New joining method for laser scanner lenses by using a shrink fitter

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Abstract

A laser scanning unit, which was designed to converge the laser beam to 4.8 μm over a wide scanning width of 30 mm, consisted of 6 optical lenses. To realize such high performance of the laser scanning unit, the optical lenses in a housing were needed to be placed with their optical axis in an exactly straight line. Usually the optical lenses in the housing are pressed on their rims by ring-shaped retainers for their location. However, the lens location is not accurate by this present method. In addition, the temperature change causes the laser spot deteriorated over the wide scanning width because the thermal expansion coefficients of the lenses are greatly different from that of the metallic housing. We have applied a shrink fitter, which is a new machine element, to the accurate location of the optical lenses. So far no one tried to attach the optical lenses into the housing by such a shrinkage fit. Because the optical lenses are brittle and fragile, the lenses must be damaged or broken by the pressure of shrinkage fit. However, a cylinder-shaped shrink fitter was made of plastic material. A Young's modulus of the plastic material is lower than that of the metal housing by about two orders. The margin of the interference became large if we used the shrink fitter. This is a contact problem between the optical lenses and the shrink fitter. The thickness of the shrink fitter and the optimum interference for the shrinkage fit of such combination had to be designed not to brake the lenses and not to extremely deform the lenses. Then the contact pressures between lenses and the shrink fitter were calculated by FEM. In the experiment, we succeeded in converging the laser beam to 5.8 μm over the wide...
scanning width of 30 mm. Moreover, this good convergence performance did not change even at the elevated temperature of 60°C.

1 Introduction

In this paper, contact problem between optical lenses and a housing for the laser scanner has been dealt with. A fθ lens for the laser scanner is a lens for imaging or converging the laser beam on a scanning plane over a wide range.

Figure 1 shows a relationship between resolution of various microscopes and their fields of view. If you use an optical microscope, you can inspect an object on a several tens of micrometer scale or so. You can observe the same object on a more fine scale with a scanning electron microscope (SEM). However, the field of view of the SEM is narrower than that of the optical microscope. Thus it can be said that the field of view narrows, as the resolution of the microscope rises. Now we are trying to make a new type of microscope that has a resolution as high as the SEM, and has much wider field of view than the SEM.

Figure 2 demonstrates a schematic diagram of the new type of microscope, a laser imager. A key technology is a scanning lens unit, fθ lens. You must converge a laser beam on the objective surface to a few micrometers over the wide scanning width. It is easy to make such a fine laser spot at the center of the scanning width. But it is difficult at the ends of the scanning width. Location of each scanning lens to the housing greatly affects the size and the shape of the laser spot, especially near the ends of the scanning width.

Figure 3 shows how to attach the scanning lenses inside the housing at present [1]. The lens rims are pressed by ring-shaped retainers for their location.
There is a clearance fit between the lenses and the housing. The gaps between the lenses and the housing are exaggerated in this figure. Thus, it is obvious that the lens location is not accurate by this conventional method. In addition, if the room temperature increases, the housing expands more than the lenses do. So small gaps between the lenses and the retainers occur in the axial direction and the clearances between the lenses and the housing increase also in the radial direction. As a result the lens location becomes worse at the elevated temperature.

In this paper, a shrink fitter, that is a new machine element developed by one
of the authors, could greatly improve performance of the scanning lenses, the fθ lens. The fitting pressure between the optical lenses and the metallic housing decreased with temperature because their coefficients of thermal expansion differed from each other. However, the shrink fitter could maintain the fitting pressure of the shrinkage fit of such combination in spite of a change in room temperature.

## 2 Shrink fitter

The shrink fitter is new machine element of cylindrical geometry [2]-[4]. When two machine elements with different thermal expansion coefficients are shrink-fitted, the fitting pressure varies with temperature. However it is possible to fix the fitting pressure by using the shrink fitter, even if the circumferential temperature changes. Until now, the shrink fitter was applied to the connection of polygon mirror and air bearing [5]. And, the research of an assembly of ceramic bearing and metal housing was also carried out to improve the performance of the ceramic bearing by using the shrink fitter.

In this paper, the shrink fitter was applied to accurately locate the lenses in the housing. The current researchers did not even think that they intended to attach the lenses to the housing by a shrinkage fit. Because the optical lenses are brittle and fragile, the lenses might be broken by the shrinkage fit. However, a cylinder-shaped shrink fitter is made of plastic material. The Young's modulus of the plastic material is lower than that of metal by about two orders. It means we can give larger interference for the shrinkage fit of such combination. If the temperature increase, the housing expands more than the lenses do. The interference will decrease without the shrink fitter at elevated temperature. However, the coefficient of thermal expansion of the plastic material is larger than that of the metal. So if you properly design the thickness of the shrink fitter, the interference will never change even at elevated temperature.

