Optimization Model Design for Temperature Curve of Reflow Furnace

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Abstract. How to adjust the temperature zone temperature and furnace speed parameters to optimize the furnace temperature curve, so as to improve the product quality is the main problem faced by the temperature curve optimization of the reflow furnace. In this paper, the heat transfer model is established by the heat convection and heat conduction equations, and the mechanism of temperature change in the welding area is analyzed. Then, by gradually determining the objective function and comprehensively establishing the optimization model according to the known conditions, the optimal parameters are solved, so as to solve the optimization problem of furnace temperature curve. According to Newton's cooling law, specific heat theorem and Laplace equation, the temperature function of the center of the welding zone is deduced and solved, and the analytic function model of the temperature change in the center of the welding area can be obtained by synthesizing the inherent size conditions of the reflow furnace. Taking the corresponding data of experimental temperature and time as the fitting data, the undetermined parameters of the model were solved by nonlinear least square fitting method and undetermined coefficient method. The square sum of fitting residuals is 5857.7, which proves that the model has good fitting effect. Using the new experimental data to solve the model, the temperature change of the welding center at each position and time in the reflow furnace is analyzed. The temperature in the center of the welding area at the middle point of the low temperature zone 3, 6, 7 and the end of the small temperature zone 8 is 143.81°C, 181.78°C, 201.33°C, 228.97°C, respectively.

Keywords: Newton cooling law, specific heat theorem, nonlinear least square method.

1. Introduction
Reflow soldering temperature curve records the temperature change during the welding process of printed circuit board. As a key influencing factor in component welding quality control, Tang Zongjian (2019) studied the influence of temperature change on different processes in production and manufacturing, which can achieve ideal effect under reasonable temperature control. Song Huiliang (2018) proposed that different temperatures affect the welding effect of components in the production process, and the good production process maximizes the production efficiency. Xu Xiaoyan (2018) proposed that electronic circuit surface assembly technology (SMT) is an assembly and assembly technology of integrated circuits. The welding technology can improve the welding quality by putting the printed circuit board with various electronic components in the reflow furnace, melting and
solidifying the preset points by heating, and reasonably setting the temperature of each temperature zone of the reflow furnace and the passing speed of the circuit board, which can improve the welding quality. This is of great significance to the production of integrated circuit board. Wu Fenggang (2014) believed that in the actual production process, according to the temperature of the heating zone, the convective thermal conductivity of the reflux furnace and the stability of the technical parameters of the reflux furnace, the more appropriate parameter values can be obtained for reference, so as to improve the work efficiency, and put forward the improvement direction of the process method and optimize the production process. The external two sides are the furnace front area and the furnace back area respectively. There are four large temperature zones in its interior: preheating zone, constant temperature zone, reflux zone and cooling zone. Each high temperature zone contains several small temperature zones, with a total of 11 small temperature zones. The circuit board is brought into the furnace by the conveyor belt at a certain speed for heating and welding on the left side.

After the start-up of the reflow furnace, the device will be preheated as a whole and reach a stable state in a short time. There is no heat source in the front, back and gap of the furnace to control the temperature. The temperature is only related to the temperature of the adjacent temperature zone, and the temperature near the boundary of each temperature zone may also be affected by the temperature of the adjacent temperature zone. The whole working process was carried out in a workshop with room temperature of 25°C. When the circuit board starts to enter the reflow furnace at a certain speed, the timing starts. When the central temperature of the circuit board welding area exceeds 30°C, the temperature sensor for measuring the central temperature of the welding area starts to work. After the temperature in the center of the welding area at some positions is measured by the temperature sensor, the furnace temperature curve can be drawn with time as the independent variable and the measured temperature as the dependent variable. The process limits that the furnace temperature curve needs to meet are shown in Table 1.

| Boundary name                                      | Minimum | Maximum | Company |
|----------------------------------------------------|---------|---------|---------|
| Rising slope temperature                          | 0       | 3       | ºC/s    |
| Temperature drop slope                            | −3      | 0       | ºC/s    |
| During the temperature rising process, the temperature is between 150°C and 190°C | 60      | 120     | s       |
| Time when temperature is greater than 217°C       | 40      | 90      | s       |
| Peak temperature                                  | 240     | 250     | ºC      |

2. Model building
The mathematical model is established to describe the temperature change rule of the welding area. According to the index of reflow furnace shown in the project line data, the corresponding furnace temperature curve is drawn according to the index, and the temperature in the center of welding area is displayed every 0.5s.

