High temperature thermal behaviour modeling of large-scale fused silica optics for laser facility*

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High temperature annealing is often used for the stress control of optical materials. However, weight and viscosity at high temperature may destroy the surface morphology, especially for the large-scale, thin and heavy optics used for large laser facilities. It is necessary to understand the thermal behaviour and design proper support systems for large-scale optics at high temperature. In this work, three support systems for fused silica optics are designed and simulated with the finite element method. After the analysis of the thermal behaviours of different support systems, some advantages and disadvantages can be revealed. The results show that the support with the optical surface vertical is optimal because both pollution and deformation of optics could be well controlled during annealing at high temperature. Annealing process of the optics irradiated by CO_2 laser is also simulated. It can be concluded that high temperature annealing can effectively reduce the residual stress. However, the effects of annealing on surface morphology of the optics are complex. Annealing creep is closely related to the residual stress and strain distribution. In the region with large residual stress, the creep is too large and probably increases the deformation gradient which may affect the laser beam propagation.

Keywords: numerical simulation, support systems, large-scale fused silica, high temperature

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1. Introduction

Fused silica is a preferred optical material for high-fluence optics in many laser applications because its high bulk purity leads to low absorption in a wide spectral range, resistance to laser damage, and good thermal and mechanical stabilities. Although the dielectric breakdown threshold of pure bulk fused silica is very high, laser-induced damage threshold (LIDT) of the surface is very low.[1] Laser damage of optical components is a main issue for high power laser systems such as the National Ignition Facility (NIF) in USA and the megajoule laser (LMJ) in France.[2–4] Although the polishing techniques of silica have been considerably improved, defects that can initiate damage are still present in the material.[5] Laser irradiations of these weak points lead to stress, cracks, and absorption. The created damage grows under subsequent irradiations and makes the component unsuitable.[6] Besides, the absorption of laser light leads to a thermal heating in a thin layer near the surface of the material which induces thermal stress. In particular, when the temperature increases over the glassy temperature T_g, optics starts to behave like a viscoelastic material and stress relaxation occurs. This relaxation can lead the residual tensile stresses during cooling to ambient temperature to exceed the tensile strength.[7] As is well known, stress may induce birefringence, reduce mechanical strength and thermal stability of optics, and even induce fractures.[8] Therefore, it is necessary to limit residual stress to an acceptable level for the lifetime extension of the expensive large-scale laser optics.

Several methods of controlling the stress of op-

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tics have been studied, such as preheating before laser irradiation[9] controlling cooling rate after laser irradiation,[10] and high temperature annealing after laser irradiation and cooling to ambient temperature. High temperature annealing is one of the methods which is more widely researched and more efficient in applications.[11−14] In this way, heavy weight and viscosity at high temperature of the large-scale optics may destroy their surface morphologies. Investigation of supporting technology is necessary to share the gravity, especially during thermal annealing. Schipani *et al.*[15] described the support system adopted for the 2.6-m primary mirror of the Very Large Telescope Survey Telescope (VST) and discussed the results of the qualification test campaign. The 2.6-m primary mirror was supported both axially and laterally and surrounded by several safe devices for earthquake protection. Noailles *et al.*[16] presented recent studies on the mechanical support system of the Laser Megajoule large dimension optical components. An original and very simple method based on an isostatic mounting together with industrial springs located on the edges of the component was presented. Gao and Ren[17] designed three kinds of support schemes applied to the ultra thin mirror and calculated the deformation of the mirror with support structure based on the finite element analysis method. However, there is no report on support system or thermal behaviour of optics at high temperature. In the present work, different support systems of the large-scale fused silica optics at high temperature are discussed by the finite element analysis method. Stress and deformation of the optics with support structure before and after thermal annealing are calculated. In addition, the effects of annealing on residual stress and deformation caused by CO_2 laser irradiation are also studied.

2. Support systems

Because of the complex structure of the optics, axial and lateral support systems should be considered. The axial support system is designed to support the component of mirror weight along the optical axis, and the lateral system supports the weight component of the mirror perpendicular to the optical axis.[15] In addition, for the optics placed at any angle, a frame may be more suitable in which the optics are embedded or clamped.[16] The large-scale fused silica optics studied in this paper are 430 mm × 430 mm × 30 mm in dimension, which will be placed in an annealing furnace horizontally or vertically with respect to its optical surface. If the optical component is horizontally located in the furnace with its entire optical surface the same as the support surface, some contaminations and unpredictable stress and deformation will probably be introduced because of the large support area. So reducing the support area is necessary. If the optical component is vertically mounted, the side face is the support area which has little influence on stress and deformation of the optical surface. Therefore, a big support area is better. According to different mounting methods, three support schemes are designed as follows:

Scheme 1 Multi-points support the horizontal optical surface. The support points are arranged to share gravity evenly. In this work, sixteen support points are designed, each of which is 10 mm × 10 mm in area as shown in Fig. 1(a).

