Optimization and simulation of furnace temperature curve based on heat

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Abstract. The welding quality of reflow welding is closely related to the setting of furnace temperature curve. Based on the law of heat transfer between heat transfer conduction and heat ionization in the process of reflow welding, the mathematical model of PCB plate heat transfer process is established based on the relationship between conveyor belt transfer speed, temperature of each temperature zone and minimum equivalent heat stress in the process of reflow welding, and the optimization model of furnace temperature curve is established with the minimum heating factor and minimum equivalent thermal stress as the optimization target. At the same time, the simulation analysis of stress strain before and after optimization is carried out by finite meta-method, and the results show that the iso-effect force after optimization is reduced by 6.5%, the warp deformation degree of the corner is also reduced to a certain extent, and the maximum iso-effect variable is reduced by 5%. The results provide reference and basis for the improvement of reflow welding process.

1. Introduction

These guidelines, Reflow welding is a key link in the production process of surface assembly technology, and the reflow welding process will directly affect the quality and reliability of electronic products [1-2]. The temperature curve of the reflow welding furnace determines the quality of the welding process, which is related to the geometry of the PCB board, the material parameters, the temperature setting of each temperature zone, the transmission speed of the conveyor belt and many other factors. In order to set the optimal furnace temperature curve, Lee [3] proposed the general quantitative index of furnace temperature curve setting by analyzing the relationship between furnace temperature curve and welding point failure form. Feng Zhigang and others [4] made a comprehensive study of the furnace temperature curve and its key indicators by using orthographic experimental method, and pointed out that the transmission speed and temperature of the conveyor belt had the most significant effect. Wang Mingquan and others [5] have explained the mechanism of temperature curve change in a concise light by establishing a furnace temperature curve regulation model based on heat conduction. Gao Jingang, etc [6], think that the quality of reflow welding is closely related to the welding process, based on the theory of heating factor, put forward the control strategy of the "cold spot" heating factor, and established the linear relationship between the heating factor and the shape and movement parameters of the furnace temperature curve according to the statistical principle, which brought great convenience to the optimization and control of the furnace temperature curve. Feng Zhigang and others [7] pointed out that the characteristic size of the circuit board is the biggest structural factor that affects the key indicators of the temperature curve of the reflow furnace. It can be seen that most of the above studies from the welding defects from the concept of avoiding welding defects, the furnace temperature curve...
of reflow welding requirements and indicators [8]. However, from the point of view of the heat transmission process of PCB board, there is not much research and optimization of furnace temperature curve.

Therefore, based on the transmission speed of the conveyor belt and the temperature of the temperature zone, this paper establishes the furnace temperature curve optimization model of reflow welding based on the theory of heat transfer, and constructs the ideal furnace temperature curve based on the response law of the furnace temperature curve to the temperature of each temperature zone.

2. Reflow welding numerical simulation and results

2.1. Analysis of the heat transmission process

In the process of reflow welding, there are three main modes of heat transfer, heat transfer $Q_k$ between contact surfaces, tsp heat exchange $Q_c$, radiation heat exchange $Q_r$, in order to facilitate model simplification and calculation, with the help of the commonly used treatment methods in engineering calculations, the radiation heat change into a two-stream heat exchange, this paper mainly considers heat transfer and flow heat exchange two heat transfer methods, with the following formula as:

$$Q = Q_k + Q_c$$  \hspace{1cm} (1)

The thermal conductivity between the contact surfaces can be described by Fourier's Law:

$$Q_k = -\lambda A \frac{dT}{dx}$$  \hspace{1cm} (2)

For model calculation purposes, only one-dimensional thermal conduction processes are considered, and changes in the direction of heat in thickness can be described as:

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} \right)$$  \hspace{1cm} (3)

The exposed surface of the PCB board and the flow of heat for heat are represented by the Newton cooling formula:

$$Q_c = hA(T_w - T_f)$$  \hspace{1cm} (4)

Type: A is the contact area between the circuit board and the gas, $T_w$ and $T_f$ are the hot air temperature and the circuit board temperature respectively, h is the average versus the heat exchange coefficient.

$$h = 0.664u^{1/2} Pr^{1/3} \lambda / (vL)^{1/2} + \frac{\sigma \varepsilon_1 \varepsilon_2 (T_1^2 + T_2^2)(T_1 + T_2)}{\varepsilon_1 + \varepsilon_2 - 1}$$  \hspace{1cm} (5)

Type: $u$ is the thermal wind speed, $L$ is the length of the substrate, $v$ is the gas viscosity, radon is the motion viscosity coefficient of the gas, $Pr$ is the Planck number, $\sigma$ is the black body radiation constant during the thermal radiation process, $\varepsilon_1$, $\varepsilon_2$ is the emission coefficient of the furnace cavity and the PCB board, $T_1$ is the absolute temperature of the furnace cavity, and $T_2$ is the temperature of a certain point on the PCB board.

