Temperature Modeling of Reflow Soldering Based on the Heat Transfer Mechanisms

Zihao Tang¹, and Binshan Huang²

College of Computer and Information Science, Southwest University, Chongqing, 400700, China

E-mail: antoine@email.swu.edu.cn, hbs2050098@email.swu.edu.cn

Abstract. In the production of integrated circuit boards, electronic components need to be automatically welded to the circuit board by a reflow oven. Reflow oven welding is the core process of producing circuit boards, and the centre temperature of the welding area is extremely important to the quality of the final product of electronic components. Based on the experimental data, we establish a non-steady heat conduction model based on Newton's cooling law, and use the method of least squares to determine the dynamic parameters, and finally use the finite difference method (FDM) to solve the models.

Secondly, the reflow oven speed will also have an impact on the product quality. At the same time, a single-objective linear programming model with the maximum furnace speed is established, then the step size is to perform a fine search to solve the problem.

1. Introduction

1.1. The Background and Significance for the Work

An extremely important part of the circuit board manufacturing process is the solder reflow process of printed circuit boards. Due to the rapid development of the electronic information industry, the solder reflow process technology has improved, and there are also higher requirements for the mounting and soldering of electronic equipment. Therefore, the requirements for the automatic temperature control technology of the solder reflow oven are correspondingly improved, but most of the current control and adjustment of the furnace temperature are only derived from the results of the test.

There are deficiencies in mechanism model, so this paper proposes a temperature distribution model based on Newton’s law of cooling[2], which not only reflects the physical process of circuit board welding, but also fits a reasonable temperature curve of the welding area.

First, the physical process of the circuit board heating in the reflow oven is simulated from the perspective of the mechanism model, which makes up for the unity of solutions to related problems in the current research field. To a certain extent, we proposed innovative solutions of the automatic control of the temperature and the speed of the solder reflow oven conveyor belt. Aiming at the unsteady heat conduction process of the composite medium, the suggestion of adjusting the temperature of the reflow oven is given from the perspective of a mathematical model, which provides a reliable idea for industrial automatic control[3, 4].

Due to the simplified assumptions, it is inevitable that the model will be biased in the actual application. At the same time, the amount of experimental data is not large enough, resulting in the model's parameters not having high universality[7]. In addition, the process of solving the heat conduction model is complicated, and it is difficult to obtain the optimal parameters in a short time.
1.2. Basic structure and principle of solder reflow oven

There are several small temperature zones inside the solder reflow oven, which can be divided into 4 large temperature zones functionally: preheat zone, constant temperature zone, solder reflow zone, and cooling zone. The two sides of the circuit board are placed on the conveyor belt, and circuit boards will be at a constant speed for heating and welding[8].

The length and total number of the small temperature zone are fixed in the experiment, and the length of each zone (or the gap between each zone) are also measured in the experiment.

Figure 1. (a): Reconditioned Reflow Oven -1707MK5_A[5]. (b): Simplified cross-sectional view of solder reflow oven[6].

After setting the temperature of each temperature zone and the furnace passing speed of the conveyor belt, the temperature of the welding area at certain positions can be tested by the temperature sensor, which is called the furnace temperature curve. The temperature sensor starts to work when the temperature in the center of the welding area reaches 30ºC, and the circuit board enters the solder reflow oven to start timing.

In the production of solder reflow oven circuit board welding, the furnace temperature curve should meet certain requirements, which is called the process limit.
2. Model establishment

2.1. Assumptions
Considered the specific experiment data, the following assumptions are made on the model:

(i) The external heat radiation is not considered.
(ii) Air convection is not considered.
(iii) It is assumed that before the circuit board enters the solder reflow oven, the temperature of each area in the furnace is stable and is not affected by the outside.
(iv) It is assumed that the heat conduction at each point on the circuit board is isotropic.
(v) When the temperature between the small temperature zones is too large, only consider the influence between the small temperature zones.
(vi) When the temperature difference between the small temperature zones is too small, the gap temperature changes linearly with the displacement.

2.2. Unsteady heat conduction model of composite media

2.2.1. Thermodynamics background
The basic heat transfer way in the thermodynamic process that need to be used heat conduction[1]. Because of the heating process in the solder reflow oven is an unstable process, the temperature of each point in the heat transfer process will increase with time, so the time factor will be included in the equation.

