Optimization And Analysis of Furnace Temperature Profile for The Processing Technology of Electronic Components

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Abstract. The soldering furnace is an important piece of equipment for processing and soldering electronic components in the integrated circuit design process. After the printed circuit boards are mounted with various electronic components, they are placed in the soldering furnace for heating so that the electronic components are automatically soldered to the circuit boards. In this process, the furnace temperature profile, which records temperature data of the electronic components, is an important reference indicator for measuring the effectiveness of electronic component processing. In the context of electronic component soldering, the transfer speed of the furnace and the setting of the temperature in each temperature zone are decisive in ensuring the quality of the component soldering. Based on the Newton's law of cooling and heat equation, this paper establishes several mathematical models to study the effect of the temperature setting of each temperature zone and the transfer speed of the soldering furnace on the furnace temperature profile with the help of multi-objective planning, circular search algorithm and other mathematical methods. Finally, the corresponding conclusions and optimization methods of furnace temperature profile are drawn, which have certain significance for the processing of electronic components.

Keywords: Integrated circuit design, electronic components, Furnace temperature profile, Newton's law of cooling, Heat equation.

1. Introduction

With the development of electronics processing technology, the soldering furnace has become one of the most important equipment in the integrated circuit surface packaging process and plays an increasingly important role in the process of electronic products [1]. In the process of soldering electronic components, the electronic components are soldered to the circuit board in the soldering furnace according to the principle of heating. The temperature setting of each temperature zone and the setting of the transfer speed are two main influencing factors for the final production of electronic components. The furnace temperature profile records the changes of the electronic components during processing, which reveals the temperature distribution of the printed circuit board, the electronic components processing stability and balance indicators. Strict control and adjustment of the furnace temperature profile should be taken rigorously, which can greatly reduce the welding error and improve the quality of packaging.

Many scholars have studied the optimization of electronic component soldering process. Ganggang Yan et al. simulated a resistance furnace control system based on Fuzzy PID algorithm [2]; Bao Qingfeng et al. modeled the temperature field of rolling steel heating furnace in metallurgical industrial process based on RHFTF [3]. Yangyang Lai et al. provided a solution to determine the optimal pre-set temperature optimization model for reflow ovens [4]; Jing Shilong et al. analyzed and optimized the oven temperature profile prediction model for high product heat capacity and poor wet ability in reflow soldering process [5].

This paper mainly analyzes the soldering process of electronic components based on certain physical background and data [6]. Firstly, the one-dimensional steady-state heat transfer equation of the soldering furnace is derived from the heat equation theory and the temperature distribution of each temperature zone is obtained as a function of the spatial variation. Subsequently, the Newton's cooling discrete equation for electronic components is derived based on the theory of Newton's cooling law. Meanwhile, the value of k is fitted out combined with the least square's method and the Cftool toolbox, by which the fitted furnace temperature profile is initially calculated and the model is further optimized. Considering the microcircuit precision condition constraint, this paper also optimizes the curve peak symmetry and derives the optimized furnace temperature curve.

2. The basic foundation of the soldering furnace data and theory

2.1. Data Analysis

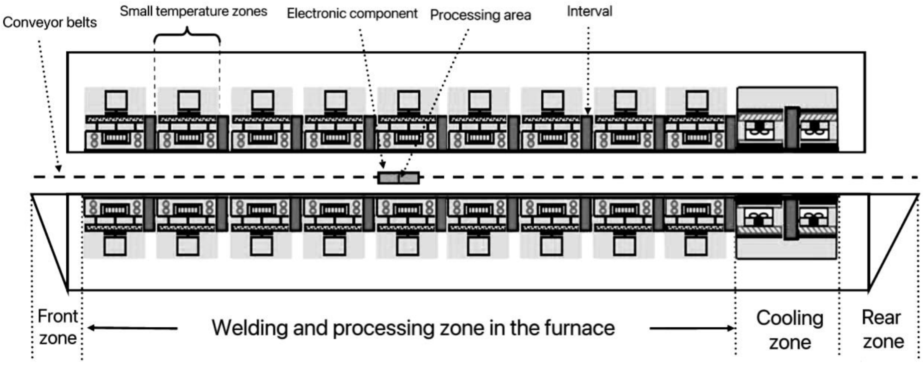

Figure 1. Structure of the soldering furnace

The soldering furnace's data used for this paper has 11 small temperature zones as well as a front zone and a rear zone. Each small temperature zone has a length of 30.5 cm, and the interval between two adjacent small temperature zones is 5 cm. The front and rear zone have the same length being 25 cm. The structure of the soldering furnace is shown in Figure 1.

