Investigation of a low-stress and low-contamination clamping method for large-aperture optics

Hui Wang¹, Kai Long¹, Zheng Zhang¹*, Congzhi Yi², Xusong Quan² and Guoqing Pei²

¹State Key Laboratory of Tribology and Beijing Key Laboratory of Precision/ Ultra-Precision Manufacturing Equipments and Control, Department of Mechanical Engineering, Tsinghua University, Beijing, China
²Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang, China

Abstract
Motivated by the need to decrease initial contact seal stress on Nd:glass coated with SiO₂ sol–gel film and effectively control the surface contaminants from film debris induced by stress in the assembly process, a novel vacuum clamping method is studied to achieve the purpose of low stress and low contamination. In this article, theoretical analyses, numerical simulations, and field experiments are used to verify the feasibility of this method. Mechanical simulation results indicate that under the same radial compression conditions, the higher the hollowness of the O-ring rubber, the less the contact stress on Nd:glass. In addition, microstructures of the SiO₂ sol–gel film are observed by scanning electron microscopy, and the damage mechanism is analyzed in order to optimize assembly stress. By optimizing the distribution of hollowness, the honeycomb structure is proved to have lower contact stress due to its larger deformation. Finally, experimental results verify that the low-stress vacuum clamping method can meet the strict surface cleanliness requirements of Nd:glass. This study also provides a promising method for clean assembly of other large-aperture optics.

Keywords
Cleanliness, stress, assembly, film, Nd:glass

Corresponding author:
Zheng Zhang, State Key Laboratory of Tribology and Beijing Key Laboratory of Precision/Ultra-Precision Manufacturing Equipments and Control, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China.
Email: zzcnjn@163.com

Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
Introduction

There are thousands of large-aperture optics installed in high-power laser facilities coated with SiO\textsubscript{2} sol–gel film, such as windows, lenses, crystals, gratings, shields, and so on. However, contact contamination from film debris introduced by manual assembly is severely destructive for all high-power laser components.\textsuperscript{1,2} Spaeth et al.\textsuperscript{3} found that the contamination on the surface of optical component can not only reduce its own laser-induced damage threshold but also enhance beam modulation in upstream optical components, resulting in changes in the beam quality.\textsuperscript{4} Surface contamination on optical components is a long-term cumulative effect, for which the cleanliness should be controlled from the whole process including manufacturing, assembly, installation, and operation.\textsuperscript{5} In the operating environment of high-power laser facilities, molecular organic matter can increase the reflection of the SiO\textsubscript{2} sol–gel film, which has loose porosities and large specific surface area.\textsuperscript{6,7} Long et al.\textsuperscript{8} found that fluorine rubber (FPM) brings the least contamination when contacting the surface of the optical component compared with other kinds of rubber materials. In order to effectively control the surface contamination on optical components, National Ignition Facility (NIF) refers to Military Standard 1246C, and 50-A/10 is used as the cleanliness standard for large-aperture optics.\textsuperscript{9} In the assembly process, contaminants are transmitted through contact and adhered to the surface.\textsuperscript{10} In order to ensure the cleanliness of the surface, most of the optical components are placed vertically on the horizontal platform with no fixing stress after cleaning to prevent any objects from contacting the light-passing plane.

On the contrary, manual assembly is not only inefficient but also difficult to effectively control the contamination generated in the assembly process.\textsuperscript{11} In order to make the assembly process of the large-aperture optomechanical unit more efficient and flexible, the robot-assisted assembly technology is applied.\textsuperscript{12} In vacuum clamping methods, the role of the seal is particularly important.\textsuperscript{13} Zhou et al.\textsuperscript{14} analyzed the seal performance of O-ring and wedge-ring rubber by using finite element methods (FEMs). Tan et al.\textsuperscript{15} found that rectangular rubber seals have many advantages compared to O-rings, for example, they have smaller initial compressibility. In theory, even if the compression of the seal ring is zero, the initial seal can be formed. While the seal ring cannot be kept in the same ideal plane with the optical surface, a certain amount of pre-compression is required to reduce the gap between them in order to form the initial seal, causing compression deformation of the O-ring rubber.\textsuperscript{16} So, it is necessary to generate a large deformation when the seal material gives a small stress to optics; then it can provide contact force and compensate for the leakage gap for sealing purpose, especially for large-aperture optics.\textsuperscript{17} Conventional vacuum clamping apparatus need applying so large pre-force on optics that it is sufficient to destroy the SiO\textsubscript{2} sol–gel film on the surface of most high-power laser components, resulting in film debris.\textsuperscript{18} Therefore, there is an urgent need for a low-stress and low-contamination clamping method.

