Heating Problem of Back Welding Furnace Based On Data Analysis

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Abstract. Based on thermodynamics and related industrial data, this paper establishes the mathematical model according to the internal heating principle of the reflow furnace, and uses the finite difference method to calculate the heating and welding process of the circuit board in the reflow furnace. Firstly, analyze the process and mechanism of the circuit board’s heat absorption in the reflow furnace, and establish a quantitative formula. Then, the transient heat model of the soldering area center is established according to the two main heat transfer modes, heat convection and heat radiation, as well as combined with the heat transfer process and data. The model assumes that the temperature of the air gap in each temperature region is the same as that of the large temperature zone, and and uses the analytical solution of the one-dimensional heat conduction equation to analyze and discuss the gap temperature, which verifies the correctness of the hypothesis. At the same time, combined with the premise of uniform distribution of gap temperature between different large temperature zones, the model is improved again. Finally, a complete transient heating model is established and solved numerically by finite difference method.

Keywords: One-Dimensional Heat Conduction Equation, Data Analysis, Transient Heating Model, Difference Equation, Computer Simulation

1. Introduction

In the production of electronic products such as integrated circuit board, the printed circuit board with various electronic components should be placed in the reflow soldering furnace, and the electronic components should be automatically welded to the circuit board by heating. In this process, the key to ensure the quality of the product is to keep the conditions of the process requirements in all parts of the back welding furnace. At present, many work in this field is to control and adjust the internal setting of several small temperature zones through experimental tests, which can be divided into four large temperature zones: preheating zone, constant temperature zone, reflow zone, cooling zone. Both
sides of the circuit board on the conveyor belt into the furnace at a uniform speed for heating welding. This paper mainly simulates the process of circuit board through mechanism model on the basis of previous research, and analyzes the speed of conveyor belt under certain conditions.

2. Analysis on Heat Transfer Mechanism of Reflow Soldering

Based on the traditional thermodynamics, the endothermic process of circuit board is analyzed, and the mathematical model of transient heating formula is established by considering the main heat transfer mode and boundary conditions in the back welding furnace.

2.1 Analysis of Endothermic Process in Circuit Board

First, a schematic diagram of the circuit board movement inside the reflow soldering furnace is given, as shown in Figure 1:

![Diagram of circuit board movement](image)

**Fig.1 Internal Schematic of Reflow Oven**

It can be seen from the diagram that reflow soldering is the process of absorbing heat in the reflow furnace at the soldering center. During this process, the formula of heat absorption in the process of reflow soldering PCBA analogized first\(^1\). The formula of heat absorption in circuit board reflow soldering furnace is obtained:

\[
Q_e = mc_p(T(t) - T(i))
\]

(1)

\(Q_e\) represents the heat absorbed by the circuit board from the initial temperature to the final temperature; \(m\) is the mass of the circuit board; \(c_p\) represents constant pressure heat capacity; \(T(t)\) represents final temperature; \(T(i)\) represents initial temperature.

2.2 Heat Transfer Mode

It is known that there are three heat transfer modes in the reflow soldering furnace: convection heat transfer, radiation heat transfer and heat conduction. Because the circuit board only absorbs relatively little heat through heat conduction on the conveyor belt, the heat conduction process is ignored, and the convection heat transfer and radiation heat transfer are mainly considered. The main formulas are expressed in formulas (2) and (3) respectively:

\[
Q_c = h_c A_e (T_{air} - T_e)
\]

(2)

The \(Q_c\) represents the heat transferred by convection per unit time, \(h_c\) the convection heat transfer coefficient, \(A_e\) the surface area of the circuit board, \(T_{air}\) the hot air temperature in each temperature zone, and \(T_e\) the circuit board area temperature.

\[
Q_r = h_r A_e (T_{sur} - T_e)
\]

(3)

\[
h_r = \varepsilon \sigma (T_{sur}^2 + T_e^2) (T_{sur}^2 + T_e^2)
\]

(4)
Among them, $Q_R$ represents the heat transferred by radiation per unit time; $\varepsilon$ represents the emissivity; Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{W/(m}^2\cdot\text{K}^{-4})$; $T_{\text{sur}}$ represents the temperature of the upper and lower walls of the reflow furnace. This question assumes that the temperature is the same everywhere in the temperature zone, so the This value is equivalent to $T_{\text{air}}$.

To sum up, the heat of circuit board in reflow furnace per unit time can be expressed as\[^2\]:

$$Q_e = Q_c + Q_R$$  \hspace{1cm} (5)

2.3 Boundary Conditions

In order to make each thermal equilibrium equation have a unique solution, it is necessary to attach certain boundary conditions and initial conditions, which are collectively called definite solution conditions. The actual welding in the back welding furnace contains the first and third kinds of boundary conditions. Because the first kind of boundary conditions can be converted to the third kind of boundary conditions, only the converted third kind of boundary conditions are considered in the simulation process to apply the load\[^3\].

