

[Article ID] 1003- 6326(2002) 02- 0287- 04

Numerical simulation of temperature field in multilayer heterogeneity lamination laser soldering^①

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[Abstract] A temperature field numerical simulation is carried out using the finite element method for laser soldering on PECT (piezoelectric ceramics transformer). A three-dimensional model of laser soldering temperature field of multilayer materials is established. Then, the model was simplified in order to perform an efficient finite element analysis. Moreover, the temperature distribution characteristic in the laser soldering is investigated and verified by experiments. In all cases, the numerical results are in good agreement with the experimental measurements.

[Key words] laser soldering; temperature field; numerical simulation

[CLC number] TG 402

[Document code] A

1 INTRODUCTION

Piezoelectric ceramics transformer (PECT), the structure of multilayer heterogeneity lamination, which is made of piezoelectric ceramic materials, has characteristics of voltage transformation. Mechanical energy can be transformed to power energy, as a result of 100 kHz high frequency mechanical oscillation, which is depended on polarization of piezoelectric ceramic materials. The internal structure of PECT is shown in Fig. 1. Effect substance of PECT is PZT-4, which only can work in possession of remain polarization. When it is heated over Curie temperature, crystal structure will be changed, which could induce perpetual expiration of piezoelectric property. Due to above-mentioned particularly material properties and structure properties, joint of lateral electrode of PECT is very strict.

The demand of PECT lateral electrode soldering process is based on the following different aspects. First, the heating state of the soldering process is controlled available so that PECT can work successfully. Second, soldered connection has good electrical conductivity and lateral electrode is connected with all layered tablets. Third, soldered connection has high mechanical properties so as to extend working period. Fourth, PECT has good joint appearance and avoid liquids solder moving to the front face. Finally, soldering has high efficiency.

Laser welding has many merits such as high power density, narrow HAZ, high speed, small structure distortion, high tensile strength of joint, and so on^[1~5]. In laser soldering whole component need not to be heated to the overflow temperature of solder so only accurate local will be heated. Moreover, controllability of laser beam is very well. Power

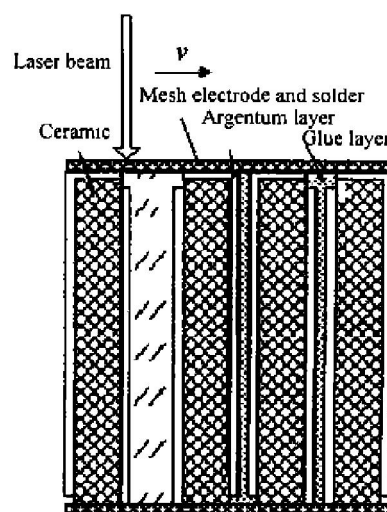


Fig. 1 Inner structure of PECT

density, beam spot size and time duration of heating can be controlled. Laser soldering becomes to the key technology of PECT production on account of the above-mentioned virtues.

When laser irradiates the solder, the laser beam energy is absorbed by the surface of the material and transfers to heat which makes the solder melt and overflow. Consequently, the heat transferred in the PECT, forms the transient temperature distribution, which can affect the properties of PECT and cause some problems such as depolarization, accelerate ageing and excess dissolving of silver lateral electrode, then making it out of work. So the temperature distribution can significantly affect the quality of PECT. However, PECT has the structure of multilayer heterogeneity lamination, high rigidity and large brittleness, so contact instrument of temperature measurement is difficult to be placed into the inside, and bore

thermocouple embedding is also unfit for measurement. Furthermore, non-contact temperature measurement is obviously unfit to the inside of PECT. Therefore, the temperature measurement of PECT during laser soldering requires special equipment. Fortunately, the laser soldering numerical simulation provides an effective way to appraise and optimize the technical parameters. In this paper, a 3D model of laser soldering temperature field of different materials and composite structure is established, then, numerical simulation of the three-dimensional transient temperature field is carried out, and the calculated result is satisfactory.

2 MATHEMATICAL MODEL

2.1 Model simplification

Generally, the calculated temperature field of laser soldering has two special aspects^[6~8]. First, the particularity of laser heat source, and the other is the material of heated workpiece. Small volume of welding pool, fast heating and cooling rate, and large temperature gradient are the characteristics of laser heat source. From the aspect of heated materials, the heated work piece is the multilayer heterogeneity materials and their properties have great differences one another. Therefore, model simplification is very necessary.

2.1.1 Heat source model

The heat source model determines the reliability of FEM analysis, which significantly affects the calculated precision of temperature field, especially to the region near the heat source.

