Heat Transfer Modeling and Oven Temperature Curve Optimization of Integrated Circuit Board Reflow Soldering

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This work was supported in part by the Hainan Provincial Natural Science Foundation of China under Grant 521RC496, and in part by the National Natural Science Foundation of China (NSFC) under Grant 51865008.

ABSTRACT In order to use mechanism model analysis instead of experimental test to control and adjust the temperature and oven temperature curve of each part of the integrated circuit board reflow oven to make it meet the process requirements, a fitting algorithm was used to establish a heat transfer model of the reflow soldering. The established reflow soldering heat transfer model was used to simulate and fit to obtain the integrated circuit board reflow soldering oven temperature curve, and compared it with the reflow soldering experiment curve to verify the reliability of the model’s simulation performance. The comparison results show that the reflow soldering oven temperature simulation curve is in good agreement with the experimental curve, and it can replace the experimental test to find the best. On this basis, the genetic algorithm was further used to optimize the temperature setting and oven temperature curve for integrated circuit boards. After optimization, the conveyor belt velocity of the integrated circuit board is preferably 1.4799 cm/s, and the set temperature of temperature zones is 179 °C at small temperature zones 1∼5, 185 °C at small temperature zone 6, 235 °C at small temperature zone 7, and 264 °C at small temperature zones 8∼9; the area of the oven temperature curve that exceeds 217 °C decreases by 831.1611 °C·s, and its symmetry with respect to the peak is better, which is much closer to the ideal oven temperature curve. The research results provide a useful reference for the design of integrated circuit board reflow soldering process.

INDEX TERMS Integrated circuit board, surface mounting, reflow soldering, oven temperature curve, optimization.

I. INTRODUCTION

With the rapid development of intelligent manufacturing equipment, the demand for integrated circuit boards is constantly increasing, which requires keeping up with the times to improve the level of integrated circuit board production technology. The Surface Mounting Technology (SMT) [1] is a new-generation electronic mechanical assembly technology, which implements electronic product assembly with high-density, high-reliability, miniaturization, low-cost and production automation, and therefore serves as the technological support for integrated circuit board production. In the 21st century, the circuit electronics manufacturing technology has transferred from the traditional through-hole manner to the surface mounting method, and in most cases, the integrated circuit board production adopts the SMT. The reflow soldering is a key procedure of the SMT and has direct impact on the yield and reliability of integrated circuit boards. Therefore, reasonable design of the reflow soldering oven temperature curve will directly determine the quality of the reflow soldering [2].

With the six-sigma improvement methodology, Jiao [3] measured the oven temperature curve by selecting three or more points on a Printed Circuit Board (PCB) and averaging the temperature measured by the mobile thermodetector. Zhao et al. [4] obtained the top reflow zone temperature at around 220 °C through metallographic analysis. If the top temperature is lower than 200 °C, bad soldering will be produced. In an ideal oven temperature curve, the area covered by the temperature exceeding 217 °C to the peak temperature...
should be minimized. Wu [5] proposed the concept of heating factor, which serves as a quantitative evaluation indicator for the reflow soldering curve optimization. With orthogonal tests on the process parameters of reflow soldering, Feng et al. [6] found that the soldering zone oven temperature and conveyor belt velocity have the greatest impact on the reflow temperature curve and each key indicator. Through study of massive samples, Feng et al. [7] had analyzed the heat absorption process of the PCB and the heat transfer process of the reflow soldering oven, and come to the conclusion that the thickness of the PCB is the key characteristic factor affecting the oven temperature curve of the reflow soldering. The preceding researches use the disadvantages of the reflow soldering as the entry point, and improve the oven temperature curve and its parameters. However, if it is to be applied to actual production, it is necessary to carry out multiple experiments for adjusting the welding process parameters to obtain a suitable oven temperature curve, which not only increases production costs, but also makes it difficult to clearly understand the mathematical law of the gap temperature changes between temperature zones with different temperatures. At present, there are few researches on the numerical simulation of reflow soldering. If the research is carried out effectively, it will greatly reduce the number of experiments and the production cost of integrated circuit boards, and obtain the mathematical law of the gap temperature changes between soldering zones with different temperatures. The preceding researches use the disadvantages of the reflow soldering as the entry point, and improve the oven temperature curve and its parameters. However, if it is to be applied to actual production, it is necessary to carry out multiple experiments for adjusting the welding process parameters to obtain a suitable oven temperature curve, which not only increases production costs, but also makes it difficult to clearly understand the mathematical law of the gap temperature changes between temperature zones with different temperatures.