In this article, Nd:glass is taken as the representative research object because it has the largest weight, the largest diameter, and the highest level of cleanliness in high-power laser facilities. Generally, Nd:glasses have the size of 810 mm × 460 mm.
× 40 mm, and 912 pieces will be installed in the front-end system in a real operating environment. Moreover, the stable operation of Nd:glass has a direct impact on the overall performance of the high-power laser facility. In this work, the theoretical and numerical models of the vacuum clamping process are first established. Subsequently, the influence mechanism of the O-ring seal rubber on Nd:glass is studied by field experiments, in which microstructures of the SiO$_2$ sol–gel film is observed by scanning electron microscopy (SEM). Based on this, a low-stress and low-contamination vacuum clamping method based on honeycomb seal material with high hollow ratio is put forward. Finally, experimental results are utilized to verify the performances of the proposed clamping method both in reducing contact stress and ensuring cleanliness of large-aperture optics.

**Theoretical analysis**

**Mooney–Rivlin model**

In the process of assembling large-aperture Nd:glass, the rubber seal in the vacuum clamping configuration plays an extremely important role. As the rubber belongs to the hyperelastic and incompressible material, its mechanical properties are usually expressed by strain energy functions. The mechanical model also exhibits complex material nonlinearity and geometric nonlinearity, which poses a challenge for the finite element solution process. In order to solve the seal problem with FEMs, the Mooney–Rivlin model is used to describe the mechanical properties of the rubber hyperelastic material under large deformation. The Mooney–Rivlin model considers strain energy density to be a polynomial function of the principal strain invariant, and it is commonly used to describe rubber-based physical nonlinear materials

$$W(I_1, I_2) = \sum_{i,j=0}^{n} C_{i,j}(I_1 - 3)^i(I_2 - 3)^j$$

(1)

where $W$ is the strain energy density, $C_{i,j}$ is the Rivlin coefficient, $I_1$ and $I_2$ are the first and second Green strain invariants

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

(2)

$$I_2 = (\lambda_1\lambda_2)^2 + (\lambda_2\lambda_3)^2 + (\lambda_3\lambda_1)^2$$

(3)

where $\lambda_1$, $\lambda_2$, and $\lambda_3$ are elongation ratios along $x$, $y$, and $z$ directions, respectively, in a single unit. If two parameters are used to describe the Mooney–Rivlin model, the formula is

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 + 3)$$

(4)

where $C_{10}$ and $C_{01}$ are Rivlin coefficients.\(^{21}\)
In elastic nonlinear finite element analysis, Mooney–Rivlin strain energy function is a widely used constitutive relationship. From the relationship between Kirchhoff stress tensor $t_{ij}$ and strain tensor $\gamma_{ij}$, formula (5) can be got

$$t_{ij} = \frac{\partial W}{\partial I_1} \frac{\partial I_1}{\partial \gamma_{ij}} + \frac{\partial W}{\partial I_2} \frac{\partial I_2}{\partial \gamma_{ij}} + \frac{\partial W}{\partial I_3} \frac{\partial I_3}{\partial \gamma_{ij}}$$

(5)

For incompressible materials such as rubber, $I_3 = 1$, from formula (5), the relationship between the principal stress $t_i$ of the rubber material and its elongation ratio $\lambda_i$ can be expressed

$$t_i = 2\left(\lambda_i^2 \frac{\partial W}{\partial I_1} + \frac{1}{\lambda_i^2} \frac{\partial W}{\partial I_2}\right) + P$$

(6)

where $P$ is the hydrostatic pressure. Three principal stress differences can be obtained from equation (6)

$$t_1 - t_2 = 2(\lambda_1^2 - \lambda_2^2) \left(\frac{\partial W}{\partial I_1} + \lambda_2^2 \frac{\partial W}{\partial I_2}\right)$$

(7)

$$t_2 - t_3 = 2(\lambda_2^2 - \lambda_3^2) \left(\frac{\partial W}{\partial I_1} + \lambda_3^2 \frac{\partial W}{\partial I_2}\right)$$

(8)

$$t_3 - t_1 = 2(\lambda_3^2 - \lambda_1^2) \left(\frac{\partial W}{\partial I_1} + \lambda_1^2 \frac{\partial W}{\partial I_2}\right)$$

(9)

where $t_1$, $t_2$, and $t_3$ are principal stress components along $x$, $y$, and $z$ directions, respectively, in a single unit, $t_i$ is the true stress associated with the deformed size.

