in order to remove those original surface contaminants. After that, samples are classified as seven groups and labeled from A to G. Then different concentrations of oil solutions are spun on the surfaces of samples.

2.2. Contaminant deposition

Different concentrations of oil solutions were prepared by diluting vacuum oil with high pure alcohol. Then 10 μL oil solutions was taken by a 10 μL counter and deposited on the surface of fused silica samples by spinning method. The rotating rate is 6000 r/min and running time is 30 s for all samples. Oil film was deposited on fused silica surface after alcohol evaporation. The quantity of the oil deposits is related with the solution concentration. The oil mass per unit area can be estimated according to Eq. (1).

$$M = \frac{\rho\, v}{\pi\, (d/2)^2} \times \mathrm{wt\%} \tag{1}$$

where M is the oil mass per unit area, ρ is the density of the oil solution and the value is 0.9 g/cm^2, v is the volume of the oil solution deposited on fused silica surface and the value is 10 μL. d is the sample diameter and the value is 30 mm, wt% is the mass percent of the oil solution. Table 1 gives the quantity of deposited oil for each sample.

2.3. Sample characterization and LIDT measurement

An optical microscopy was used to observe the morphology of the contaminated layer. A Lambda 950 UV–vis spectrometer was used to measure the transmission spectra of samples. A photo-thermal microscopy was employed to characterize the photo-thermal absorption of samples at 355 nm.

The laser damage thresholds were tested by a single longitudinal mode tripled Neodymium doped Yttrium Aluminum Garnet (Nd:YAG) laser operated at a wavelength of 355 nm with pulse duration τ=6.3 ns. The spatial beam profile is Gaussian shape with a 1/e^2 diameter of 0.8 mm. R-on-1 test procedure according to the standard ISO11254-1 was used to test LIDTs [14]. “Damage” is defined as having occurred when a visible modification is detected with CCD camera. The laser test apparatus has been described in previous work [15,16].

Table 1
The quantity of deposited oil for samples.

Samples	Clean	Contaminated					
	A	B	C	D	E	F	G
Wt%	0	0.01	0.02	0.03	0.05	0.1	0.2
M (ng/mm^2)	0	1.27	2.54	3.81	6.35	12.7	25.4

3. Experimental results

3.1. Morphology of contaminated layer

Fig. 1 reveals the microscopic images of contaminated layer for different levels of oil contaminations. A large number of oil droplets with a diameter of several microns appear on the contaminated coating, which is caused by the superficial tensions of liquid vacuum oil. The results indicate that the number of oil droplets increases with the increasing oil concentration, and the size of oil droplets does not change significantly at low oil concentration. However, oil droplets tend to aggregate when the oil concentration is higher than 0.2%.

3.2. Influence of oil contamination on transmissivity

Transmissivity is an important property for optical components. Since fused silica glass has excellent transmission property over a wide wavelength range including ultraviolet (UV) band, it is quite welcomed in the high power laser system. However, the transmission of the fused silica is probably degraded if its surface suffers from oil contamination. In this section, the influence of oil contamination on the transmission of fused silica is investigated.

Fig. 2 shows the transmissivity of fused silica with different oil contaminated levels. Fig. 2a exhibits the transmissivity of each contaminated sample in the wavelength range from 192 nm to 800 nm, which indicates that the transmissivity loss is related to the concentration of oil solution, especially in UV band. Fig. 2b shows the relationship between the oil mass and transmissivity of fused silica at 355 nm. The result reveals that the transmissivity of fused silica decreases with the increasing oil mass. It can be fit as: $T = 92.72273 - 0.22148\mathrm{m} - 0.00861\mathrm{m}^2$, and $R^2 = 0.99835$. According to this formula, the transmissivity decreases 1% if the oil mass is accumulated to 4 ng/mm^2. In addition, the oil contaminated levels can be estimated according to the decreasing of transmissivity. The transmissivity loss of fused silica is attributed to the light scattering and absorption of oil droplets. Since the light scattering and absorption strengthen with the increasing oil contaminated level, the transmissivity of fused silica decreases with the increasing oil mass.

3.3. Influence of oil contamination on LIDT

Fig. 3 shows the LIDTs of fused silica varying with the oil mass deposited on input and output surfaces. For oil on input surface, the LIDTs can be fit as exponent: $F_{input} = 7.26714\,\exp(-m/13.56809) + 6.309$, $R^2 = 0.98742$. For oil on output surface, the LIDTs can be fit as secondary polynomial: $F_{output} = 13.3479 - 0.01943\mathrm{m} + 0.0035\mathrm{m}^2$, $R^2 = 0.98742$. According to the results, two conclusions can be deduced. Firstly, the LIDT of fused silica decreases with the increasing oil mass for both on output and input surfaces at 355 nm, and F_{input} decreases faster than F_{output}. The LTDT decreases 10% if the oil mass accumulated to 6 ng/mm^2 on input surface or 17 ng/mm^2 on output surface. Secondly, the LIDT for oil on output surface is higher than oil on input surface at same contamination level. The reasons will be discussed in Section 4.

4. Discussion

Since contamination induced laser damage of fused silica is a significant factor to reduce laser reliability and lifetime, it is important to understand the main mechanism responsible for the damage. In this work, the mechanisms of photo-thermal absorption and electric-field modulation are proposed based on the microscopic morphology of the contaminated layer. Photo-thermal

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