Numerical analysis revealed the thermal behavior during the laser joining of two glass plates using a low melting point glass frit as an adhesive. The proposed model is a structure consisting of a straight line glass frit sandwiched between glass plates. The numerical solutions of three associated heat equations were provided by the finite difference method. The constant heat flux model predicted the temperature at the contact interface between the glass frit pattern and the glass plate. The influence of heat source shape on temperature distribution was compared using circular and elliptical beams. Irradiation with the elliptical beam extended the softening domain of the glass frit pattern further than the circular beam. The increase in softening domain depended on the major diameter of the elliptical beam. Thermal diffusion had no influence on the glass plate domains at distances greater than 1 mm from the edge of the glass frit pattern. Laser frit sealing is an effective means of resolving the issue of heat influence on electronic devices.

Keywords: glass frit, laser, sealing, temperature, elliptical beam

1. Introduction

Organic electroluminescence displays and dye-sensitized solar cells are sealed between glass plates [1–8]. Low-temperature hermetic sealing under 400°C is required in order to maintain the performance of these devices and ensure their high function and high precision [9]. Direct bonding by pulse laser irradiation has been proposed as a method of joining such glass plates [10–12]. Although it has been difficult to achieve hermetic sealing with pulse laser spot welding, this problem was solved by repetitive irradiation at 250 kHz. Meanwhile, laser joining using a low melting point glass frit as an adhesive is expected to be useful for joining glass plates that need improved hermetic sealing [9, 13–19]. The laser joining of glass plates is important as a basic technology of laser glass machining [20–24].

Our previous study on the laser joining of glass plates using a vanadium-based glass frit yielded knowledge on how to reduce defects such as separation or bubbles, and increase bond strength [9]. However, the processing conditions that allowed high bond strength led to a problematic increase in the width of the joined glass frit [9]. This result indicated the importance of predicting the thermal behavior of the glass frit heated by laser irradiation.

One purpose of heating the glass frit by laser irradiation is to obtain wettability [25, 26] with the glass plate. Heating the glass frit beyond its softening point increases fluidity and decreases viscosity. Increased fluidity allows the glass frit to diffuse through the microstructure of the glass surface by capillary action [25]. Fluidity in particular depends on the temperature above the softening point of the glass frit. Increased flow time for the liquid glass frit increases the width of the joint, while shortened flow time results in insufficient wettability and increased joining defects. In other words, joint quality depends on the time-temperature control to control the fluidity of the glass frit. Therefore, prediction of the thermal behavior of the glass frit during laser irradiation is important. In our previous study, we examined the feasibility of laser joining glass plates using a vanadium-based glass frit [9]. A qualitative agreement was obtained between the experimental results and the results of the numerical analysis model [9]. However, further clarification was necessary because a detailed report of the numerical analysis model was not accomplished.

The purpose of the present study is to clarify the behavior of the predicted temperature change under the softening conditions of glass frit using a temperature analysis model. The temperature analysis model was based on a structure in which a vanadium-based glass frit was sandwiched between aluminoborosilicate glass plates. The difference in thermal behavior caused by circular and elliptical laser beams was also clarified.

2. Numerical Analysis Model

Figure 1 shows a schematic of the process of laser joining using a glass frit. A glass plate on which a device has been formed is prepared. The glass frit is printed on a second glass plate and sintered. The glass plate with frit is then placed on top of the glass plate containing the device. The glass frit is irradiated with a laser to completely
Fig. 1. Schematic diagram of the process of laser joining with glass frit: (a) preparation of the glass frit pattern; (b) overlaying process; (c) laser joining for sealing; (d) cross section of A-A.

Fig. 2. Temperature rise model of laser frit sealing.

Sealed device between the plates. The glass frit absorbs the laser beam, and its temperature increases near its softening point. Because the laser beam passes through the glass plate, no heat is generated inside the glass plate. However, the glass plate undergoes a temperature change owing to the conduction of heat from the glass frit. Importantly, the sandwiched electronic device can be affected by this temperature rise caused by heat conduction.

