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Thermodynamic Study on Laser Induced Damage of Glass Components

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Abstract: *Regarding the damage characteristics caused by impurities in glass, the experiment explored the damage characteristics inside the glass under laser-induced conditions. Based on thermodynamic equations, the influence of the size of impurity particles on the degree of damage in glass components was simulated. Based on the thermal conduction equation, the thermal stress in the components and the internal stress generated during impurity gasification were analyzed. Based on simulation results, the damage mechanism of optical components in the presence of impurities was analyzed.*
Keywords: *Laser induced damage; Thermodynamic effects; impurity particles; filamentous destruction.*

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I. Introduction

In ICF systems, the laser damage threshold of optical components has a serious impact on the energy output of nanosecond level lasers [1,2]. For nanosecond laser pulses, the damage is mainly based on the absorption of laser pulse energy by optical materials[3]. The energy absorbed by the material causes an increase in temperature, resulting in phase transition and ultimately damage [4]. There are a large number of optical components in optical systems, among which the most common should be optical glass, such as filters, various mirrors, etc. However, optical glass inevitably introduces some impurities during processing or production [5, 6], and the presence of impurities can seriously reduce the damage threshold of optical components, leading to unstable operation of laser systems.

Impurities, as a substance different from bulk dielectric materials, have thermodynamic parameters that are different from those of bulk materials. Their presence often reduces the laser damage resistance of components and modulates the light field in the system [7]. With the continuous development of high-power lasers, the ability of optical components to resist laser damage directly affects the system's ability to output laser. In order to improve the output capability of laser systems, it is necessary to study the damage characteristics of optical components when there are impurity particles in the components.

This chapter analyzes and experimentally verifies the thermodynamic effects of defect particle induced damage, obtains the damage characteristics of defect particles under nanosecond pulse laser, and explains the main reasons for the formation of internal cracks in glass, which helps to deepen the understanding of the mechanism of internal crack formation in glass.

II. Experiment

The experimental setup can be found in reference [8]. The sample was irradiated with a pulsed laser with a wavelength of 1064 nm, a pulse width of 10 ns, and an output frequency of 1 Hz. The focal length of the focusing mirror was f=200 mm, and the spot radius at the focal point was 300μm. Under the action of pulsed laser, the damage morphology inside the glass is shown in Figure 1. Obviously, there are granular impurities in the transmission path of the laser. When the laser is irradiated on the impurity particles, obvious fractures can be seen in the glass around the impurities, and the fractured cracks expand in all directions. Around the impurity particles, damage to the surrounding glass caused by phase transition due to high temperature can be seen. At the same time, in the direction of laser transmission, a series of damages that occur inside the glass can be clearly seen. On the one hand, it is due to the self focusing of the laser inside the glass. On the other hand, the presence of impurity particles in the front forms a micro lens, which concentrates the light field and causes damage to the glass [9].

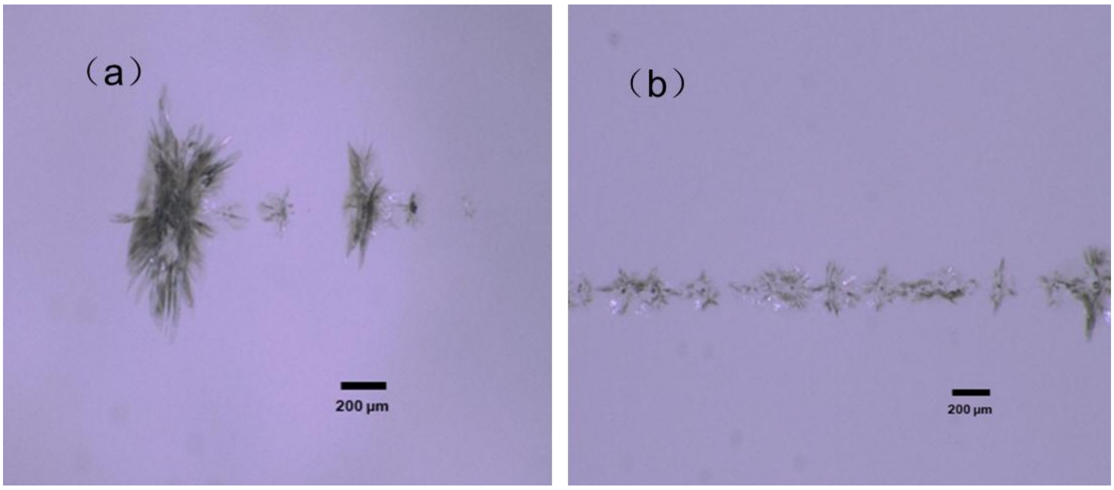

Figure 1 Typical Damage Morphology

III. Thermodynamic Analysis

3.1 Deposition effect of impurity particles on laser energy

In order to explain the causes of glass failure, an impurity defect induction model is established here. When there are impurity particles in the material, the absorption of laser energy by the impurity particles will cause uneven temperature distribution inside the material, thereby causing damage to the material. Assuming that the uniform electric field formed by the laser inside the material is E_0, the electric field at the impurity particles is $E' = \frac{3\varepsilon}{2\varepsilon+1}E_0$,