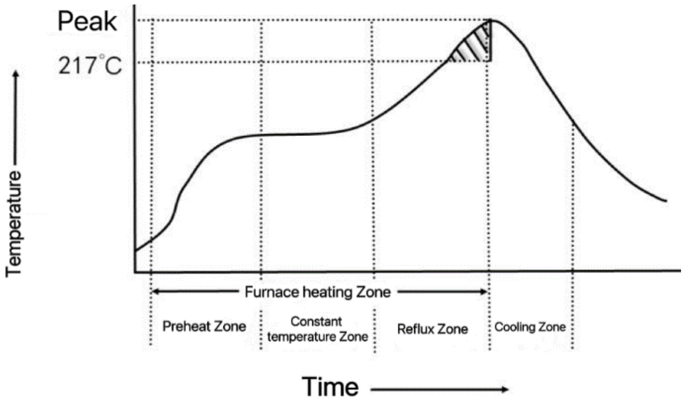

Figure 2. Furnace temperature profile

The temperature of each small temperature zone in the reflow oven is stabilized for a short period of time then welding begins. After setting the temperature of each temperature zone and the transfer speed, the temperature sensor can be used to measure the temperature data of the center of the welding area in each temperature zone, called the furnace temperature profile. The front zone, the rear zone and the intervals are not subject to a specific temperature limit but are influenced by the temperature of the adjacent areas, and the room temperature is set at 25ºC. The furnace temperature profile trend as well is shown in Figure 2.

2.2. Theoretical introduction

2.2.1. Newton's cooling law theoretical analysis

Since the board thickness is generally small and the board can reach a consistent equilibrium in a short period of time in the high temperature environment of the soldering furnace, the paper introduces Newton's law of cooling to model and solve the furnace temperature profile in order to optimize the structure of the problem.

Newton's law of cooling is the study of heat exchange between a high temperature object and its surroundings [7-8], when a higher temperature object is in an environment lower than its temperature, due to heat conduction, the heat dissipated per unit time from the unit area of the object is proportional to the difference in temperature. Applied to the physical model of this paper, the following relationship can be obtained:

$$\frac{dT(t)}{dt} = k\left(T_{\mu}(t) - T(t)\right) \tag{1}$$

Where $T_{\mu}(t)$ refers to the temperature of the environment at the moment t after the processing of the circuit board begins, $T(t)$ refers to the temperature of the solder center at the moment t when the circuit board begins to work and k is the heat transfer coefficient.

2.2.2. Analysis of heat conduction theory

As electronic components are soldered in the soldering furnace, there will be a certain temperature difference between the temperature zone and environment, so the temperature change effect of each temperature zone caused by heat convection needs to be considered [9]. The theoretical analysis diagram is shown in Figure 3.

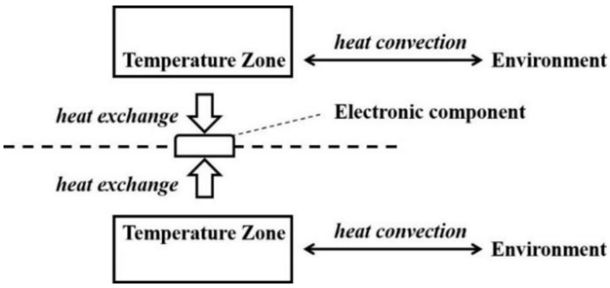

Figure 3. Schematic analysis of heat conduction theory for soldering furnace

3. Mathematical modeling and solving of the furnace temperature profile

3.1. Functional model for temperature distribution of temperature zones

3.1.1. Temperature distribution analysis of small temperature zones

First of all, the small temperature zone inside the soldering furnace is discussed. Because the soldering furnace begin to work when the temperature of the air inside the soldering furnace temperature zone is stabilized, at this time the temperature of these small temperature zones equals to the set temperature:

$$T_f(x,t) = T_{set} \tag{2}$$

In the formula (2), T_{set} is the set temperature of small temperature zone, which is 173ºC in zone 1-5, 198ºC in zone 6, 230ºC in zone 7, 257ºC in zone 8-9 and 25ºC in zone 10-11.