Basic assumptions: the temperature change of small temperature zone 1 is small, and the heat transfer intensity to the furnace front area is approximately unchanged; in the welding process, the heat exchange generated by heat radiation is small enough to be ignored compared with the heat convection, the air at the gap is stable, and its heat transfer mode can be regarded as heat conduction; the temperature of heating area and cooling area in the furnace is stable, which is approximately equal to the temperature of corresponding low temperature zone; at any time, the temperature of heating zone and cooling zone in furnace is stable, which is approximately equal to that of corresponding low temperature zone, The results show that the temperature distribution in the welding area is approximately stable, and the influence of the quality of electronic components on the temperature sensing and welding efficiency can be ignored.
Table 2. Symbol representation

| Symbol | Company | definition |
|--------|---------|------------|
| $x_{l(i)}$ | Cm | Low temperature zone $i$ The left boundary coordinate value of |
| $x_{r(i)}$ | Cm | Low temperature zone $i$ Right boundary coordinate value of |
| $q_d$ | J/s | Heat intensity |
| $K$ | $W/(m \cdot k)$ | Air thermal conductivity |
| $L_f$ | cm | Length of furnace front area |
| $L_b$ | cm | Length of furnace back zone |
| $T_i$ | ℃ | Low temperature zone $i$ The temperature of |
| $T_0$ | ℃ | Room temperature |
| $A$ | $cm^2$ | Contact area between welding area and air |
| $v$ | m/s | Passing speed of conveyor belt |

According to the diagram of reflow furnace, the coordinates are established. The temperature distribution in front of the furnace and in the back of the furnace can be described by the temperature distribution in the front and rear zones of the furnace. According to Newton's cooling law and specific heat theorem, the analytic function of temperature related to hot air temperature and time can be derived and solved. The original experimental data are used to fit the analytic function by least square method, and the parameters of the analytic function are obtained by combining with the undetermined coefficient method. Then, the temperature and furnace temperature curve of each position can be solved by substituting the experimental setting index set by the industry into the function.

The hot air temperature distribution function of point heat source temperature field can be expressed as follows:

$$ T_w(x) = \frac{q_d}{4k\pi(\alpha - x)} + T_0 $$

Among them, $q_d$ Represents the heat intensity, $\alpha$ Represents the temperature correction factor, $T_0$ Represents room temperature. According to the conveying speed and time, the length of the zone in front of the furnace can be known $L_f$, Satisfy:

$$ x = -L_f + vt $$

Low temperature zone $i$ The hot air temperature distribution function of the corresponding heating area can be expressed as follows:

$$ T_w(x) = T_i, x_{l(i)} \leq x \leq x_{r(i)} $$

The analytical function of the gap temperature distribution is as follows:

$$ T_w(x) = \frac{T_{j+1} - T_j}{x_{l(j+1)} - x_{r(j)}} x - \frac{T_{j+1} - T_j}{x_{r(j)} - x_{l(j)}} x_{r(j)} + T_j, x_{l(i)} \leq x \leq x_{r(i)} $$

The temperature distribution in the area behind the furnace is as follows:

$$ T_w(x) = T_0, x_{r(11)} \leq x < x_{r(11)} + b $$

Heat analysis of welding area:

1) Air exchange analysis:

According to Newton's law of cooling, the heat transferred from air heat to welding area in a certain period of time can be expressed as
The heat absorbed by the welding area is expressed as:

\[ Q_c = cm(T(t_2) - T(t_1)) \]

Among them, \( c \) is the specific heat capacity of the material in the welding area, \( m \) is the quality of the welding element, \( T(t_1) \) is the initial temperature of the welding area, \( T(t_2) \) is the stable temperature of welding area.

3) The relationship between temperature change and time is deduced

\[ T(t) = T_w - e^{-\lambda \tau + b} \]

Among them, \( \lambda = \frac{hA}{cm} \), \( \lambda \) and \( b \) are undetermined parameters.