In addition, the heat conduction process will use Fourier's law of heat transfer as the basis of the model, which describes the relationship between temperature difference and heat flux density.

\[ q = \lambda_f \frac{dT}{dx} \]  

\[ q \] is the heat flux density, \( \lambda_f \) is the thermal conductivity in Fourier's law, and \( \frac{dT}{dx} \) is the change of temperature with time. Since Newton's cooling theorem is a discretization extension of Fourier's law, Fourier's law is mainly considered in this article.

Secondly, when there are gaps with unequal temperatures on both sides, there is a heat conduction equation:

\[ \frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( \alpha \frac{\partial u}{\partial x} \right) \]  

Figure 2. The change trend of temperature when the temperature on both sides of the gap is not equal

2.2.2. Heat conduction model
Based on the assumptions put forward in the previous article, we model the solder reflow oven problem.
First of all, the most important point is that before the circuit board enters the solder reflow oven, the temperature of various internal positions has reached a steady state, that is, the temperature of each point in the reflow oven is a fixed value, and the temperature control module of the reflow oven will compensate in time, so that the temperature inside the reflow oven can be regarded as constant.

Because the solder reflow oven has various small temperature zones that can adjust temperature independently, we can assume that the temperature of the place where the distance between the inside is equal to that of the entrance. In this way, we simplify the temperature inside a complex three-dimensional structure to a function of distance and temperature:

$$T_m = f(x)$$

(3)

$$T_m$$ is the temperature at position $$x$$ in the solder reflow oven, and $$f(x)$$ is a piecewise function. If the continuous form is used, many problems will be generated when solving the problem, and considering the solvability of the problem, we make an important approximation in the problem. We divide the solder reflow oven with a total length of $$L$$ into $$N$$ micro-intervals. In this micro-interval, we consider the temperature to be the same. In this way, we simplified the model of the temperature inside the solder reflow furnace as follow:

$$T_m = f(nx) \quad n = 1, 2, \ldots$$

(4)

$$nx$$ can only take discrete values, and by our assumption, $$n$$ takes an integer. From the question, we divide the internal temperature of the solder reflow oven into several parts for model. The temperatures of these parts are independent of each other and affect each other.

At the same time, in order to facilitate the establishment and solution of the model, we introduce specific experimental data and give a specific basic structure of the solder reflow oven, which can make the analysis easier.

![Figure 3. structure of a certain solder reflow oven.](image)

The area in front of the oven is in direct contact with the outside room temperature air. According to the law of convective heat transfer, the heat will quickly escape. After entering the first temperature zone of the solder reflow oven, the temperature will change due to the effect of the heating period. Based on this rule, we model the temperature of the oven front area and the 1st small temperature zone as an exponential function, increasing from room temperature to the set temperature of the 1st to 5th temperature zone.
\[ f(nx) = \exp(nx) \quad x_{before\ furnace} < nx \leq x_{after\ 1st\ zone} \] (5)

1\textsuperscript{st} to 5\textsuperscript{th} temperature zone: The temperature of this area, except for the temperature of 1\textsuperscript{st} temperature zone, is affected by the convection and heat conduction of hot air, so it is incorporated into the function related to the furnace front, and the temperature of other parts is regarded as the setting fixed value, including the partition in the middle. The basis for this is that this area includes the small temperature 2\textsuperscript{nd} to 5\textsuperscript{th} zone, and the length accounts for almost half of the working area of the entire reflow oven, so the temperature should be stable.

\[ f(nx) = T_{Preset\ temperature} \quad x_{before\ 1st\ zone} < nx \leq x_{after\ 5th\ zone} \] (6)

The interval of zones 5\textsuperscript{th} to 6\textsuperscript{th}, 6\textsuperscript{th} to 7\textsuperscript{th}, 7\textsuperscript{th} to 8\textsuperscript{th}: We regard the partitions between the zones of the reflow oven are isotropic, and according to the law of contact heat conduction. When both ends are at a constant temperature, the temperature change in the partition is regarded as an arithmetic change.

\[ f(nx) = k_1nx \quad x_{before\ 5th\ zone} < k_1nx \leq x_{before\ 6th\ zone} \] (7)
\[ f(nx) = k_2nx \quad x_{before\ 6th\ zone} < k_2nx \leq x_{before\ 7th\ zone} \] (8)
\[ f(nx) = k_3nx \quad x_{before\ 7th\ zone} < k_3nx \leq x_{before\ 8th\ zone} \] (9)

Zone 8\textsuperscript{th} to 9\textsuperscript{th}: The method is similar to that of zone 1\textsuperscript{st} to 5\textsuperscript{th}.