II. EXPERIMENT TO OBTAIN THE OVEN TEMPERATURE CURVE OF REFLOW SOLDERING

A. EXPERIMENTAL MATERIALS AND EQUIPMENT

The integrated circuit board with the soldering zone thickness of 0.15 mm and the reflow soldering oven as shown in FIGURE 1 is used for the temperature collection experiment. The reflow soldering oven is composed of four functional parts: the pre-heating zone, the constant temperature zone, the reflow zone, and the cooling zone. The integrated circuit boards are carried by the conveyor belt and move into the oven in a constant velocity for heated soldering. After the temperature in each constant temperature zone and the conveyor belt velocity in the oven are configured, the temperature sensor can be used to test the temperature in the center of the soldering zone within each temperature zone. After fitting,
the obtained temperature curve is called the oven temperature curve (also is the central temperature curve of the soldering zone). The distribution characteristics of the curve are shown in FIGURE 2.

B. EXPERIMENTAL METHOD AND PROCESS
There are 11 small temperature zones in the experiment. Each small temperature zone has the length of 30.5 cm, and two neighboring small temperature zones have a gap of 5 cm, and measure the temperature of the center of the welding area every 0.5 s and record it in the table. The length is 25 cm for both zones in front and behind the oven. Small temperature zones 1 to 5 are pre-heating zones, small temperature zones 6 and 7 are constant temperature zones, small temperature zones 8 and 9 are reflow zones, small temperature zones 10 and 11 are cooling zones with the temperature is fixed to 25 °C indoor temperature, as shown in FIGURE 3 [8].

C. EXPERIMENTAL RESULTS AND PURPOSES
Use MATLAB software to fit the experimentally recorded data ($T^{real}_i$) to obtain the following oven temperature curve. As shown in Figure 4, the experimental results will be compared with the first oven temperature curve simulated by the reflow soldering heat transfer model established below to verify the pros and cons of the model’s simulation performance.

III. HEAT TRANSFER MODEL OF THE REFLOW SOLDERING
A. TEMPERATURE DISTRIBUTIONS IN THE SMALL TEMPERATURE ZONE GAPS
If there is great difference between configured temperatures of two neighboring small temperature zones, the temperatures of the edges of the two small temperature zones will be greatly impacted. If a small temperature zone is of high temperature, the zone is greatly heated, and the resistance to the impact is
strong on the edge [9]. Thus, it is assumed that the distance between the stable point and the edge of a small temperature zone is inversely proportional to the temperature of the small temperature zone, and is proportional to the configured temperature difference of two neighboring temperature zones, which is as follows.

\[ l_j = \frac{T_{oven j+1} - T_{oven j}}{r T_{oven j}} \]  

In the above equation, \( T_{oven j} \) indicates the configured temperature of the jth small temperature zone, \( r \) indicates the inverse proportional coefficient to be solved, and \( l_j \) indicates the impacted range of the jth small temperature zone edge, as shown in FIGURE 5.

**B. PHYSICAL MODEL OF REFLOW SOLDERING HEAT TRANSFER**

In the soldering process, the reflow soldering oven transfers heat to the integrated circuit board, heating up the integrated circuit board. There are three ways of heat transfer in the oven, including heat convection, heat radiation, and heat transfer [10]. The reflow soldering oven heats up the board through air-convection heat transfer, and the temperature difference between integrated board and the heating zone heats up the board through heat radiation. Because the integrated board is not in contact with the heating zone and is carried by conveyor belt, and the heat transfer process can be neglected [11].

