Research on Furnace Temperature Curve Based on Linear Regression Model

Jianting Xue¹, Xuerong Wei¹, Qiang Liu¹, Yuanyuan Mao²*

¹,² College of Information Engineering, Shandong Management University, Jinan, Shandong, 250300, China
*Corresponding author’s e-mail: 14438120191332@sdmu.edu.cn

Abstract. With the rapid development of social science and technology, various industries have higher and higher requirements for the quality of electronic products. SMT surface mount technology is the most popular process in the electronics assembly industry, and reflow soldering is one of the SMT mounting processes. Reflow soldering is mainly used to solder the circuit boards with components already attached. The solder paste is melted by heating to fuse the chip components and the circuit board pads together, and then the solder paste is cooled by the cooling of the reflow soldering, and the components are soldered. The plates are solidified together, and the furnace temperature curve records the temperature changes of the circuit board during this process. This article focuses on the printed circuit board welding production problem, through optimizing the furnace temperature curve for high-efficiency and quality-guaranteed production, and researches on the changes of the furnace temperature curve at different temperatures.

1. Introduction
The printed circuit board (PCB) reflow soldering process is an important part of the SMT technology. The electronic components are rigidly connected to the PCB printed circuit board through the solder paste of the solder pad and the reflow soldering. In this production process, temperature is the main influencing factor of component welding quality, and setting the furnace temperature curve correctly is a prerequisite for guaranteeing welding quality [¹]. Regarding the furnace temperature curve, scholars have conducted a lot of research. Feng Zhigang and others studied the influence of reflow soldering process parameters on the temperature curve [²]; Lv Li SMT reflow soldering product quality control based on the Six Sigma method [³]; Tang Zongjian and others on the control analysis of the reflow soldering furnace temperature curve [⁴]. Combining the attached data and consulting related information, we establish a reasonable and efficient mathematical model and solution method for the following problems: establish a mathematical model for the law of temperature changes in the welding area. Given the speed of the conveyor belt and the temperature of the small temperature zone in the furnace based on the title, give the temperature change in the center of the welding area, and draw the corresponding furnace temperature curve.

The data comes from question A of the 2020 Higher Education Club Mathematical Modeling Competition, including the data of the furnace temperature curve in a certain experiment, the furnace passing speed of the conveyor belt and the thickness of the welding area. In order to solve the problem, the following assumptions are put forward: Assume that the air temperature in the furnace is stable at the beginning of processing; Assume that the temperature of the welding processing area is stable; Assume that the influencing factors in the system are independent of each other, ignoring the
smallness of the variables Relevance; It is assumed that the influence of the material quality of electronic components on the temperature sensor and welding efficiency is not considered; It is assumed that no heat loss occurs inside.

2. Model establishment and solution for problem 1

2.1. Data analysis

Based on the data, the linear regression equation is used to obtain the temperature change rate table of each temperature zone, as shown in Table 1, and the RSS saddle furnace temperature curve diagram is drawn with the help of Python, as shown in Figure 1.

| Division of temperature zones | Time required to pass through each temperature zone (Ti/s) | Temperature change rate of each temperature zone (Vi/°C/s) |
|------------------------------|-----------------------------------------------------------|------------------------------------------------------------|
| Furnace area                 | 21.5                                                      | 0.35                                                       |
| Small temperature zone 1-5   | 148                                                       | 0.91                                                       |
| gap                          | 4                                                         | 0.19                                                       |
| Small temperature zone 6      | 26                                                        | 0.39                                                       |
| gap                          | 4.5                                                       | 0.53                                                       |
| Small temperature zone 7      | 26                                                        | 1.05                                                       |
| gap                          | 4.5                                                       | 0.76                                                       |
| Small temperature zone 8-9    | 56.5                                                      | 0.55                                                       |
| gap                          | 4.5                                                       | 0.12                                                       |
| Small temperature zone 10-11  | 56.5                                                      | -1.24                                                      |
| Area behind the furnace       | 21                                                        | -1.25                                                      |

Combining Table 1 and Figure 1 can be analyzed: the overall trend of the RSS saddle furnace temperature curve is to increase first and then decrease, from the initial temperature of 30.03°C to the peak value of 242.28°C, and then uniformly decline; the first stage is the temperature increase, which The trend is uniform, the second stage is constant temperature, the upward trend is gentle, the third stage is reflux, the temperature continues to rise, its trend is uniform, the fourth stage is cooling, the temperature drops, and its trend is uniform.