9\textsuperscript{th} zone: Considering that the back of the 9\textsuperscript{th} zone is the 10\textsuperscript{th} to 11\textsuperscript{th} zone, and the latter two zones are used for rapid cooling, we model the temperature dropped linearly to room temperature during 9\textsuperscript{th} zone to the end of the furnace area.

\[ f(nx) = k_4nx \quad x_{before\ 8th\ zone} < k_4nx \leq x_{after\ furnace} \] (10)

The following figure shows the temperature change of the circuit board in each area. We establish a piecewise function to describe temperature of the reflow oven.

![Figure 4. Furnace temperature distribution chart 1](image)
Then we selected a window of appropriate length to smooth the piecewise function. Figure 5. Furnace temperature chart after smoothed

In this way, we finally get the approximate temperature of each micro-zone in the reflow oven. Knowing that the solder reflow oven is divided into \( N \), then the length of each micro-section can be known. Combined with the running speed \( v \) of the conveyor belt, we can know the time \( t \) of the circuit board in each micro-section.

\[
t = \frac{L}{Nv}
\]  

(11)

Knowing that in physics, we have a formula for thermal conductivity,

\[
Q = \frac{\Delta T(T - T_m)}{t}
\]  

(12)

In addition, we have a heat capacity formula that describes the temperature change of an object after absorbing (releasing) a certain amount of heat,

\[
Q = Cm(T_1 - T_2)
\]  

(13)

\( C \) is the specific heat capacity of the material, \( m \) is the quality of the circuit board, combining the above two formulas,

\[
Cm(T_1 - T_2) = \frac{\Delta T(T - T_m)}{t}
\]  

(14)

Note that our circuit board is regarded as a uniform material during the welding process, the quality is almost unchanged, and the shape parameters have not changed either, so we integrate these parameters into \( \lambda \), and the formula is expressed as,

\[
(T_1 - T_2) = \lambda t(T - T_m)
\]  

(15)

Therefore, the temperature of the circuit board when it enters the nth micro interval can be expressed as a recursive formula,

\[
(T_n - T_{n-1}) = \lambda t(T_{n-1} - T_m^{n-1})
\]  

(16)

When the circuit board enters the first micro interval, the temperature should be room temperature, so \( T_1 \) is known. In addition, \( T_m^{n-1} \) is the temperature of the \( n - 1 \)th micro interval. Therefore, the above recurrence can be expressed as,

\[
T_n = \lambda t \sum_{1}^{n-1}(T_{n-1} - T_m^{n-1}) + 25
\]  

(17)

If value of \( \lambda \) is given, then we can get the furnace temperature curve. However, the value of the coefficient \( \lambda \) is now unknown. We use the furnace temperature curve to fit \( \lambda \).
Specifically, we build an objective function based on the mean square error criterion,

$$mse = \sum_{k} ||T_k - T_k||$$

Now our goal is to minimize an objective function, which is,

$$J = \arg\min \sum_{k} ||T_k - T_k||$$

2.3. Single objective linear programming model

In order to verify the correctness of the model, the specific process limits are given (as shown in Table 1), which are divided into 5 constraint conditions. The first two constraint conditions limit the range of temperature rise and fall slope values. Constraints 3 and 4 ensure that the circuit board is sufficiently heated in the reflow oven, and the range is limited in time. The final constraints to limit the peak temperature range of the central area. So, the mathematical form is:

Decision variable: Conveyor belt speed $v$.