2.4 Transient heating process analysis\[^5\]

The plane diagram of the adjacent small temperature zone inside the back welding furnace is shown in figure 2.

![Heat transfer diagram](image)

**Fig. 2** Heating mode in temperature zone of Reflow Oven schematic

It is understood from the diagram that the circuit board moves in the welding furnace through the conveyor belt, and the temperature zone is heated by hot convection to the welding area. And when the welding area center enters each temperature zone, it can be regarded as instantaneous heating. The transient heating process is analyzed below:

First of all, the formula of heat transfer part is obtained as follows:

$$mc_p(T(t) - T(i)) = [h_c + h_i]A_c(T_{\text{air}} - T_e)$$  \hspace{1cm} (6)

Then the transient heat transfer formula can be expressed as follows:

$$-[(h_c + h_i)(T_{\text{air}} - T_e)]A_c = \rho Vc_p \frac{dT}{dt}$$  \hspace{1cm} (7)

The instantaneous heat transfer formula is transformed into an integral form as follows:
\[ T(t) - T(i) = \frac{1}{\rho c_p L} \int_0^t \left\{ [h_c + h_f] (T_{air} - T_v) \right\} dt \]  

(8)

Among them, \( \rho \) is the average density of the circuit board, \( L \) the thickness of the circuit board, that is, the thickness of the soldering area. Select the appropriate time increment \( \Delta t \), and calculate the temperature center of the circuit board welding area at time \( t = \Delta t, 2 \Delta t, 3 \Delta t... \) through the right part of the upper formula.

3. Treatment of Small Temperature Zones

According to the basic setting of this problem, there is an air gap between the small temperature areas. When the back welding furnace starts, the air temperature in the furnace will be stable in a short time. In order to determine the stable temperature distribution in air, the gap temperature is numerically simulated by the analytical solution of one-dimensional heat conduction equation. Using 175°C and 195°C given in the title as examples, the other temperatures are similar. The corresponding definite solution problem is divided into two categories: one with the same constant boundary temperature condition (175°C) and the other with different constant boundary temperature conditions (175°C on the left and 195°C on the left):

\[
\begin{align*}
&\begin{cases} 
    u_x = a^2 u_{xx}, & 0 < x < 5, t > 0 \\
    u(x,t)|_{x=0} = 175, & u(x,t)|_{x=5} = 175 \\
    u(x,t)|_{t=0} = 25 
\end{cases} \\
&\begin{cases} 
    u_x = a^2 u_{xx}, & 0 < x < 5, t > 0 \\
    u(x,t)|_{x=0} = 175, & u(x,t)|_{x=5} = 195 \\
    u(x,t)|_{t=0} = 25 
\end{cases}
\]  

(9)

(10)

In the formula, \( u(x,t) \) represents the temperature \( t \) at the time \( x \) inside the gap, and \( a^2 = k/c_p \), obtained from the basic parameters of air (heat conduction coefficient \( k=0.0267 \) W/m-k, density \( p=k/c_p, 1.293^3 \), specific heat capacity \( c =1.003 \) kJ/(kg*K)). According to the theory of partial differential equation [6], we can see that the above two definite solutions with non-homogeneous boundary conditions can be obtained according to the method of separating variables:

\[
\begin{align*}
&u(x,t) = \sum_{n=1}^{\infty} \frac{300}{n \pi} \left( \cos n\pi - 1 \right) e^{-\frac{x^2}{25}} \sin \frac{n\pi}{5} x + 175 \\
&u(x,t) = \sum_{n=1}^{\infty} \frac{300}{n \pi} \left( \cos n\pi - 1 \right) e^{-\frac{x^2}{25}} \sin \frac{n\pi}{5} x + 175 + 4x
\end{align*}
\]  

(11)

(12)

After gridding the \( x \) axis, the temperature axis and the time axis respectively, the simulation results of the above analytical solutions are drawn into the flow field diagram (Fig.3).
Fig. 3 3Simulation results of heat conduction in the small temperature gap

(a) The diagram shows the temperature distribution at the boundary temperature of 175°C at both ends of the gap. It can be seen that when the temperature of the small temperature zone at both ends is equal, the gap air will reach the same temperature quickly. The results verify that the assumption that the small temperature region of the same layer is the same as the gap temperature is reasonable[7].

(b) The diagram shows the temperature distribution of the left end boundary temperature of the gap is 175°C and the right end boundary temperature is 195°C. The temperature inequality of the small temperature region at both ends can be seen, and the gap air will quickly reach the temperature field from high to low obey the uniform distribution. Based on the above theory, we can calculate the gap temperature between the small temperature regions for subsequent calculation. Therefore, if the temperature change between these gaps is fitted by function, the temperature transition in the center of the welding area can be simulated more accurately under the setting of the new temperature zone temperature and conveyor belt speed.

According to the difference of temperature change, there are five gaps where the temperature increases gradually. They are: the gap between the front zone of the furnace and the small temperature zone 1-5; the gap between the small temperature area 5 and the small temperature zone 6; the gap between the small temperature zone 7 and the small temperature zone 8.

