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Optimal Model of Reflow Furnace Temperature Curve

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Abstract

In the production of electronic products such as integrated circuit boards, keeping all parts of the reflow furnace at the temperature required by the process is essential to product quality. The lead-free solder paste commonly used in production has a melting point of 217°C. Excessive temperature will affect the performance of the circuit board, so the temperature should not exceed 217°C. Starting from Fourier's law, Newton's law of cooling and the law of conservation of energy, a model of convective heat transfer across the plate is established. With hypothetical conditions, the model can be used to calculate the best speed of the conveyor belt, the best temperature in each temperature zone, and the best temperature curve. The ANSYS simulation software was used to simulate the actual working process of the reflow furnace, and two control groups were set up, and the solution result of the verified model was the best temperature curve.

Keywords

Newton's law of cooling, thermal convection, ANSYS.

1. Introduction

In the production of electronic products such as integrated circuit boards, the printed circuit boards containing electronic components need to be placed in a reflow furnace and heated to automatically solder the electronic components to the circuit board. This process is called SMT (Surface Mounted Technology) Patch processing. In the SMT production process, reflow soldering is a more important step. Whether each part of the reflow furnace can maintain the temperature required by the process has an important impact on the quality of the product.

Nowadays, there have been some researches on reflow soldering. Jiao Jinli's "Six Sigma Method in Improving the Quality of SMT Reflow Soldering Process" adopts the improvement method of Six Sigma DMAIC, and establishes a large fluctuation in the quality of the SMT reflow soldering process. Quality control and improvement model with many influencing factors. Tang Zongjian et al. "Analysis of the Control and Control of Reflow Soldering Furnace Temperature Curves" aimed at the factors affecting the use of temperature measurement boards to obtain reflow soldering temperature curves, and analyzed the potential failure effects of the temperature measurement process. It is found that frequent furnace temperature tests with temperature measuring boards have a higher risk factor. Through the monitoring and analysis of the temperature of each temperature zone of the reflow furnace, it is found that the process capability of the reflow furnace is in a good state, and the risk factor of potential failure effects is low.

Aiming at the existing technical approach, this research proposes the research goal: to establish a mathematical model for solving the optimal speed of the conveyor belt, the optimal temperature of each temperature zone, and the optimal temperature curve.

2. Mathematical model

2.1. Mathematical simplification of practical problems

Convective heat transfer is the heat transfer process that occurs when the fluid flows through the solid wall due to the difference in temperature between the two. The convective heat transfer method in the reflow furnace can be approximately regarded as the convective heat transfer of the single-sided hot air sweeping the plate. In the process of establishing the model, we calculated the basic thermal parameters of the circuit board from the data commonly used in actual industrial production, and applied the circuit board to the model establishment and solution process.

2.2. Build a model

Convection heat transfer is based on the Newtonian cooling formula. The temperature of the heat transfer fluid is T0 and it is put in the fluid of temperature T, and the heat transfer area is A. After time t, the convective heat transfer is:

$$Q_c = h_c(T - T_0)At \tag{1.1}$$

One of the boundary conditions in the reflow furnace is convection. According to the Newtonian cooling formula:

$$q_{conv} = h_c(T - T_0) \tag{1.2}$$

The unknown in the formula (1.1) and (1.2) is the convective heat transfer coefficient, W/m2·K. The convective heat transfer in the furnace can be approximately regarded as the convective heat transfer of the double-sided hot air sweeping the flat plate. In this way,

$$Nu_m = 0.664Re_l^{\frac{1}{2}}Pr^{\frac{1}{3}} \tag{1.3}$$

$$Re_l = \frac{uL}{v} \tag{1.4}$$

$$P_r = \frac{\eta c_p}{\lambda} \tag{1.5}$$

From this we can find h_c:

$$\begin{aligned} h_c &= \frac{Nu_m\lambda}{L} \\ &= \frac{0.664Re_l^{\frac{1}{2}}Pr^{\frac{1}{3}}\lambda}{L} \\ &= \frac{0.664\left(\frac{uL}{v}\right)^{\frac{1}{2}}\left(\frac{\eta c_p}{\lambda}\right)^{\frac{1}{3}}\lambda}{L} \\ &= \frac{0.664u^{\frac{1}{2}}(\eta c_p)^{\frac{1}{3}}\lambda^{\frac{2}{3}}}{(vL)^{\frac{1}{2}}} \end{aligned} \tag{1.6}$$