3.1.2. Temperature distribution analysis of other temperature zones

For the interval, the front zone and the rear zone, soldering furnace does not do special temperature control, but the temperature of these areas are affected by the temperature of the adjacent temperature zone and a binary function of time and location, which requires further establishment of a one-dimensional heat transfer equation based on heat transfer theory:

$$\frac{\partial T_f(x,t)}{\partial t} = a^2 \frac{\partial^2 T_f(x,t)}{\partial^2 x} \tag{3}$$

Since the internal temperature is already stable when the soldering furnace starts working, the temperature of each area does not change so that an equation can be obtained as follows:

$$a^2 \frac{\partial^2 T_f(x,t)}{\partial^2 x} = \frac{\partial T_f(x,t)}{\partial t} = 0 \tag{4}$$

Ultimately, it can be concluded that the temperature in the other zones should be a linear function of position x.

$$T_f(x,t) = ax + b \tag{5}$$

3.1.3. Model solving

Based on the set temperature in the small temperature zone and the temperature distribution, the spatial distribution function of the temperature change with the movement distance can be established by solving for the relevant coefficients. The resulting distribution function $T_f(x,t)$ of the temperature zones in the furnace is shown below:

$$T_f(x,t) = \begin{cases} 5.92x + 25, & 0 \le x < 25.5 \\ 173, & 25.5 \le x < 197.5 \\ 5x - 814.5, & 197.5 \le x < 202.5 \\ 198, & 202.5 \le x < 233 \\ 6.4x - 1293.2, & 233 \le x < 238 \\ 230, & 238 \le x < 268.5 \\ 5.4x - 1219.9, & 268.5 \le x < 273.5 \\ 257, & 273.5 \le x < 339.5 \\ -46.4x + 16009.8, & 339.5 \le x < 344.5 \\ 25, & 344.5 \le x \le 435.5 \end{cases} \tag{6}$$

The spatial distribution of temperature can be obtained in Figure 4.

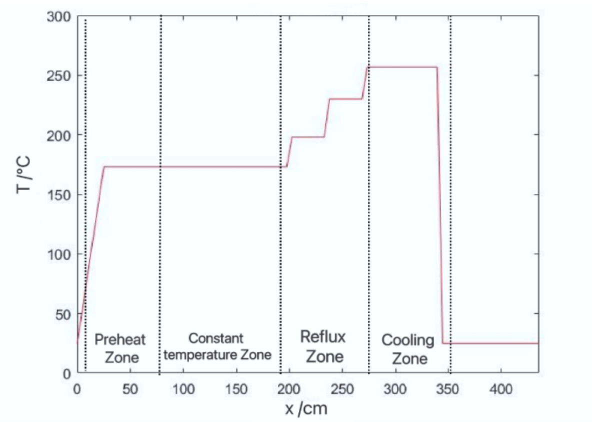

Figure 4. Temperature distribution of the temperature zones

3.2. Fitting Model for optimization of furnace temperature profile

3.2.1. Characterization of heat transfer coefficient

- **Non-constant**

The heat transfer coefficient k can be extracted by using the function discretization method, and the following relation can be obtained:

$$k = \frac{\Delta T}{\Delta t\left(T_\mu(t) - T(t)\right)} = \frac{T(t+\Delta T) - T(t)}{\Delta t\left(T_\mu(t) - T(t)\right)} \tag{7}$$

As can be seen from the above equation, the heat transfer coefficient k is not a constant and its value varies with time and temperature.

- **Stage constancy**

During the soldering furnace's work, its internal temperature has a significant phase change with time, and in some phase time the soldering furnace temperature remains constant. Since the value of k is related to time and temperature, k has the nature of a constant phase so that k can be set to different values in different areas to simplify the model

3.2.2. Numerical solution of heat transfer coefficient

This paper further divides the soldering furnace into six regions, which are the front zone, preheat zone (small temperature zone 1~5), constant temperature zone (small temperature zone 6~7), reflux zone (small temperature zone 8~9), cooling zone (small temperature zone 10~11) and rear zone. The value of k are fitted and assigned by the least squares method and Cftool toolbox and the results are shown in Table.1.