### Table 1 Mechanical and thermal properties of each lens

<table>
<thead>
<tr>
<th>Lens No.</th>
<th>Materials</th>
<th>E (GPa)</th>
<th>Poisson’s ratio</th>
<th>α(1/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>SF10</td>
<td>62.0</td>
<td>0.230</td>
<td>7.1×10⁻⁶</td>
</tr>
<tr>
<td>L2, L6</td>
<td>LLF2</td>
<td>61.7</td>
<td>0.216</td>
<td>8.8×10⁻⁶</td>
</tr>
<tr>
<td>L3, L5</td>
<td>SK5</td>
<td>83.0</td>
<td>0.253</td>
<td>5.8×10⁻⁶</td>
</tr>
<tr>
<td>L4</td>
<td>LaSK02</td>
<td>122.9</td>
<td>0.294</td>
<td>6.3×10⁻⁶</td>
</tr>
</tbody>
</table>

E: Young's modulus, α: Thermal expansion coefficient
3 Experimental details

Table 2 Mechanical and thermal properties of the shrink fitter and the housing

<table>
<thead>
<tr>
<th>Materials</th>
<th>E (GPa)</th>
<th>Poisson’s ratio</th>
<th>$\alpha(1^\circ\text{C})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast nylon</td>
<td>3.3~3.8</td>
<td>0.35</td>
<td>$80 \times 10^{-6}$</td>
</tr>
<tr>
<td>A5056B</td>
<td>69.0</td>
<td>0.34</td>
<td>$24 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

E: Young’s modulus, $\alpha$: Thermal expansion coefficient

3.1 Specimens

The f0 lens unit used consisted of six optical lenses of different shapes. The lenses are referred to as L1, L2 ..., L6 in turn from the right side as shown in Fig.3. The L1 was attached to the L2 with an ultraviolet curing adhesive. Thus, five lenses from the L2 to the L6 had to be shrink-fitted to the housing. Table 1 shows the mechanical properties of each lens.

The cast nylon was used as the shrink fitter material. Its mechanical properties and thermal expansion coefficient are shown in Table 2. The material of the housing is aluminum alloy A5056. The mechanical properties and thermal expansion coefficient are shown in Table 2.

It is possible to keep the interference constant regardless of the temperature change, when the radial thickness of shrink fitter is sufficiently designed. That is to say, the fitting pressure is not dependent on the temperature and becomes constant. The outer radius, $r_o$, of the shrink fitter could be calculated as follows.

$$r_o = \frac{\left(\alpha_l - \alpha_s\right)}{\left(\alpha_h - \alpha_s\right)} r_i$$

\(\alpha_n, \alpha_s, \alpha_h\): thermal expansion coefficients of the lens, the shrink fitter and the housing

\(r_i, r_o\): inner and outer radii of the shrink fitter

The inner radius of the shrink fitter was almost same as the outer radius of the lens. To determine the optimum thickness of the shrink fitter for the L2 and the L3, the average value of their thermal expansion coefficients was used. Similarly for the L4, the L5 and L6 the average value of their thermal expansion coefficients was used.

The location accuracy of the shrinkage fit is best among other mechanical joining methods. However if you a little bit strongly tightened the lens, radius of curvature of the lens would change, and the spot size would become larger compared with the designed value. So we must limit the deformation of each lens in the axial direction within half of the wave length of the laser used. The limitation
of the deformation was 266nm.

Small interference causes small deformation of the lens, but it's not good for the location accuracy of the lens. We prefer maximum interference that does not deform the lens over the limitation.

A finite element method was used to determine the maximum interference. The L6 lens was easily deformed. So we limited the area where the pressure was applied as shown in Fig.4. Table 3 shows the allowable interference of each lens. The smallest interference was 14.0 µm for the L3 lens. And the largest interference was 53.5 µm for the L6 lens. Table 3 also shows the actual interferences given in the experiment. The actual interferences did not exceed the allowable ones.

