A New Solving Method of the Athermal Bonding Thickness in Lens Mount

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Abstract: Adhesives are widely used in the design of optical and mechanical structures. For optics fixed by adhesive bonding, the mismatch of the thermal expansion coefficient of the materials among the lens, the adhesive layer and the frame will bring thermal stress in the radial direction of the lens, which will affect the imaging of entire optical system. Studies have shown that by changing the thickness of the adhesive layer can reduce or even eliminate the radial stress caused by temperature changes, so it is critical to obtain the thickness with low(zero) radial stress. Based on the derivation of the existing athermal bond thickness equation, this paper proposes a new bonding layer constraint condition assumption, introduces the thermal expansion coefficient scale factors $k_1$, $k_2$, and derives a novel athermal bond thickness equation. Then, using the finite element method, the thermal stress simulation analysis of two adhesive lens assemblies with different count materials is solved, by comparing the simulated value with the analytical solutions, it’s found that the errors of both are within 10%, which shows that the newly derived equation has sufficient accuracy to meet the needs of engineering application.

1. Introduction

Correctly fixing the lens and mirror on the supporting structure is one of the main considerations in the opto-mechanical design. The optoelastic effect caused by thermal stress has become a major concern. The mismatch of the thermal expansion coefficients of glass, RTV and metal substrates can cause stress on the optical components. Most RTVs are almost incompressible, so the stress can build up in thin layers of these materials, which makes the problem worse\cite{1}. Choosing the right bonding material and bonding thickness can minimize or even eliminate the effects of thermal stress. How to solve equation athermal bond thickness is critical.

The problem of athermal bonding thickness was first proposed by Bayar\cite{2}, and then several articles discussed it with series of analytical equations derived. On the basis of earlier studies, this paper proposed a new constraint condition assumption of bonding layer, and then, using the finite element method to compare the simulated value with the analytical solutions to verify the accuracy of the new equation.
2. Athermal bond thickness equation

2.1 Theoretical basis

The schematic diagram of common continuous bonding is shown in Figure 1. It is assumed here that the RTV fills the entire gap between the lens and the mount\(^3\). The geometric structure parameters used in the following discussion and the three directions of radial, axial and tangential are all defined in the figure.

![Figure1.Monut of a continuous bonding](image)

Most of the analytical solutions of athermal thickness are derived from the Hooke's law matrix that characterizes the three-dimensional stress. The solution of the athermal bonding thickness is to eliminate the radial stress \(\sigma_r\), so only the expression of the radial stress needs to be paid attention to in the solution process. It can be expressed as\(^3\):

\[
\sigma_r = \frac{E}{(1+\nu)(1-2\nu)} \left[(1-\nu)\varepsilon_r + \nu(\varepsilon_z + \varepsilon_\theta)\right]
\]

(1)

Where \(\nu\) is Poisson ratio, \(E\) means Elastic Modulus, and \(\varepsilon_r\), \(\varepsilon_z\), \(\varepsilon_\theta\) are respectively indicate strains of the radial, axial and tangential. According to equation (1), to obtain the athermal bonding thickness, the radial stress \(\sigma_r\) needs to be zero, that is:

\[
(1-\nu)\varepsilon_r + \nu(\varepsilon_z + \varepsilon_\theta) = 0
\]

(2)

The bonding layer is constrained between the lens and the mount in the radial direction. The radial strain is a quantity directly related to the bonding thickness and is easy to determine. The strain in the other two directions needs to be obtained through certain assumptions.

The radial strain \(\varepsilon_r\) is a function of the radial deviation \(\delta h\), which is defined as the difference between the unconstrained thickness change and the actual thickness change when the temperature changes, that is\(^4\)

\[
\varepsilon_r = \frac{\delta h}{h} = \Delta T [\alpha_b - \alpha_m - \frac{r_0}{h} (\alpha_m - \alpha_0)]
\]

(3)

Where, \(\alpha_0\), \(\alpha_m\), \(\alpha_b\) are respectively indicate the thermal expansion coefficients of lens, bonding layer and count.

Using the average thermal expansion of the lens and the frame as the constrained size of the bonding layer under heating, the axial and tangential strain can be expressed as\(^5\):

\[
\varepsilon_\theta = \frac{\delta L}{L} = (\alpha_0 - \frac{\alpha_0 + \alpha_m}{2}) \Delta T
\]

(4)

The constrained size of the bonding layer under heating conditions is determined by the free thermal expansion of the lens, the frame and the bonding layer. The expansion size is firstly distributed according to the ratio of the thermal expansion coefficient, and then averaged.
Where, the constraint size of the lens and the bonding layer is:

$$L \cdot \alpha_0 \cdot \Delta T - \frac{\alpha_0}{\alpha_0 + \alpha_b} + h \cdot \frac{\alpha_b}{\alpha_m + \alpha_b} \cdot \Delta T$$  \(5\)

The constraint size of the count and the bonding layer is:

$$L \cdot \Delta T - \frac{\alpha_m}{\alpha_m + \alpha_b} + h \cdot \frac{\alpha_b}{\alpha_m + \alpha_b} \cdot \Delta T$$  \(6\)

Introducing two scale factor of thermal expansion coefficient \(k_1, k_2\):

$$k_1 = \frac{\alpha_b}{\alpha_0}, k_2 = \frac{\alpha_b}{\alpha_m}$$  \(7\)