Scheme 2 Four edges support the horizontal optical surface. The support position is not designed in the centre of the optical surface but at the edges. The influence on the effective region of the optical surface is avoided by toughening the support material. Here, the support is a rectangle frame with 10-mm width mounted at the edges of the optical surface as shown in Fig. 1(b).

Scheme 3 Side-face supports the vertical optical surface. One of the side faces of the optics is the support surface and the optical surface is vertical. So the support area is the whole side face as shown in Fig. 1(c).

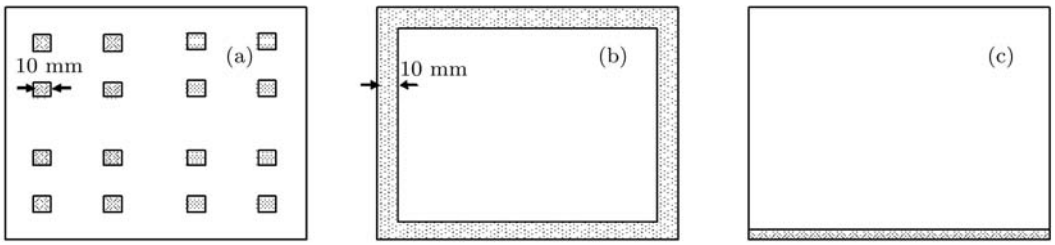


Fig. 1. Schemes 1 (a), 2 (b), and 3 (c) of support system of large-scale fused silica optics.

3. Numerical simulation method[18]

Numerical simulation and finite element analysis are performed with ANSYS software. Temperature, stress, and deformation evolutions of optics are calculated with the thermal module and the structure module of ANSYS. Furthermore, creep theory is used to simulate viscosity behaviours of the optics at high temperature.

For the isotropic non-linear thermal material, the finite element form of the transient heat conduction equation can be described as

$$[C(T)]\left\{\dot{T}(t)\right\} + [K(T)]\{T(t)\} = [Q(t)], \quad (1)$$

where $[C(T)]$ and $[K(T)]$ are the heat capacity matrix and conductivity matrix corresponding to temperature T, respectively; $\{T(t)\}$ and $\{\dot{T}(t)\}$ are the temperature vector and temperature rate vector of nodes at time parameter t, respectively; $\{Q(t)\}$ is the heat flux vector of nodes at time t.

The isotropic elastic constitutive equation can be written as the matrix formulation

$$\{\sigma\} = [D(E,\mu)]\{\varepsilon_{\rm el}\}, \quad (2)$$

where $\{\sigma\}$ and $\{\varepsilon_{el}\}$ are the stress vector and the strain vector, respectively. $[D(E,\mu)]$ is the elastic matrix related to Young's modulus E and Poisson's ratio μ.

Plasticity is a nonconservative, path-dependent phenomenon. Plastic behaviour occurs when stress exceeds the yield strength of a material. Plasticity theory provides a mathematical relationship that characterizes the elastoplastic response of material. There are three ingredients in the rate-independent plasticity theory: yield criterion, flow rule, and hardening rule. Von Mises yield criterion is adopted for the isotropic material and expressed as

$$\sigma_{\rm e} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_1-\sigma_3)^2\right]}, \quad (3)$$

where σ_1, σ_2, and σ_3 are the principal stresses, and $\sigma_{\rm e}$ is the equivalent stress. When the equivalent stress is equal to material yield strength, the material will induce plastic strain. Flow rule determines the amount and direction of plastic straining

$$\{{\rm d}\varepsilon_{\rm pl}\} = \lambda\left\{\frac{\partial Q}{\partial \sigma}\right\}, \quad (4)$$

where $\{{\rm d}\varepsilon_{\rm pl}\}$ is the increment of the plastic strain vector, λ is the plastic multiplier which determines the amount of plastic straining, Q is the function of stress termed the plastic potential which determines the direction of plastic straining. Hardening rule describes the changing of the yield surface with progressive yielding, so that the conditions for subsequent yielding can be established. For isotropic material, isotropic hardening is adopted in which the yield surface remains centred about its initial centerline and expands in size as the plastic strain develops.