The distance of the glass frit from the electronic device is important to estimate its thermal influence. Fig. 2 shows the temperature prediction model used in this work. The straight pattern of the glass frit on a glass plate is predictable by decreasing the contact area of the glass frit pattern relative to the surface area of the glass plate. The position of the laser beam incident on the surface is denoted with x-y coordinates. The normal incidence direction of the laser beam is the z-coordinate. As for subscripts, the glass frit is 1, the upper glass plate is 2, and the bottom glass plate is 3. A three-level structure is constructed in the order: bottom glass substrate 3, low melting point glass 1, and upper part glass substrate 2, along the positive direction of the z-axis. The length, width, and thickness of the model structure are defined by \( L \) [mm], \( H \) [mm], and \( D \) [mm], respectively. The dimensions of the glass frit pattern are \( L_1 = 12 \text{ mm} \) and \( H_1 = 0.6 \text{ mm} \). The dimensions of the glass plates are \( L_2 = L_3 = 15 \text{ mm} \), \( H_2 = H_3 = 6 \text{ mm} \), and \( D_2 = D_3 = 0.5 \text{ mm} \). The straight line pattern of the glass frit is located at the center of the glass plate.

The sandwich structure is simply supported at the bottom glass plate to simplify the calculation. Because the surfaces of the upper and bottom glass plate are in contact with the atmosphere, both convective and radiant heat transfer. The sidewall area of the sandwich structure is smaller than the top and bottom surface areas. The boundary condition is adiabatic because the heat transfer from the side is small. The heat transfer in the domain where the glass plate makes contact with the glass frit pattern is expressed by the overall heat transfer coefficient \( h_{i,j} \) \((i = 1, j = 2, 3)\). The overall heat transfer coefficient is affected by a constant heat flux condition. A precondition is that the glass frit pattern and glass plate completely adhere. Therefore, the overall heat transfer coefficient is based on heat conduction:

\[
\begin{align*}
    h_{1,2} &= \frac{1}{\frac{D_1}{K_1} + \frac{D_2}{K_2}} \\
    h_{1,3} &= \frac{1}{\frac{D_3}{K_1} + \frac{D_3}{K_3}}
\end{align*}
\]

where \( K \) is the thermal conductivity. The heat transfer between areas at the top and bottom of the glass plate that occupy a non-contact domain and the glass frit pattern is ignored to simplify the calculation.

A laser beam was chosen to penetrate the glass plate, which was absorbed by the glass frit. The resulting heat generation per unit volume \( Q \) [W/m³] was averaged in the thickness \( D_1 \) of the glass frit. There was a temperature gradient in each thickness direction in the glass frit and glass plate at the initial stage of heating. To simplify the calculation, the average temperature along the thickness was used. The precise temperature was \( T_i(x, y, z, t) \), but this model used \( T_i(x, y, t) \). Here, the temperature \( T_i \) expresses the change from an initial temperature. As a result, the coupled thermal conduction problem [9] is given as follows.

\[
\frac{\partial T_1}{\partial t} = k_1 \left( \frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} + \frac{\partial^2 T_1}{\partial z^2} \right) + \frac{Q(x, y, t)}{\rho_1 c_1} - \frac{h_{i,2}}{\rho_1 c_1 D_1} (T_1 - T_2) - \frac{h_{i,3}}{\rho_1 c_1 D_3} (T_1 - T_3) \quad (X_{03} \leq x \leq L_1, \ Y_{03} \leq y \leq H_1, \ 0 \leq t)
\]