In order to express the temperature change of welding area, combined with the solid heat absorption formula, the circuit board heat absorption is connected with its temperature:

$$\Phi = cm \Delta T$$  \hspace{1cm} (6)

It can be found from the analysis that in the circuit board reflow welding, the temperature of the circuit board can be set to an ambient temperature of 25 degrees C before the circuit board happens to enter the furnace area.

$$T(x, 0) = T_0 \hspace{1cm} (0 \leq x \leq \delta)$$  \hspace{1cm} (7)

Its boundary conditions fall into the third category:

$$h[T(\delta, t) - T_w] = \lambda \frac{\partial T(x, t)}{\partial x} \bigg|_{x=\delta}$$  \hspace{1cm} (8)
In order to show the relationship between the temperature and time of the welding area, the data on the temperature and time of the welding area provided by the 2020 Higher Education Association Cup Chinese University Student Mathematical Modeling Competition are used [9], and the data fitting results are shown in Figure 1 below.

![Figure 1. The fitting curve of the weld temperature and time](image)

2.2. PCB simulation model
Select a PCB plate as an example, without affecting the accuracy of the simulation, it is reduced to include copper foil and substrate two materials of the plate, its size is 83mm ×68mm×2mm, because the distribution of the PCB copper foil line is very complex, in the simulation process is not easy to handle, so it is approximately a layer of copper foil [10]. It consists of the upper layer of copper foil and the lower layer of FR4, the thickness of the upper layer of copper foil is 0.336mm, the thickness of the lower layer of FR4 is 1.664mm, the copper foil side of the component packaging. The temperature change process of reflow welding is simulated by ANSYS software, and its temperature field, warping deformation and thermal stress condition can be obtained [11].

2.3. Material mode
Sufficiently accurate material parameters are essential for accurately simulating and calculating the temperature change of the circuit board during the reflow welding process, which affect the distribution of the temperature field and the change of stress strain state, which vary with the temperature. Take the circuit board's thermal capacity and mass of \( c=1.47 \text{kJ/kg} \cdot \text{K}^{-1} \), m is 100g. The current velocity is the conveyor belt transfer speed, and some of the parameters of the copper foil and FR4 substrate are shown in Table 1 and Table 2 below. At the same time, in order to improve the accuracy of the model, more accurately reflect the actual process production requirements. The N2 used in the return flow welding is 90% of the protective gas in the back welding furnace, of which N2's fixed pressure ratio heat, power stickiness coefficient and thermal conduction coefficient, the rest of the material data can be found in the literature.

| Temperature/℃ | 20   | 80   | 120  | 160  | 200  | 225  | 240  |
|---------------|------|------|------|------|------|------|------|
| \( K / (\text{W}\cdot\text{m}^{-1}\cdot\text{℃}^{-1}) \) | 521.5| 532.0| 539.0| 546.0| 553.3| 557.7| 560.0|
| \( c_p / (\text{J}\cdot\text{kg}^{-1}\cdot\text{℃}^{-1}) \) | 0.3568| 0.3755| 0.3880| 0.4004| 0.4128| 0.4206| 0.42553|
Table 2. FR4 substrate’s thermal capacity

| temperature/℃ | 20  | 70  | 120 | 240 | 250 |
|---------------|-----|-----|-----|-----|-----|
| \(c_p\) (J kg\(^{-1}\)℃\(^{-1}\)) | 1200 | 1380 | 1500 | 1650 | 1600 |

2.4. Reflow furnace temperature setting
In this paper, the infrared hot air reflow dry furnace is selected, its internal setting has a number of small temperature zones, from the function is divided into four large temperature zones, including warm-up area, thermostat area, reflow zone, cooling zone, conveyor belt homogeneous speed of the circuit board into the furnace for welding heating. It can also be divided into 11 small temperature zones with a length of 30.5cm, with an interval of 5cm between adjacent small temperature zones and a 25cm front and back area outside the furnace. The temperature is set at 173℃ (small temperature zone 1 to 5), 198℃ (small temperature zone 6), 230℃ (small temperature zone 7) and 257℃ (small temperature zone 8 to 9); The temperature sensor starts to work when the temperature in the center of the welding area reaches 30℃ and the circuit board enters the welding furnace to start timing.