Among them ε is the relative dielectric constant of glass, $\varepsilon > 1$, so the damage threshold around impurities in the glass is lower, making it more prone to damage.

Assuming that the impurity particles in the glass are spherical ideal conductors with a radius of R, the glass temperature at a distance r from the surface of the impurity particles is [10]:

$$
\begin{aligned}
T = {} & \frac{3\varepsilon_\lambda JR^2}{2C_{vi}(R+x)D_g m}[(q-m)^{-1} erfc\frac{x}{2(D_g t)^{1/2}} - (q-m)^{-1}\exp(\frac{(1-m)x}{2R} + \frac{(q-m)^2 D_g t}{4R^2}) \\
& \times erfc(\frac{x}{2(D_g t)^{1/2}} + \frac{(q-m)^2 (D_g t)^{1/2}}{2R}) - (q+m)^{-1} erfc\frac{x}{2(D_g t)^{1/2}} + (q+m)^{-1} \\
& \times \exp(\frac{(q+m)x}{2R} + \frac{(q+m)^2 D_g t}{4R^2}) \times erfc(\frac{x}{2(D_g t)^{1/2}} + \frac{(q+m)(D_g t)^{1/2}}{2R})]
\end{aligned} \quad (1)
$$

The parameters of the glass and impurities used in the calculation are shown in Table 5.1, where E is the laser energy density and T_0 is the ambient temperature, $q = 3C_v / C_{vi}$, $m = \sqrt{q(q-4)}$.

The parameters of glass substrate and impurity defects are shown in Table 1. Figure 5.2 shows the radial distribution of temperature inside the glass along the impurities at different energy densities when the impurity particle radius is 12 μm.

Table 5.1 Material Property Parameters [10]

Impurity		Glass	
Density ρ (g/cm3)	21.5	Density ρ (g/cm3)	2.202
Specific heat c (J/g·K)	1.296×10^{-1}	Specific heat c (J/g·K)	0.752
Thermal conductivity κ (J/cm·s·K)	6.688×10^{-1}	Thermal conductivity κ (J/cm·s·K)	1.4×10^{-2}
Melting point T/K	2042	Young's modulus E/Pa	7.303×10^{10}
Boiling point T/K	4100	thermal diffusivity coefficient α/K^{-1}	4.2×10^{-7}
Absorption coefficient η	0.3	Gruneisen constant γ	2.54

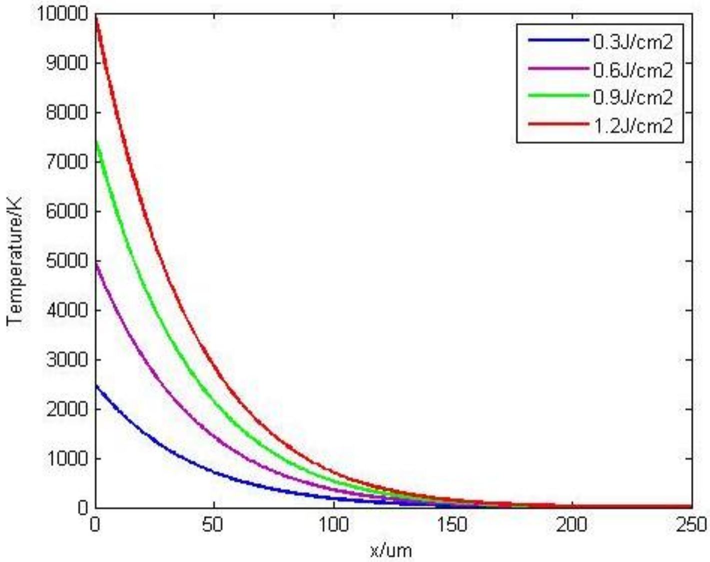

Figure 2 Temperature distribution of glass at x distance from the surface of impurity particles

From Figure 2, it can be seen that the temperature inside the glass increases with the energy density of the pulsed laser. However, as the distance from the impurity surface increases, the temperature inside the glass rapidly decays. When the distance from the impurity particles exceeds 200 μm, the temperature of the glass hardly changes with the increase of radial distance, indicating that when impurity particles exist inside the glass, their thermal effect on the substrate only exists in the micrometer scale. Due to the softening point of fused quartz glass being around 2273 K , it can be seen that when the laser energy is 0.3 J/cm^2, it will cause softening of the glass around impurities, resulting in damage to it.

