Modeling analysis and optimization of temperature curve of welding furnace

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Abstract. Re flux welding is widely used in SMT (surface patch technology) During this production process, the quality of the product is essential to maintain the temperature and the furnace speed required by the process. The furnace temperature curve in the furnace is an important form of reaction welding process. In order to improve the process efficiency of the return furnace, the heating welding process model is established based on the Fourier heat conduction law, 1D heat conduction model and Newton cooling law and draws the furnace temperature curve model. Then, the upper boundary of the conveyor speed using the boundary analysis and multiple target planning, and further explore the research and optimization direction of subsequent process flow. At the same time, this paper examines and analyzes the modeling process and results, and effectively demonstrates the scientific nature and accuracy of the model. Finally, the paper analyzes the significance of the above model and research in chip processing.

Key words: Furnace temperature curve; process optimization; marginal analysis; mathematical modelling.

1. Introduction
Reflow welding is the main means to realize SMT (surface patch technology). Several small temperature zones are set in the return furnace. whose working principle is to melt the PCB plate through the temperature zone of the tin paste attached to the PCB(printed circuit board, hereinafter referred to as the "circuit board") board before cooling, and finally realize the stable combination of PCB and the electronic components. The following diagram is the structural diagram of the return furnace.

Fig. 1 Schematic diagram of return section
After setting the temperature of each temperature zone and the furnace speed of the conveyor belt, the temperature at the center of the welding area at some locations can be tested as the furnace temperature curve (center temperature curve of the welding area) through the temperature sensor. The furnace temperature curve is an important characterization of the quality of the return furnace welding process[2], which is specifically reflected in the following aspects: 1, the temperature in the center of the welding area exceeds 217 ºC should not be too long, and the peak temperature should not be too high. That is, the furnace temperature curve shall minimize the area covered over 217 ºC to the peak temperature; 2, the furnace temperature curve exceeding 217 ºC on both sides of the center line shall be as symmetrical as possible. The optimization of the furnace temperature curve is mainly changed by changing the conveyor belt transmission speed and the temperature setting of each temperature zone.

In the welding production of the return furnace circuit board, the furnace temperature curve shall meet certain requirements, known as the process limits (see the table below):

| Bound name                                             | Minimum | Maximum | Unit |
|--------------------------------------------------------|---------|---------|------|
| Temperature rise slope                                 | 0       | 3       | ºC/s |
| Temperature drop slope                                 | −3      | 0       | ºC/s |
| Time of 150 ºC~190 ºC during the temperature rise     | 60      | 120     | s    |
| Time with a temperature greater than 217 ºC            | 40      | 90      | s    |
| Peak temperature                                       | 240     | 250     | ºC   |

To simplify the modeling process, this paper makes the following assumptions on the working conditions of the return furnace: First, the furnace temperature and belt rate are only changed for each operation, the material characteristic value and the thermal physical performance of the protective gas do not change with temperature; second, the temperature in the furnace remains stable during heat, without considering the heat loss in the gap area; 3, the intermittent temperature is not affected by other external factors, but only by the separated interval; 4, the workshop is an infinite constant temperature environment, not considering the temperature change brought by the workshop heat transfer. In the construction of the furnace temperature curve model, the process condition is the setting value of 78 cm/min, temperature zone of 173 ºC(Small temperature zone 1~5), 198 ºC(small temperature zone 6), 230 ºC(small temperature zone 7) and 257 ºC(small temperature zone 8~9) are based on the study of 182 ºC(small temperature zone 1~5), 203 ºC(small temperature zone 6), 237 ºC(small temperature zone 7), 254 ºC(small temperature zone 8~9).

2. Modeling and analysis of the welding process

2.1. Modeling and analysis of the welding process

During the backflow welding heating process, the model of the heated PBC and its elements is a flat plate body, and the topic gives the thickness of the center of the heating area of 0.15mm, and passes through the return furnace at a certain speed, so the heat transfer process in the small temperature area can be considered as air convection between the upper and lower surface and the furnace during movement. For easy study, the model of PBC and its components is equivalent to the fine bars in the following figure. Since the heat conduction direction goes reversed the velocity, the heat conduction of the visual element is one dimensional.