4) Synthesis of hot air temperature distribution function in front of furnace and average temperature function of welding area

The analytic function of the average temperature of some welding areas in front of the furnace with time is

\[ T(t) = \frac{q_d}{4k\pi(25 - vt + \alpha)} - e^{-\lambda \tau + b} + T_0, 0 \leq t \leq \frac{L_f}{v} \]

5) Synthesis of hot air temperature distribution function and welding area average temperature function in small temperature region

The time range of the circuit board in each gap is as follows:

\[ \frac{L_f}{v} + \frac{x_{r(i)}}{v} \leq t < \frac{L_f}{v} + \frac{x_{r(i)}}{v} \]

The analytical function of the average temperature of some welding areas in the gap region with time is obtained as follows

\[ T(t) = \frac{T_{j+1} - T_j}{x_{r(j+1)} - x_{r(j)}} - e^{-\lambda \tau + b} - \frac{T_{j+1} - T_j}{x_{r(j+1)} - x_{r(j)}} \left( x_{r(i)} + L_f \right) + T_j, \frac{L_f}{v} + \frac{x_{r(i)}}{v} \leq t < \frac{L_f}{v} + \frac{x_{r(i)}}{v} \]

6) Synthesis of hot air temperature distribution function and average temperature function in welding area

According to the furnace passing speed, the right boundary point of small temperature zone 1 and the length of the furnace back area, the time range of the circuit board in the furnace rear area is as follows:

\[ \frac{L_f}{v} + \frac{x_{r(l)}}{v} \leq t < \frac{L_f + L_b}{v} + \frac{x_{r(l)}}{v} \]

It can be seen that the analytic function of the average temperature of some welding areas in the back of the furnace with time is as follows:

\[ T(t) = T_0 - e^{-\lambda \tau + b} - \frac{L_f + L_b}{v} + \frac{x_{r(l)}}{v} \leq t < \frac{L_f + L_b}{v} + \frac{x_{r(l)}}{v} \]

7) Analysis of temperature change of welding zone center in furnace

At each time, the temperature distribution of the welding area is approximately regarded as a stable state, so the temperature distribution is a linear function of the position. The heating and temperature distribution diagram of the welding area is shown in Fig. 4. Among them, \( d \) is the thickness of the welding area.

\[ \nabla^2 T_m = 0 \]
Therefore, the temperature of the welding area is:
\[ T_w (y) = \beta y + T_p \]
Among them, \( T_p \) Represents the temperature in the center of the welding area, so
\[ T_p = T(t) - \frac{\beta d}{4} \]

According to the basic condition function of the welding area, the analytic function model of the center temperature change of the welding area can be determined as follows:

\[
T_p = T(t) - \frac{\beta d}{4} \\
T(x) = \begin{cases} \\
\frac{q_d}{4k\pi(25-\nu t+\alpha)} - e^{-2t+b} + T_0, & 0 \leq t \leq \frac{L_f}{v} \\
T_i - e^{-2t+b} + \frac{L_f}{v} + \frac{x_{l(i)}}{v} & \leq t < \frac{L_f}{v} + \frac{x_{r(i)}}{v} \\
T_{j+1} - T_j - e^{-2t+b} - \frac{T_{j+1} - T_j}{x_{j(i+1)} - x_{j(i)}} \left( x_{j(i)} + L_f \right) + T_j, & \leq t < \frac{L_f}{v} + \frac{x_{r(i)}}{v} \\
\frac{L_f}{v} + \frac{x_{l(i)}}{v} & \leq t < \frac{L_f}{v} + \frac{x_{r(i)}}{v} \\
T_0 - e^{-2t+b} + \frac{L_f}{v} + \frac{x_{j(11)}}{v} & \leq t < \frac{L_f}{v} + \frac{x_{r(11)}}{v} \\
\end{cases}
\]

\[ x_{l(i)} = (i-1)(L+l) \]
\[ x_{r(i)} = (i-1)(L+l) + L \]
\[ i = 1, 2, 3, \ldots, 11 \]
\[ j = 1, 2, 3, \ldots, 10 \]

3. Model solving
Taking the inherent geometry size and existing experimental parameters of the reflow furnace as the definite solution conditions, the fitting program is written by MATLAB software, and the non-linear least square fitting is used to fit the non-furnace front area, and part of the parameters of the central temperature function of the welding area are solved. According to the relationship between the furnace front area and the heating area in the furnace, the equation for solving the parameters is listed. Through the undetermined parameter method, the parameters of the central temperature function of partial welding zone in the furnace front area are solved, and the analytic function model of the temperature variation law with known parameters is obtained. The model is used to replace the furnace passing speed and the temperature in the small temperature zone under the new experimental conditions. The MATLAB software is used to search the time range with fixed step size to obtain the temperature change rule results.