\[
X_{03} = \frac{L_2 - L_1}{2} , \ Y_{03} = \frac{H_2 - H_1}{2}
\]
\[
\frac{\partial T_2}{\partial t} = k_2 \left( \frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} \right) + \frac{h_{1,2}}{\rho c_2 c D_2} (T_1 - T_2)
\]
\[
- \frac{h_a}{\rho c_2 c D_2} T_2 = \frac{h_r}{\rho c_2 c D_2} \left[ (T_2 + T_a)^4 - T_a^4 \right]
\]
\[
(0 \leq x \leq L_2, 0 \leq y \leq H_2, 0 \leq t)
\] . . . (5)

\[
\frac{\partial T_3}{\partial t} = k_3 \left( \frac{\partial^2 T_3}{\partial x^2} + \frac{\partial^2 T_3}{\partial y^2} \right) + \frac{h_{1,3}}{\rho c_3 c D_3} (T_1 - T_3)
\]
\[
- \frac{h_a}{\rho c_3 c D_3} T_3 = \frac{h_r}{\rho c_3 c D_3} \left[ (T_3 + T_a)^4 - T_a^4 \right]
\]
\[
(0 \leq x \leq L_3, 0 \leq y \leq H_3, 0 \leq t)
\] . . . (6)

\[
h_r = \varepsilon \beta \]
\[
k = \frac{K}{\rho c} \]
\[
T_a = 273.15 + T_R \]
\[
t = 0, \quad T_1 = T_2 = T_3 = 0 \]
\[
(10)
\]

where \(k\) is thermal diffusivity, \(\rho\) is density, \(c\) is the specific heat, \(h_a\) is the convective heat transfer coefficient, \(h_r\) is the radiative heat transfer coefficient, \(\varepsilon\) is the emissivity, \(\beta\) is the Stefan–Boltzmann constant \((5.67 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4))\), and \(T_R\) is the initial temperature. The origin of the \(x\)-\(y\) coordinate system is the lower left of glass plate 3. \(X_{oa}\) is the distance from the left origin of the glass plate to the left end of the glass frit in the \(x\)-direction. \(Y_{oa}\) is the distance from the left origin of the glass plate to the left end of the glass frit in the \(y\)-direction.

A semiconductor laser beam was used for an experiment [9]. The space profile of a circular beam and an elliptical beam was confirmed to be a Gaussian distribution by measurement with the knife-edge sweep method. The elliptical beam was formed using cylindrical lens. With regard to the heat source, the intensity distribution of the laser beam is Gaussian type, as shown in Fig. 3. The circular and elliptical beams are defined by:

\[ Q(x, y, t) = Q_0 \exp \left( -2 \left( \frac{(x - V_0 t)^2}{r_x^2} + \frac{y^2}{r_y^2} \right) \right) \]

\[
(0 \leq t)
\] . . . (13)

\[ Q_0 = \frac{I_0}{D_1} \quad \text{[W/m}^3] \]

\[
I_0 = \frac{2P_0}{r_x r_y \pi} \quad \text{[W/m}^2] \]

\[
(14)
\]

\[
(15)
\]

where \(Q_0\) is heat intensity, \(I_0\) is the absorbed power density, \(P_0\) is the absorbed power, and \(V_0\) is the movement velocity. The beam diameter is same as that used in our previous study [9]. The diameter of the circular beam is \(2r_1 = 2.2\) mm. The major and minor diameters of the elliptical beam are \(2r_3 = 3.7\) mm and \(2r_2 = 1.4\) mm, respectively. The diameters \(2r_3\) and \(2r_2\) are the beam diameters when optical power becomes \(1/e^2 (= 0.135)\). Therefore, the irradiation area of the circular beam is \(3.8\) mm\(^2\), while that of the elliptical beam is \(4.1\) mm\(^2\). For the same absorbed power, the maximum power density of the circular beam is 1.1 times higher than that of the elliptic beam, as shown by Eq. (15).