In the formula, u is the conveyor belt speed, m/s; L is the length of the circuit board, m; V is the fluid viscosity of the air, m^2/s; η is the dynamic viscosity of the air, m^2/s; c_p is the heat capacity of the air, J/(kg·K); λ is the cloud dynamic viscosity coefficient of air, W/(m·K); Nu_m is the Nusselt number, which represents the strength of convective heat transfer;Re_l is the Reynolds number, which reflects the forced flow of fluid, The relative magnitude of the inertial force and

the viscous force; Pr is the Prandtl number, which reflects the relative magnitude of the fluid momentum diffusivity and thermal diffusivity.

In engineering calculations, heat radiation is often converted to heat convection. In this way, written in the form of the Newtonian cooling formula:

$$q_{rad} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = h_r(T_1 - T_2) \tag{1.7}$$

$$h_r = \frac{\sigma\varepsilon_1\varepsilon_2(T_1^2 + T_2^2)(T_1 + T_2)}{\varepsilon_1 + \varepsilon_2 - 1} \tag{1.8}$$

In the formula, σ is the Stefan-Boltzmann constant, or black body radiation constant;ε_1, $\varepsilon_2$are the emission coefficients of a certain point on the furnace cavity and PCB and its components respectively; T_1 is the absolute temperature in the small temperature zone of the reflow furnace, K ;T_2 is the absolute temperature of a certain point on the circuit board and its components, K; h_r is the convective heat transfer coefficient after radiation conversion, J/(m²·K).

Sum of the convective heat transfer coefficient and the convective heat transfer coefficient of radiation conversion:

$$h = h_c + h_r \tag{1.9}$$

In the formula, h is the total convection coefficient, J/(m²·K).

Combining Newton's law of cooling and the specific heat capacity formula together can get the recurrence formula of the circuit board temperature at a certain moment:

$$T_x = T_0 + \frac{h(T - T_0)t}{c_p l\rho} \tag{1.10}$$

In the formula, T_x is the temperature of the circuit board at a certain moment, K; T is the temperature of the exothermic fluid (or solid), K; T_0 is the temperature of the heated card fluid (or solid), K; l is the thickness of the circuit board, m; ρ is the density of a flame-resistant material with a flame-resistant grade of FR-4, kg/m³. Solving the recurrence formula in matlab, you can get the furnace temperature at any time.

In the production of circuit board reflow soldering, the furnace temperature curve should meet certain requirements, which is called the process limit. The common process limits in production are shown in Table 1:

Table 1 Process limits

Boundary name	Lowest value	Highest value	Unit
Slope of heating zone	1	3	℃/s
Slope of preheating constant temperature zone	0.3	0.8	℃/s
Heating time of heating zone	60	90	s
Preheating constant temperature zone heating time	60	120	s
Heating time of reflow soldering zone	30	70	s
Peak temperature	230	250	℃
Minimum cooling rate	2.5	3	℃/s
Maximum cooling rate	6	10	℃/s

The fixed step enumeration method is used to solve the problem with the help of matlab traversal within the range limited by the process boundary. The solution model is as follows:

$$\begin{cases} S_j = \sum_{i=1}^{n} \Delta s_i = \sum_{i=1}^{n} \frac{(2T_i + \Delta T_i)\Delta t_i}{2} \\ S = min\{S_1, S_2, \dots, S_m\} \\ Q = h_c(T - T_0)At \\ q = h_c(T_1 - T_2) \\ h_c = \frac{0.664u^2(\eta c_p)^{\frac{1}{3}}\lambda^{\frac{2}{3}}}{(vL)^{\frac{1}{2}}} \\ h_r = \frac{\sigma\varepsilon_1\varepsilon_2(T_1^2 + T_2^2)(T_1 + T_2)}{\varepsilon_1 + \varepsilon_2 - 1} \\ T_x = T_0 + \frac{h(T - T_0)t}{c_p l\rho} \end{cases} \tag{1.11}$$

$$\begin{cases} 0 \le \left|\frac{\Delta T}{\Delta t}\right| \le 3 \\ 100 \le t_1 \le 120 \\ 40 \le t_2 \le 90 \\ 240 \le T_{max} \le 250 \end{cases} \tag{1.12}$$

Among them, t_1 represents the time during the temperature rise at 150 ℃ ~190 ℃ , t_2 represents the time when the temperature is greater than 217 ℃, T_{max} represents the peak temperature, $\frac{\Delta T}{\Delta t}$ represents the slope of the furnace temperature curve, T_i represents the temperature of the soldering area of the circuit board at time i, ΔT represents the temperature change during 0.5s at time i, and Δt_i represents the difference between two adjacent moments.