By setting x to 0 in equation (1), the relationship between the surface temperature of impurity particles after laser action and the particle radius R can be obtained, as shown in Figure 5.4. When the energy density of the laser is greater than 0.3 J/cm^2, the temperature of the impurities is higher than their melting point. When the energy density of the laser is greater than 0.6 J/cm^2, the temperature will be higher than the boiling point of the impurity particles, and the impurities will undergo phase transition due to high temperature, generating internal pressure inside the glass.

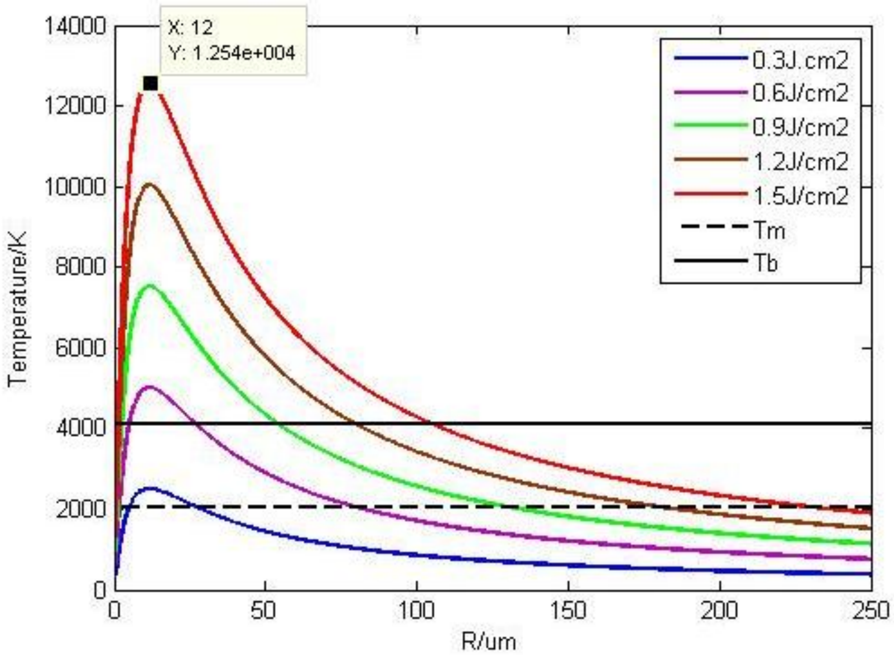

Figure 3 Relationship between surface temperature of impurity particles and particle radius R

Meanwhile, as shown in Figure 3, under the same laser energy density, the temperature of impurity particles first increases and then decreases with the increase of particle radius. When the radius of impurity particles is smaller, the energy absorbed per unit volume increases, and at the same time, thermal diffusion is also faster; When the radius of impurity particles is large, under the same laser energy, the energy absorbed per unit volume of impurity particles is relatively small. If the laser energy absorbed by impurities is not enough to reach their melting or boiling point, it will not cause damage to the glass. Therefore, when Pt particles are present in quartz glass and the particle size is about 12 μm, according to the figure, the temperature that the particles can reach is the highest, which is more likely to cause damage to quartz glass.

3.2 Thermodynamic Expansion Process

When impurity particles absorb the energy of laser, they act as an internal heat source in optical components, and the heat diffuses outward. The center temperature of impurity particles is high, and the temperature gradually decreases from the impurity surface along the interior of the glass. When the temperature of impurity particles is higher than their boiling point, they will vaporize and generate high pressure, resulting in uneven stress distribution inside the glass. Due to the uneven distribution of temperature inside the glass, radial and circumferential stresses will be generated. For impurities existing inside the glass, circumferential stress is the main cause of glass cracking, and the stress in various directions satisfies the following equation:

$$\sigma_{rr} = -\frac{2\alpha E}{1-\nu}\frac{1}{r^3}\int_a^r Tr^2 dr + \frac{EC_1}{1-2\nu} - \frac{2EC_2}{1+\nu}\frac{1}{r^3} \quad (3)$$

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\frac{1}{r^3}\int_a^r Tr^2 dr + \frac{EC_1}{1-2\nu} - \frac{EC_2}{1+\nu}\frac{1}{r^3} - \frac{\alpha ET}{1-\nu} \quad (4)$$

