Modeling and Analysis of Heat transfer of Resolder Furnace based on Thermodynamics

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Abstract. In the production process, the printed circuit board with all kinds of electronic components is placed in the rewelding furnace and the electronic components are automatically welded to the circuit board by heating. In this production process, the temperature control of the resolder furnace is very important to ensure the product quality. In this paper, by analyzing the heat transfer characteristics of rewelding furnace, the three-dimensional problem is transformed into one-dimensional problem, and the transient heat transfer process is studied and analyzed. Considering the two heat transfer modes of heat conduction and heat convection, the partial differential equation model of one-dimensional double-layer heat conduction is constructed, and the classical mathematical and physical method is used to model and simulate the heat conduction in the welding process of printed circuit board. The variation diagram of the furnace temperature curve and the temperature in the center of the welding zone at different positions in the small temperature zone are obtained.

Keywords: One-dimensional double-layer transient heat transfer partial differential equation; simulation analysis; finite difference method; heat transfer.

1. Introduction
The welding of PCB is the key process to complete the welding process of circuit installation technology, and how to control and adjust the rewelding furnace to make each part keep the temperature required by the process is related to the yield of the product. This paper intends to analyze and study this aspect through the mechanism model.

The total length of the rewelding furnace and the speed of the conveyor belt have been given, and a group of data have been used to solve the furnace temperature curve of a new group of data by using the furnace temperature curve measured by the temperature sensor. According to the information of the topic, and considering various heat transfer modes and boundary conditions, an one-dimensional double-layer transient heat conduction model is established. Then it can be solved by simulation.
2. Basic theory

2.1. Reflow soldering and resoldering furnace

Reflow soldering: a welding technology in which the solder paste pre-printed on the PCB pad is heated and melted to form a solid solder joint to realize the mechanical and electrical connection between the pins of electronic components and the PCB pad.

Reflow furnace: equipment required for reflow soldering. After the placement of the plate through high temperature, so that the tin paste attached to the board melted and then cooled, so that the parts after placement to achieve a stable combination of equipment.

2.2. Fourier law of heat transfer

Fourier law is the basic law of heat conduction, which describes the relationship between temperature difference and heat flux density.

\[ q = -\lambda \frac{du}{dx} \]  

In the formula: \( Q \) is the heat flux and \( \lambda \) is the temperature difference on the space node.

For the part of \( \frac{du}{dx} \) considering heat conduction, the model is mainly based on Fourier law.

2.3. Newton's law of cooling

The basic calculation formula of convective heat transfer is the Newtonian cooling formula, which describes the heat transfer process between the fluid and the surface of the body.

\[ q = h\Delta t \]  

In the formula: \( h \) represents the convective heat transfer coefficient. For the problem of convective heat transfer, the surface heat transfer can be calculated by Newton's cooling formula.

3. Model establishment and solution

Modeling-transient heat conduction of one-dimensional multilayer plates

Heat transfer control equation

\[ k_n \frac{\partial^2 u_n}{\partial x^2} = \frac{\partial u_n}{\partial t}, x_n \leq x \leq x_{n+1} (n = 1, 2) \]  

3.1. Definite solution condition

1) Initial conditions:

\[ u_n(x,t)|_{t=0} = u_0^{n-1} \]  

Boundary conditions
Continuity conditions:

\[
\begin{align*}
\frac{\partial u_1(x,t)}{\partial x} \bigg|_{x=0} &= \alpha_1 [u_1(0,t) - u_{n+1}(t)] \\
\frac{\partial u_2(x,t)}{\partial x} \bigg|_{x=x_2} &= \alpha_2 [u_{n+2}(t) - u_2(x_2,t)]
\end{align*}
\]

(5)

Continuity conditions:

\[
\begin{align*}
&\begin{cases}
    u_n(x_n,t) = u_n(x_n',t) \\
    \lambda_{n+1} \frac{\partial u_{n+1}(x_{n+1},t)}{\partial x} = \lambda_{n+1} \frac{\partial u_{n+1}(x_{n+1},t)}{\partial x}
\end{cases}
\end{align*}
\]

(6)

3.2. Model solving

Because the temperature expression of the transient heat conduction equation of a single layer plate is as follows:

\[
u_n(x,t) = (A_{in} + B_{in}x) + \sum_{i=1}^{n} (A_{in} \cos(w_{in}x) + B_{in} \sin(w_{in}x))e^{-k_{in}w_{in}^2t}
\]