### 3.2 Experimental apparatus

Figure 5 shows a schematic picture of the test apparatus to measure the laser spots. The laser beam of He-Ne, \( \lambda = 640 \text{nm} \) became a parallel ray through a collimator, passing through a stop of 15mm in diameter, and reached a 45-degree inclined mirror of aluminum. The laser beam could be scanned by manually rotating

![Fig.5 Schematic diagram of test apparatus for measuring the laser spot](image)
this mirror. The scanning width was 30 mm on the image plane. The fθ lens was designed so that the laser spot became about 4.8 μm in diameter over the wide scanning width of 30mm. The laser spots at the several given positions were measured by a Spotscan, model 0390, Photon Inc. Fig.6 shows the schematic diagram of the intensity distribution of the laser spot. The size of the laser spot measured was a width where the laser power was 1/e² times as low as the peak value of the intensity distribution. X axis was coincident with the scanning direction. Y axis was taken perpendicular to the X axis. The laser spots were measured in both X and Y directions.

To heat or cool the fθ lens the test apparatus was covered with the acrylic plates. An electricity heater was put in the acrylic cover to heat the fθ lens. In the meantime, the dry ice was put in the cover to cool the fθ lens. The temperature was measured by the thermocouple placed near the fθ lens.

4 Experimental results

4.1 Lens deformation

Deformation of the lens spherical surface was measured by a laser interferometer (FUJINONF601) in order to confirm that the interference calculated in FEM was appropriate. The measurement accuracy of laser interferometer is 1/10. Only the left sides of both L3 and L4 shown in Fig3 were measured. Figs.7(a) and 7(b) show spherical shapes of the lenses before being assembled. They are displayed as even disks, if their spherical surfaces are shapes along the designed value. In the lens L3 there was 42.2nm form error from the designed shape. Figs.7(c) and 7(d) show the spherical shapes of the L3 and L4 after being assembled. It can be said that the deformation of the L3 and L4 are 78 nm and 39 nm and they are within the
limitation of $\lambda/2$. Thus it is obvious that the interferences calculated by FEM was adequate to the shrinkage fit for the lenses. The spherical surfaces of other lenses could not be evaluated since they were in the range which could not be measured by our laser interferometer.

4.2 Laser spot sizes

Fig.8(a) shows the laser spot sizes measured at 25 °C. The conventional f0 lens gave spot diameters of about 6.5 µm within the scanning width of ±5mm. However, in the scanning width over it, the spot diameter increased and became 9 µm at ±15mm. In the meantime, The shrink fitted fB lens gave almost constant spot size of 5.9 µm using the shrink fitter over the whole scanning width. When the temperature was raised to 30 °C, the spot diameter in the conventional fB lens deteriorated over the whole scanning width. However, there was almost no deterioration of the spot diameter in the shrink-fitted fB lens. In addition, the experiment was carried out in the temperature range from 5 °C to 60 °C. In the fB lens using the shrink fitter, the deterioration of the spot diameter could not be accepted at all temperatures.

The fB lenses were put in an electric furnace at 75 °C for 5 hours and were cooled by air. Fig.9 shows the spot sizes measured at 25 °C. In the conventional fB lens, the spot diameter increased to 18 µm at the scanning width of 15mm. It seems that the temperature change caused optic axes of the lenses to deviate. However, the spot diameter did not deteriorate under such severe temperature condition, when the shrink fitter was used. The slippage of the optic axes of the lenses was prevented since the shrink fitter expanded or shrunk following the temperature change.
5 Discussion

Fig. 8 Measured spot sizes at various temperatures, (a) at 25 °C and (b) at 30 °C

Usually the inside of the housing is processed by the lathe. The housing inner surface after the processing has the form error of the triangle state, because the housing is located between the three nail chuck of the lathe. The typical out-of-roundness of the housing inside lay in the range from 4 μm to 20 μm. The housing inside was not concerned in the conventional connection method. The housing for the shrink fitter was carefully turned because the form error might affect the deformation of the lens, and the spot diameter is also affected. As a result the out-of-roundness lay from 1 μm to 4 μm. In the future we must examine the effect of the form error of the housing and the shrink fitter on the positioning accuracy of the lenses.

Except for the conventional method shown in Fig. 3, the lens can be assembled together by the adhesive in the housing. However, there is the failure in which the curvature of the lens has been transformed over the limitation in the thermal deformation as the adhesive stiffens even in this method. And,
decomposition/re-assembly is difficult in the method using the adhesive. In this connection method using the shrink fitter decomposition re-assembly is possible, and positioning accuracy of the lens does not deteriorate after decomposition re-assembly.

6 Conclusions

The shrink fitter was applied to the assembly of the optical lenses to the housing. It improved the performance of the laser scanner unit, fθ lens. Especially, the fθ lens using the shrink fitter excelled the conventional fθ lens on the performance under the high temperature.

References


![Graph showing measured spot sizes after 5 hour saving in 75 °C](image_url)

Fig.9 Measured spot sizes after the 5 hour saving in 75 °C