Among them, E , ν , α and are respectively Young's modulus, Poisson's ratio, and specific heat coefficient. When considering the situation where impurities vaporize into steam, assuming the pressure of impurity vaporization is p and acting on the surrounding substrate, as for $\mathrm{r} = \infty$， $\sigma_{rr} = 0$， we obtain C1=0. As for $r = a$ 时， $\sigma_{rr} = -p$， we get $C_2 = [p(1+\nu)/2E]a^3$, and substitute it into (3) and (4).

$$\sigma_{rr} = -\frac{2\alpha E}{1-\nu}\frac{1}{r^3}\int_a^r Tr^2 dr - p\frac{a^3}{r^3} \quad (5)$$

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\frac{1}{r^3}\int_a^r Tr^2 + \frac{p}{2}\frac{a^3}{r^3} - \frac{\alpha ET}{1-\nu} \quad (6)$$

Considering the case where the gas pressure is static pressure, for the convenience of analyzing the results, it is assumed that the impurity maintains a constant volume during vaporization. The pressure can be obtained from the three term equation of state

$$p(V,T) = p_x(V) + p_{TN} + P_{Te}(V,T) \quad (7)$$

Among them, the first term is cold pressing, and the second term is crystal hot pressing; The third term refers to the thermal contribution of free electrons, while the first term can be ignored. When the temperature is less than 10 kK, the thermal contribution of free electrons can also be ignored, further simplified as

$$p = pTN = \frac{\gamma(V)}{V}\cdot\frac{3RT}{\mu} \quad (8)$$

Among them, γ is the Gruneisen constant, V is the mass volume, and R is the molar gas constant, μ is a molar mass.

3.3 Thermal stress

The thermal stress distribution of impurities inside the glass without phase transition is shown in Figure 4, with a particle radius of 12 μm. It can be seen from the figure that when the impurities inside the glass do not undergo phase transition, there are compressive and tensile stresses around the impurities. Among them, the circumferential stress around the impurities is compressive stress, and the stress at a distance from the impurities is tensile stress. The compressive strength of quartz glass is 3 GPa, and the tensile strength is 0.5 GPa. Obviously, whether it is tensile stress or compressive stress, the thermal stress at this time is not enough to cause the glass to crack or crush.