(7)

The expression of the heat flux density of the transient heat conduction of the n-layer plate is as follows:

\[
\lambda_n \frac{\partial u_n(x,t)}{\partial x} = \lambda_{n+1}B_{0n} + \sum_{i=1}^{n} (\lambda_{n+1}w_{in}B_{in} \cos(w_{in}x))e^{-k_{in}w_{in}^2t}
\]

(8)

The continuity conditions between layer n and layer n + 1 are as follows:

1) The density of heat flux at the junction of layer n and layer n + 1 at any time is equal:

\[
\lambda_n \frac{\partial u_n(x_n,t)}{\partial x} = \lambda_{n+1} \frac{\partial u_{n+1}(x_{n+1},t)}{\partial x} (x = x_n)
\]

(9)

Bring it into the above:

\[
\lambda_n B_{0n} + \sum_{i=1}^{n} (\lambda_{n+1}w_{in}A_{in} \sin(w_{in}x_n) + \lambda_{n+1}w_{in}B_{in} \cos(w_{in}x_n))e^{-k_{in}w_{in}^2t}
\]

\[
= \lambda_{n+1}B_{0n+1} + \sum_{i=1}^{n} (\lambda_{n+1}w_{in+1}A_{in+1} \sin(w_{in+1}x_n) + \lambda_{n+1}w_{in+1}B_{in+1} \cos(w_{in+1}x_n))e^{-k_{in+1}w_{in+1}^2t}
\]

(10)

2) At any time, the temperature at the junction of the nth layer and the n + 1 layer is equal:

\[
u_n(x_n,t) = u_{n+1}(x_n,t) (x = x_n)
\]

(11)

Bring it into the above:
\[(A_{0n} + B_{0n}x_n) + \sum_{i=1}^{\infty} (A_{in} \cos(w_{in}x_n) + B_{in} \sin(w_{in}x_n))e^{-k_{in}^2x_n^2}t = (A_{n+1} + B_{n+1}x_n) + \sum_{i=1}^{\infty} (A_{in+1} \cos(w_{in+1}x_n) + B_{in+1} \sin(w_{in+1}x_n))e^{-k_{in+1}^2x_n^2}t \]  
(12)

We need to satisfy the continuous consistency of interlayer temperature and heat flux density with time, but because the exponential function cannot be used as a basis function to express any function, there is an expression sub \(k_{n}w_{in}^2 = k_{n+1}w_{in+1}^2\). Therefore, the eigenvalues of the adjacent layers are related. From the above continuity conditions:

\[
\begin{align*}
A_{0n} + B_{0n}x_n &= B_{0n+1}x_n + A_{0n+1} \\
\lambda_{in}B_{0n} &= \lambda_{in+1}B_{0n+1} \\
A_{in} \cos w_{in}x_n + B_{in} \sin w_{in}x_n &= A_{in+1} \cos w_{in+1}x_n + B_{in+1} \sin w_{in+1}x_n \\
-\lambda_{in}w_{in}A_{in} \sin w_{in}x_n + \lambda_{in}w_{in}B_{in} \cos w_{in}x_n &= -\lambda_{in+1}w_{in+1}A_{in+1} \sin w_{in+1}x_n + \lambda_{in+1}w_{in+1}B_{in+1} \cos w_{in+1}x_n
\end{align*}
\]

(13)

Where \(I\) is the intrinsic value.

It is easy to see that the definite solution conditions of the equation can be given as long as the surface layer is convenient. Convective boundary conditions on the surface of the beginning and the end. The assembly process usually gives the parameters in the form of preheating, heating, reflux and cooling. If the parameters of hot air temperature changing with time in the tubule area are known, the following model can be established.

1) Exponential model

\[u_{\infty,1}(t) = u_{\infty,2}(t) = \begin{cases} 
 u_1(0 < t < t_1) \\
 u_1 + (u_2 - u_1)(1 - e^{-\gamma_1(t-t_1)})(t_1 \leq t \leq t_2) \\
 u_2 + (u_0 - u_2)(1 - e^{-\gamma_2(t-t_2)})(t_2 \leq t \leq t_3)
\end{cases} \]

(14)

2) Linear model

\[u_{\infty,1}(t) = u_{\infty,2}(t) = \begin{cases} 
 u_0 + (u_1 - u_0) \frac{t}{t_0}(0 < t < t_1) \\
 u_1 + (u_2 - u_1) \frac{t-t_1}{t_2-t_1}(t_1 \leq t \leq t_2) \\
 u_2 + (u_0 - u_2) \frac{t-t_2}{t_3-t_2}(t_2 \leq t \leq t_3)
\end{cases} \]

