Research on Furnace Temperature Curve

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Abstract. The furnace temperature curve of the reflow furnace records the temperature changes during the soldering process of the printed circuit board components, which is the main factor influencing the quality of component soldering. Given the temperature of each temperature zone and the furnace passing speed, use the conveyor belt model, Fourier's law and Newton's law of cooling to establish a mathematical model to find the midpoint temperature of each temperature zone and obtain the furnace temperature curve. A search algorithm is further set up to obtain the maximum conveyor belt passing speed.

1. Introduction
With the continuous development of Internet technology, the miniaturization and integration of electronic products has become the general trend of technological development in the world today. PCB (Printed Circuit Board) is an indispensable part of modern electronic products. The new electronic components not only meet the requirements of the demanders for welding reliability, but also reduce the environmental damage of the process auxiliary materials. To understand how to automatically solder electronic components to the PCB at the right temperature in the reflow furnace is an extremely important step in the production process of electronic products. The furnace temperature curve drawn according to the temperature of each temperature zone and the furnace passing speed of the conveyor belt can monitor the temperature detection of the reflow furnace throughout the process, so that the temperature of each part of the reflow furnace maintains the process requirements, and minimizes welding defects. This article is a further exploration and expansion of the topic of the 2020 Mathematical Contest in Modeling.

2. Introduction of Reflow Furnace

2.1. Composition of reflow furnace
There are several small temperature zones inside the reflow furnace, which can be functionally divided into 4 large temperature zones: preheating zone, constant temperature zone, reflow zone, and cooling zone (as shown in Figure 1). The two sides of the circuit board are placed on the conveyor belt and enter the furnace at a constant speed for heating and welding.
Figure 1. Schematic diagram of cross section of reflow furnace

In the preheating zone, the main purpose of the preheating stage is to activate the solder paste and quickly heat the circuit board to volatilize too much solvent with a lower melting point in the solder paste. But also pay attention to the heating rate during the heating process. Too high a heating rate will damage the production quality of the components, and will cause the solder paste to collapse and cause the danger of short circuits. If the heating speed is too slow, the solder paste will over-sensitize the temperature, and there is not enough time for the PCB to reach the active temperature.

Constant temperature zone, the main purpose of the constant temperature zone is to stabilize the temperature of the components in the reflow furnace and minimize the temperature difference. The constant temperature stage has two functions. One is to make the entire PCB reach a uniform temperature (about 175°C). The purpose of the constant temperature is to reduce the impact of thermal stress entering the reflow zone and other soldering defects such as component lifting (tombstone) Wait. Another important function of the constant temperature stage is that the flux in the solder paste begins to react until the reflow stage begins. At the end of the constant temperature stage, the oxides on the pads, solder balls and component pins are removed under the action of the flux, and the surface wettability (and surface energy) of the soldering parts is increased, so that the molten solder can be very good Wett the surface of the weldment.

In the reflow zone, the temperature rapidly rises to the melting point of the solder paste, so that the solder paste melts and a wetting reaction occurs, and an intermetallic compound layer is formed. It reaches the highest temperature, then begins to cool down, and falls below the reflow line, where the solder solidifies. In the reflow zone, the heating rate should also be considered so that the components cannot be subjected to thermal shock. The maximum temperature of the reflow zone is determined by the temperature resistance of the temperature-sensitive components on the PCB. The time in the reflow zone should be as short as possible under the premise of ensuring good soldering of the components, generally 30-60 seconds is the best, too long reflow time and higher temperature, such as reflow time greater than 90 seconds, the highest temperature is greater than 260 °C, it will cause the intermetallic compound layer to thicken and affect the long-term reliability of the solder joints.

In the cooling zone, the importance of the cooling stage is often overlooked. At this stage, the temperature is cooled to below the solid phase temperature to solidify the solder joints. Similarly, the cooling rate will also affect the strength of the solder joints, so reflow soldering must provide a good cooling curve, neither too slow to cause poor cooling, nor too fast to cause thermal shock to the components.

2.2. Parameter setting of reflow furnace
The set temperature of each temperature zone is 175°C (small temperature zone 1~5), 195°C (low temperature zone 6), 235°C (low temperature zone 7), 255°C (low temperature zone 8-9) and 25°C (low temperature zone) 10~11; the furnace passing speed of the conveyor belt is 70 cm/min; the thickness of the welding area is 0.15 mm. The temperature sensor starts to work when the temperature
in the center of the welding area reaches 30ºC, and the circuit board enters the reflow furnace to start timing.

In actual production, the product quality can be controlled by adjusting the set temperature of each temperature zone and the furnace passing speed of the conveyor belt. On the basis of the above experimental set temperature, the set temperature of each small temperature zone can be adjusted within the range of ±10ºC. During the adjustment, the temperature in the small temperature zone 1~5 should be kept the same, the temperature in the small temperature zone 8~9 should be kept the same, and the temperature in the small temperature zone 10~11 should be kept at 25ºC. The speed adjustment range of the conveyor belt is 65~100 cm/min.