The heated object is a thin board with the upper and lower surfaces heated by the heating zone, and the heat convection and radiation both take place on the upper and lower surfaces. Therefore, the length and width of the integrated circuit board can be neglected, and we only consider the heat transfer in one dimension of thickness [12]. To facilitate calculation, the heat transfer can be converted into the form of the Newton’s law of cooling, and integrated into the heat convection formula. In this way, the overall equivalent heat convection heat transfer can be simplified, as shown in FIGURE 6.

Convection is a heat energy movement phenomena that is caused by the relative displacement of a moving fluid particle and complies with the Newton’s law of cooling. That is, for an object with the temperature \( T \) in the fluid with the temperature of \( T_0 \), and the heat transfer zone of \( A \), the heat convection is calculated as follows.

\[ Q_c = h_c A (T_0 - T) \]  

In the formula, \( h_c \) indicates the heat transfer coefficient (W/m\(^2\)-K), \( T \) indicates the temperature (K) of the exothermic object, and \( T_0 \) indicates the temperature (K) of the heated fluid.

Radiation is an energy transfer method in which objects send and receive electromagnetic waves. When the temperature of an object is above absolute zero, it constantly sends electromagnetic waves to the outside. The radiation and absorption capability of a black body complies with the Stefan-Boltzmann law [13].

\[ M = \Lambda \sigma T^4 \]
In this formula, \( \sigma \) indicates the radiation coefficient. For a general object with the radiation coefficient smaller than that of the black body, the following formula can be used according to experience.

\[
\sigma = \varepsilon \sigma_0
\]  

If the reflected electromagnetic waves in the oven are neglected, and only the radiation from the heating zone to the integrated circuit board is considered, the following formula can be used to calculate the radiation exchange between the heating zone and the integrated circuit board.

\[
M = \varepsilon \sigma_0(T_{oven}^4 - T^4)
\]  

In this formula, \( T_{oven} \) and \( T \) indicate the heating zone temperature and the integrated circuit board temperature, respectively. Based on the preceding theory, assume that the emission coefficients of the heating zone and the integrated circuit board are \( \varepsilon_1 \) and \( \varepsilon_2 \), respectively, and the area of the integrated circuit board soldering zone is \( A \). Then, the following formula can be used to calculate the radiation heat transfer.

\[
Q_r = \frac{\varepsilon A(T_{oven}^4 - T^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}
\]  

If the equivalent emission coefficient \( \varepsilon \) is used to replace the reciprocal in (6), the following formula is obtained.

\[
Q_r = \varepsilon \sigma A(T_{oven}^4 - T^4)
\]  

In engineering, to facilitate calculation, the radiation heat transfer is converted into the Newton’s law of cooling, which is as follows.

\[
Q_r = h_r A(T_{oven} - T)
\]  

In this formula, \( h_r \) indicates the convection heat exchange coefficient (W/m²·K) after radiation transfer.

\[
h_r = \frac{\sigma \varepsilon_1 \varepsilon_2 (T_{oven}^2 + T^2)(T_{oven} + T)}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2}
\]  

The formula to calculate the heat on upper and lower surfaces in the soldering zone is as follows.

\[
Q_e = h_e A(T_{oven} - T)
\]  

If the heat radiation and heat convection are superposed, making \( h = h_c + h_r \), the following formula can be used to calculate the equivalent heat convection on the upper and lower surfaces in the soldering zone.

\[
Q = h A(T_{oven} - T)
\]  

Set the specific heat capacity of the soldering zone to \( c_p \), and the mass to \( m \), and assume that the heat transferred from the reflow soldering oven to the soldering zone is transferred to the internal energy [14] of the soldering zone, which is as follows.

\[
mc_p \frac{dT}{dt} = h A(T_{oven} - T)
\]  

where the surface heat transfer coefficient \( h = 25 \text{w/m}^2 \cdot k \), solid thermal conductivity \( \lambda = 0.21 \text{w/m} \cdot \text{k} \), characteristic length \( \delta = 0.15 \text{mm} \).