2.5. Finite meta analysis and calculation results
The above parameters are calculated in the model to calculate the temperature of the small temperature zone 3, 6 and 7 mid-point, respectively, 66.46 ℃, 144.432 ℃, 175.577 ℃, and the temperature of the welding area center at the end of the small temperature zone 8 is 202.765 ℃, and the furnace temperature curve of the whole process and the thermal effort of the PCB plate profile under each temperature zone can be obtained, as shown in Figure 2 and Figure 3.
From the change of temperature in Figure 3, it can be seen that the temperature of the PCB board after entering the warm-up zone rises faster and changes greatly, when the temperature distribution of the PCB board is not balanced, after entering the thermostat zone, because the temperature difference is set small, the temperature rise is relatively uniform, in the reflow zone, the temperature value of the board reaches the peak, the maximum temperature reaches 244.62 °C, and then enters the cooling zone gradually cools down.

In the process of reflow package, due to the presence of thermal stress, it will cause warping of the plate surface, affect the co-face of the structure, and then cause various quality and reliability problems such as chip breakage, layering of different interfaces and welding spot defects. Therefore, it is necessary to simulate the warping and stress strain state of the PCB board under the maximum temperature condition, as shown in Figure 4 and Figure 5 below.
As can be seen from the figure above, the equivalent thermal stress of the PCB board, the distribution of the response variables is extremely unbalanced, the stress value around is significantly greater than the stress value near the center, the ratio of the maximum to the minimum of the equivalent thermal stress is 38.5:1, and the maximum value of the equivalent thermal stress is $1.6894 \times 10^7$ Pa. Accordingly, the variable around the board is large, and the maximum iso-effect variable is $8.5881 \times 10^{-6}$ m. This is due to the difference of thermal expansion coefficients of different materials, the materials in the process of temperature change constraints on each other, resulting in different thermal stress strain conditions, and caused uneven distribution of stress strains.

3. Furnace temperature curve optimization

3.1. Furnace temperature curve response system

The furnace temperature curve of reflow welding can be divided into two parts, in order to obtain the best furnace temperature curve, we can compare the production method of furnace temperature curve, because the growth of furnace temperature curve in each interval has essential similarity, that is, the response of the curve to temperature is exponentially increased, and the temperature growth in the same heating interval is close to the difference between the temperature set in the interval and the previous temperature zone, showing the same exponential growth law [14].
In each heating time period, there is a temperature increase corresponding to the temperature increase, which is always close to the heat source temperature difference in the heating area. Therefore, it represents the relative difference between the settings of the different temperature zones in the welding furnace, in order to combine all the temperature control parameters in the furnace into a parameter $Th$, assuming that the temperature control parameters of each heating zone are $T_i,i=1,2,3…9$, and $T_0=25\,^\circ C$, then $T_i=T^0_{i}-\Delta T_0,i=1,2,3…8$.

The curve heating portion can be divided into nine corresponding time periods, indicated by $t_{j1}$, $t_{j2}$, $t_{j3}…t_{j9}$, as shown in Figure 7 below, the approximation process between the temperature increase and the heat source temperature difference in the heating zone is shown in Figure 8.

![Figure 7. Division of temperature growth values](image)

![Figure 8. The temperature increase value at the same stage and the temperature of the temperature zone are approaching](image)

3.2. Heating factor and thermal stress

In the welding process, in order to ensure the quality of welding part production, it is necessary to optimize the furnace temperature curve, the typical Sn-Ag-Cu alloy furnace temperature curve is shown in the following figure [15].