The interfacial temperatures \(T_{i,2}\), \(T_{i,3}\) where the glass frit touches the glass plates, were estimated using the model shown in Fig. 4. In the case of complete contact, the heat flux flowing through the contact interface from the glass frit is constant. Furthermore, the heat flux flowing through the glass plate from the contact interface is also constant. This theory was applied to both glass plates 2 and 3. As a result, the following relation is provided for constant heat flux:

\[
q_{1,2} = -K_1 \frac{T_1 - T_{i,2}}{D_1} = -K_2 \frac{T_{i,2} - T_2}{D_2} \]

\[
(16)
\]
$$q_{1,3} = -K_1 \frac{T_1 - T_{1,3}}{D_1} = -K_3 \frac{T_{1,3} - T_3}{D_3} \ldots (17)$$

The interfacial temperature is obtained by:

$$T_{1,2} = \frac{T_1 + a_{1,2} T_2}{1 + a_{1,2}}, \quad a_{1,2} = \frac{K_2 D_1}{2K_1 D_2} \ldots (18)$$

$$T_{1,3} = \frac{T_1 + a_{1,3} T_3}{1 + a_{1,3}}, \quad a_{1,3} = \frac{K_3 D_1}{2K_1 D_3} \ldots (19)$$

Thus, it is possible to estimate the interfacial temperature from the average temperatures of the glass frit and the top and bottom glass plates. However, this expression is limited to the area of contact.

The numerical computation method is explained below. The discretization of the partial differential equations was based on the full-imPLICIT finite difference method. The simultaneous equations used for the calculation are shown in the following matrix:

$$\begin{vmatrix} a_{11} & -a_{12} & -a_{13} \\ -a_{21} & a_{22} & a_{23} \\ -a_{31} & a_{32} & a_{33} \end{vmatrix} \begin{vmatrix} T_{1,i,j}^{p+1} \\ T_{2,i,j}^{p+1} \\ T_{3,i,j}^{p+1} \end{vmatrix} = \begin{vmatrix} B_1 + C_1 \\ B_2 + C_2 \\ B_3 + C_3 \end{vmatrix} \ldots (20)$$

$$T_1(x,y,t) = T_1(i\Delta x, j\Delta y, p\Delta t) = T_{1,i,j}^p \ldots (21)$$

$$T_2(x,y,t) = T_2(i\Delta x, j\Delta y, p\Delta t) = T_{2,i,j}^p \ldots (22)$$

$$T_3(x,y,t) = T_3(i\Delta x, j\Delta y, p\Delta t) = T_{3,i,j}^p \ldots (23)$$

$$B_1 = T_{1,i,j}^p + \frac{\Delta Q_{i,j}}{\rho c_1}$$

$$C_1 = \gamma_s \left[ \frac{T_{1,i+1,j}^{p+1} + T_{1,i-1,j}^{p+1}}{2} \right] + \gamma_y \left[ \frac{T_{1,i,j+1}^{p+1} + T_{1,i,j-1}^{p+1}}{2} \right],$$

$$\gamma_s = \frac{k_1 \Delta t}{\Delta x^2}, \quad \gamma_y = \frac{k_1 \Delta t}{\Delta y^2},$$

$$a_{11} = 1 + 2\gamma_s + 2\gamma_y + \frac{\Delta t h_{1,2}}{\rho c_1 D_1} + \frac{\Delta t h_{1,3}}{\rho c_1 D_1},$$

$$a_{12} = \frac{\Delta t h_{1,2}}{\rho c_1 D_1}, \quad a_{13} = \frac{\Delta t h_{1,3}}{\rho c_1 D_1},$$

$$B_2 = T_{2,i,j}^p - \frac{\Delta t h_r}{\rho c_2 D_2} \left[ \frac{T_{1,i+1,j}^{p+1} + T_{1,i-1,j}^{p+1}}{2} + T_{2,i,j}^p \right] - T_a^4, \ldots (24)$$

$$C_2 = \gamma_s \left[ \frac{T_{2,i+1,j}^{p+1} + T_{2,i-1,j}^{p+1}}{2} \right] + \gamma_y \left[ \frac{T_{2,i,j+1}^{p+1} + T_{2,i,j-1}^{p+1}}{2} \right],$$

