Thermal deformation analysis of Spliced high energy laser emission window

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Abstract. When laser work continuously, laser and external environment will cause damage to the laser window. The paper analyses the working environment of the equipment and the main factors that cause the window damage. Emulate mirror deformation of the laser emission window under the coupling of force and heat, fit the shape change law of different material windows in force thermal coupling by MATLAB. The results show that high energy laser will have a serious influence on the surface microstructure of windows, splicing window can greatly reduce the influence of window deformation on laser emission, ZnSe characteristic of materials is best suited for producing wide band iraser emission windows.

1. Introduction
High energy laser is widely used in laser drilling, Machining and Material surface modification. window is the key component to ensure the normal operation of laser emission equipment[1,2]. The window protects the interior of the device from the outside environment[2-4],enhances the environmental adaptability of the equipment and improves the service life and reliability of the equipment. The thermal deformation occurs when the window absorbs the laser energy, which causes the wavefront distortion [4,5], the center shift of the laser beam and affects the laser beam quality and transmission characteristics. When the thermal damage beyond the material damage threshold will produce a series of irreversible, such as oxidation, hot melt breakage[6-8], stress and microstructure of the material will produce corresponding changes such as the change of phase inter phase coupling and micro crack propagation[9,10]. Splicing window can effectively improve the stiffness of the window, reduce the window thickness, increase the window cooling and reduce the laser heat deposition and window temperature rise. Paper analysis a splicing high energy laser emission window according to actual engineering needs, the temperature distribution of splicing window and ordinary window is simulated by finite element software, The material property of common light materials in windows are analysed, the thermal deformation of different material windows is fitted by MATLAB. The results of the correlation analysis can provide the design basis for the engineering application of the splicing window.

2. Window design and calculation
2.1. Window structure design
The basic structure of the splicing window is shown in Figure 1, the window is made up of 5 SnSe lenses, the center is a circular lens with a diameter of 160mm, the outer layer is four inner diameter 80mm outer diameter 320mm fan-shaped lens, The round lens has low laser capacity and is rigidly fixed. The fan-shaped lenses bear high laser energy and are supported by flexible hinges to reduce the thermal stress of the lenses.

![Figure 1. Sketch map of spliced laser emission window.](image)

2.2. Analysis of laser emission windows working environment
The working environment of the splicing window is shown in figure 2. After the high energy laser beam enters the laser launcher, 80% of the capacity is reflected into the sector lens through the primary mirror, 20% of the energy passes through the center of the mirror into the round lens. The working environment of the high energy laser emission system is shown in Figure 3, the inner window is mainly affected by high energy laser beam, the outside is mainly affected by the environmental medium in the equipment working environment, When the window surface temperature is lower than the material damage threshold, the influence of high energy laser beams on windows is dominated by thermal deformation, When the temperature in the irradiated area reaches a certain critical point, irreversible oxidation such as oxidation, melting and gasification will occur in the window. The mirror damage on the inner side of the window is mainly caused by the thermal deformation of the high energy laser beam, Outside the window is the atmosphere, the air flow quickly and equipped with cooling air to assist cooling, the mirror surface thermal deformation can be neglected.

![Figure 2. Spliced window working environment.](image)

2.3. Analysis of influence of machining accuracy on laser beam
Mosaic window is spliced by lens, when there is a parallel deviation behind the window, it will produce a prism effect on the emitted laser, which will affect the pointing accuracy of the laser. The relation between the divergence angle $\theta$ of the beam and the window thickness and the parallelism between the front and back surfaces is shown in Figure 3, $\alpha$ is the angle of inclination resulting from
the installation error of the window, $\alpha + \beta$ is the deviation of the parallel between the front and back surfaces of the window, $r_i$ and $r_3$ is incidence angle, $r_2$ and $r_o$ exit angle, $r_4$ is divergence angle, $h$ is the thickness of the window at the incident point.