The value of Bi is:

\[
B_i = \frac{\delta h}{\lambda} = 0.00893
\]

Setting \( k = \frac{h A}{mc_p} \), and setting the initial temperature in the soldering zone to \( T_0 \), then the differential equation is solved to obtain the following formula.

\[
T = T_{oven} - (T_{oven} - T_0)e^{-kt}
\]

### IV. Solving the Model and Optimizing the Oven Temperature Curve

#### A. Calculation of K Value

The temperature of the different small temperature zones of the welding oven is different. The edge temperature of the small temperature zone will be affected by the adjacent small temperature zone, and the gap between the small temperature zone will also be affected by the small temperature zone on both sides. The temperature distribution of the gap and the edge of the small temperature zone The temperature distribution is still unknown, but the temperature in the 1-5 small temperature zone is the same, and the length of the gap is much smaller than the length of the small temperature zone. It can be considered that except for the left edge of the 1 small temperature zone and the right edge of the 5 small temperature zone, 1-5 small temperature The temperature in the zone is a constant value. Based on the previous assumptions, when
the welding area is outside the phase transition temperature range, the specific heat capacity and thermal conductivity do not change. The temperature in the 1-5 small temperature zone has not reached the phase transition temperature of the welding area, so the value is constant. The value can be calculated according to the data in the 1-5 small temperature zone in the experiment.

The method of traversal search is used, for each \( k \), the temperature at each time point was calculated by equation (13), and then compare it with the experimental data. When the estimated temperature is closest to the actual temperature, the optimal value of \( k \) is obtained.

\[
\sum_{i=1}^{N} (T_i - T_i^{real})^2
\]  

(14)

\( T_i \) is the temperature estimated by the \( k \) value, and \( T_i^{real} \) is the actual temperature in the experiment. When the formula (14) reaches the minimum value, the corresponding \( k \) value is the most ideal value.

\[
\min_k \sum_{i=1}^{N} (T_i - T_i^{real})^2
\]  

(15)

The data from 40s to 169s in the experiment are selected, and traverse the calculation solution to get \( k = 0.0199 \). The estimated temperature and actual temperature are shown in the following FIGURE 7:

It can be seen that the estimated temperature from 40s to 169s is very close to the actual temperature, but it separates from 0 to 40s, presumably because the temperature in the front of the oven to the first small temperature zone does not reach 175 °C, and the temperature is gradually rising. The temperature does not reach 175 °C until a certain point in the first small temperature zone.

From the calculated value of \( k \), the temperature in the oven can be deduced inversely, and formula (12) is transformed into a difference format using the forward Euler formula:

\[
\frac{T_{i+1} - T_i}{\Delta t} = k (T_{oven} - T_i)
\]  

(16)

\( \Delta t \) is the time step, slightly changed:

\[
T_{oven} = \frac{T_{i+1} - T_i}{k\Delta t} + T_i
\]  

(17)

The air temperature in the oven at each time point is calculated from the formula (17), but there is a premise to use this formula, the value of \( k \) is unchanged. If there is a phase change in the welding area, then the \( k \) value will change and (17) will not apply. The calculated air temperature in the oven are drewed into an image as shown below (FIGURE 8).

It can be seen that the temperature does not reach a stable value of 175 °C until about 20cm from the left edge of the first small temperature zone. Since then, the temperature has been stable at 175 °C until the temperature near the right edge of the fifth small temperature zone rises again. From the first half of the curve, it can be seen that the temperature between the small temperature zones of different temperatures changes roughly in a straight line. In the second half of the curve, when the welding element is transferred to 270cm-290cm, the temperature is convex downward. It is presumed that the temperature of the welding area has entered the phase transition temperature range, the welding area has undergone a phase change, and the specific heat capacity, heat transfer coefficient, etc. have all changed, which leads to the change of \( k \) value, then the welding area is completely melted into a liquid state, and the value of \( k \) has returned to stability, so the curve is stable again, but the temperature is slightly larger than 255 °C, indicating that the \( k \) value changes after the welding area is completely liquid, which is slightly larger than the \( k \) value in the solid state. Then the component enters the cooling zone, the temperature changes drastically, and the \( k \) value also fluctuates drastically. The calculation

![FIGURE 7. Actual curve and fitting curve of the preheating section.](image-url)
formula (17) of the air temperature in the oven is no longer applicable.