$$\gamma_s = \frac{k_2 \Delta t}{\Delta x^2}, \quad \gamma_y = \frac{k_2 \Delta t}{\Delta y^2},$$

$$a_{22} = 1 + 2\gamma_s + 2\gamma_y + \frac{\Delta t h_a}{\rho c_2 D_2},$$

$$a_{21} = \frac{\Delta t h_{1,2}}{\rho c_2 D_2}, \quad a_{23} = 0 \ldots (25)$$

The placement domain of the glass frit is limited to the center of the glass plate. It is important that the solution of the simultaneous equation considers this placement. The numerical computation of the simultaneous equation was based on the iteration method. The iterative computation was carried out at every time step and had a relative error of less than 0.1%, which is an acceptable level for engineering. The element size $\Delta t = \Delta y$ of the spatial coordinates was 1/10 of the beam radius $r_a$. The temperature integers $i, j, p$ represent the indexing numbers of the space segments and the number of time intervals $\Delta t$, respectively.

Because a simple support was applied to the sandwich structure of this model, the boundary conditions of upper glass plate 2 and bottom glass plate 3 were the same. This means that $T_2 = T_3$. Therefore, glass frit $T_1$ and glass plate $T_3$ are discussed hereafter.

Our previous experiment [9] used a laser diode (wavelength: 808 nm). The reflectance and transmissivity of the glass frit for this particular laser wavelength were important for estimating the heat generation. However, there were many uncertain factors in these optical properties. Therefore, temperature calculation based on absorption power is discussed. The laser beam parameters used for the calculation are shown in Table 1. The scanning speed is 10 mm/s. The start position is the left edge of the glass plate as shown in Fig. 2. The time taken for the laser beam to move across the length $L_2$ (= 15 mm) was 1.5 s. The softening point of the glass frit is 370°C.

<table>
<thead>
<tr>
<th>Parameters of laser beam</th>
<th>Circular beam</th>
<th>Elliptical beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2r_a$ : mm</td>
<td>2.2</td>
<td>3.7</td>
</tr>
<tr>
<td>$2r_a$ : mm</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Scan speed : mm/s</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Absorbed power density : MW/m²</td>
<td>0.5 - 3.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Glass plate</th>
<th>Glass frit</th>
</tr>
</thead>
<tbody>
<tr>
<td>K : W/(m·K)</td>
<td>1.09</td>
<td>0.55</td>
</tr>
<tr>
<td>ρ : kg/m³</td>
<td>2380</td>
<td>3700</td>
</tr>
<tr>
<td>C : J/(kg·K)</td>
<td>768</td>
<td>750</td>
</tr>
<tr>
<td>h : W/(m²·K)</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>Softening point : °C</td>
<td>696-970</td>
<td>370</td>
</tr>
</tbody>
</table>
Good wettability with the liquid glass frit is necessary for the successful joining of the glass. Therefore, the temperature of the contact interface must be higher than the softening point of the glass frit. Furthermore, the contact interface temperature must be lower than the softening point of the glass plate to minimize its effect on the electronic device. Therefore, the interface temperature was set to approximately 500°C.

3. Calculation Results

The absorbed power densities required for an interface temperature of 500°C were calculated for the circular and elliptical beams. An absorbed power density of 2.53 MW/m² was obtained for the circular beam, while that for the elliptical beam was 2.36 MW/m². From the same calculation, absorption power of 4.8 W was also obtained. The absorbed power density of the circular beam was 1.07 times higher than that of the elliptical beam. The assumed initial temperature was 22°C. The calculation results discussed in the next section are based on irradiation conditions yielding an interface temperature of 500°C.