2.2. The establishment and solution of linear regression model

Perform data training based on known data such as time and temperature. On the basis of the kinematic formula, the following formula is derived to obtain the temperature and the temperature change rate at a certain time when the welding center passes through each temperature zone:

\[ W_i = w_i + V_i T_i \]  

\( W_i \) represents the temperature at a certain moment; \( w_i \) represents the initial temperature entering each temperature zone; \( V_i \) represents the temperature change rate of each temperature zone; \( T_i \) represents the time required to pass through each temperature zone.

Combining the known data and the above formula inversely deduce the temperature change rate of each interval under the data set in Problem 1, and get the following table:
Table 2. The temperature change rate table of each temperature zone under the data set in Question 1

| Division of temperature zones       | Time required to pass through each temperature zone(T/s) | Temperature change rate of each temperature zone(V/℃/s) |
|-------------------------------------|----------------------------------------------------------|------------------------------------------------------|
| Furnace area                        | 19.23                                                   | 0.389                                                |
| Small temperature zone 1~5          | 132.69                                                  | 1.012                                                |
| gap                                 | 3.8                                                     | 0.197                                                |
| Small temperature zone 6            | 23.46                                                   | 0.442                                                |
| gap                                 | 3.8                                                     | 0.624                                                |
| Small temperature zone 7            | 23.46                                                   | 1.163                                                |
| gap                                 | 3.8                                                     | 0.895                                                |
| Small temperature zone 8~9          | 50.77                                                   | 0.608                                                |
| gap                                 | 3.8                                                     | 0.140                                                |
| Small temperature zone 10~11        | 50.77                                                   | -1.385                                               |
| Area behind the furnace             | 19.23                                                   | -1.465                                               |

Combining the data in Table 2 and using Python software to design a temperature curve that fits the solder paste standard, as shown in Figure 2, to ensure product quality and yield.

Figure 1. RSS saddle furnace temperature curve  
Figure 2. Problem 1 Furnace temperature curve

Combining Table 2 and Figure 2 can be analyzed: Problem 1 The overall trend of the furnace temperature curve is to first rise and then fall, from the initial temperature of 25ºC to the peak value of 242.308ºC, and then uniformly decline; the first stage is the temperature rise, and its trend is uniform, The second stage is constant temperature, the rising trend is gentle, the third stage is reflux, the temperature continues to rise, its trend is uniform, the fourth stage is cooling, the temperature drops, and its trend is uniform.

3. Model establishment and solution for problem 2

3.1. problem analysis
Knowing that the distance remains the same, the faster the speed, the shorter the time will be. Combining problem one, it is known that the same substance is at different speeds and different ranges of temperature, and the starting and ending temperatures of each range are the same. It can be seen that the speed will be in a range. Through the mechanism analysis of the heat exchange system, the transfer function can be obtained, and then the maximum transmission speed can be derived.

3.2. Heat Exchange Process
When the reflow furnace is started, all the temperature zones will start to work at the same time, and a certain analysis of the reflow furnace system is required before it can be improved and designed.
accordingly. The K-type thermocouple transmits the temperature data collected in real time to the temperature control unit of the PLC, through its internal complex intelligent control algorithm for data processing, and sends out PWM signals to control the on and off of solid state relays to achieve precise temperature control effects and finally achieve return flow. The temperature control accuracy of the zone is within ±1°C of the set temperature, and the temperature control accuracy of other temperature zones is within the range of ±2°C of the set temperature. Multi-temperature zone reflow oven.

3.3. Heat transfer function

The thermodynamic equilibrium equation is \( \sum W_{\text{input}} = \sum W_{\text{output}} \). Take the heating process of the \( i \)-th temperature zone \( (i=1,2,3...) \) of the reflow oven as an example, suppose the total heat obtained in the \( i \) temperature zone is \( W_i \), the heat obtained by the heating rod after the power is turned on, and the heating rate of the furnace Set to \( \frac{d\theta}{dt} \), that is \( C \frac{d\theta}{dt} = W_i \). Among them, \( C \) is the proportional coefficient, that is, the specific heat capacity of the furnace.

\[
C \frac{d\theta}{dt} = W_i - W_1 - W_2 - W_3 - W_4 - W_5
\]

(2)

The total heat \( W_i \) in the temperature zone is \( W_i = W_2 + W_3 + W_4 + W_5 \), Therefore

Since the heat loss is proportional to the temperature, let:

\[
W_i' = k\theta = \frac{\theta}{R}, 
W_i = \frac{\theta}{R_2} + \frac{\theta}{R_3} + \frac{\theta}{R_4} + \frac{\theta}{R_5} = \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5}
\]

(3)

Among them, \( R' \) is defined as the total resistance of heat transfer in each temperature zone except for the heat absorption of the furnace wall[5].