In the production of reflow furnace circuit board welding, the furnace temperature curve should meet certain requirements, which is called the process limit (see Table 1).

Table 1. Process limits

| Boundary name                                      | Lowest value | Highest value | Unit |
|---------------------------------------------------|--------------|---------------|------|
| Temperature rise slope                            | 0            | 3             | ºC/s |
| Temperature drop slope                            | -3           | 0             | ºC/s |
| 150ºC~190ºC time during the temperature rise      | 60           | 120           | s    |
| Time when the temperature is greater than 217ºC   | 40           | 90            | s    |
| Peak temperature                                  | 240          | 250           | ºC   |

3. Information about building the model

3.1. Model assumptions
(1) Assume that the change of gas temperature in the temperature zone is uniform.
(2) Assume that there is no friction between the conveyor belt and the object.
(3) It is assumed that damage in a small temperature zone will not affect the entire welding system.
(4) Assume that the time the object is subjected to heat conduction is zero.
(5) It is assumed that the heat loss during the transfer process is ignored.
(6) In the case of temperature changes, the value of k in Newton’s law of cooling is the same.

3.2. Noun explanation and symbol explanation

Table 2. Symbol description table

| Symbol         | Description                  | Unit |
|----------------|-----------------------------|------|
| $L_a (a = 1,2,3,4)$ | The length of each partition | cm   |
| $\nu$         | Temperature change rate     | ºC/s |
| $t_a (a = 1,2,3,...9)$ | Time period at initial temperature | s    |
| $t_b (b = 1,2,3,...9)$ | Time period at new temperature | s    |
| $T$           | Temperature                  | ºC   |
| $\phi$        | Calories                     | W    |

4. Model establishment and solution for problem 1

4.1. Data analysis
By the time speed distance formula $S_{end} = S_{start} + \nu \Delta t$, The temperature time speed formula required in this question can be derived by analogy, so as to obtain the temperature change speed and the temperature at any moment, $\frac{T_{end} - T_{start}}{\Delta t} = \nu$, $\nu \Delta t + T_{start} = T_{end}$. 
Solve according to the above steps, through the data of the conveyor belt speed and the length of each temperature zone given in the question, combined with the formula, the time of the circuit board in and out of each zone can be obtained. Through the time and temperature given in the attachment, the heat exchange coefficient and the temperature change rule at the original temperature can be found, which pave the way for the derivation of the temperature change rule set for the second time. Get the temperature at any time and draw the furnace temperature curve. The above formula is as follows:

\[
\begin{align*}
  \frac{L}{v} &= t \\
  T_{\text{end}} - T_{\text{start}} &= v \\
  \frac{\Delta t}{v} &= T_{\text{start}} + T_{\text{end}} \\
  h &= \Phi / A\Delta T
\end{align*}
\]

(1)

4.2. Result analysis
When the conveyor speed is 78 cm/min, the temperature settings of each temperature zone are 173ºC (small temperature zone 1~5), 198ºC (low temperature zone 6), 230ºC (low temperature zone 7) and 257ºC (small temperature zone 7). In temperature zone 8~9), the temperature curve at the center of the welding zone is shown in the figure below. When in the furnace front zone, the electronic components slowly heat up to 30°C, and they begin to work on the conveyor belt. When the electronic components enter the heating zone, the temperature rises from 30°C to 166.74°C. Immediately after entering the buffer zone between the heating zone and the constant temperature zone, the electronic components rose to 167.49°C. When the element enters the constant temperature zone, the temperature rises to 177.86°C, and the temperature change rate gradually becomes smaller than that of the heating zone. The buffer zone of the constant temperature zone and the reflux zone makes the electronic components rise from 177.86 to 180.23°C. After that, the electronic components enter the reflow zone, and the temperature rises to 241.75°C. Finally, the electronic components enter the cooling zone, and the temperature drops to 171.96°C until the area after entering the furnace drops to 143.79°C. It can be seen from the chart that the temperatures at the midpoints of small temperature zones 3, 6, and 7 and the center of the welding area at the end of small temperature zone 8 are 99.21°C, 172.79°C, 194.18°C, and 225.18°C, respectively.