Objective function: The objective is the maximum transmission speed that the circuit board can withstand to meet the process limit.

$$\max V = v$$

Restrictions:

\[
S, t \begin{cases} 
-3 \leq \frac{\Delta T}{\Delta t} \leq 3 \\
60 \leq t_1 (150 \leq T_1 \leq 190) \leq 120 \\
40 \leq t_2 (T_2 > 217) \leq 90 \\
240 \leq T_{\text{peak}} \leq 250 \\
65 \leq v \leq 100
\end{cases}
\]

Among them, $t_1 (150 \leq T_1 \leq 190)$ is the time between 150℃~190℃ during the temperature rise; $t_2 (T_2 > 217)$ is the time when the temperature is greater than 217℃; $T_{\text{peak}}$ is the peak temperature; $v$ indicates the furnace speed.

| Table 1. Process boundary table |
|-------------------------------|
| Limits                        | Min   | Max   | unit |
| Temperature rise slope        | 0     | 3     | °C/s |
| Temperature drop slope        | -3    | 0     | °C/s |
| 150℃~190℃ time during the temperature rise | 60 | 120 | s |
| Time when the temperature is greater than 217℃  | 40 | 90 | s |
| Peak temperature              | 240   | 250   | °C   |

3. Solution of models

In order to verify the correctness of the model better, it is necessary to introduce the corresponding specific data solution model, and the obtained results provide a real reference index for the model and rational evaluation. Of course, to a certain extent, its limitations are also revealed.

3.1. Solution of Heat conduction model

3.1.1. Solution of the optimal parameters in the heat conduction model

Because the boundary value conditions of the established unsteady heat conduction model are difficult to solve and analyse, the finite difference method is used to replace the limited fixed solution area with effective discrete points to form a network, and the continuous function on the fixed solution area is used as discrete variable function approximation. The circuit board temperature is obtained by continuous iteration, and then The method of least squares is used to determine the optimal parameters. Specifically, use MATLAB to code for optimization, and find the optimal $\lambda$ value through search optimization:
\[ \lambda = 0.023 \]  

3.1.2. Solution of the temperature and conveyor speed in different temperature zones in the heat conduction model

After the optimal value of the parameter \( \lambda \) of the heat conduction model is set, the setting parameters of the solder reflow oven are applied into the following table:

| Zone            | Temperature (°C) | Conveyor Speed (cm/s) |
|-----------------|------------------|------------------------|
| 1st to 5th zone | 173              | 25                     |
| 6th zone        | 198              | 78                     |
| 7th zone        | 230              |                        |
| 8th to 9th zone | 257              |                        |
| 10th to 11th zone | 25               |                        |

At the same time, the furnace temperature curve under the optimal value is made through data fitting.

3.2. Solution of Single objective linear programming model

Use a multiple search algorithm to search for the conveyor speed \( v \) twice respectively, the first time to get the approximate value of the maximum value of \( v \), and then the second time to search again near the approximate maximum value obtained in the first time. The second search will search in smaller steps.

- In the speed range of [65,100], the step length is 1 to determine the maximum value of the constraint condition. After preliminary search, the maximum boiler speed is about 80cm/min.
- By observing the relationship between the temperature change slope, heating time, the time when the temperature is greater than 217°C and the peak temperature, it can be approximated that the function with the furnace speed as the target variable is a monotonic function. It will not be non-global optimal solutions but local optimal solutions. Based on the above, a precise...
step length search is carried out at about 80cm/min, and finally 79cm/min is the optimal solution that satisfies the constraints.

The figure below shows the furnace temperature curve corresponding to the maximum speed and the temperature corresponding to the relevant important time spots.

![Furnace Temperature Curve](image)

**Figure 7. Figure of furnace temperature corresponding to maximum speed**

4. Conclusion

When considering the industrial production process of reflow oven heating the circuit board, how to adjust the furnace temperature and the furnace speed to meet the constraints is a tough challenge. In this article, it is found that a possible way to simplify the problem based on the theory of Thermodynamics, and use very little time to find the optimal solution. The numerical solution obtained by the finite difference method fits well with the experimental observed value. It not only describes the temperature change during the component welding process, but also proposes optimization model for more effective automatic control. However, due to the simplification in dimensions, the mobility of the model may not be good enough. In addition, the influence of heat radiation cannot be ignored in real life. This is also the motivation which keeps the research to improve in the future.

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