The component enters the 8-9 small temperature zone. When the temperature of the welding area exceeds the phase transition temperature range, the welding area becomes completely liquid. At this time, the $k$ value is stable. In order to calculate the $k$ value in the liquid state of the welding area, similar to the previous calculation of the $k$ value in the solid state, the method of traversal search is adopted. The experimental data within 243.5s-280s were selected and calculated to obtain $k = 0.0218$ when the welding area is completely liquid. The estimated temperature and actual temperature are shown in FIGURE 9 below. It can be seen that when the element is located in the 8-9 small temperature zone, the estimated temperature is very consistent with the actual temperature. At about 290s, the element is located near the right edge of the 9 small temperature zone, and the air temperature in the oven begins to drop due to the influence of the cooling zone. At this time, the estimated temperature and the actual temperature curve begin to separate.

When the element enters the cooling zone for a long distance, the element is fully cooled and completely solid, and the air temperature in the oven is also stable at 25 °C, the $k$ value is stable again. According to the previous calculation method, the data of 340s-373s in the experiment were selected and calculated to obtain $k = 0.0100$ after the welding area is fully cooled. The estimated temperature and actual temperature are as follows (FIGURE 10). At 396.7cm, the air temperature in the oven dropped to 25 °C. The change of the $k$ value reflects the change of the ambient temperature where the component is located or the phase change of the welding area itself. The equation (17) is transformed to obtain the calculation formula of the $k$ value:

$$k = \frac{T_{i+1} - T_i}{\Delta t (T_{oven} - T_i)}$$  (18)

According to the previous analysis, the air temperature near the right edge of the small temperature zone 9 begins to drop linearly until the temperature at 396.7cm drops to 25 °C. The equation (18) was used to calculate the $k$ value at each time point from the edge of the 9th small temperature zone to the end of the oven area. As shown in the blue curve in FIGURE 11 below, the violent fluctuations between 290s and 300s are because the air temperature drops to the temperature of the welding area during this time, and then the welding area begins to cool, changing from liquid to solid. The air temperature drops drastically during this process. At the same time, the welding area is also undergoing phase change. During the phase change, latent heat will be released, and its specific heat capacity and heat transfer coefficient will also change. These changes are reflected in the change of the $k$ value. $k$ mainly changes with the temperature of the welding area itself. For this reason, a cubic polynomial is used to fit the function of $k$ on the temperature of the welding area during the phase change of the welding area during cooling. Using the polyfit function of MATLAB, the function of $k$ on the temperature is calculated by the least square method. Regarding the temperature function, the $k$ value calculated by the fitting function is shown by the red asterisk in the figure, which is consistent with the actual $k$ value. When the welding area is completely solid, $k$ returns to stability, and $k = 0.0100$ at this time.

The welding area will also undergo a phase change process when the temperature of the welding area rises, but this phase change process lasts for a short time, and the air temperature in the oven does not change much during this process. At this time, the temperature distribution between small temperature zone 7 and small temperature zone 8 is unknown. In order to simplify the model, the change process of $k$ during this phase transition can be ignored. It is considered that $k$ changes directly from 0.0199 to 0.0218 when the temperature of the welding area reaches 200 °C.
In summary, the value of $k$ is divided into four stages:

- $k = 0.0199$ when the welding area has not undergone phase change in the heating stage;
- $k$ becomes 0.0218 when the temperature of the welding area reaches 200 °C;
- when the welding area has not completely become solid during the cooling process, $k$ is a function of the temperature of the welding area; $k=0.0100$ after the welding area is completely solid (19), as shown at the bottom of the next page.

### B. PARAMETER DETERMINATION

After the value of $k$ is determined, the traverse searching method is used for each $r$, to obtain the approximation of between the calculated temperature distribution and the actual temperature distribution. The approximation can be indicated by the following formula.

$$
\sum_{j=1}^{n} (T_j - T_{j}^{\text{real}})^2
$$

(20)

$T_j$ is the temperature calculated through the value of $r$, and $T_j^{\text{real}}$ is the actual temperature. When the value of the preceding formula reaches the minimum, the corresponding value of $r$ is the optimal value. Using the forward Euler method, the numerical value of (15) is solved, and the following temperature calculation formula is obtained.