Creep is important in high temperature stress analysis. Creep is a rate-dependant material nonlinearity in which the material continues to deform under a constant load. Conversely, if a displacement is imposed, the reaction force (and stress) will diminish over time. This phenomenon is also named stress relaxation. Creep equation is expressed by creep strain rate as

$$\dot{\varepsilon}_{\rm cr} = A\sigma^B\varepsilon_{\rm cr}^C t^D, \quad (5)$$

where $\dot{\varepsilon}_{\rm cr}$ is the creep strain rate, σ is the equivalent stress, $\varepsilon_{\rm cr}$ is the equivalent creep strain, t is the time, A, B, C, and D are the creep constants obtained from experiments.

4. Numerical simulation results and discussion

The modeling and finite elements calculations are performed with the ANSYS software. First, annealing processes of ideal optics with different support systems are discussed to compare their advantages and disadvantages. Then the annealing process of optics irradiated by CO_2 laser with the optimal support system is analysed to understand the evolutions of residual stress and surface morphology induced by high temperature annealing. The optics are 430 mm × 430 mm × 30 mm in dimension. During annealing, the optics are heated from ambient temperature to 800 °C slowly and kept at 800 °C for 10 h, and then cooled to ambient temperature in the furnace.

In order to determine the creep constants of fused silica at 800 °C, shear stress distribution of optics irradiated by CO_2 laser and the stress evolution of optics annealed at 800 °C are simulated. The maximal shear stress appears at the edge of the irradiated area as shown in Fig. 2(a). During annealing, the yield strength of material may decrease as the temperature increases. In Fig. 2(b), plastic deformation occurs which leads to destressing when the yield strength is less than the residual stress. After that,

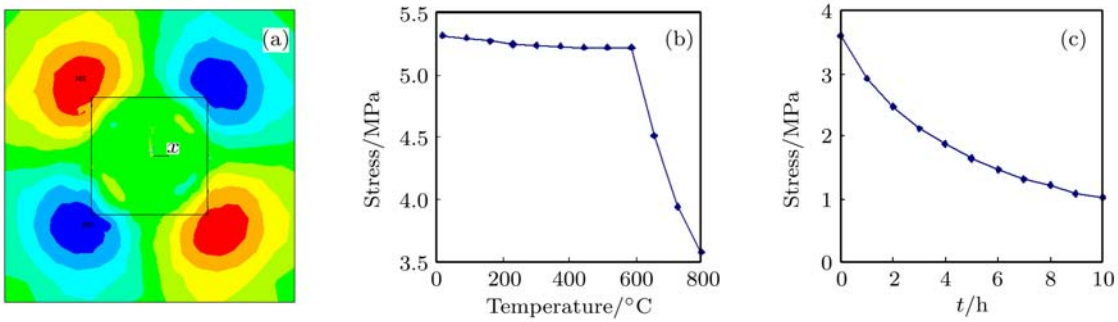


Fig. 2. (colour online) Shear stress distribution of optics irradiated by CO_2 laser (a) and stress evolutions in heating process (b) and insulation process (c).

the temperature is maintained at 800 °C for 10 h. Destressing caused by creep gradually slows down as shown in Fig. 2(c). Simulation results are basically consistent with the experimental ones.[19] The creep constants at 800 °C of fused silica are calculated as follows: $A = 1.4\,\mathrm{e}^{-22}\ \mathrm{s}^{-1}\cdot\mathrm{Pa}^{-2}$, $B = 2$, $C = 0$, and $D = 0$.

4.1. Ideal optics

The stress and strain distributions before annealing for different support systems are shown in Figs. 3 and 4.

The results of numerical simulation show that distribution characteristics of stress and strain do not change but the value of stress and strain are varying. In addition, there is no plastic behaviour but elastic strain and creep occur. It is known that elastic strain is recoverable when the load is removed while the creep deformation is permanent. Therefore, creep is the main factor that destroys the surface morphology. Destressing and creep induced by annealing are shown in Fig. 5.

After comparing the results of the different support systems, some advantages and disadvantages can be deduced. For Scheme 1, the small and scattered support points lead to the minimal elastic strain. The elastic strain is large in the centre of the optical surface and small at the edges. The annealing creep is less than those of the other two schemes. However, the stress is the largest and concentrated on the support points. And the contamination caused by support material may reduce the laser damage resistance capability of optics. For Scheme 2, the stress is less than that of Scheme 1 and concentrated at the edges of the optical surface. The pollution caused by support material occurs at the edges, which may not affect the laser beam propagation. However, the elastic strain is large and the maximum stain lies in the centre of the optical surface. The annealing creep is the biggest among the three schemes. For Scheme 3, both stress and strain are the least and evenly distributed. The annealing creep is far less than that of Scheme 2. The pollution caused by support material may not affect the beam propagation. But the big support area may lead to large local stress because of inconsistent deformation between the optics and the support. According to the above analysis, it can be concluded that Scheme 3 is optimal because the influences on both pollution and deformation of optics are minor after annealing at high temperature.