![Diagram of the beam window](image)

**Figure 3.** Affect the surface shape of the beam window

According to the sine theorem:

$$\frac{\sin r_i}{\sin r_o} = \frac{\sin r_i}{\sin (r_o)} = \frac{n_0}{n_i}$$

(1)

The actual values of each angle in Fig. 3 are small, therefore equation 2 can be simplified as:

$$\frac{r_2}{r_i} = \frac{r_3}{r_o} = \frac{n_0}{n_i}$$

(2)

According to the relationship between the outside and inside of the triangle:

$$r_3 = \alpha + \beta - r_2 = \alpha + \beta - \frac{n_0}{n_i} r_i$$

(3)

$$r_0 = \frac{n_0}{n_i} \beta + (\frac{n_1}{n_0} - 1) \alpha$$

(4)

$$r_4 = \frac{(n_1 - n_0)(\beta + \alpha)}{n_0}$$

(5)

In equation $n_1$ is the refractive index of laser beam in window material, ZnSe’s refractive index of the output laser beam is about 2.328, $n_0$ is refractive index of laser beams in air, It can be seen by type 5: the beam divergence angle is about 1.328 times of the parallelism error before the window, which is independent of the window thickness and the installation error.

3. Thermal deformation simulation of laser emission window

3.1. Boundary condition analysis

Window surface heat flux:

$$q = h \cdot (T_c - T_0) + \alpha \varepsilon \sigma (T_c^4 - T_0^4)$$

$$= \frac{k}{A} \left( \frac{g \beta c T_s - T_0 - \rho c}{v} \right)^{1/4} \cdot (T_c - T_0) + \alpha \varepsilon \sigma (T_c^4 - T_0^4)$$

(6)

In equation $\rho$ is air density, $c$ is specific heat of air, $T_0$ is initial temperature of environment, $T_c$ is actual temperature of window surface, $\alpha$ is radiation coefficient, $\varepsilon$ is emissivity, $\sigma$ is stefan-biltmann
constant, \(\sigma = 5.669 \times 10^{-4} \text{W/(cm}^2\text{K}^4\)), \(h_{sg}\) is window surface heat exchange coefficient. According to equation 6, the main factors affecting the heat flux on the window surface are the thermodynamic properties of the material, the velocity of the air at the window surface and the power density of the emitted laser. There are 5m/s cooling air flow both inside and 15m/s cooling air flow outside the window. Therefore, when the laser power density is fixed, the main factor affecting the heat flux of the window surface is the thermodynamic properties of the window material.

3.2. Light intensity distribution of high energy laser beam

The laser for high order Gauss beams, the distribution of electric field strength meet the electric field distribution of Hermite Gauss beam:

\[
E(x, y, z) = \frac{A_{mn} w_0}{w(z)} H_m \sqrt{2} \frac{x}{w(z)} H_n \sqrt{2} \frac{y}{w(z)}
\]

\[
= \exp \left[ -\frac{x^2 + y^2}{w^2(z)} - i \frac{k(x^2 + y^2)}{2R(z)} \right] \cdot \exp \left\{ -i[kz - \phi(z)] \right\}
\]

In equation \(w\) is emission laser spot radius, The distribution law of laser light intensity and electric field intensity satisfies the following relation:

\[
I_0 = \frac{1}{2} \left( \frac{\varepsilon_0 R^2}{\mu_0} \right)^{1/2} E^2
\]

In equation, \(n\) is refractive index of a window emitting laser, \(\varepsilon_0 = 8.854 \times 10^{-12} \text{F/M}\), is Positive dielectric constant of a laser beam; \(\mu_0\) is vacuum permeability. Refractive index, vacuum dielectric constant and vacuum permeability are constant, Therefore, the intensity distribution of the window surface is proportional to the square of the electric field intensity of the emitted laser. The power density distribution of laser can be obtained by MATLAB fitting, as shown in Figure 4.