Now, the constrained size of the bonding layer is:

$$\frac{\Delta T}{2} \left[ L \cdot \left( \frac{\alpha_0}{1 + k_1} + \frac{\alpha_m}{1 + k_2} \right) + h \cdot \alpha_b \right]$$  \(8\)

Thus, the axial strain of the bonding layer is:

$$\varepsilon_z = \Delta T \left[ L \cdot \left( \frac{\alpha_0}{1 + k_1} + \frac{\alpha_m}{1 + k_2} \right) + h \cdot \alpha_b \right]$$  \(9\)

Combining the equations (2), (3), (4) and(9), a new equation of athermal bonding thickness is derived as:

$$h = \frac{r_0(\alpha_m - \alpha_0)}{\alpha_b - \alpha_m + \frac{v}{1 - \nu}\left(2 - \frac{\nu}{2}\right)\alpha_b - \frac{1}{2}\left(1 + \frac{1}{1 + k_1}\right)\alpha_0 + \frac{1}{1 + k_2}\alpha_m}$$  \(10\)

We know that, the relationship among the coefficient of thermal expansion of the optical components, the adhesive layer and the frame is \(\alpha_0 > \alpha_m > \alpha_0\). The effect of \(\frac{1}{1 + k_1}\) and \(\frac{1}{1 + k_2}\) can be ignored, and getting the simplified equation of equation (10):

$$h = \frac{r_0(\alpha_m - \alpha_0)}{\alpha_b - \alpha_m + \frac{v}{1 - \nu}\left(2 - \frac{\nu}{2}\right)\alpha_b - \frac{1}{2}\left(\alpha_0 + \alpha_m\right)}$$  \(11\)

2.2 Analysis of finite element simulation

Taking the lens assembly with the largest optical imaging channel of a telescope imaging spectrometer as the research object, the assembly size and material parameters are shown in Table 1, 2. The model established in the finite element software is shown in Figure 2. Obtained the stress and deformation of the lens under different bonding thicknesses, and also the thickness of the bonding layer when the radial stress of the assembly is zero, that is athermal bonding thickness.

| Table 1. Dimensions of the assembly (mm) |
|----------------------------------------|
| parameter     | Semi-diameter | Lens thickness | Bond width | Mount thickness |
| Assembly      | 49            | 10.6           | 10.6       | 23             |

| Table 2. Material parameters |
|-----------------------------|
| Material parameter         | \(\rho/(g\cdot cm^{-3})\) | \(E/MPa\) | \(v\) | CTE/\(^{\circ}\)C |
| BSM51Y                     | 3.36           | 7.6×10\(^4\) | 0.26  | 6.3×10\(^4\) |
| RTV                        | 1.1            | 3.5           | 0.49  | 2.8×10\(^4\) |
| Al alloy                    | 2.77           | 7.1×10\(^4\) | 0.33  | 23×10\(^6\)  |
| Structural Steel            | 7.85           | 2×10\(^4\)   | 0.3   | 12×10\(^6\)  |

The reference temperature of the environment in which the assembly is located is 26\(^{\circ}\)C, and the temperature load in the limit state is -30\(^{\circ}\)C. Except for the different lens base materials, the other parameters of the two assemblies remain the same.
The temperature load is applied to the established finite element model, and the thermal stress coupling analysis is performed by the direct method to obtain the stress distribution diagram of the model. Taking multiple values for the thickness of the bonding layer in the assembly, perform finite element thermal stress analysis, and establish the relationship between the radial stress and the bonding thickness of each assembly through the results of the analysis, as shown in Figure 3.

3. Comparison and discussion

It can be seen from Figure 3 that the absolute value of the radial stress of the lens gradually decreases
with the increase of the thickness of the adhesive layer for the assembly of the two lens holder materials. The radial stress of the adhesive layer of the aluminum alloy lens holder is 1.2mm after the thickness increases. The change is small and close to zero. After interpolation calculation, the bond thickness when the radial stress is zero is 1.38mm, which is the non-thermal bond thickness. But after the bonding thickness reaches 1.2mm, the radial stress is very small and the change is also small, so the thickness value of 1.2mm-1.38mm can also be used as the non-thermal bonding thickness. In the same way, the non-thermal bonding thickness of structural steel is in the range of 0.38mm-0.5mm.

|                  | Simulation (mm) | Equation solution(mm) | errors   |
|------------------|-----------------|------------------------|----------|
| Al alloy         | 1.2             | 1.087                  | -9.45%   |
| Structural Steel | 0.38            | 0.3563                 | -6.24%   |

Under the same conditions, use the analytical equations analyzed and derived in the previous section to find the analytical solution of the non-thermal bonding thickness, which is listed in Table 3 and compared with the results of the finite element simulation analysis. The error is within 10%, which is acceptable.

4. Conclusions
In this paper, based on the existing research, a new hypothesis is proposed for the constraint conditions of the bonding layer, and two coefficients of thermal expansion scale factors are introduced to obtain a new athermal bonding thickness equation.

Further, for a certain lens assembly, establishing a finite element model with different materials of mount, and then, applying a temperature load to obtain the thickness when the radial strain of the lens comes to zero. Finally, comparing the results between simulation and equation solution, the error is within 10%, which indicate that the new equation is credible to meet the needs of engineering application.

Acknowledgments
This research was financially supported by the National Natural Science Foundation of China (NSFC). The number of NSFC is 11573048.

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