2.3. Solving assumptions

Assume that there are 11 small temperature zones in a reflow furnace, and the front and back areas of the furnace. The length of each small temperature zone is 30.5 cm, and there is a gap of 5 cm between adjacent small temperature zones. The front area and the back area of the furnace The length of the area is 25 cm. Suppose the size of the circuit board is 40mm×30mm×1mm, and the ambient temperature is 25°C.

According to the assumptions, the mathematical model is used for calculation:

First, design multiple for loops to traverse all possible temperature zones and conveyor belt speeds, and list all possible results.

Secondly, in the production process of the reflow furnace, the furnace temperature curve must meet the requirements of the process limit. Therefore, starting from the requirements of the process boundary, all possible results listed are screened.

Then, for the possible results filtered through the process boundaries, draw the furnace temperature curve diagrams. Using the method of trapezoidal integration, find the area covered by the furnace temperature curve from exceeding 217°C to the peak temperature.

Finally, compare the calculated area values to get the minimum value, which is the optimal furnace temperature curve.

When the conveyor belt speed is 97.8cm/min, the temperature settings of each temperature zone are 171℃ (small temperature zone 1~5), 191℃ (small temperature zone 6), 231℃ (small temperature zone 7) and 264 ℃ (small temperature zone 8~9), the area covered by the furnace temperature curve exceeding 217 ℃ to the peak temperature is the smallest, which is 3.5494×10^4℃·s.

3. Simulation calculation and analysis

This paper uses ANSYS software to carry out simulation experiments to verify that the conveyor belt speed solved by the mathematical model is the optimal speed. The simulations were carried out under the conditions of belt speeds of 97.8cm/min, 95.8 cm/min, and 99.8cm/min respectively. By comparing the area greater than 217℃ in the simulation result curves under the three belt speeds, the belt speeds solved by the mathematical model were verified. It is the optimal belt speed.

3.1. Geometric model

The internal structure of the reflow furnace is complex, and large errors are likely to occur when modeling and simulation analysis is performed on it. Therefore, the plate representing the circuit board is kept stationary, and the circuit board is simulated through various temperature zones by changing the ambient temperature over time.

$$T_n = n\frac{C}{u} \tag{2.1}$$

In the formula, T_n is the time to pass through a temperature zone of a certain temperature, s; C is the total length of the temperature zone, cm; n is the number of temperature zones at a certain temperature.

Establish a geometric model as shown in the Figure 1:

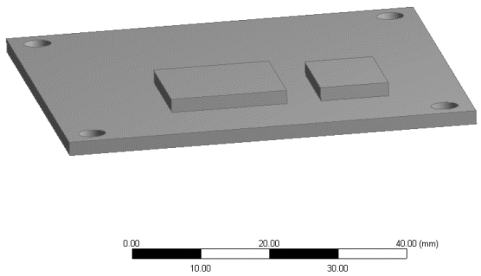

Figure 1 Geometric model

3.2. Meshing

Free meshing is adopted, because free meshing has no special requirements for the solid model. For any geometric model, whether it is regular or not, it can be meshed, and there is no specific criterion. After the division is completed, as shown in the Figure 2 and Figure 3:

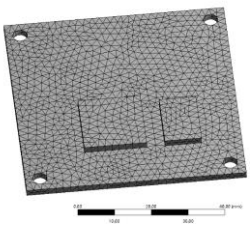

Figure 2 Mesh division

Statistics	
Nodes	17398
Elements	9602

Figure 3 Meshing results

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3.3. Loading and solving1

According to the temperature in the small temperature zone and the conveyor belt speed in the assumed conditions, the time for the circuit board to pass through the small temperature zone of different temperatures in the actual processing is calculated. When the circuit board passes through the small temperature zone, the temperature changes linearly. The heating temperature changes as shown in the Table 2:

Table 2 Heating temperature setting

The First Group (Model Solution Temperature)						
Temperature /℃	25	171	191	231	264	25
Time /s	0—7.67	15.34—121.17	124.24—142.95	146.02—164.73	167.8—208.29	211.5—276.85
The Second Group						
Temperature /℃	25	171	191	231	264	25
Time /s	0—7.84	15.67—123.81	126.95—146.07	149.2—168.32	171.46—212.83	216.5—282.34
The Third Group						
Temperature /℃	25	171	191	231	264	25
Time /s	0—7.51	15.02—118.63	121.64—139.96	142.96—161.28	164.28—203.92	207.02—271.57

In ANSYS, the thermal load can be loaded on the node or the surface. In this simulation, the thermal load is loaded on the surface.

