Influence of roundness error of hohlraum on assembly stress for TMP component of target

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Abstract. In order to solve the problem of uneven distribution of assembly stress in thermal-mechanical package (TMP) component, the influence of the roundness error of hohlraum on the assembly stress of TMP component is studied. Firstly, five sets of hohlraum contour models with different random roundness errors are described by Hermite interpolation method, a three-dimensional model of hohlraum with random roundness error is established by inverse modeling method. Then, the contact nonlinear solution is solved for the hohlraum and the aluminum shell of the five groups of TMP component by finite element method. Finally, the five sets of simulation data is obtained and the polynomial fitting is performed, the relationship between the roundness error of the hohlraum and the maximum stress-strain of the TMP component is obtained. The conclusions provide a theoretical basis for the strength check of the hohlraum contact design, and provide theoretical guidance and technical support for a reasonable hohlraum assembly process.

1. Introduction
During the machining process, the shape error will inevitably occur, and the shape error distribution of the parts will be uneven, which will cause non-uniform contact between the parts during assembly [1]. In addition, inaccurate control of the size of the assembly force can also cause a non-uniform contact stress field in the assembled part. When the parts are assembled, if there is an interference fit between the parts, the shape error will seriously affect the assembly stress distribution state of the assembly, and influencing the stability of the structure [2]. If the parts are gap-fitted, the shape error will accelerate local wear and shorten the working life of the parts. For precision assembly structures such as ICF targets, the distribution state of the assembly stress is more sensitive to the shape error of the part and has a significant impact on assembly accuracy and structural stability [3, 4, 5].

The object of this study is the TMP component in the inertial confinement fusion (ICF) target, which is assembled by 9 parts [6]. The hohlraum belongs to the deep thin-walled part, its wall thickness is only 0.1 mm, and its roundness error can significantly affect the assembly stress distribution state of the TMP component, thus affecting the structural stability of the ICF target. Therefore, the influence of the roundness error of the hohlraum on the assembly stress of the TMP component is studied, and the mapping relationship between the roundness error of the hohlraum and the maximum stress of the assembled TMP component is obtained, which provides theoretical guidance and technical support for the assembly of ICF key components [7].
2. Modeling of random roundness error in hohlraum

The roundness error of the hohlraum will affect the interference fit property of the hohlraum and the aluminum shell. The hohlraum will cause random variation of the roundness error of the surface during processing. The roundness error of the hohlraum affects the interference fit characteristics of the hohlraum and the aluminum shell. The hohlraum will have a random variation in surface roundness during processing, which results in uneven contact between the hohlraum and the aluminum shell surface. In this paper, a three-dimensional model of hohlraum is established by considering the randomness of the roundness error of the hohlraum.

2.1. Establishment of the round contour model of hohlraum

According to the roundness error range of the hohlraum, the maximum outer circle radius of the hohlraum is $\theta = R$, the minimum inner circle radius is $r$, the roundness tolerance is $\delta = R - r$, and the hohlraum actual diameter size is $d = 4.570 \text{mm}$, and the interference is $0.001 \text{mm}$. Assume that the sequence of radial discrete values of the roundness error of the hohlraum is $f_k (k = 1, 2, \ldots, n, n \in N)$, and the corresponding polar coordinate is $\theta_k (k = 1, 2, \ldots, n, n \in N)$, the coordinates of the discrete points are $(\theta_k, f_k)$, $\theta_k$ is an equidistant distribution, and the ordinate satisfies the $f_k$ mixed congruence theory:

$$f_k = (a f_{k-1} + c) (\text{modm})$$  \hspace{1cm} (1)