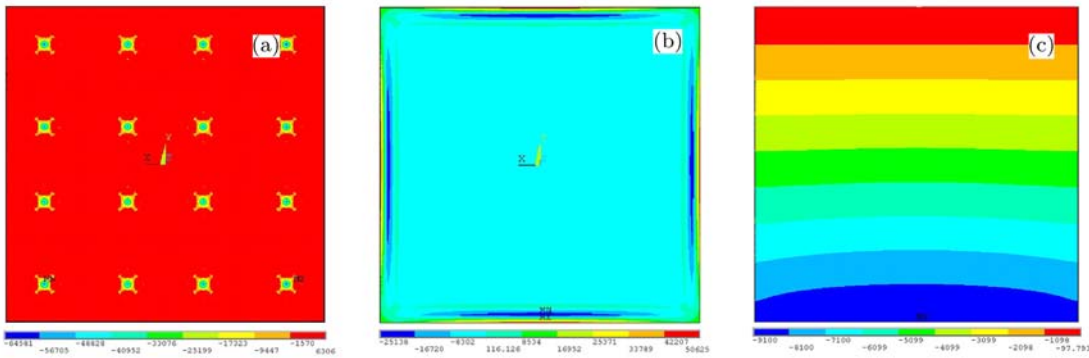


Fig. 3. (colour online) Stress distributions before annealing for different support systems, (a) Scheme 1, (b) Scheme 2, (c) Scheme 3.

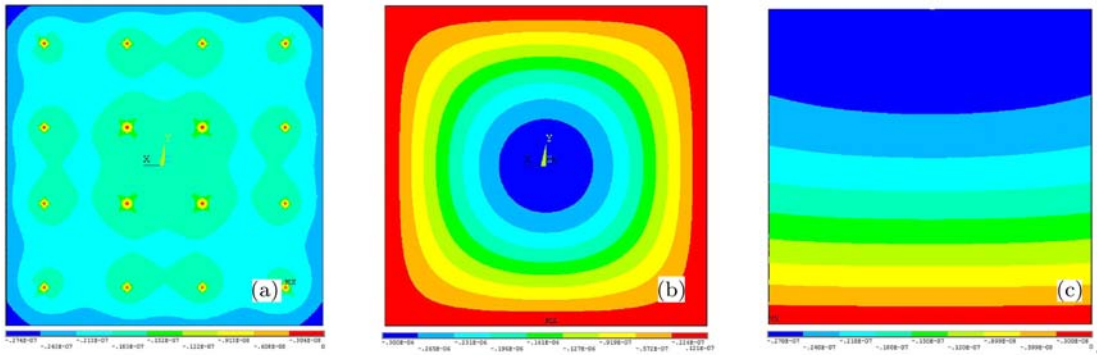


Fig. 4. (colour online) Strain distributions before annealing at different support systems, (a) Scheme 1, (b) Scheme 2, (c) Scheme 3.

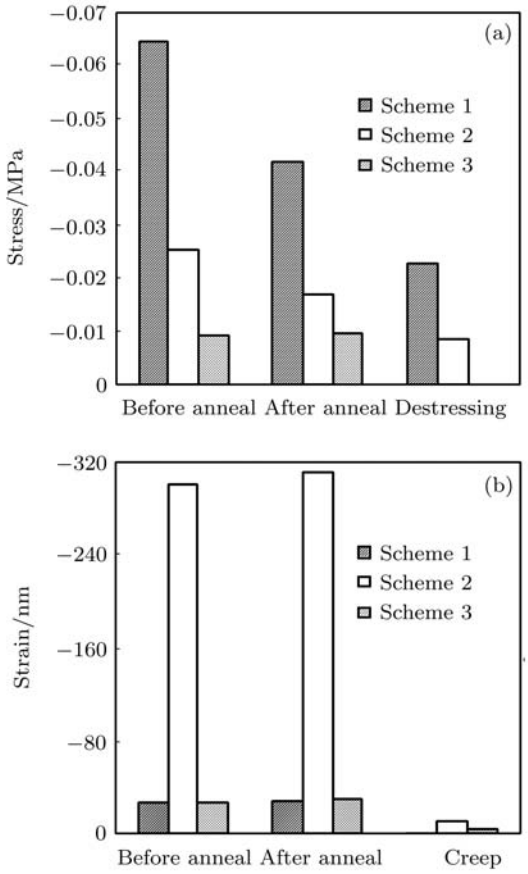


Fig. 5. Stresses (a) and strains (b) induced by annealing for different support systems.