In order to determine the two coefficients of the Mooney–Rivlin model including $C_{10}$ and $C_{01}$, the material is assumed to be incompressible, $I_3$ can be expressed by the following equation

$$I_3 = (\lambda_1 \lambda_2 \lambda_3)^2$$

(10)

In the special case of uniaxial stretching, using formula (7), the rubber stress–strain equation can be expressed as follows

$$\frac{\sigma}{2(\lambda - \lambda^{-2})} = C_{10} + \frac{C_{01}}{\lambda}$$

(11)

where $\sigma$ is the engineering stress. The relationship between initial shear modulus $G$ and Rivlin coefficients is

$$G = 2(C_{01} + C_{10})$$

(12)

If the material is assumed to be incompressible, then the modulus of elasticity $E$ is

$$E = 6(C_{01} + C_{10})$$

(13)
The Shore hardness of rubber $H_A$ can also be used to obtain its modulus of elasticity $E$

$$E = \frac{15.75 + 2.15H_A}{100 - H_A}$$  \quad (14)

The parameters of superelastic materials are generally obtained through experiments. If the analyst can only get one parameter $C_{10}$ and want to include non-zero $C_{01}$ in the model, the empirical formula can be used to get Rivlin coefficients $C_{10}$ and $C_{01}$

$$C_{01} = 0.25C_{10}$$  \quad (15)

Through the aforementioned formula, for the rubber material with $H_A = 70$, the basic parameters of the rubber material can be got including $C_{10} = 0.7389$ MPa, $C_{01} = 0.1847$ MPa, the uncompressible rate $D_1 = 0$ Pa according to formulas (12)–(15). However, it is hard to analytically solve these equations. The FEM is a solution to the mathematical problems effectively by using the parameters obtained earlier. The basic solution idea is to divide the computational domain into a finite number of non-overlapping units and solve the differential equations discretely.\textsuperscript{22}

**Finite element model**

In order to maintain the cleanliness of Nd:glass during assembly, the vacuum clamping method is used. The geometric model is shown in Figure 1. In this clamping apparatus, support plate, O-ring rubber, and Nd:glass form a vacuum chamber, so the Nd:glass can be clamped under the negative pressure. For nonlinear elastic sealing rubber, the compression model is established and mechanical properties are analyzed by the FEM. Due to the complexity of the boundary conditions, the support plate, O-ring rubber, and Nd:glass are analyzed integrally. Based on their geometries, materials, and boundary conditions, the model can be simplified to an axisymmetric plane, and the two-dimensional (2D) model includes 2681 elements.

![Figure 1. Geometric model of the vacuum clamper.](image)
and 8412 nodes after being meshed. At the bottom of the Nd:glass, a fixed constraint is applied. On the support plate, a zero displacement constraint is applied in the $x$ direction and a varying displacement constraint is applied in the $y$ direction. For O-ring rubber, a zero displacement constraint is applied in the $x$ direction and freely constrained in the $y$ direction. The 2D finite element model after being meshed and constraint application model are shown in Figure 2.

To simplify the analysis process, the following assumptions are made: (1) O-ring rubber has a defined modulus of elasticity and Poisson’s ratio; (2) the O-ring rubber has the same tensile and compressive creep properties; (3) the longitudinal compression experienced by the O-ring is considered to be caused by the specified displacement of the constrained boundary; and (4) creep does not cause volume changes.

The details of the materials properties are mentioned in Table 1.

### Experimental methods

#### Mechanical experiment

In order to measure the contact force required to form the pre-compression amount, the following experiments are performed. The experimental setup is shown in Figure 3, it mainly includes the following:

![Simulation analysis model](image)

**Figure 2.** Simulation analysis model: (a) 2D finite element mesh model and (b) constraint application model.

**Table 1.** Materials properties of the vacuum clamber components.

| Components | Material    | Young’s modulus (GPa) | Poisson’s ratio | Density (g/cm$^3$) |
|------------|-------------|------------------------|-----------------|-------------------|
| Support plate | Stainless steel | 193 | 0.31 | 7750 |
| O-ring rubber | Fluoro rubber | $7.84 \times 10^{-3}$ | 0.47 | 1800 |
| Nd:glass | Phosphate | 79.2 | 0.21 | 2690 |
1. vacuum clamper, O-ring rubber as the seal material;
2. Nd:glass, the size is 330 mm × 200 mm × 40 mm;
3. robotic arm, carrying the vacuum clamper;
4. dial indicator, accuracy 0.001 mm, used for measuring the initial compres-
sion of O-ring rubber and displacement of vacuum clamper; and
5. Kistler 9255C dynamometer, accuracy 0.01 N, used for measuring the initial
compressive force.