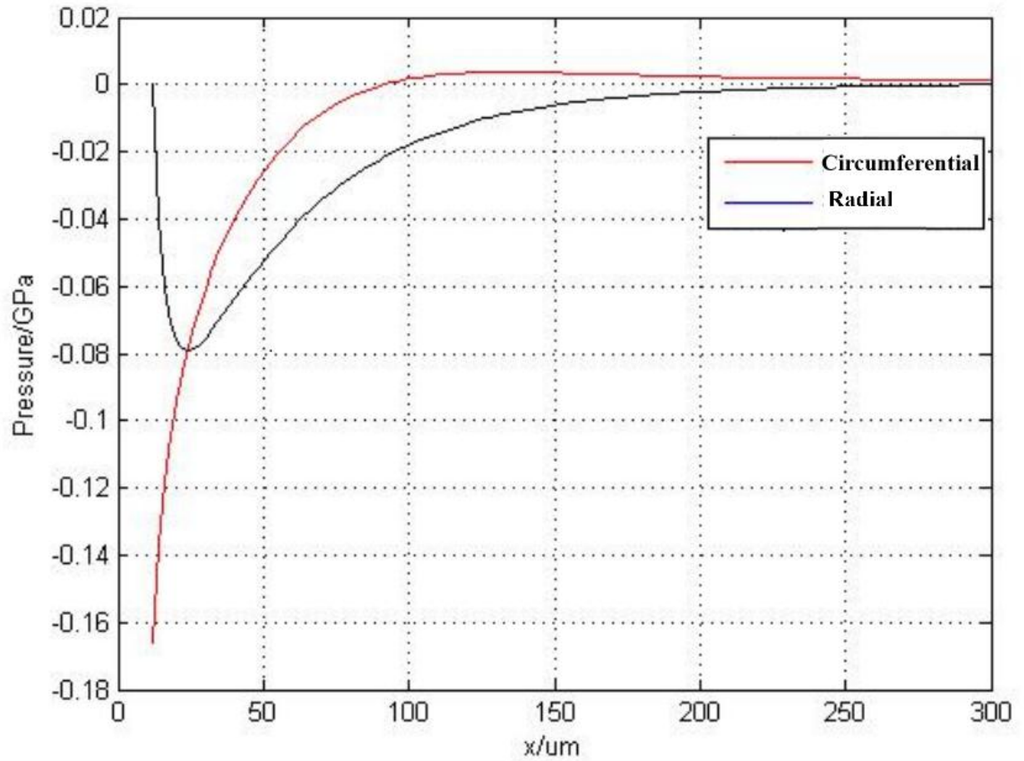

Figure 4 Thermal stress generated by temperature gradient

3.4 Stress generated by phase transition

When the impurities inside the glass exceed their own vaporization threshold due to the absorption of laser energy, the impurities vaporize and generate a large vapor pressure inside the glass, which acts on the glass around the impurities. The vapor pressure increases with the temperature. When the impurities vaporize, the vapor pressure generated by the vaporization of the impurities will become the main stress for the material to produce strain rather than the thermal stress generated by the temperature gradient. After the impurities vaporize, the temperature is 4500 K. According to equation (5-6), the vapor pressure at this time is about 31 GPa, and the radial stress caused by the vapor pressure is compressive stress, and the circumferential stress is tensile stress. From the figure, it can be seen that the pressure generated by the vapor at this time exceeds the compressive strength of the material, which will cause the material to produce strain. Localized fractures.

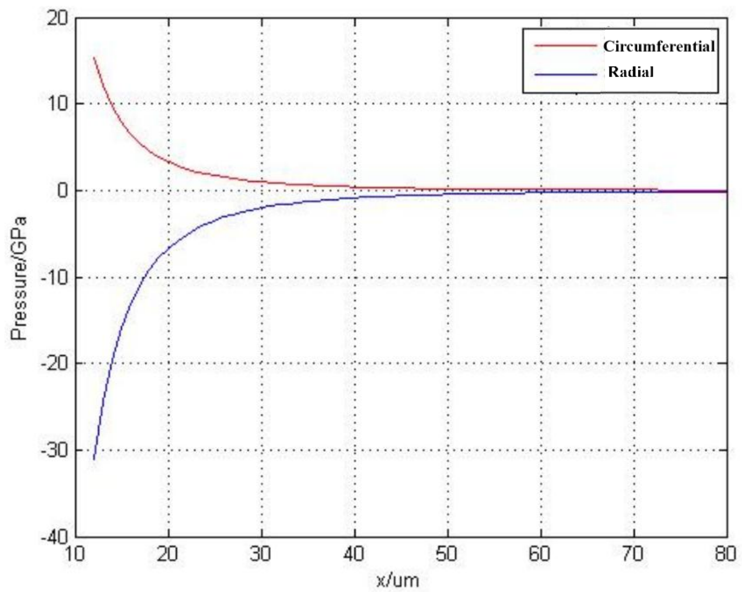

Figure 5 Stress generated by phase transition

Due to the presence of absorbing impurities in the substrate, the impact strength of quartz glass decreases to several tens of MPa. According to Figure 5, the thermal stress generated by the temperature gradient is not sufficient to cause the substrate to fracture. When impurities vaporize inside the glass, the internal pressure causes the glass around the impurities to fracture. At the same time, due to the impact effect of plasma, the degree of fracture inside the glass further increases. Further theoretical analysis is needed regarding the effect of impurities absorbing laser energy and generating plasma inside glass on glass fracture.

3.5 Causes of string damage and filamentous destruction

The string like damage characteristics inside the glass body are generally believed to be caused by the nonlinear effects of laser [11]. For the series of explosion points shown in Figure 5.1 (b), there are mainly strong particle defects in the laser action zone, which absorb more laser energy, produce higher free electron density, and cause micro explosions [12]. When laser is applied to defect points with strong absorption, point like explosions will occur inside the material, as shown in Figure 5.1 (a). The macroscopic damage morphology observed is filamentous damage.

IV. Conclusion

This chapter explores the damage characteristics of laser to optical components in the presence of absorbing impurities through experiments and theory. The theoretical analysis results show that when there are impurities inside the component, due to the stronger absorption ability of the impurities on the laser than the substrate, the temperature of the impurities will increase. With the increase of laser energy, the temperature inside the glass gradually increases, and the stress around the impurities also changes accordingly. From the analysis, it can be seen that the thermal stress generated by temperature has little effect on the glass. The main source of damage to the glass is due to the gasification of impurities and the impact of plasma, which leads to stress imbalance inside the glass and the formation of large-area fracture of the glass. Moreover, in the process of component damage caused by impurities, there is a size that is prone to component damage. When the impurity particles in the component are larger than 12 μm or smaller than 12 μm, the highest temperature that the impurities can reach under the same laser energy is lower than the temperature at that size. Therefore, the production of impurities of this size should be avoided when manufacturing optical components.

Acknowledgments

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