![Fig. 2 One-dimensional uniform fine line](image)
To simplify the content, the symbols required for the following modeling process are first shown in the following table:

| Symbolic name | Symbol description |
|---------------|--------------------|
| $T(x,t)$      | Temperature of any point $x$ of the element at $t$ time |
| $T$           | Absolute temperature for heating the central area of the element |
| $T_i$         | Absolute temperature in the $i$ temperature zone furnace |
| $T_{i0}$      | Initial absolute temperature of the element going into the $i$ temperature zone |
| $q_c$         | Density of heat flow rate |
| $\lambda$    | Thermal conductivity |
| $h$           | Convective heat-transfer coefficient |
| $Q$           | Heat required to increase the temperature by $\Delta T$ |
| $q$           | Heat in unit time over the unit cross-section product |
| $C$           | Complement specific heat capacity |
| $S$           | Element cross section |
| $\rho$        | Component density |
| $m$           | Element quality |

Oberved by Fourier's Law [3]:

$$q_c = -\lambda \frac{\partial T}{\partial t}$$  \hspace{1cm} (1)

The heat conduction equation is derived, and a section of microelements from $x$ to $x + \Delta x$ is selected. According to Fourier's experimental law and the energy conservation law, the net inflow of heat is equal to the heat required for the temperature increase of the element during this time. As follows:

$$Q = Q_1 - Q_2 + Q_3$$  \hspace{1cm} (2)

Then

$$C \cdot \rho S \Delta x \cdot \Delta T = -\lambda T_x \cdot S \Delta t + \lambda T_{x+\Delta x} \cdot S \Delta t + (x, t) \cdot \Delta t \cdot S \Delta x$$  \hspace{1cm} (3)

Simplified as

$$C \cdot \rho \cdot \frac{\Delta T}{\Delta t} = \lambda \cdot \frac{T_{x+\Delta x} - T_x}{\Delta x} + T(x, t)$$  \hspace{1cm} (4)

It is seen from the equation that, under the conditions given by $T(x, t)$, the rate of change in the element temperature is proportional to the temperature difference at both ends of the element. Based on the above analysis, the mathematical model of the temperature change of the welding area is further simplified. Because we monitor the temperature of a point in the center of the heating area, the distance of the proton point moving during the time of $\Delta t$ is $\Delta x$. Then based on the above analysis, the proton temperature difference in the time of $\Delta t$ can be seen as the temperature difference between the two proton sites from $\Delta x$. Then the temperature rate of change of the element is proportional to the temperature difference and the temperature of the element.

According to the Newton cooling formula [4]:

$$q = h(T_1 - T)$$  \hspace{1cm} (5)

The time is integrated on both sides of the formula child, and the heat absorbed per unit area is:

$$\int q dt = \int h(T_1 - T) dt$$  \hspace{1cm} (6)

With the specific heat capacity is $C$, heating center area mass $m$, the heat absorbed can be represented as:

$$Q = Cm(T - T_{i0})$$  \hspace{1cm} (7)
By formula (6) and formula (7),

\[ Q = C(T - T_i) = S \times h(T_i - T)dt \]  

(8)

The differential equation for time:

\[ \frac{dT}{dt} = \frac{sh}{cm} \cdot (T_i - T) \]  

(9)

\[ \frac{sh}{cm} = k \]

\[ T = T_i - \frac{C}{k} \cdot e^{-kt} \]  

(10)

(10) is the one-dimensional heat conduction model of the welding furnace. With this formula, the furnace temperature curve can be calculated according to the temperature zone length, conveyor belt speed and temperature zone setting temperature.

2.2. Optimization analysis of the furnace temperature curve

Based on the one-dimensional linear heat transfer model, constructing the function of the temperature of the welding center area under the second problem and turning t into the electronic plate displacement to the conveyor speed, thus establishing the binary function between the temperature of the welding center area and the position of the electronic plate:

\[ T = F(x, t) \]  

(11)

The temperature over time in welding center area of electronic plate is:

\[ T_i = T_{i0} - \frac{C}{k_i} \cdot e^{-kt} \quad i = 1,2,3,...,8 \]  

(12)

\[ t = \frac{x}{v} \]  

(13)

The temperature change function of each section simultaneously satisfies the following recursive relationship:

\[ T_{i-1}(t_{end}) = T_i(t_0) \]  