The measuring principle of dynamometer is shown in Figure 4. The Kistler
9255C dynamometer has four square-distributed sensors on the same plane. The
signal collector has eight channels, which can measure eight original force signals
including \( F_{x_1} + F_{x_2}, F_{x_3} + F_{x_4}, F_{y_1} + F_{y_4}, F_{y_2} + F_{y_3}, F_{z_1}, F_{z_2}, F_{z_3}, F_{z_4} \), where \( F_{ij} \)
stands for the force in the direction \( i \) of the sensor, and the number of the sensor is
\( j \). Then, the total forces, \( F_x, F_y, F_z \), and total moments, \( M_x, M_y, M_z \), can be obtained
by calculating the original signals.
\[
\begin{align*}
F_x &= F_{x1} + F_{x2} + F_{x3} + F_{x4} \\
F_y &= F_{y1} + F_{y2} + F_{y3} + F_{y4} \\
F_z &= F_{z1} + F_{z2} + F_{z3} + F_{z4} \\
M_x &= b \times (F_{z1} + F_{z2} - F_{z3} - F_{z4}) \times kM_x \\
M_y &= a \times (-F_{z1} + F_{z2} + F_{z3} - F_{z4}) \times kM_y \\
M_z &= b \times (-F_{x1} - F_{x2} + F_{x3} + F_{x4}) + a \times (F_{y1} + F_{y4} - F_{y2} - F_{y3}) \times kM_z
\end{align*}
\]

In mechanical experiments, first, control the vacuum clamper to approach the Nd:glass placed on the optical table at the speed of 1 mm/s until getting to the critical point where O-ring rubber contacts the Nd:glass. Second, turn on the vacuum pump, set the vacuum degree at 100 mbar, and clear the dial indicator and the dynamometer. Third, the vacuum gripper continues approaching the Nd:glass at a speed of 1 mm/s; at this time, the O-ring rubber is compressed. Finally, stop moving the vacuum clamper until the Nd:glass is absorbed, and the Nd:glass leaves the optical platform at the same time. Then, the force in z-direction that the Nd:glass receives during the clamping process can be obtained through dynamometer, and the displacement of the vacuum clamper and the compression amount of the O-ring rubber after the Nd:glass’s being adsorbed can be got through dial indicator. Next, repeat the aforementioned steps at the speed of 5 and 10 mm/s, respectively.

**Cleanliness experiment**

In order to measure the amount of film debris particles produced by contact stress, a static adsorption experiment is conducted. In this experiment, dark field scanning is used to measure particulates on the optical surface. Charge-coupled device (CCD) imaging is an easy on-line detection technology with high resolution (10 μm). In the dark field imaging mode, particulate is a bright spot. Dark field scanning optical transmission test platform is shown in Figure 5. After image processing, the size and the quantity of particulates on the surface on Nd:glass are calculated by the computer. In cleanliness experiment, the highest vacuum degree is applied at 800 mbar.

**Figure 5.** Particulate measurement experiment: (a) dark field scanning experiment and (b) dark field scanning principle.
According to MIL-STD-1246C (Military Standard Product Cleanliness Levels and Contamination Control Program), the cleanliness level of the particles is given by the following formula:

\[
\lg(n/10) = 0.926\left(\lg^2 L - \lg^2 d\right)
\]

where \(d\) is the size of the particulate, \(n\) is the number of particulates larger than \(d\) per ft\(^2\), 0.926 is the correction value, and \(L\) is the cleanliness level of surface particulates. For large optical surfaces, the surface particulate level as-assembled is 50 \(\mu m\), which means that the concentration of particulates larger than 50 \(\mu m\) is 1/ft\(^2\) and the concentration of particulates larger than 5 \(\mu m\) is 1785/ft\(^2\).

**Results and discussion**

**Mechanical properties**

Only if the O-ring rubber and the Nd:glass are completely good fit under the action of the compressive force, the initial sealing can be achieved. In order to study the stress on the Nd:glass, different radial displacements are applied on the model in Figure 2 to simulate the compression of the O-ring rubber. By changing the hollowness of 0%, 5%, 25%, 40%, 55%, and 75%, the maximum equivalent stress of the Nd:glass is obtained under the same radial compression. From the simulation results as shown in Figure 6, the maximum equivalent stress occurs in the central area of contact between the Nd:glass and the O-ring rubber. As the radial compression of the O-ring rubber increases, the maximum equivalent stress on the Nd:glass increases sharply for the hollowness of 0% and 5%. For the O-ring rubbers which have the same diameter, the maximum equivalent stress on the surface of Nd:glass decreases with the increase in the hollowness under the same radial compressive deformation. With the increase in the radial compression amount of the O-ring rubber, when the hollowness is more than 25%, the maximum equivalent stress on the optical element does not increase significantly, while it is in a flat state. This is because during the compression process of the O-ring rubber, the higher the hollowness, the more easily the O-ring rubber is deformed, and the area contacting with the Nd:glass is increased, thereby weakening the stress on the optical element.