Finally get the transfer function: \( G_s(s) = \frac{K}{TS + 1 + \delta} \).

3.4. Result analysis

Combining the transfer function and the data in the process limit of Table 2 with the help of Matlab’s CFtool function fitting tool, the maximum conveyor belt passing speed is 68cm/min under the condition of the title.

4. Finding the optimal furnace temperature curve under the process limit based on the least square method

4.1. Research ideas

During the welding process, there will be an optimal furnace temperature curve to maximize the production efficiency due to the different temperatures in each temperature zone and the setting of the conveyor belt passing speed. Based on the linear regression model, the influence of temperature on the furnace temperature curve has been obtained. Therefore, under this premise, the optimal furnace temperature curve is explored.

According to the process limits, the temperature at the center of the welding area should not exceed 217°C for a long time and the peak temperature of the furnace temperature curve should not be too high. Solve the optimal furnace temperature curve that meets the above conditions and the area covered by the peak temperature is the smallest.

First of all, when the peak temperature coverage area is the smallest, the time that the PCB passes through this area is also the minimum, that is, the speed of the PCB in the reflow area should be as fast as possible. Secondly, the shadow area is processed through the basic integral equation, and the
expression of the shadow area is expressed linearly. Use temperature constraints to find the maximum value. Finally, because the process of determining the time is relatively complicated, we use the Python software to determine the time range by using the control variable method, and then fit the optimal furnace temperature curve.

4.2. Control variable method to find the temperature range
The controlled variable method is one of the techniques to reduce variance. When estimating a certain variable, the known information is used to reduce the estimation error. The process of the control variable method is:

First, control the thickness of all PCBs to be equal, and test the effect of temperature on reflow soldering in different areas by changing the area of the PCB. As the area increases, the heat absorbed by the PCB also increases. If the heat is constant, the temperature of the PCB naturally rises more slowly. This question uses the SMT patch process. According to this process, it can be known that the temperature change of the PCB soldering point is conducted by the hot air. The hot air area is much larger than the heating area of the PCB, so no matter how the PCB area changes, the final impact on the reflow soldering is almost negligible.

4.3. Integral principle to find the minimum coverage area
During the soldering process, the time for the temperature in the center of the soldering area to exceed 217ºC should not be too long, because after the preheating zone is over, the temperature of the PCB board rises to the liquidus of the tin powder alloy at a relatively fast rate, and the solder begins to melt. Continue to linearly increase the temperature to the peak temperature and then hold for a period of time and then begin to drop to the solidus. The peak temperature should not be too high, because setting the temperature in this zone too high will cause the temperature rise slope to exceed 2~5ºC per second, or reach the reflux peak temperature higher than recommended. This situation may cause excessive curling, delamination or burnout of the PCB, and damage the integrity of the component.

5. Summary
Aiming at the problem of the reflow furnace temperature curve, this paper uses Python software combined with a linear regression model to obtain the furnace temperature curve at different temperatures, and further uses the least square method to optimize the optimal furnace temperature curve. Based on the above analysis, the following suggestions are made for the welding process of components:

(1) Make full use of existing data and adopt SPC control to guide the timing of repair and maintenance of the reflow soldering furnace.

(2) In actual production, under the condition of ensuring that the reflow furnace is in good working condition, strictly control the temperature and the passing speed of the conveyor belt in order to reduce the cost of the factory, form a price advantage, and enhance the competitiveness of the factory.
References

[1] Zanhua Cheng, Weifeng Xu, Kai Meng. Application of Through Hole Reflow Soldering (PIP) in the OSP Surface Treatment PCB Lead-Free Process [J]. Electronics Quality, 2016(07): 48-54.

[2] Zhigang Feng, Dingwen Yu, Yunhe Zhu. The influence of reflow soldering process parameters on temperature curve [J]. Electronics Process Technology, 2004(06): 243-246+251.

[3] Li Lu. Quality Control of SMT Reflow Soldering Products Based on Six Sigma Method [J]. Electronic Technology & Software Engineering, 2019(11): 144.

[4] Zongjian Tang, Bingtang Xie, Geying Liang. Management and control analysis of reflow soldering furnace temperature curve [J]. Electronics Quality, 2020(08): 15-19+23.

[5] Jun Cui. Research on the combined welding process of PCB and aluminum substrate [J]. Practical Electronics, 2020(12): 95-96.