Figure 2. Problem one furnace temperature curve

5. Model establishment and solution for problem 2

5.1. Analysis and optimization of temperature control system for reflow oven
Regardless of the heating method, reflow soldering\(^{[3][4]}\) is a key process in MST production. Reasonable furnace temperature curve setting and accurate realization are the keys to ensuring the quality of reflow soldering. Inside the welding furnace, there are mainly hot air blowers, heating
elements, thermocouples, air equalizers, chains, mesh belts, speed controllers, etc. The functional cooperation between these elements ensures the independence of temperature control in the temperature zone. At present, in SMT, according to the specific electronic components and the needs of the product, the soldering state of the components on the PCB is mainly divided into single-sided full-attachment, double-sided full-attachment, single-sided mixed packaging, double-sided mixed packaging, etc. For single-sided fully-attached PCBs, the main process flow is: silk screen solder paste-patch-reflow soldering.\(^{(5)}\)

### Table 3. Boundary conditions

| Boundary name                                      | Boundary property | Boundary condition |
|---------------------------------------------------|-------------------|--------------------|
| Workshop temperature                             | Constant          | 25°C               |
| Small temperature zone 1–5                       | Change in scope   | 175 ±10°C          |
| Small temperature zone 6                          | Change in scope   | 195 ±10°C          |
| Small temperature zone 7                          | Change in scope   | 235 ±10°C          |
| Small temperature zone 8–9                        | Change in scope   | 255 ±10°C          |
| Small temperature zone 10–11                      | Constant          | 25°C               |
| Temperature rise slope                            | Change in scope   | 0 ~ 3°C/s          |
| Temperature drop slope                            | Change in scope   | -3 ~ 0°C/s         |
| 150~190 time during the temperature rise          | Change in scope   | 60 ~ 120s          |
| Time when the temperature is greater than 270°C    | Change in scope   | 40 ~ 90s           |
| Peak temperature                                  | Change in scope   | 240 ~ 250°C        |

5.2. **Laws of Thermodynamics**

The commonly used laws of thermodynamics mainly include the first law of thermodynamics, the second law of thermodynamics, and Frugel's formula. The first law of thermodynamics is also called the law of conservation of energy; the second law of thermodynamics is also called the principle of entropy increase. The thermodynamic equilibrium equation is \(\sum W_{\text{input}} = \sum W_{\text{output}}\). Taking the heating process of the \(i\)-th temperature zone of the reflow oven as an example, suppose the total heat obtained in the \(i\) temperature zone is \(w_i\), and the heating rate of the furnace chamber is set to \(\nabla V\) after the power is turned on due to the heating of the heating rod, namely:

\[
\begin{align*}
A \times \Delta V &= W_i \\
W_i &= W_1 + W_2 + W_3 + W_4 + W_5 \\
A \frac{d\theta}{dt} &= W \cdot \theta - W_1 \cdot \theta - W_2 \cdot \theta - W_3 \cdot \theta - W_4 \cdot \theta - W_5 \\
W_i &= k \theta = \frac{\theta}{R} \\
W_i &= \frac{\theta}{R_1} + \frac{\theta}{R_2} + \frac{\theta}{R_3} + \frac{\theta}{R_4} + \frac{\theta}{R_5}
\end{align*}
\]

So when the setting values of each temperature zone are 173.5°C (small temperature zone 1~5), 203°C (small temperature zone 6), 237°C (small temperature zone 7), 254°C (small temperature zone 8~9) According to the boundary conditions in Table 2, we can conclude that the peak temperature varies from 240°C to 250°C. The higher the peak temperature, the faster the conveyor belt speed. Then, according to the formula and formula (12) and formula (13) speed The change function of is \(G_s(s) = \frac{K}{TS + 1 + \delta}\). After the change range of the peak temperature is brought into the formula (14), the maximum speed of the conveyor belt we seek is 1.121 cm/s.
6. Summary
This article comprehensively considers various mathematical models and boundary conditions and applies them to the problem of high-temperature welding in the reflow furnace. The model and solution process established in this paper have the following characteristics:

6.1. Model and Evaluation of Question One
In the entire transmission process of problem 1, the speed and length of the conveyor belt have been determined. The core of solving this problem is to find out the temperature, the change law of temperature and time at different speeds, and calculate the temperature corresponding to every 0.5 according to the change law of temperature and time found. The temperature curve changes continuously during this process. It should be noted that there is a temperature difference between different temperature zones. In the process of solving the problem, we must make reasonable assumptions about the temperature change, because the heat conduction of the object also takes time.

6.2. Model and Evaluation of Question 2
In the second problem of heat transfer, the heat emitted by each temperature zone can be conducted to the circuit board through the air. In the question, the set value of the temperature of each temperature zone is changed again, and the maximum conveyor speed is calculated on the basis of the temperature determination of the different temperature zones. First determine the temperature change in the temperature zone and calculate the time to reach that temperature. According to the process limit table, the time when the temperature is greater than 127°C is only 40s~90s. And the speed adjustment range of the conveyor belt is 65~100 cm/min. In the case of the same distance, the shorter the passing time, the greater the speed. According to the mathematical model, we get the knowable data to find the correct interval.

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