In actual production, the reflow furnace transfers heat through air, and the air temperature is basically the same as the heating temperature to heat the circuit board. In ANSYS, the heat load is added to the surface of the circuit board at a distance of 0.1mm.

After the loading is completed, the time post-processing is entered, and finally the temperature curve of the reflow soldering process of the point on the volatilized paste with time can be obtained. Use three sets of temperature data to simulate, and finally get the temperature curve as shown in Figure 4:

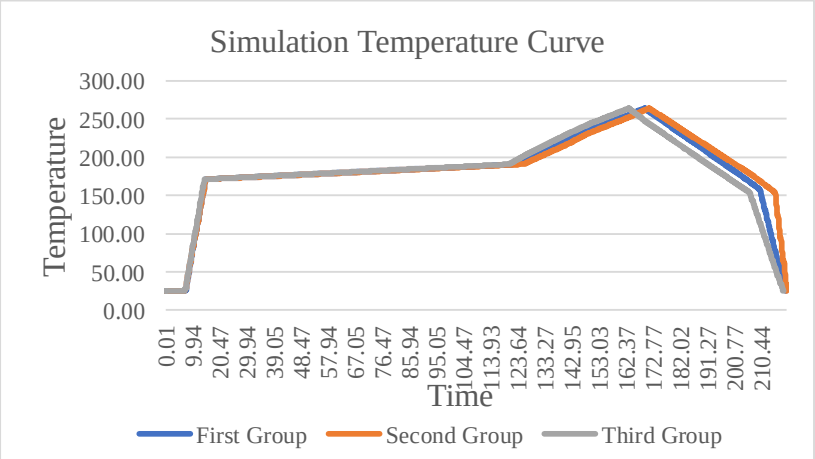

Figure 4 Simulation temperature curve

3.4. Area comparison

Convert the temperature curve into an area graph, and select the best temperature curve by comparing which group has the smallest area above 217°C.

Using the trapezoidal integral function of matlab software to calculate separately, the results are shown in the Table 3:

Table 3 Area calculation results

	First Group	Second Group	Third Group
Proportion	3.5494×104℃·s	3.752×104℃·s	3.767×104℃·s

It can be seen from the calculation results that the area of the first group is the smallest, that is, the temperature curve solved by the model is the best temperature curve.

4. Summary

In this paper, based on Fourier's law, Newton's law of cooling, and the law of conservation of energy, a convective heat transfer model of a longitudinally swept flat plate is established. Using the fixed-step enumeration method to solve the process boundary traversal, the optimal conveyor belt passage under each temperature zone can be obtained. Speed, so as to obtain the best temperature profile of the reflow furnace. Solving the model according to the above assumptions, the best results can be obtained: When the conveyor belt speed is 97.8cm/min, the temperature settings of each temperature zone are 171℃ (small temperature zone 1~5), 191℃ (small temperature zone 6), 231℃ (small temperature zone 7) and 264 ℃ (small temperature zone 8~9), the area covered by the furnace temperature curve exceeding 217℃ to the peak temperature is the smallest, which is 3.5494×10^4℃·s.

Use ANSYS software to simulate, set up two control groups, the conveyor belt speed of the control group is 97.8±2cm/min, respectively, perform simulation simulation to obtain the temperature curve, and use the trapezoidal integral function of Matlab to calculate the area of the temperature curve above 217℃. It is calculated that the area of the model is the smallest under the belt speed of 97.8 cm/min, which is 3.5494×10^4℃·s, and the area is 5% smaller than that of the control group.

In summary, through ANSYS simulation and area comparison, it is proved that the optimal speed of the conveyor belt can be obtained through the model solution introduced in this article, and the best quality of reflow soldering products can be ensured.

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