The uniform distribution is selected as the distribution method of random points. According to the mixed congruence method theory and the rand function in MATLAB, the distribution interval of random points is $[0, 0.003]$ (mm), and the roundness tolerance is $\delta = \frac{R - r}{2} = 0.003$ (mm). The piecewise cubic Hermite interpolation method is adopted, and the model description of the circular outer contour is obtained by the interpolation point. The interpolation function $f(\theta)$ satisfies the following conditions:

$$f_k(\theta) \in [\min(f_k, f_{k+1}), \max(f_k, f_{k+1})]$$  \hspace{1cm} (2)

$$f_k(\theta_k) = f_k, f_{k+1}(\theta_{k+1}) = f_{k+1}$$  \hspace{1cm} (3)

$$\dot{f}_k(\theta_k) \in 0 (k = 1, 2, \ldots, n)$$  \hspace{1cm} (4)

The expression of $f_k(\theta)$ on the interval $[\theta_k, \theta_{k+1}]$ is:

$$f_k(\theta) = \left(\frac{\theta - \theta_{k+1}}{\theta_k - \theta_{k+1}}\right)^2 \left[1 + 2 \frac{\theta - \theta_k}{\theta_{k+1} - \theta_k}\right] f_k + \left(\frac{\theta - \theta_k}{\theta_{k+1} - \theta_k}\right)^2 \left[1 + 2 \frac{\theta - \theta_{k+1}}{\theta_k - \theta_{k+1}}\right] f_{k+1}$$  \hspace{1cm} (5)

$k = 1, 2, \ldots, n - 1$ in the formula

According to the random function in MATLAB, the interpolation point coordinate value $(\theta_k, f_k)$ is obtained. And the five interpolation points are substituted into the interpolation function respectively to obtain the interpolation function fitting curve, and the polar coordinate system is converted into the Cartesian coordinate system, the circle is obtained and shown in Figure 1, the radius of hohlraum is $d = 4.590 \text{mm}$.

The distribution intervals of random points are changed to $[0, 0.004]$, $[0, 0.005]$, $[0, 0.006]$, and the above steps are repeated to obtain the hohlraum outer contour model under different random roundness errors. The difference is shown in Table 1.

Table 1. Maximum value of roundness tolerance.

| Distribution interval of random points /mm | Maximum value of roundness tolerance /mm |
|------------------------------------------|----------------------------------------|
| [0, 0.003]                               | 0.0018                                 |
| [0, 0.004]                               | 0.0025                                 |
| [0, 0.005]                               | 0.0040                                 |
| [0, 0.006]                               | 0.0052                                 |
2.2. Establishment and assembly of three-dimensional model of hohlraum

A three-dimensional model of hohlraum is established by means of the reverse modeling method in Creo. The three-dimensional model of the hohlraum is shown in Figure 2.

The first step of target assembly is to insert the aluminum shell into the silicon arm jaws, and ensure the coaxiality between the silicon arm jaws and the aluminum shell is less than 2um. The second step is to assemble the hohlraum and the aluminum shell, the coaxiality between the hohlraum and the aluminum shell is required to be less than 3 um. It is not possible to fix the aluminum shell and the hohlraum by bonding, that need an interference fit to fix the parts [8]. The three-dimensional model of the TMP component is shown in Figure 3.
3. Analysis of assembly mechanical properties of hohlraum

3.1. Boundary conditions

The stress magnitude of the TMP component and the hohlraum is analyzed based on the fourth intensity theory. The equivalent stress and equivalent strain clouds of the TMP components with five random roundness errors of hohlraum are obtained. The hohlraum material is uranium, the silicon arm material is silicon, and the aluminum shell material is aluminum. The material parameters are shown in Table 2.

Table 2. The material parameters.

| Components | Elastic Modulus /GPa | Poisson's Ratio | Yield Strength /MPa |
|------------|----------------------|-----------------|---------------------|
| hohlraum   | 190                  | 0.22            | 200                 |
| aluminum shell | 110              | 0.34            | 20-90               |
| silicon arm | 112.4               | 0.25            | 2600                |

The contact nonlinear solution is solved by Workbench, and the deformation and stress distribution at any point on the contact body are obtained quickly and accurately. In the actual assembly process, the contact surface of the hohlraum and the aluminum shell will be slightly relative to each other due to the interference deformation and the force. Therefore, the frictional contact between the two is set to 0.2. Apply full constraint to the contact surface of the silicon arm jaws to ensure the correctness and accuracy of the simulation results. Meshing the contact area by means of the Sweep method, and the contact lines of two parts are divided into 200 parts [9, 10].