The absorbed power density dependence of the maximum temperature of each element of the model was calculated as basic information of the thermal characteristics. Fig. 5 shows the absorption power density dependence of the maximum temperature increase. The model included the glass frit, glass plates, and contact interfaces. The temperature field of the domain except for each end of the glass frit was in a quasi-steady state in the moving heat source. The maximum temperature was the momentary value obtained when the heat source passed the center (the glass plate center) of the glass frit. The spatial distribution of the evaluated heat source was circular or elliptical, according to the corresponding beam shapes. When the interface temperature reached 500°C, the temperature of the glass frit increased to 600°C–700°C. The glass plate showed a temperature increase of 90°C–140°C. Thus, the interface temperature was 3.8 times higher than the temperature of the glass plates, and the temperature of the glass frit was five times higher than that of the glass plates.

At constant absorbed power density, the elliptical beam produced a temperature rise 1.1 times higher than that by the circular beam. The reason for this may be understood from Eq. (14). The absorbed power density was inversely proportional to the spot area. Thus, the wider total area irradiated by the elliptical beam absorbed 1.1 times more power than the area irradiated by the circular beam, and therefore reached a higher temperature. Conversely, the power density of the elliptical beam decreased when the absorbed power was constant. In this case the circular beam resulted in a higher temperature. These results show that the temperature rise was proportional to the absorbed power density. A constant irradiation power condition was chosen.

Next, the change in the temperature distribution during the movement of the heat source is shown at interface temperature of 500°C. Fig. 6 shows the calculated results. The heat source movement speed was set to 10 mm/s. Fig. 6(a) shows the change in temperature distribution...
during the movement of the circular beam. Fig. 6(b) shows the change in temperature distribution during the movement of the elliptical beam. The temperature distributions in the glass frit and glass plate are shown separately. The results shown in Fig. 6 are only the temperature distribution of the glass frit on the glass substrate. The results shown in Fig. 6 are only the temperature distribution of the glass plate formed by heat conduction from the glass frit. The laser beam was moved at constant speed from the left edge of the glass plate \( x = 0 \) mm to the end of the right side \( x = 15 \) mm. The 12-mm-long straight line pattern of the glass frit was placed from \( x = 1.5 \) mm on the glass plate. The elapsed time is shown in Fig. 6. The center of the laser beam passed the center of the glass plate in 0.75 s. A temperature rise was observed at the moment when the laser beam arrived at the start of the glass frit. Thermal diffusion to the glass plate was observed upon the rise in glass frit temperature. The temperature distributions of the glass frit and glass plate were in a quasi-steady state. In other words, the temperature distribution had the same shape in each of the elements as it moved with the heat source, except at both ends of the glass frit pattern. The influence of the heat source shape was unknown under the conditions shown in Fig. 6. Therefore, the expansions in temperature distributions were used to clarify the influence of the heat source shape.

Figure 7 shows expansions of the temperature distributions shown in Fig. 6 for further comparison of the circular beam and elliptical beam heat sources. Fig. 7(a) shows only the temperature distribution of glass frit on the glass substrate. Fig. 7(b) shows only temperature distribution of the glass plate formed by heat conduction from the glass frit. The central location of the laser beam is shown by the dashed line in Fig. 7. The black arrow in the figures indicates the direction of the beam movement. The green lines show the isothermal line of 370°C (glass frit softening point). The maximum temperature increase appeared behind the moving heat source. This tendency agreed with experimental results [9]. The temperature distribution in the glass frit was clearly influenced by the heat source shape. Irradiation with the circular beam created a circular temperature distribution, while the elliptical beam irradiation formed an elliptical temperature distribution. The length of the softening domain of the glass frit pattern differed for each heat source shape. Elliptical beam irradiation resulted in a softening domain 2 mm in length. Circular beam irradiation resulted in a softening domain 1.2 mm in length. Thus, although the spot areas of the elliptical and circular beams differed by a factor of 1.1, the length of the softening domain differed by a factor of 1.7. The reason for this is that the major diameter of the elliptical beam was 1.7 times longer than the diameter of the circular beam.