(15)

3.3. Determination of initial conditions and undetermined constants.

Let the initial temperature of the k-th temperature zone of the circuit board entering the reflux furnace be \(u(x,0) = u_0(k)\), so any layer should be established at the initial time when it enters the k-th temperature zone:

\[\sum_{i=1}^{\infty} (A_{in} \cos(w_{in}x)) = u_0(k) - [A_{0n}(k) + B_{0n}(k)x](n = 1, 2) \]

(16)
Because the rewelding furnace has 12 temperature zones, the initial temperature of the circuit board in each temperature zone is different, so the final temperature value of the last temperature zone in the center of the circuit board welding zone is taken as the initial temperature value of the current temperature zone. It can be obtained by making a series of transformations to the matrix by using the knowledge of algebra.

\[
\begin{align*}
\begin{pmatrix}
A_{in} \\
B_{in}
\end{pmatrix} &= \left( \prod_{q=1}^{n-1} G_q \right) \begin{pmatrix}
A_{in} \\
B_{in}
\end{pmatrix} \\
G_q &= \begin{bmatrix}
\cos w_{iq+1}x_n & -\sin w_{iq+1}x_n \\
\sin w_{iq+1}x_n & \cos w_{iq+1}x_n
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
0 & \sqrt{\lambda_q/b_q} + \lambda_q/b_q
\end{bmatrix} \begin{bmatrix}
\cos w_{iq}x_q & \sin w_{iq}x_q \\
-\sin w_{iq}x_q & \cos w_{iq}x_q
\end{bmatrix}
\end{align*}
\]

From this, the \( A_{in} \ (i = 1, 2) \) and \( B_{in} \ (i = 1, 2) \) of the nth layer can be determined.

So far, the definite solution of the one-dimensional double-layer transient heat conduction partial differential equation has been determined.

### 3.4. Selection of related parameters of reflow soldering

The one-dimensional double-layer transient heat conduction model established in the previous section is used to simulate the reflux process of the printed circuit board, and the simulation parameters are determined according to the specific steps of the printed circuit board process. Suppose the reflow soldering furnace used at this stage uses hot air to heat Liu cycle up and down, the maximum temperature is set to 250°C, and the chain speed range is 65-100cm/min.

At present, the transmission speed is the full length of the resoldering furnace, and the printed circuit board has experienced large reflow soldering.

Approximately required, the temperatures of the 11 temperature zones are shown in the following table:

| Temperature zone          | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|
| Upper temperature zone.   |    |    |    |    |    |    |    |    |    | 25 |    |
| Temperature \( (^{\circ}C) \) | 175 | 195 | 235 | 255 |    |    |    |
| Lower temperature zone.   |    |    |    |    |    |    |    |    |    |    | 25 |
| Temperature \( (^{\circ}C) \) | 175 | 195 | 235 | 255 |    |    |

Then the furnace temperature curve obtained from the furnace temperature test based on the parameters given above is shown in the following figure:

### Tabel 2. Problem one problem solving

| Variable                                      | Types       | Value |
|-----------------------------------------------|-------------|-------|
| Low temperature zone 3 midpoint temperature \( /{^\circ}C \) | Design variable | 175   |
| Low temperature zone 6 midpoint temperature \( /{^\circ}C \) | Design variable | 201   |
| Low temperature zone 7 midpoint temperature \( /{^\circ}C \) | Design variable | 234   |
| Temperature at the end of low temperature zone \( 8 /{^\circ}C \) | Design variable | 255   |
4. Conclusion
In this paper, the corresponding mathematical model is established for the temperature change law of the welding zone. The passing speed of the conveyor belt is 78cm/min, the temperature in the low temperature zone 1-5 is 173 degrees Celsius, the temperature in the low temperature zone 6 is 198 degrees Celsius, the temperature in the low temperature zone 7 is 257 °C and the temperature in the low temperature zone 8-9 is 257 °C. This paper gives the temperature change of the center of the welding zone, lists the temperature of the center of the welding zone at the middle point of the small temperature zone 3, 6, 7 and the end of the small temperature zone 8, draws the corresponding furnace temperature curve, and stores the temperature data of the center of the welding zone every 0.5s in the provided result.csv.

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