(14)

According to the welding process of the return furnace, the two major determinants of the easy welding process are the heating rate and welding time of the electronic plate, and the control conditions directly related to these two factors are the set temperature of the return furnace in different temperature sections and the rate of the electronic version of the conveyor belt transmission; Through the process limit, the temperature rise slope and peak temperature limit the set temperature of the temperature rise process at 150°C —— 190°C and the duration greater than 217°C limit the transmission rate. When the set temperature of the return furnace in different temperature sections has been set, the maximum transmission rate of the conveyor belt is required to be found from the duration of 150°C —— 190°C and the duration greater than 217°C;

The boundary analysis model is used to solve the optimal value of multi-constraint and multiple range selection, mainly considering the boundary extreme value. At the same time, the boundary is considered. Obviously, the greater the transmission speed of the conveyor belt, the shorter the temperature of the temperature section of the return furnace, the plate meets the application conditions of the boundary analysis model and can be applied;
3. Modeling results and discussion

3.1. Drawing of the furnace temperature curve

According to the assumption, the gap in the temperature zone does not have special temperature control, the difference between the gap in the overall temperature zone and the temperature in each small temperature zone can be continuous, the different temperature zones is dependent on the set temperature value of the two temperature zones, and the furnace temperature curve is divided according to the furnace temperature of different locations in different locations of the temperature zone. As follows:

| Tab. 3 Division of furnace temperature zone |
|---------------------------------------------|
| Division of furnace temperature zone | Stop of the PBC board in the corresponding temperature zone Leave the time for / s | Temperature zone temperature/℃ |
| Small temperature zone 1 —— 5 | 13.2.7 | 137 |
| Clearance between small temperature zone 5 and 6 | 3.8 | 167.5 |
| Small temperature zone 6 | 23.5 | 198 |
| Clearance between small temperature zone 6 and 7 | 3.8 | 214 |
| Small temperature zone 7 | 23.5 | 230 |
| Clearance between small temperature zone 7 and 8 | 50.8 | 243.5 |
| Small temperature zone 8 —— 9 | 3.8 | 257 |
| Clearance between small temperature zone 8 and 9 | 3.8 | 141 |
| Small temperature zone 10 —— 11 | 50.8 | 25 |

According to the experimental conditions and experimental data given by the topic, the functions are fitted in sections according to the temperature zone division, and then the k values, constant c and Ti. of each stage are calculated. As follows:

| Tab. 4 Parameters of division of furnace temperature zone |
|----------------------------------------------------------|
| Division of furnace temperature zone | k | c | Ti/℃ |
| Small temperature zone 1 —— 5 | 0.0198 | 148.01 | 173 |
| Clearance between small temperature zone 5 and 6 | 0.0146 | 106.26 | 185.5 |
| Small temperature zone 6 | 0.0068 | 735.37 | 198 |
| Clearance between small temperature zone 6 and 7 | 0.0090 | 191.35 | 214 |
| Small temperature zone 7 | 0.0090 | 261.35 | 230 |
| Clearance between small temperature zone 7 and 8 | 0.0214 | 3419.14 | 243.5 |
| Small temperature zone 8 —— 9 | 0.0193 | 2830.83 | 257 |
| Clearance between small temperature zone 8 and 9 | -0.0047 | 28.71 | 141 |
| Small temperature zone 10 —— 11 | -0.0047 | 786.71 | 25 |

The given data is calculated using MATLAB, and the furnace temperature curve and process limit data are drawn:
3.2. Upper bound study of some indicators
Firstly, solve the binary function of the temperature of the welding center area in the small temperature zone 1 —— 5:

\[ T_i = 182 - 157 \cdot e^{-0.0198 \frac{x}{v}} \]