From the laser theory, space amplitude distribution of laser can be calculated as follows:

$$u(r, z) = \frac{u_0 w_0}{w(z)} \exp\{-r^2/w(z)^2\} \quad (1)$$

where r is the distance off facular center, and z , origin according to the girdling is the distance along the direction of laser beam transmission, w_0 is the radius of girdling, u_0 is the light intensity of the girdling and $w(z)$ is the facular radius. Here $w(z)$ is

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2} \quad (2)$$

where λ is wavelength of the laser.

Due to light intensity is proportional to the square to the amplitude, then

$$I(r) = \frac{A}{w(z)^2} \exp[-2r^2/w(z)^2] \quad (3)$$

where A is the absorptivity of the metal.

The output light intensity of laser can be written as

$$I_0 = \int_0^\infty I(r) 2\pi r dr = \frac{\pi A}{2} \quad (4)$$

Power density distribution of laser can be calculated as

$$I(r) = \frac{2I_0}{\pi w(z)^2} \exp[-2r^2/w(z)^2] \quad (5)$$

Thus, heat flow distribution of the PECT end face can be written as:

$$q(x, y) = \frac{2Aq_0}{\pi w^2} \exp(-2r^2/w^2) \quad (6)$$

where q_0 is the total power of laser.

Heat input of laser soldering has the characteristic of local concentration, which provides the reference to simplify the laser heat source during the temperature field analysis. In the distance with same magnitude of the heat source size, heat flow density distribution of heat source significantly affects the temperature field, but in the area far from the heat source, the influence of heat source is very slightly. As the limitation of concentrated heat source, the region near the heat source is very difficult to be simulated, and especially in the center of heat source temperature will increase to infinity. The current researches show that using surface heat source with gauss distribution as heat source density can obtain perfect result during laser soldering.

On the other hand, as heat source of laser soldering has the characteristic of short duration time, the heat flow can be assumed with constant density inducing to the structure during the heat source operation.

2.1.2 Material physical parameters

Dealing with thermo physical parameters is one of the most important problems in the heat transfer process of laser soldering. In this paper, thermo physical parameters of materials can be assumed as follows^[9~12]: first, the heated materials are uniform and isotropic substances, respectively. Second, optic properties and thermodynamics parameter of materials are independent of the temperature, which can be adopted the average values in some specified range, respectively.

2.1.3 Paste form solder

Physical property parameters of paste form solder are very difficult to be confirmed precisely^[13]. In the interval from room temperature to the solder melting point, solder can be treated as a mixture of Sn-Pb eutectic alloy and liquid organic compound. Organic matter included in the soldering flux can absorb portion energy during the evaporation and decomposition process. The alloy included in the solder is melted and centralized to a whole at melting point, then soldering flux is excluded to the exterior. Following the decrease of the temperature, solder alloy can be solidified and cooled to the room temperature. During the process of paste form solder melting and solidification, the evaporation and decomposition processes of organic matter always exist. Moreover, the alloy powder absorbs the latent heat of crystallization at the beginning, and then gives out the latent heat of crystallization. So the whole process is very complex and

the physical property parameters are multivariate.

Since the solder addition is very little, it can be simplified relatively to the matrix. Assuming solder only includes Sn-Pb eutectic alloy powder, and ignores the influence of the latent heat of crystallization.

2.2 Governing equations

Three-dimensional transient non-linear heat conduction equation can be written as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q \quad (7)$$

where T is the temperature, which is a function of space and time; t is the time, x , y and z are the coordinates of space point, ρ is the material density; k is the thermal conductivity of material; Q is the inner heat source intensity; c is the heat capacity of material.

If T_0 is the temperature of the environment, the initial condition is:

$$T_{t=0} = T_0(x, y, z) \quad (8)$$

As the laser irradiation process attributes to the surface heating process, it can be treated with boundary condition. The boundary condition of laser soldering including heat flow input and heat convection is as follows

$$k \frac{\partial T}{\partial n} = -q + \alpha(T - T_a) \quad (9)$$

where n is the direction of the surface; q is the outer heat flow input of unit area; α is the surface heat transfer coefficient; T_a is the temperature of the surrounding medium.

3 SIMULATION RESULTS AND DISCUSSION

Since laser soldering is a rapid change process of temperature along with time and space, the temperature gradient is extremely great. The principal problems in the numerical simulation involve the choice of the optimal mesh discretization under the traveling laser beam. The mesh near the heat source should be very fine, but the mesh far from the heat source should be divided sparsely, which can not only assure

the computational accuracy but also reduce the calculation amount and time.

It is very important that the adaptive unit mesh and time step are selected during numerical simulation of temperature field.

Fig. 2 shows the unit mesh division of PECT.