3.2. Simulation results and analysis

3.2.1. Hohlraum without roundness error. Figure 4 shows the equivalent stress and equivalent strain distribution in the case of the hohlraum without roundness error. The interference is 0.001 mm. The maximum equivalent stress appears in the root of the hohlraum. The maximum equivalent stress value is 162.08 MPa, lower than the failure strength of hohlraum. The maximum equivalent stress of the hohlraum gradually decreases from the root to the bottom, because the wall thickness of the aluminum shell gradually decreases from the root of the shell to the port, and the influence of interference stress gradually becomes larger. On the contrary, from the root to the port of hohlraum, the influence of interference stress is gradually reduced, so the maximum strain position appears at the port of the aluminum shell, and the maximum strain value is 0.00183391 mm.

![Figure 4](image)
3.2.2. Hohlraum has a roundness error. The TMP components with random roundness error are analyzed by Workbench. The fourth set of equivalent stress-strain distribution clouds is shown in Figure 5. The maximum equivalent stress appears at the root of the hohlraum, this position contains a random roundness error. The maximum stress value is 215.57 MPa, higher than the yield strength of hohlraum, and hohlraum produces plastic deformation. The maximum deformation position at the hohlraum port, the figure shows that the maximum strain value is 0.016 mm.

![Equation](image)

\[
\sigma_{\text{max}} = A_\sigma e^3 + B_\sigma e^2 + C_\sigma e + D_\sigma
\]

\[
\varepsilon_{\text{max}} = A_\varepsilon e^2 + B_\varepsilon e + C_\varepsilon
\]

\(\sigma_{\text{max}}\) is the maximum equivalent stress, \(e\) is the roundness tolerance, \(\varepsilon_{\text{max}}\) is the maximum equivalent strain. \(A_\sigma=2.325, B_\sigma=-0.09776, C_\sigma=23.17, D_\sigma=200.4, A_\varepsilon=716, B_\varepsilon=0.3428, C_\varepsilon=0.001505\).

The fitting results are shown in the Figure 6.

The blue dashed line in Figure 6(a) is the data curve of the stress, and the red curve is the fitting curve of the stress. The blue dashed line in Figure 6(b) is the data curve of the strain, and the red curve is the fitting curve of the strain. The maximum equivalent stress-strain of the hohlraum increases with the increase of the roundness error. When the roundness error reaches 0.0023 mm, the maximum equivalent stress reaches 200 MPa. If the roundness error continues to increase, the maximum stress will exceed the yield limit of hohlraum and cause plastic deformation. It can be concluded from the figure that when the roundness error is less than 0.0023, the maximum equivalent strain increase rate...
is stable, and when the roundness error exceeds 0.0023 mm, the rate of increase of the maximum equivalent strain will increase due to plastic deformation of the hohlraum.

![Stress data curves](image1)

![Fitted curve](image2)

**Figure 6.** Equivalent stress-strain fitting results.

4. Conclusions
Random points in the distribution interval are obtained by the uniform distribution method and the mixed congruence method theory. The model description of the outer contour of the hohlraum roundness is obtained by the piecewise cubic Hermite interpolation method. Finally, using the reverse modeling method in Creo, a three-dimensional model of hohlraum with random roundness error is established.

The contact nonlinearity of the contact state of hohlraum and aluminum sleeve is solved by Workbench, and the equivalent stress-variation distribution cloud diagram of TMP component is obtained. The polynomial is used to fit the simulation result data to obtain the mapping relationship...
between the holhlauum random roundness error and the maximum stress of the assembled TMP component.

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