The distance between the edge of the glass plate and the edge of the glass frit pattern is important to reduce the heat influence on the electronic device. The 3 mm distance between the parallel lines at the top and bottom of the plots in Fig. 7(b) show the limit (\( \Delta T = 0 \)) at which no temperature increase occurred in the glass plate. Because the width of the glass frit pattern was 0.6 mm, the distance between the edge of the glass frit pattern and the area unaffected by temperature was \((3 \text{ mm} \sim 0.6 \text{ mm})/2 = 1.2 \) mm. It is necessary to check this limit line in further detail.

The temperature distribution in the \( y \)-axis direction was calculated for the center of the glass plate. Fig. 8 shows the locations used to evaluate the heat influence from the glass frit and the influence of the beam shape at the center of the glass frit. The temperature distribution along the
straight line C-D is helpful to evaluate the heat influence
from the glass frit. The temperature distribution along the
beam movement direction A-B was used to evaluate the
influence of the beam shape.

Figure 9 shows the change in temperature distribution
in the glass plate along C-D with time. Figs. 9(a) and (b)
show the results for the circular beam and, elliptical beam,
respectively. The center of both the elliptical and circular
beams passed through the center of the glass plate after
0.75 s. The central part of the glass plate reached a max-
imum temperature of 100°C (circular beam) and 120°C
(elliptical beam) within 0.8 s, after the center of the heat
source crossed the C-D line. The glass plate was cooled
by lateral thermal diffusion in 1 s or more. The results
show that the temperature of the glass plate at a position
1 mm away from the edge of the glass frit increased by
up to 20°C after the heat source passed. This temperature
rise will not negatively affect the electronic device. In
other words, the electronic device may be safely placed
as close as 1 mm from the glass frit pattern edge.

A difference between the thermal effects of the circular
and elliptical beams was observed. The temperature of
the glass frit must be increased above its softening point
(370°C, but 400°C was assumed to maintain sufficient wet-
tability. As a guide, a line was drawn to mark this temper-
ature (400°C) in Fig. 10. Domains above this temperature
were liquids. The glass frit spatial domains above 400°C
were compared. For the circular beam, the length of the
spatial domains was 1.09 mm. For the elliptical beam, the
length of the spatial domains was 1.92 mm. The length
of the softening domain created by elliptical beam irradi-
ation was 1.7 times longer than that the softening domain
created by circular beam irradiation. This shows that a
larger spot area is more effective in increasing the size of
the softening domain.

In order to increase the time during which a tempera-
ture higher than the softening point is obtained, the use
of a wide spot area beam is advantageous. Fig. 11 shows
the temperature change in the glass plate during the move-
ment of the heat source across the center point (intersec-
tion of A-B and C-D lines). As in Fig. 10, the evalua-
tion temperature was 400°C, at and above which the glass
frit is a liquid. In the case of elliptical beam irradiation,
the glass frit liquefied in 0.65 s and solidified in 0.90 s.
Thus, the glass frit was liquid for 0.25 s. In the case of
the circular beam, the glass frit liquefied in 0.70 s and
solidified in 0.85 s, a liquid time of 0.15 s. At constant
absorption power of 4.8 W, the glass frit was liquid for
a longer time with the elliptical beam because it was ap-
proximately 1.7 times longer than the circular beam.

4. Discussion

(1) Packaging density

The results of Figs. 7 and 9 reveal the possibility of
placing an electronic device on a glass plate as close as
1 mm from the edge of the glass frit pattern. The thermal diffusion from the edge of the glass frit pattern depends on the properties of the glass plate. However, a problem arises when the electronic device is located within the spot domain of the laser beam. This means that the electronic device will be subjected to the irradiation of the laser beam, and hence direct heating. The solution to this problem is to restrict the spot domain of the laser beam to a rectangular shape using a slit. Using a slit with the appropriate shape will make it possible for the device to approach the edge of the glass frit pattern, thereby improving the packaging density of the device. In summary, hermetic sealing by laser beam irradiation resolves the issue of heat influence on electronic devices and contributes to the improvement of packaging density.