Table.1. Heat transfer coefficient fitting results

Zone	Front zone	Preheat zone	Constant temperature zone
k	0.026	0.019	0.033
Zone	Reflux zone	Cooling zone	Rear zone
k	0.032	0.016	0.009

3.2.3. Model solving

The k values taken for each region in Table.2 are brought into the discretized equation (10) for solution, and the furnace temperature profile is obtained by Matlab programming, as shown in Figure 5.

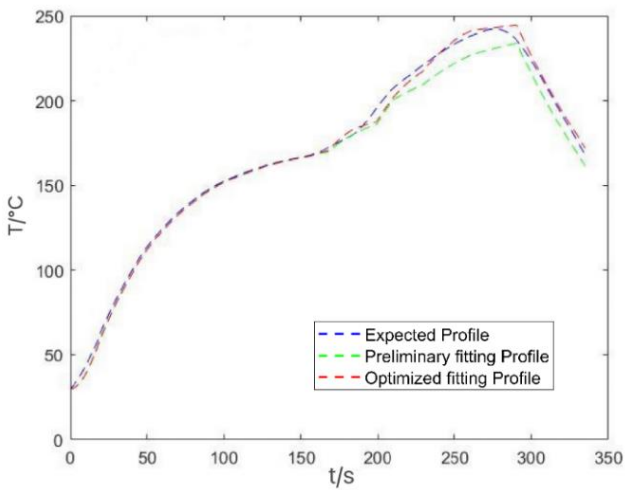

Figure 5. Results of temperature fitting profile

As can be seen from Figure 5, the preliminary fitting profile basically overlaps with the expected furnace temperature profile in front 200s, while after 200s there are slight fluctuations, which may be related to the impact of the interval temperature. In order to achieve a better result, the effect of interval temperature is considered into the model and the optimized k values are calculated and shown in Table.2.

Table.2. Optimized k values

Zone	Front zone	Preheat zone	Constant temperature zone
k	0.027	0.020	0.045
Zone	Reflux zone	Cooling zone	Rear zone
k	0.032	0.032	0.009

With the optimized k values shown in Table.2, the optimized furnace temperature profile is obtained and shown in Figure 5. In order to test the accuracy of the model, the sum of squared errors (SSE), mean squared errors (MSE) and goodness-of-fit indexes (R^2) of both the preliminary model and the optimized mode are calculated, which are shown in the Table.3.

Table.3. Model accuracy test results

Index	SSE	MSE	R^2
Preliminary model	26256.20	39.13	0.96
Optimized model	5243.96	7.82	0.98

It can be seen in the Table.3 that the optimized SSE and MSE values have decreased compared with the preliminary model, while the R^2 have been improved, which shows that the analysis of this paper is correct, the accuracy of the optimized model has been improved and the furnace temperature profile fitting is more accurate.

3.3. Improved Model for peak symmetry of furnace temperature profile

3.3.1. Introduction of asymmetry

In order to meet the purpose of the peak of the furnace temperature curve on both sides as symmetrical as possible, the degree of asymmetry l is introduced, which is defined as the squared sum of the difference between the value of the function of the point at the longer side of the temperature 217°C to the peak temperature and the value of the function to the peak symmetry point. The formula is as follows.

$$l = \sum_i^n (T_{+i} - T_{-i})^2 \tag{8}$$

Where T_{+i} represents the temperature at a point on the side of 217℃ longer from the peak temperature, and T_{-i} represents the point on the temperature where the distance from the horizontal coordinate to the peak point is equal to the distance from the horizontal coordinate to the peak point of T_{+i}.

3.3.2. Model establishment

While considering the symmetry requirement of the curve above 217ºC about the peak point, it should also be noted that the period of high temperature processing should not be too long and the peak temperature should not be too high to avoid damage to electronic components [10].

For this reason, the area covered by the furnace temperature curve above 217ºC to the peak temperature is introduced as an index *S* called the high temperature processing risk. A multi-objective nonlinear programming model is established as follows.