![Figure 9. Furnace temperature curve for typical Sn-Ag-Cu alloys](image)

Since the quality of IMC is directly related to the temperature and time in the reflow process, Wu Yiping [16] put forward the theory of heating factor, which is to integral the temperature $T(t)$ and time $t$ of the reflow curve on the welding liquid phase line, and define this integral value as the heating factor $Q_n$.

$$Q_n = \int_0^t (T(t) - T_m) dt$$

(8)
In the series (8), Tm is to reach the temperature of the liquid phase line, $t_1$、$t_2$ is the starting time to reach this temperature, in this paper, $T_n$ is 217 ℃ combined with the reflow temperature curve, the value of the heating factor Qn is the area on the liquid phase line, it can be reduced to an extruded sine curve.

$$Q_n = \frac{\Delta t \cdot \Delta T}{\pi} \int_{0}^{\pi} \sin t dt = \frac{2}{\pi} \Delta t \Delta T$$

(9)

3.3. Furnace temperature curve optimization

The solution target is the minimum heating factor and the minimum thermal stress, and the temperature of each temperature zone is the optimization variable, and the following conditions are constrained by the following conditions: ① the slope value of the temperature rise interval is between [0,3], the slope of the drop interval is between [-3,0], and ②During the temperature rise process, the time between 150 and 190 ℃ does not exceed 120s, not less than 60s, ③ the temperature greater than the temperature of the liquid phase cooling line shall not exceed 90s, not less than 40s, and ④ the peak temperature shall not exceed 120s, and the peak temperature shall not exceed 90s, and the peak temperature shall not exceed 240 ℃ and 250 ℃.

$$\min Q = \frac{2}{\pi} \Delta t \Delta T$$

$$\min \sigma = \alpha E \Delta T$$

(10)

$$s.t. \begin{cases} 0 < \frac{\Delta T(t)}{\Delta t} < 3 \\ 60 < t_i - t_j < 120 \quad i = 2, 4 \quad j = 1, 3 \\ 240 < T_{\max} < 250 \\ 40 < t_6 - t_5 < 90 \end{cases}$$

4. Simulation calculation results and analysis

Through the above model, it is calculated that the heating factor value is 674.6 and the minimum thermal stress is $1.5 \times 10^7$Pa, the temperature is set in each temperature zone: the temperature of the preheating zone is 170.33 ℃; The temperature of the temperature zone is 226.73 ℃, the temperature of the reflow zone is 248.85 ℃, the temperature of the cooling zone is 25 ℃, the transmission speed of the conveyor belt is 74 cm/min, and the ideal furnace temperature curve is fitted.

Figure 10. The optimal furnace temperature curve in an ideal state
As can be seen from Figure 11,12, the maximum stress value of the PCB board is $1.5789 \times 10^7$Pa, and the maximum value of the variable should be $8.158 \times 10^{-6}$m. The maximum iso-effect force decreased by 6.5% and the maximum iso-effect variable decreased by 5%. It can be seen that the furnace temperature curve calculated by the model is reasonable, which can reduce the warp deformation value of the plate to a certain extent, and can achieve the goal of reducing the thermal stress of the welding process and reducing the deformation of the welding process.

5. Conclusions

Based on the thermal conduction and heat convensional process of PCB plate, this paper establishes the welding process heat transmission model, and from the point of view of the law of the temperature response of the furnace temperature curve to the temperature zone, the ideal furnace temperature curve model is established with the minimum heating factor and the minimum equivalent thermal stress as the optimization goal. And the ANSYS software is used to simulate the temperature change process of PCB in simulating reflow welding. The following conclusions can be drawn:

(1) The calculated value of the model is close to the simulation results, which shows that it is reasonable to analyze the established mathematical model and simulation process from the perspective of heat transmission process.

(2) Starting from the response law of furnace temperature curve to temperature in temperature zone, the iso-effect force value of the optimized plate is $1.5789 \times 10^7$Pa, which is 6.5% lower than before
optimization, and the warp deformation degree also has a certain degree of decline. From $8.5881 \times 10^{-6}m$ to $8.158 \times 10^{-6}m$, a decrease of 5%, it can be seen that the best furnace temperature curve obtained by this law, the stress strain condition of the plate has improved to a certain extent.

(3) From the simulation results, it can be seen that in the process of reflow welding, the stress and strain value of the four peripheral corners of the PCB board is the largest, so the four peripheral corners are prone to component virtual welding, fracture and other reliability problems.

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