(2) Beam shape

The space intensity distribution of the laser beam affected the joint quality. With the elliptical beam, the glass frit pattern remained in the liquid phase for 1.7 times longer than with the circular beam. According to our previous study [9], elliptical beam irradiation achieved better joining results than circular beam irradiation. The intensity distribution of the longer axis direction of the elliptical beam produced a uniform temperature distribution and preheating effect. It is thought that the preheating effect in the shape of the elliptical beam contributes to the decrease in defects such as air bubbles or the separation of the glass frit pattern during heating and cooling processes. Because the elliptical beam showed a heating time 1.7 times longer than that of the circular beam, the probability that the ingredients of the glass frit will diffuse to the inside of the glass plate becomes higher, which should result in better joining. Although this diffusion phenomenon has not yet been confirmed, this prediction is in agreement with the results of prior experiments [9]. No conclusion was obtained on the most suitable beam shape. A rectangular beam [5] is ideal, but realization is difficult. Analysis of the temperature effects of irradiation using the combination of an elliptical beam and a slit is necessary in the future. Elliptical beams have been discussed both experimentally and theoretically in terms of welding phenomena and as a new heat source in the field of industrial products [27–29]. Although the advantages of using an elliptical beam were discussed in this study, the areas irradiated by the circular and elliptical beams were not identical. As quoted previously [9], the area irradiated by the elliptical beam was more than 8% wider than the area irradiated by the circular beam. Seal processing of L-form corners may be difficult with the application of an elliptical laser beam by with a non-axis symmetric shape. However, seal processing is possible by choosing the appropriate beam shape. Although a suitable choice of beam shape is necessary depending on the purpose, comparisons using equivalent irradiated areas are needed.

(3) Usefulness and issue

The model used in this study was a sandwich structure consisting of two kinds of materials. Because each layer was defined with the average temperature in the thickness direction, the construction of the plane stress model using information on the temperature field was possible. A combination of acceptable materials was obtained by evaluating the residual thermal stress that may occur with differences in the coefficient of thermal expansion. Because the fluidity of the low melting point glass affected joint quality, fluid prediction based on the temperature field is important. The optimization of the heat source shape in relation to the glass frit was possible based on fluid and temperature analyses. This provided optimized laser irradiation conditions, including power, scanning speed, and spot shape. The construction of a model including these factors is a future task.

(4) Validity of proposed model

The reliability of the high-temperature domain of the proposed model is low because the temperature dependence of material properties was assumed to be constant in this study. In addition, the mean temperature in the thickness direction of each layer was used. When the temperature gradient in the thickness direction of the glass frit with thickness 0.01 mm was considered, the Fourier number in the thickness direction abnormally increased. The increase in Fourier number indicates a decrease in temperature gradient and formation of uniform temperature in the thickness direction. Thus, the temperature gradient in the thickness direction of the glass frit was not considered in order to simplify the calculation. When temperature variations in the thickness direction of the glass plate were considered, the results obtained with this model had low reliability. Nonetheless, the behavior of the average temperature change during laser sealing predicted by this model was valid.
5. Conclusion

Using numerical analysis, this study clarified the thermal behavior during the laser joining of two pieces of glass plates using glass frit as an adhesive. The influence of the heat source shape on temperature distribution was compared using circular and elliptic beams. When the beam irradiated area was constant, the increase in the size of the softening domain of the glass frit pattern was greater with the elliptical beam than with the circular beam. With an elliptical beam and circular beam of scanning speed of 10 mm/s, no thermal diffusion was observed in the glass plate domain at a distance of 1 mm from the edge of the glass frit pattern. Therefore, hermetic sealing by laser beam irradiation resolves the issue of heat influence on electronic devices and is an effective means of improving packaging density.

References:


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