$$
\begin{cases}
T_{i+1} = T_i + k \Delta t (T_{\text{oven}} - T_i) & (i = 1, 2 \cdots N) \\
T_1 = T_0
\end{cases}
$$

(21)

The initial temperature $T_0 = 25$ °C, the time step $\Delta t$ is 0.01s, and the optimal ratio value obtained by calculation is $r=0.051$. According to equation (1), $l_j$ is estimated as: $l_1-l_4 = 0$, $l_5 = 2.24$, $l_6 = 4.02$, $l_7 = 1.67$, $l_8 = 0$, $l_9 = -17.69$, $l_{10} = 0$. Then the oven temperature simulation curve can be calculated according to (21), and compare it with the actual oven temperature curve obtained in the previous experiment. As shown in FIGURE 12, it can be seen that
the two are very consistent. At this time, the area of the oven temperature curve exceeding 217 °C is calculated by MATLAB is 1267.24 °C·s.

C. PARAMETER DETERMINATION

1) DETERMINING THE TARGET FUNCTION

In production, the configuration or adjustment of the oven temperature curve of reflow soldering for the integrated circuit board is verbose, and quantitative basis is lack. To quantify the temperature control, the temperatures of the pre-heating zone, the constant temperature zone, the reflow zone, and the cooling zone and the conveyor belt velocity are selected as the optimization variables [15], and the heating factor and symmetry are introduced as quantified indicators.

Heating factor

Generally, for complicated integrated circuit boards, the temperatures for pre-heating and reflow can be increased moderately, or prolonging the time for pre-heating and reflow can make the temperature equally distributed and the reflow adequate on each component of the integrated circuit board, reducing defects on the appearance [16]. However, some integrated circuit boards have good soldering dots on the appearance, in fact, the board stays in the high temperature zone for too long or withstands too high temperature, so the mechanical and electrical properties of the components deteriorate and the reliability of the soldering dot decreases. Such above defects are hardly detected in production, but will show after a period of using [17]. To make the time of staying in the fluid phase for the soldering zone as short as possible on the basis of ensuring sufficient soldering [17], the heating factor $\eta$ is introduced.

\[
S_\eta = \int_{t_1}^{t_2} (T(t) - T_M) \, dt
\]  

(22)

In the formula, $T_M$ indicates the melting point temperature of the solder, and $t_1$-$t_2$ indicates the time staying in the fluid phase. Therefore, $\eta$ also indicates the area of staying in the fluid phase.

② Symmetry Indicators $K$ and $M$

The residual stress of the soldering has great impact on the quality and reliability of the integrated circuit board. The residual stress is produced during the cooling process, particularly produced by uneven shrinkage caused by different cooling velocity resulting from different temperatures because of the length of the integrated board during the transformation from the fluid phase to the solidity phase. Therefore, to ensure the quality of the integrated circuit board, the temperature should be as symmetrical as possible in respect with the peak for the parts of the oven temperature curve that exceed the melting point of the solder for the temperature [18], and two symmetrical performance indicators $K$ and $M$ are introduced.

\[
K = |(t_2-t_1) - (t_3-t_2)|
\]  

(23)

\[
M = |\int_{t_1}^{t_2} \rho dt - \int_{t_2}^{t_3} \rho dt|
\]  

(24)

\[
k = \begin{cases} 
0.0199 & \text{Phase change has not happened in the heating stage of the soldering zone} \\
0.0218 & \text{The temperature reaches 200 °C in the soldering zone} \\
0.0100 & \text{The solidity status has been not reached during the cooling process} \\
a_0 + a_1T + a_2T^2 + a_3T^3 & \text{The solidity status has been fully reached in the soldering zone}
\end{cases}
\]  

(19)
In the formula, $\rho$ indicates the curvature of the oven temperature curve, $t_1$ indicates the time point when the temperature reaches 217 °C, $t_2$ indicates the time point of the temperature peak, and $t_3$ indicates the time point when the temperature drops to 217 °C.