As shown in Figure 7, it can be seen from the strain simulation results of the O-ring rubber that as the radial compression increases, the maximum isotropic strain on the Nd:glass increases, especially for the O-ring rubber having a hollowness of 5%, when the compression is greater than 0.5 mm, the strain magnitude exceeds the strain with a hollowness of 0%. Mainly due to the circle curvature of the O-ring rubber with 5% hollowness is too small. When the compression is applied to it, the maximum strain occurs in the minimum curvature position. Under the same radial compression, the greater the hollowness, the smaller the maximum equivalent strain on the O-ring rubber.

In order to verify the force on the Nd:glass in the clamping process, the O-ring rubber with a hollowness of 75% is used as the experimental object, and the
During the clamping process of the Nd:glass, the maximum contact forces are 545, 537, and 594 N when the vacuum clamper approaches the Nd:glass at speeds of 1, 5, and 10 mm/s, respectively. When stably absorbed by the vacuum clamper, the force that Nd:glass receives from the vacuum clamper is 510 N. Therefore, the contact forces required to form the initial seal are 35 N (545–510 N), 27 N (537–510 N), and 85 N (594–510 N), respectively. Therefore, in order to reduce the initial seal force, it is necessary to reduce the speed of the vacuum clamper approaching the Nd:glass.

Then, the effect of vacuum degree on the force of Nd:glass is studied. From Figure 9, it is found that when the vacuum degree is in the range of 100–400 mbar, the impact force decreases with the increase in the vacuum degree. When the vacuum degree is set to 100 mbar. The experimental results are shown in Figure 8.

Figure 6. Equivalent stress under different hollowness: (a) equivalent stress distribution of O-ring rubber and Nd:glass and (b) maximum equivalent stress curve on the surface of Nd:glass.
vacuum degree is in the range of 400–600 mbar, the impact force increases as the vacuum degree increases. The main reason is that the impact force on Nd:glass contains two parts when Nd:glass is adsorbed by the vacuum clamper. One part is used to form the initial seal, which requires a certain pre-contact force to be applied to the Nd:glass. The other part is that after forming the initial seal, the Nd:glass actively compresses the O-ring rubber under the action of the vacuum pressure. Therefore, when the degree of vacuum becomes larger than 400 mbar, the impact force becomes greater. From the experimental results, it is found that the impact force and the compression of the O-ring rubber have a consistent trend. Therefore, in the process of adsorbing large-aperture Nd:glass, under the premise of ensuring sufficient vacuum adsorption force, the vacuum degree should be controlled around 400 mbar, which can reduce the impact force and improve stability of clamping.

Figure 7. Equivalent strain under different hollowness: (a) equivalent strain distribution of O-ring rubber and (b) maximum equivalent strain curve of O-ring rubber.
Cleanliness properties

From the dark field scanning result, it can be seen that contact stress has a very obvious destructive effect on the SiO₂ sol–gel film. From the point of distribution of film debris, as shown in Figure 10, most of the film debris is concentrated in the zone of contacting with O-ring rubber. While in the vacuum zone, there are no obvious film defects. Through SEM image, Figures 11 and 12 show the damage morphology of SiO₂ sol–gel film and the size of the debris, which are enlarged by 500 and 1000 times, respectively. So, under the normal pressure, the film is pressed...
into fine debris and taken away by the O-ring seal rubber. As the rubber ring continues to squeeze the optical film, the O-ring rubber expands laterally and induces the formation of many debris at the same time, as shown in Figure 11. From the point of the size of debris, as shown in Figure 12, many debris are above 10 \( \mu \text{m} \), up to tens of microns. There is no obvious increased defect in the vacuum zone. This shows that the vacuum system does not bring new particles to the optical components, so the vacuum system has certain advantages in maintaining cleanliness. Table 2 is the comparison of surface particulates after vacuum clamping with the O-ring rubber. From the dark field scanning results, it can be seen that, the amount of particulates has increased a lot, but for the whole surface of Nd:glass, the amount of particulates meets the requirement of Level 50.

**Mechanical optimization**

From the analysis of section “Mechanical properties,” it can be seen that the higher the hollowness, the smaller the contact force required to form initial seal. However,
the larger the hollowness, the more difficult it is to maintain the stability of its shape, this problem also increases the uncertainty of the required amount of deformation. Therefore, this phenomenon can be modified by changing the hollowness.

**Figure 11.** Breakage mechanism of film under the stress of O-ring rubber. Most of the film debris on the bare substrate are carried away by the sealing rubber ring. When the sealing rubber ring is continuously compressed, it tends to expand in the lateral direction which also damages the film, and the resulting debris remains on the optical surface.