The transmission speed range of the conveyor belt is 65 —— 100 cm/min. According to the length relationship of the return section, the time range of electronic plates through the four temperature sections is shown in the following table:

| Tab. 5 Division of furnace temperature zone |
|--------------------------------------------|
| Division of furnace temperature zone        | Location range (cm) | The total time-consuming time (s) |
| Small temperature zone 1 —— 5              | [0,172.5]           | [103.50,156.82]               |
| Clearance between small temperature zone 5 and 6 | [172.5,177.5]     | [106.50,161.36]               |
| Small temperature zone 6                    | [177.5,208.0]       | [124.80,189.09]               |
| Clearance between small temperature zone 6 and 7 | [208.0,213.0]     | [127.80,193.63]               |
| Small temperature zone 7                    | [213.0,243.5]       | [146.10,221.36]               |
| Clearance between small temperature zone 7 and 8 | [243.5,248.5]     | [149.10,225.90]               |
| Small temperature zone 8 —— 9              | [248.5,314.5]       | [188.70,285.90]               |
| Clearance between small temperature zone 8 and 9 | [314.5,319.5]     | [191.70,290.44]               |
| Small temperature zone 10 —— 12            | [319.5,385.5]       | [231.30,350.44]               |

First find the arrival of 150℃, let \( T_i = 150 \), we can get \( t = 80.33 s \). On the left side of the interval \([103.50,156.82]\), it can be concluded that the electronic plate must reach a welding temperature in the temperature zone 150℃ regardless of the belt speed, where the electronic plate is 80.33 cm/s; The boundary condition at the fastest speed is that the duration of the electronic board at 150℃ —— 190℃ and above 210℃ within the required interval or above 217℃ is the shortest 40 minutes and the duration of the electronic board at 150℃ —— 190℃ should be within the required interval; in both cases the conveyor belt speed with smaller score is selected. In this regard, establishes the cycle, passes the transmission speed value of the conveyor belt, and establishes the recursive function of different temperature sections at different speed values. Since 80.33 seconds reaches 150℃ is a fixed value, then
the temperature of the electronic plate at 140.33 seconds cannot be greater than 190℃ in 140.33 seconds, which is an important condition for us to judge whether the speed is legal. We first assume that the conveyor belt speed is 100cm/min. In order to meet the requirements, through the position and maximum passage time limit of each temperature section, we calculate and find that the electronic plate temperature of the 190℃ is be in the temperature zone 7; The calculation process is shown in fig.3.

After calculation, when the conveyor belt speed is at 83cm/min, the electronic board shall last at least 60 minutes at 150℃—— 190℃ and within the required range; when the conveyor belt is at 87cm/min, the shortest above 217℃ and the electronic plate at 150℃—— 190℃ shall be within the required range, the allowable maximum conveyor belt over furnace speed is.

![Fig. 4 The calculation process](image)

3.3. Model inspection and error analysis

This paper compares the experimental data with the furnace temperature curve model with the effect. It is clearly found that both curves are roughly the same in data and highly fit. Meanwhile, after the comparative calculation of data in each temperature zone, the residual value on each temperature interval are 0.82%, 0.97%, 0.31%, 0.27% and 0.71%, with the mean of 0.74%, which further shows that the model has high accuracy.
Fig. 5 Comparison diagram of model curve and experimental curve fitting

4. Summary

4.1. Research Significance
This paper starts with the welding process, the Fourier heat conduction law, one-dimensional heat conduction model and Newton’s cooling law, draws the furnace temperature curve and fit with the experimental data to verify the accuracy and scientificity of the model construction process and results. Subsequently, the maximum value of the transfer speed of the conveyor belt and explores the index range and direction of the improvement process. This paper adopts the positive mechanism analysis in furnace temperature curve model. The one-dimensional heat conduction model based on Fourier's heat conduction law, one-dimensional heat conduction model and Newton's cooling law is the basis and starting point for analyzing the furnace working process, studying process efficiency and improving process level, which lays the foundation for subsequent research. The welding furnace is crucial to the processing and welding of chips and other electronic components such as chips. The quality of the processing process and welding effect has a decisive impact on the performance of electronic components. Therefore, optimizing the processing process of the welding furnace has a positive role in promoting the quality and industrial efficiency of related products.

4.2. Research and promotion
The paper is the working mechanism and the establishment of furnace temperature curve model and the upper bound of the transmission speed of the conveyor belt under the furnace temperature. On the basis of the research work, we can further relax the constraints, construct the process optimization model with the ideal furnace temperature curve in the introduction, and study how to regulate the temperature and the transmission speed of the transfer belt, optimize the furnace temperature curve and improve the performance of the return furnace.

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