4.2. Optics irradiated by CO_2 laser

In order to understand the destressing of residual stress by high temperature annealing, the residual stress distribution of optics irradiated by CO_2 laser and the influences of stress and strain caused by annealing are given in Fig. 6. Laser irradiation parameters used are laser power 70 W, beam radius 2 mm, Gaussian distribution of laser intensity, and irradiation time 5 s.

The first principal stress distribution of the optics irradiated by CO_2 laser is shown in Fig. 6(a). The number in the figure represents the level of stress. The stress is maximum in Region 5 where the distance from the centre is about 1 mm while the stress is minimum in Region 1 where the distance from the centre is larger than 5 mm. The stress in Region 1 is negative which shows compressive stress while other regions are positive, which shows tensile stress. In summary, there is large tensile stress near the irradiated area and small compressive stress in the area away from it. Moreover, the maximal stress does not appear in the irradiated center but in the periphery because the material in the centre has melted.

Six positions on the optical surface are selected to study. The distances between the six positions and the CO_2 laser irradiation centre are 0, 1, 2, 3, 4, and 5 mm, respectively. The residual stress is effectively reduced by high temperature annealing as shown in Fig. 6(b). The destressing is more obvious at the position with large residual stress. The stress tends to distribute uniformly across the whole optical surface. In Fig. 6(c), the size of annealing creep is far less than the strain induced by CO_2 laser irradiation, and the direction of annealing creep is opposite to the strain induced by CO_2 laser irradiation. It seems that annealing creep can reduce the material deformation. However, the size of annealing creep is disproportionate to the strain induced by CO_2 laser irradiation. In the region with large residual stress, the creep is too/very large, which probably results in the increase of deformation gradient. In the region of 0–1 mm, the deformation gradient increases from 0.00187 to 0.00196 while it decreases in other regions. It indicates that the effect of high temperature annealing on surface morphology is closely related to the residual stress and strain.

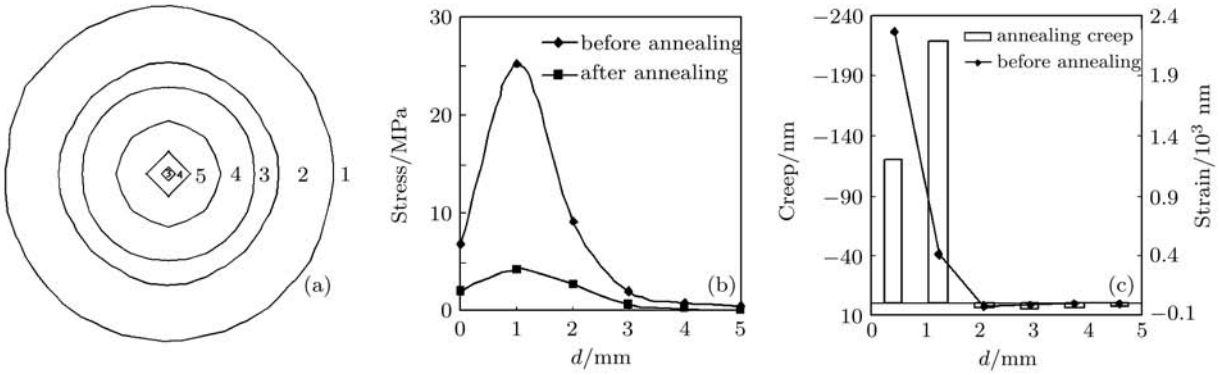


Fig. 6. Residual stress distributions of optics irradiated by CO_2 laser (a) and the influences of stress (b), and strain (c) caused by annealing.

5. Conclusion

Three support systems of the large-scale fused silica optics at high temperature are designed. Stress and deformation of the optics with support structure before and after annealing are simulated. The results show that the support with the optical surface vertical is relatively ideal to control pollution and annealing creep. In addition, high temperature annealing can reduce the residual stress effectively. However, the effects of annealing on surface morphology of the optics are complex. The deformation gradient may increase in some regions and decrease in other regions.

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