**Figure 12.** Sizes of debris under the stress of O-ring rubber.

the larger the hollowness, the more difficult it is to maintain the stability of its shape, this problem also increases the uncertainty of the required amount of deformation. Therefore, this phenomenon can be modified by changing the hollowness.
distribution in the seal material. The O-ring rubber contacts Nd:glass in line at the beginning, the stress concentration tends to appear. Then, the O-ring rubber is replaced by a rectangular honeycomb seal material, just like sponge, as shown in Figure 13. At the same time, in order to ensure the cleanliness during assembly, the surface of the sponge material has a thin layer of fluoro rubber, which contacts Nd:glass directly. Besides, the measuring equipment and experimental methods are the same as in Figure 2.

In order to analyze the finite element model of the honeycomb structure, 5161 points and 1385 elements are applied on the 2D model, and it has the same material properties and constraints as section “Finite element model.” It can be seen from the simulation results that the maximum equivalent strain of the honeycomb structure appears at thinnest parts which connect the adjacent voids, as shown in Figure 14. While the maximum equivalent stress on the surface of Nd:glass appears at the thickest parts of honeycomb structure on the contrary. Compared with the O-ring rubber, the maximum equivalent stress on the surface of Nd:glass brought by honeycomb structure decreases greatly, as shown in Figure 15, while honeycomb structure has a significantly increased strain with the same compression conditions and same hollow-ness, as shown in Figure 16. This is because most of the energy from the compression is stored in the honeycomb structure, and only a small amount of energy will be transferred to the Nd:glass. As a result, the maximum equivalent stress decreases.

| Range of particle diameter $d/\mu m$ | Debris | Comparison | Level 50 (standard) |
|-----------------------------------|--------|------------|---------------------|
| >50                               | 0      | =          | 0                   |
| >20                               | 65     | <          | 79                  |
| >10                               | 316    | <          | 369                 |

Figure 13. Optimized geometric model of vacuum clamper and measurement experiment.
In order to verify the clamping performance of the honeycomb structure, 75% hollowness sponge is used as the experimental object, and the vacuum degree is set to 100 mbar. From the experimental results, as shown in Figure 17, it can be seen that when the vacuum clamper approaches the Nd:glass at a speed of 1, 5, and 10 mm/s, the maximum contact forces are 512, 515, and 518 N. So, the initial seal forces are 2 N (512–510 N), 5 N (515–510 N), and 8 N (518–510 N), respectively. Vacuum clamper with a sponge seal structure decreases initial seal force obviously when it is compared with the results in Figure 8. This shows that the experimental results are consistent with the simulation results.

**Figure 14.** Equivalent stress distribution of honeycomb structure and Nd:glass.

**Figure 15.** Maximum equivalent stress on Nd:glass compressed by O-ring rubber and honeycomb structure.

In order to verify the clamping performance of the honeycomb structure, 75% hollowness sponge is used as the experimental object, and the vacuum degree is set to 100 mbar. From the experimental results, as shown in Figure 17, it can be seen that when the vacuum clamper approaches the Nd:glass at a speed of 1, 5, and 10 mm/s, the maximum contact forces are 512, 515, and 518 N. So, the initial seal forces are 2 N (512–510 N), 5 N (515–510 N), and 8 N (518–510 N), respectively. Vacuum clamper with a sponge seal structure decreases initial seal force obviously when it is compared with the results in Figure 8. This shows that the experimental results are consistent with the simulation results.
From the aforementioned analysis, it is found that the use of a honeycomb structure can form the initial seal under a low contact force, and it is in good agreement with the engineering requirements. The time from the contact critical state to the stable adsorption of Nd:glass is used as a measure of the clamping performance. As can be seen from Figure 18, when the vacuum degree is increased, the time required to form a stable adsorption decreases, especially when the vacuum degree increases from 100 to 300 mbar. However, when the vacuum degree is greater than 400 mbar, there is no significant decrease in time. Therefore, 400 mbar is a proper degree of...
vacuum, which can not only reduce the impact force on Nd:glass but also improve assembly efficiency.

**Comparison of cleanliness after optimization**

When the distributions of film debris between Figures 9 and 19 are compared, honeycomb structure sponge has a larger contact area with Nd:glass, so the stress on per area is smaller. Through SEM images which are enlarged by 10,000 times, Figures 20 and 21 show the damage morphology of SiO₂ sol–gel film and the size of the debris under the stress of honeycomb structure sponge. It also can be seen that when the sealing sponge is continuously compressed, crack propagation occurs in the SiO₂ sol–gel film, then optical film becomes tiny debris and they detach from the substrate. Most of the film debris is carried away by the honeycomb structure sponge at last. From the point of the size of debris, as shown in Figure 21, most of the debris is below 10 μm. Table 3 is the comparison of surface particulates after vacuum clamping with honeycomb structure sponge. The dark field scanning results show that the amount of particulates has increased. When it is compared with Table 2, it is found that the amount of particulates larger than 10 μm has

---

**Figure 18.** Clamping time in different vacuum degrees.

**Table 3.** Particulates stressed by honeycomb structure sponge on the Nd:glass surface (6.6 ft²).

| Range of particle diameter d/μm | Debris | Comparison | Level 50 (standard) |
|---------------------------------|--------|------------|--------------------|
| >50                             | 0      | =          | 0                  |
| >20                             | 48     | <          | 79                 |
| >10                             | 204    | <          | 369                |
decreased a lot. At the same time, for the whole surface of Nd:glass, the amount of particulates also meets the requirement of Level 50.