![Power density (W/cm²)](image)

**Figure 4.** Emission laser power density distribution

3.3. Thermal mechanical coupling analysis and surface shape matching

First of all, assume the ambient temperature is 55 °C, the window material is ZnSe, the absorption coefficient of the light source is 5 \(\times 10^{-3}\)/cm, the absorption coefficient of the surface coating is 2.3 \(\times 10^{-3}\), the laser power is 11000 watts, the 10.6 m laser is 10000 watts and the 6.6 m laser is 1000 watts. According to the distribution law of laser power density calculated by equation 8, The thermal load is applied to the window physical model to fit the temperature field of the thermal deformation of the window, Heat cell types are converted into structural units using sequential coupling method, the gravity load \(G\), the wind pressure load \(Q\) and the corresponding boundary condition are applied to the finite element model. Finally, the distribution pattern of the splicing window and the common window surface is fitted, as shown in Figure 5.
As can be seen from Fig5: The center deformation of sector lens is larger and the deformation of edge is smaller. The main reason is that the intensity distribution of laser is too strong and weak. The deformation of each sub lens’ edges is small, and the deformation of the fan-shaped lens’ edge is approximately zero, mainly because of the mechanical stress of the clamping mechanism. Due to the occlusion of the laser beam by the secondary mirror bracket, the shape of the window surface is not uniformly distributed along the corner direction. The amplitude of the window shape along the corner is less than 0.1μm. Using the same method, the surface distribution of the conventional whole window is obtained, as shown in Figure 6.

As shown in Fig6: the change of the shape of the conventional whole window is about two times that of the mosaic window, The maximum deformation is at the center of the window, this is mainly because the window center is slow to cooling and the heat is easy to assemble.

4. Thermal deformation analysis of infrared window materials

Test results show: the properties of common window materials and materials used in wide band infrared laser transmitting windows are shown in Table 1.

| Material | Density (g / cm$^3$) | Melting point (°C) | Coefficient of thermal expansion (1/k) | Thermal conductivity (W/m·K) | Wavelength range (μm) | absorption coefficient (l/cm) | Thermal coefficient (dn/dt) |
|----------|----------------------|-------------------|--------------------------------------|-----------------------------|-----------------------|-------------------------------|-----------------------------|
| ZnSe     | 5.27                 | 1525              | 7.1e$^{-6}$                          | 18.0                        | 0.5~22                | 2e$^{-4}$                     | 6.1e$^{-5}$                 |
| ZnS      | 4.09                 | 1827              | 6.6e$^{-6}$                          | 16.7                        | 1~14                 | 3.2e$^{-4}$                   | 4.1e$^{-5}$                 |
| CaF$_2$  | 3.18                 | 1360              | 18.8e$^{-6}$                         | 9.71                        | 0.13~10               | 2.2e$^{-4}$                   | 15e$^{-6}$                  |
| GaAs     | 5.32                 | 1238              | 5.7e$^{-6}$                          | 55                          | 1~14                 | 1e$^{-2}$                     | 13e$^{-5}$                  |
| Ge       | 5.33                 | 936               | 6.1e$^{-6}$                          | 58.61                       | 2~12                 | 2.3e$^{-2}$                   | 4.1e$^{-4}$                 |

Table 1 shows in many window materials: ZnSe absorption coefficient is the lowest, through a wide range of wavelength, the best overall performance. ZnS have the highest melting point, coefficient of thermal expansion is smaller than ZnSe, but absorption coefficient is bigger than ZnSe. GaF$_2$ have the lowest transmittance after ZnSe in near infrared band, but GaF$_2$’s Coefficient of thermal expansion is high. GaAs and Ge’s optical properties are lower than that of the above three kinds of materials. The thermal deformation of the window is analyzed by using the characteristics of the materials mentioned above, and the deformation is fitted by the Zernike polynomial. The distribution law of the shape of the window surface along the radius is fitted as shown in Figure 7.
5. Conclusions

According to the above analysis, we can draw the following conclusions: 1) The thermal deformation of the splicing window is only half of the normal window, 2) The laser emission window made by ZnSe has the least thermal deformation, followed by ZnS, and and CaF2, and GaAs, and and Ge have the most serious thermal deformation.

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Acknowledgments

Fundamental Research Funds for the Central Universities (15CX02123A). The authors greatly appreciate the financial support of the National Natural Science Foundation of China (51405511) and the Fundamental Research Funds for the Central Universities (16CX02005A)