In order to simplify the calculation and approximate the temperature change at these places as a linear change treatment, the following functions of temperature and time are obtained.

\[ T = T_i + (T_f - T_i) \frac{d}{y} \Delta t \quad (13) \]

\[\Delta t = t - t_{\text{before}} \quad (14)\]

4. Modeling and Simulation of Heating Process in Reflow Soldering Furnace[4][8][9][11]

4.1 The Parameters of Each Interval in the Simulation Process are as Follows[4]

| Table 1. Calculation of Temperature Parameters |
|-----------------------------------------------|
| Temperature zone | T₁  | T₂  | T₃  | T₄  | T₅  | T₆  | T₇  | T₈  | T₉  | T₁₀ | T₁₁ |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| hₜ               | 23.29 | 35.6 | 37.5 | 40.3 | 43.4 | 45  | 48  | 52  | 52  | 11  | 19  |
| ρ                | 8893 |      |      |      |      |      |      |      |      |      |      |
| cₜ                | 1400 |      |      |      |      |      |      |      |      |      |      |

4.2 The Reflow Curve under this Particular Condition is Shown Below

Note: Data from A questions of the National Mathematical Modeling Competition for College Students in 2020
5. Solving Maximum Transmission Speed of Conveyor Belt

It is known that on the basis of the above-mentioned experimental setting temperature, the setting temperature of each small temperature region can be adjusted within the scope of ±10°C. During the adjustment, the temperature in the small temperature region 1~5 is consistent, the temperature in the small temperature region 8~9 is consistent, and the temperature in the small temperature region 10~11 is 25°C. The speed adjustment range of conveyor belt over furnace is 65~100 cm/min. Therefore, the following eight physical quantities change properties and range of changes as shown in the table below:

| Description                      | Nature     | Scope          |
|----------------------------------|------------|----------------|
| Over furnace speed               | Variable   | 65-100 cm/min  |
| Welding area thickness           | Constant   | 0.15 mm        |
| Temperatures 1-5                 | Changes within range | 175±10°C |
| Small temperature zone 6         | Changes within range | 195±10°C |
| Small temperature zone 7         | Changes within range | 235±10°C |
| Temperature zone 8-9             | Changes within range | 255±10°C |
| Small temperature zone 10-11     | Constant   | 25°C           |
| Production workshop temperature  | Constant   | 25°C           |

In the welding production of circuit board of reflow soldering furnace, the temperature curve of furnace should meet certain requirements, which is called process boundary:

![Fig.4 Reflow profile](image-url)
Table 3. Process boundary

| Boundary Name                                      | Minimum value | Maximum value | Unit   |
|---------------------------------------------------|---------------|---------------|--------|
| Temperature rising slope                          | 0             | 3             | °C/s   |
| Decline in temperature                            | -3            | 0             | °C/s   |
| 150℃~190℃ time during the temperature rise       | 60            | 120           | s      |
| Time when the temperature is greater than 217℃    | 40            | 90            | s      |
| Peak temperature                                  | 240           | 250           | °C     |

According to the limit of process boundary, the limit condition of temperature change rate is:

\[-3 \leq \frac{dT}{dt} \leq 3\]  

(15)

Then consider that in the process of temperature rise, the time range of 150℃~190℃ is:

\[60s \leq t \leq 120s (150^{°}C \leq T \leq 190^{°}C)\]  

(16)

Circuit board temperature continues to rise, eventually more than 217℃ can last the time range is:

\[40s \leq t \leq 90s (T > 217^{°}C)\]  

(17)

Consider the peak temperature acceptable for the circuit board to function properly:

\[240^{°}C \leq \max(T) \leq 250^{°}C\]  

(18)

The above four restricted condition models are solved, that is, the final model is as follows:

\[
\begin{aligned}
&\left\{- \left[h_e + h_r \left(T_{aw} - T_i\right)\right] A_e = \rho V c_p \frac{T_1 - T_2}{t_1 - t_2}, \\
&-3 \leq \frac{dT}{dt} \leq 3, \\
&60s \leq t \leq 120s (150^{°}C \leq T \leq 190^{°}C), \\
&40s \leq t \leq 90s (T > 217^{°}C), \\
&240^{°}C \leq \max(T) \leq 250^{°}C
\end{aligned}
\]  

(19)

6. Summary
When the reflow furnace is started, it’s better to use one-dimensional heat conduction for numerical simulation in the temperature of the intermediate gap. The speed is better to control around 76cm/min, when the set values of temperature in each temperature zone are 182℃ (small temperature zone 1~5), 203℃ (small temperature zone 6), 237℃ (small temperature zone 7), 254℃ (small temperature zone 8~9). The temperature of different temperature regions can be analyzed by the same method.

Acknowledgments
This study is grateful for the data provided by the National Mathematical Modeling Competition for College students in 2020.

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