**Conclusion**

During assembly of large-aperture Nd:glass, in order to decrease initial contact seal stress on Nd:glass coated with SiO₂ sol–gel film and effectively control the surface contaminants from film debris induced by stress, a low-stress and low-contamination clamping method is proposed by increasing the hollowness of the seal ring. Numerical analysis shows that the higher the hollowness, the lower the stress on the surface of the Nd:glass. Through mechanical experiment, the results show that the impact force on the surface of large-aperture Nd:glass is not only related to the hollowness of the seal ring but also related to the vacuum degree. Therefore, proper vacuum degree can effectively decrease the impact force. From the SEM images of the SiO₂ sol–gel film, the damage mechanism is analyzed. Based on this, the optimization of the assembly stress is conducted. By optimizing the distribution of hollowness in the seal material,

![Figure 19](image.png)

*Figure 19.* Distribution of film debris under the stress of honeycomb structure sponge: (a) before adsorption and (b) after adsorption.
it is found that the honeycomb hollow structure is able to achieve a flexible assembly method with a lower initial seal force. The results of the cleanliness experiment and SEM images also show that the low-stress vacuum clamping method can meet the requirements of cleanliness.

Figure 20. Breakage mechanism of film under the stress of honeycomb structure sponge. When the sealing sponge is continuously compressed, crack propagation occurs in the SiO₂ sol–gel film, then optical film becomes tiny debris and they detach from the substrate. Most of the film debris are carried away by the honeycomb structure sponge at last.

Figure 21. Sizes of debris under the stress of honeycomb structure sponge.

it is found that the honeycomb hollow structure is able to achieve a flexible assembly method with a lower initial seal force. The results of the cleanliness experiment and SEM images also show that the low-stress vacuum clamping method can meet the
requirements in particulates from film debris. From the aspects of hollowness, adsorption speed, and vacuum degree, this article provides meaningful suggestions for the clean assembly of large-aperture Nd:glass, which also provides reference for assembly of large-aperture windows, lenses, crystals, and other coated optical components in high-power laser facilities.

Acknowledgements
The authors also appreciate the contributions and efforts of the researchers and engineers in the Research Center of Laser Fusion, China Academy of Engineering Physics.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported in part by National Natural Science Foundation of China (51575310), National Natural Science Foundation of China (51975322), and National Key Research and Development Plan of China (2016YFF0101907).

ORCID iD
Zheng Zhang https://orcid.org/0000-0003-2123-6592

References
1. Ren ZY, Zhu JQ, Liu ZG, et al. Optimizing the cleanliness in multi-segment disk amplifiers based on vector flow schemes. High Power Laser Sci Eng 2018; 6: e1.
2. Wang H, Zhang Z, Long K, et al. Back-support large laser mirror unit: mounting modeling and analysis. Opt Eng 2018; 57(1): 015109.
3. Spaeth ML, Manes KR and Honig J. Cleanliness for the NIF 1ω laser amplifiers. Fusion Sci Technol 2016; 69(1): 250–264.
4. Li SS, Wang YL, Lu ZW, et al. Hundred-Joule-level, nanosecond-pulse Nd:glass laser system with high spatiotemporal beam quality. High Power Laser Sci Eng 2016; 4: e10.
5. Pryatel JA, Gourdin WH, Frieders SC, et al. Cleaning practices and facilities for the National Ignition Facility (NIF). In: Proceedings of the SPIE, laser-induced damage in optical materials, Boulder, CO, 14–17 September 2014.
6. Yang L, Xiang X, Miao X, et al. Influence of outgassing organic contamination on the transmittance and laser-induced damage of SiO2 sol-gel antireflection film. Opt Eng 2015; 54(12): 126101.
7. Suratwala TI. Review of anti-reflection sol-gel coatings in high energy lasers, 2016, https://e-reports-ext.llnl.gov/pdf/819427.pdf
8. Long K, Pei GQ, Yi CZ, et al. Optimization of large-aperture optics clean assembly method. In: *Proceedings of the SPIE 10847, optical precision manufacturing, testing, and applications*, Beijing, China, 22–24 May 2018.

9. Stowers IF. Optical cleanliness specifications and cleanliness verification. In *Proceedings of the SPIE 3782 optical manufacturing & testing III*, Denver, CO, 18–23 July 1999.