Objective function:

$$\begin{cases} \min\ S \\ \min\ \ l \end{cases} \tag{9}$$

Constraints:

$$\begin{cases} \text{Temperature change slope constraint: } -3 \le \frac{dT}{dt} \le 3 \\ \text{Residence time constraints : } \begin{cases} 60 \le t_{150 \le T \le 190} \le 120 \\ 40 \le t_{T \ge 270} \le 90 \end{cases} \\ \text{Transmission speed constraint: } v \in [65,100] \\ \text{Extreme temperature constraint: } T_{MAX} \in [240,250] \\ \text{Temperature distribution constraints: } \begin{cases} T_1 \in [165,185] \\ T_2 \in [185,205] \\ T_3 \in [225,245] \\ T_4 \in [245,256] \end{cases} \end{cases} \tag{10}$$

3.3.3. Model solving

In order to simplify the problem, a new objective function $f = S \cdot l$ is introduced, which transforms the multi-objective problem into a single-objective problem.

A rough search is first performed with temperature step 2 and velocity step 1, and the range of parameter intervals in which the minimum value of the objective function f lies can be derived, as shown in Table.4.

Table.4. Rough search of furnace speed and temperature intervals

Speed (cm/min)	Temperature zone 1-5(℃)	Temperature zone 6(℃)	Temperature zone 7(℃)	Temperature zone 8-9(℃)
90-95	169-173	185-193	225-229	249-253

Then shorten the temperature step to 1 and the speed step to 0.5 for detailed search, and the final results are shown in Table.5.

Table.5. Detailed search of furnace speed and temperature intervals

Speed (cm/min)	Temperature zone 1-5(℃)	Temperature zone 6(℃)	Temperature zone 7(℃)	Temperature zone 8-9(℃)
90.60	170	185	225	252

The optimal furnace temperature curve is obtained by substituting the solved parameters into the model, as shown in Figure 6.

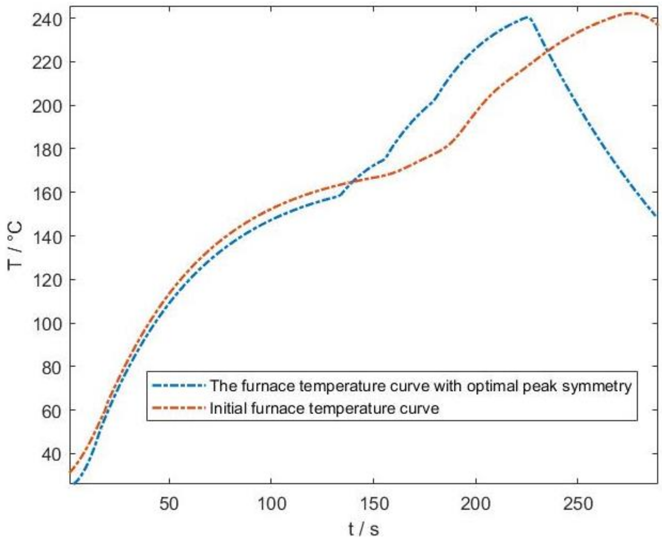

Figure 6. Optimal furnace temperature profile

It can be seen in Figure 6 that the optimized furnace temperature profile is significantly more symmetrical near the temperature peak than the initial furnace temperature profile and the high-temperature processing region is significantly shifted to the left as well as the risk index S is reduced. Meanwhile, the high-temperature processing time span is significantly reduced, which indicates that the model established in this paper has a good solution effect and is of great significance for the optimization and improvement of the furnace temperature profile.

4. Conclusions

As integrated circuit technology matures, more sophisticated methods of soldering and packaging of electronic components will emerge. This paper focuses on the process of electronic components in the soldering furnace and establish a number of mathematical models to optimize the furnace temperature curve based on Newton's law of cooling and the law of heat conduction. Meanwhile, the model is improved by considering the peak symmetry and the risk of high-temperature processing, and the optimal furnace temperature curve and its parameter indexes are derived. The models established in this paper have a certain reference role for both the actual processing of electronic components and the study of other welding processes or processing technology has a greater value.

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