According to the inherent geometric size of the reflow furnace and the existing experimental parameters, the length, temperature and passing speed of each temperature zone can be determined as follows:
\[
\begin{align*}
& l = 5\text{cm}, \\
& L = 30.5\text{cm} \\
& T_1 = B = T_5 = 175^\circ\text{C} \\
& T_6 = 195^\circ\text{C} \\
& T_7 = 235^\circ\text{C} \\
& T_8 = T_9 = 255^\circ\text{C} \\
& T_{10} = T_{11} = 25^\circ\text{C} \\
& v = 70\text{cm} / \text{min}
\end{align*}
\]
According to the geometric size and furnace passing speed, the time period of each area where the circuit board is located can be obtained, as shown in Table 3. It can be seen from the table that the circuit board begins to enter the furnace heating area at 21.4s.

| Different parts                  | Time (s)   |
|---------------------------------|------------|
| Furnace front area              | 0-21.4     |
| Furnace heating area            | 21.4-295.3 |
| Cooling zone                    | 295.3-351.9|
| Furnace back area               | 351.9-373.3|

After 21.4s, the circuit board leaves the furnace front area and enters the reflow furnace. The temperature change function is fitted by nonlinear least square method, and the undetermined parameters can be solved \( \lambda, \beta, b \).

| Study area                     | \( \lambda \) | \( b \)     | \( \beta \) | \( \lambda \) | \( b \) | \( \beta \) |
|--------------------------------|---------------|-------------|-------------|---------------|------|-----------|
| Temperature zone 1-5, gap 1-4  | 0.01887       | 4.959       | -74.06      | Gap 5         | 0.01892 | 2.111     | -51.02   |
| Low temperature zone 6         | 0.01908       | 3.31        | -27.97      | Gap 6         | 0.02387 | 2.827     | -46.02   |
| Low temperature zone 7         | 0.02866       | 3.997       | -64.08      | Gap 7         | 0.02436 | 3.306     | -41.96   |
| 8-8 temperature gap            | 0.02007       | 3.786       | -19.84      | Gap 9         | 0.01380 | 2.555     | 149.4    |
| Low temperature zone 10-11     | 0.00754       | 5.381       | 318.6       | Behind the furnace | 0.01014 | 4.985     | 0.452    |

In the actual production process, the critical temperature conditions are met
\[
\frac{q_d}{4k \pi \left( 25 - 21T + \alpha \right) } - e^{-21T+b} + T_0 = T_{-1}
\]
Among them, \( T_{-1} \) Represents the hot air temperature on the left side of the entry point of small temperature zone 1 temperature function, which can be determined in 21s by substitution
\[
T_{-1} = T(21) + e^{-21T+b}
\]
It can be solved as follows: \( q_d = 238740, \alpha = 45.60807 \).
According to the boundary conditions, the temperature results of different temperature regions are shown in Table 5.

Table 5. Temperature results of different temperature regions

| Temperate zone                                      | temperature (°C) |
|----------------------------------------------------|------------------|
| Middle point temperature of small temperature zone 3 | 143.81           |
| Mid point temperature of small temperature zone 6  | 181.78           |
| Mid point temperature of small temperature zone 7  | 201.33           |
| Temperature at the end of small temperature zone 8 | 228.97           |

4. Model evaluation and extension

1) In this paper, a new model is established. Based on the theory of heat transfer, Newton's law of cooling and heat conduction equation are used to calculate the function of temperature change in the center of welding area, which is in good agreement with the experimental data.

2) The influence of thermal radiation is ignored. Although the solution of the equation is simplified, the error of the obtained model will increase at high temperature.

3) The model approximates the temperature distribution of the welding area as a linear distribution, although it simplifies the calculation process, it has a slight deviation from the actual production temperature distribution.

4) In the model, the temperature in the small temperature region is assumed to be uniform distribution, which will deviate from the assumed temperature distribution due to the influence of instrument longitude and environment.

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