10. Cheng W and Farhang K. A model for contaminant transport in lubricated contact of rough surfaces. In: *Proceedings of the STLE/ASME 2006 international joint tribology conference*, San Antonio, TX, 23–25 October 2006.

11. Pryatel JA, Gourdin WH and Gourdin WH. Clean assembly practices to prevent contamination and damage to optics. In: *Proceedings of the SPIE laser-induced damage in optical materials*, Boulder, CO, 19–21 September 2006.

12. Horvath JA. Assembly and maintenance of full-scale NIF amplifiers in the Amplifier Module Prototype Laboratory (AMPLAB). In: *Proceedings of the third international conference on solid state lasers for application to inertial confinement fusion*, Monterey, CA, 7–12 June 1998, vol. 3492, pp. 601–608. Bellingham, WA: SPIE.

13. Ke YC, Yao XF, Yang H, et al. Gas leakage prediction of contact interface in fabric rubber seal based on a rectangle channel mode. *ASLE Trans* 2016; 60(1): 146–153.

14. Zhou CL, Zheng JY, Gu CH, et al. Sealing performance analysis of rubber O-ring in high-pressure gaseous hydrogen based on finite element method. *Int J Hydrogen Energ* 2017; 42(16): 11996–12004.

15. Tan J, Yang WM, Ding YM, et al. Finite element analysis of rectangular rubber seals. *Lubr Eng* 2007; 32(2): 36–39.

16. Liao BP, Sun B, Yan MC, et al. Time-variant reliability analysis for rubber O-ring seal considering both material degradation and random load. *Materials* 2017; 10(10): 1211.

17. Shen MX, Peng XD, Meng XK, et al. Fretting wear behavior of acrylonitrile–butadiene rubber (NBR) for mechanical seal applications. *Tribol Int* 2016; 93: 419–428.

18. Shen J, Liu Y, Wu GM, et al. Sol-gel derived contamination resistant antireflective coatings. In: *Proceedings seventh international conference on thin film physics and applications*, Shanghai, China, 24–27 September 2010.

19. Shao JD, Dai YP and Xu Q. Progress on the optical materials and components for the high power laser system in China. *Proc SPIE* 2012; 8206(1): 2.

20. Zhou CL, Chen GH and Liu PF. Finite element analysis of sealing performance of rubber D-ring seal in high-pressure hydrogen storage vessel. *J Fail Anal Prev* 2018; 18: 846–855.

21. Wang W and Deng T. Determination of material constants for Mooney-Rivlin rubber model. *Spec Purp Rubber Prod* 2004; 58: 241–245.

22. Liang YC, Su RF, Liu HT, et al. Analysis of torque mounting configuration for nonlinear optics with large aperture. *Opt Laser Technol* 2014; 58(6): 185–193.

23. Yang CM and Xie YJ. Ansys analysis of the sealing performance of rubber O-sealing ring. *Elastomer* 2010; 20(3): 49–52.

**Author biographies**

Hui Wang is an associate professor in the Department of Mechanical Engineering, Tsinghua University, China. He received his BS and MS degrees in mechanical engineering from Northwestern Polytechnical University in 2000 and 2003, respectively, and his PhD in...
mechanical engineering from Tsinghua University in 2007. He also spent 2 years in Worcester Polytechnic Institute for postdoctoral research. His current research interests include computer-aided precision manufacturing, optical assembly, and optomechanical analysis.

Kai Long is a master student in the Department of Mechanical Engineering, Tsinghua University, China. He received his BS degree in mechanical engineering from Beijing Jiaotong University in 2016. His current research interests include assembly automation, mounting design and opto-mechanical analysis.

Zheng Zhang is a PhD candidate in the Department of Mechanical Engineering, Tsinghua University, China. He received his BS degree in mechanical engineering from Shandong University in 2015. His current research interests include surface control, adaptive Nd: glass, precision assembly and opto-mechanical analysis.

Congzhi Yi is a research assistant at the Research Center of Laser Fusion, CAEP, Mianyang, China. Her current research interests include clean assembly of large-aperture optical component, clean precision measurement, and low-stress clamping method.

Xusong Quan is a research assistant at the Research Center of Laser Fusion, CAEP, Mianyang, China. He received his BS and MS degrees in mechanical engineering from Beijing Institute of Technology in 2012 and 2015, respectively. His current research interests include opto-mechanical precision assembly-rectification, precision measurement, and opto-mechanical analysis.

Guoqing Pei is a research assistant at the Research Center of Laser Fusion, CAEP, Mianyang, China. He received his BS and MS degrees in mechanical engineering from Harbin Institute of Technology in 2015 and 2017, respectively. His current research interests include clean clamping of large-aperture optical component, low-stress clamping method, and precision measurement.