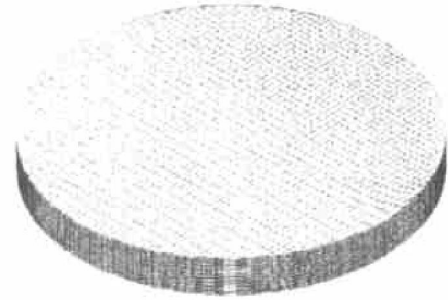


Fig. 2 Unit mesh division of PECT

The thickness of PECT is about 2 mm, the thickness of every ceramic layer is about 0.15 ~ 0.24 mm, and the argentums thickness is 10 μ m, and the glue layer thickness of cementing structure is about 20 μ m.

Laser heat source is treated as three-dimensional surface heat source. Application time of heat source is about 10 s and laser power is 200 W. The absorptivity of test specimen is 0.75.

The heat transfer coefficient to air on the surface of model is chosen as $h = 12$ W/mK, which is the natural convection coefficient of air. The initial temperature of the PECT is 30 $^{\circ}$ C.

In order to calculate temperature rise, the material parameters need to be known. Table 1 provides a summary of the materials constants.

Fig. 3 shows the computation results of laser soldering temperature field of monolithic PECT at 10 s and 20 s.

Index point of A_1 and A_2 are chosen on the PECT surface. Thermocouple was built in A_1 and A_2 point using destructive way before laser soldering. Thermocouple temperature measurements are carried out during laser soldering. The contrast curves between measured temperature and theoretical calculation temperature are shown in Fig. 4.

Fig. 4 shows that the numerical simulation temperature curves of PECT conform to the measured

Table 1 Thermal physical parameters of materials

Materials	Thermal capacity/($10^6 \text{ J} \cdot \text{m}^3 \cdot \text{K}^{-1}$)	Thermal conductivity/($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)	Thermal diffusivity/($10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$)
Copper mesh	3.207	106	33.052
PZT-4 ceramics	3.192	1.2	0.376
Ag layer	2.455	428	174.338
Epoxy resin glue	1.920	0.15	0.078
Sn-Pb eutectic alloy	1.7	50	29.412

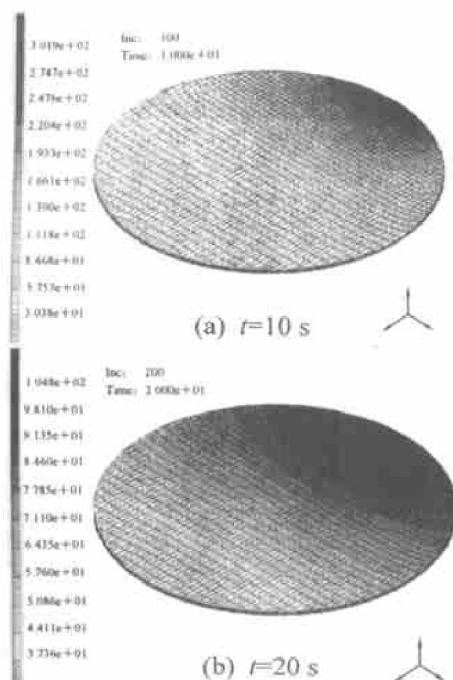


Fig. 3 Laser soldering temperature field of PECT

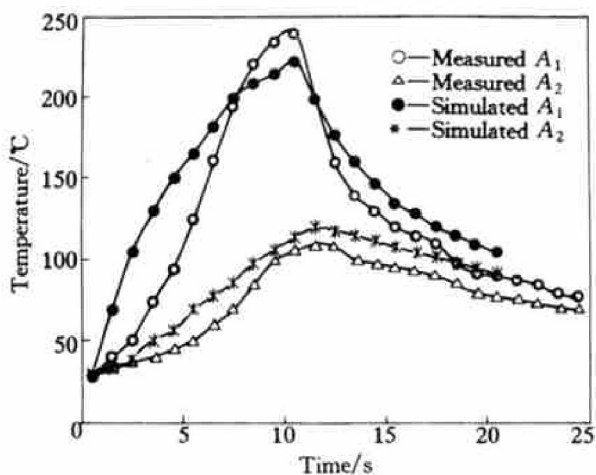


Fig. 4 Contrast curves of measured temperature and simulated temperature

temperature curves. There exists a little error between the calculation temperature and measured temperature because A_1 point near the heat source has higher temperature gradient. However, A_2 point far from the heat source, whose temperature variation is uniform, the calculated values are well conformable to the measured values.

4 CONCLUSIONS

1) A mathematical model of three-dimensional temperature field in laser soldering is established. The reasonable simplification of heat source, materials physical parameters and solder are proposed. Then, the governing equation of heat transfer is derived. Furthermore, the reasonable temperature distribution is acquired.

2) The computed results based on numerical

simulation are in good agreement with those of measured, which provides the theory reference for determining correct process and optimizing joint properties.

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(Edited by HE Xue-feng)