In theory, if the parts in the oven temperature curve exceeding 217 °C are symmetrical by the peak value, the time from 217 °C to the peak should be symmetrical with that from the peak to 217 °C, and $K = 0$. If the parts in the oven temperature curve exceeding 217 °C are not strictly symmetrical by the peak value, a smaller value of $K$ indicates a smaller time difference between temperature rise and drop.

Obviously, the indicator $K$ is not sufficient. For example, if the temperature of the heating process is uniformly rising and the temperature of the cooling process drops quickly at first and then drops slowly, the value of $K$ can be 0. Therefore, on the basis of considering only the time indicator, another indicator $M$ is added. If the parts in the oven temperature curve exceeding 217 °C are symmetrical by the peak value, the slope changes of the temperature rise and drop are identical, the curvature difference is 0. If the parts in the oven temperature curve exceeding 217 °C are not strictly symmetrical by the peak value, a smaller value of $M$ indicates more identical curvature change. Thus, the following target function can be determined.

$$J_{T} \arg \text{et} = \min \left\{ w_1 \int_{t_1}^{t_2} (T - 217) \, dt + w_2 |(t_2 - t_1) - (t_3 - t_2)| + w_3 |\int_{t_1}^{t_2} \rho \, dt - \int_{t_2}^{t_3} \rho \, dt| \right\}$$  \hspace{1cm} (25)$$

In this formula, $\rho$ indicates the oven temperature curve curvature, $t_1$ indicates the time point when the temperature rises to 217 °C, $t_2$ indicates the time point of the temperature peak, $t_3$ indicates the time point when the temperature drops to 217 °C, and $w_i$ ($i=1,2,3$) indicates the weight coefficient.

After multiple adjustments, when $w_1 = 0.5$, $w_2 = 0.25$, and $w_3 = 0.25$, the slopes for the temperature rise and drop are most close to each other, and the symmetry is the optimal.

2) CONSTRAINTS

In the reflow soldering process for integrated circuit boards, to ensure that the components are not burned out, the top temperature of the soldering is between 240 °C to 265 °C; to ensure full soldering and a short time for staying in the high temperature stage, the time staying exceeding 217 °C should be between 40s to 90s; to ensure full pre-heating, the time for the temperature staying between 150 °C to 190 °C during temperature rise should be 60s to 120s; to prevent sudden temperature rise or drop, the absolute value of the slope for temperature rise or drop should be less than 3. According to the preceding basis, the optimization rules in Table 1 are formulated:

3) GENETIC ALGORITHM SOLVING FOR THE MODEL

The genetic algorithm is a calculation method that uses computer programs to simulate the natural biological evolution process to search for the optimal solution [19]. This algorithm transforms the process for solving problems into the process similar to chromosomes crossover and variations in biological evolution, and search for the optimal results by constantly keeping the “genes” that highly complies with the target function. The following parameters should be configured if the genetic algorithm is used to solve problems:

1) Population size and evolution algebra. The population size indicates the number of individuals in the population, and the evolution algebra indicates the genetic algebra. According to actual experience, a larger population size and more evolution algebras make it easier to find the optimal value. However, a too
large population size and excessive evolution algebras can largely increase the calculation cost.

2) Mating probability. The mating probability indicates the ratio of the mating chromosome in all chromosome. Mating is a vital method of generating new population. A too large mating probability can easily sabotage the original advantageous mode and increase the randomness, causing the loss of optimal individual. However, a too small mating probability is not effective in renewing the population [20].

3) Variation probability. The variation probability indicates the ratio of the variation chromosome genes in all chromosome genes. The value should not be too large. Otherwise, the situation does not comply with the actual genetic variation, and effective genes will quickly be lost. However, if the variation probability is too small, the diversity of the population will drop too fast.

The genetic algorithm model formulated by Hou et al. [21] is referred to. In this paper, the population size is set to 50, the evolution algebra is set to 1000, the mating probability is set to 0.9, and the variation probability is set to 0.1(Generally speaking, the crossover probability is between 0.9-0.97, and the mutation probability is between 0.1-0.001). MATLAB is used to search for the optimal calculation according to the process shown in FIGURE 13. FIGURE 14 shows the change of the optimal adaptive value with the genetic algebra, and Table 2 lists the final optimization results.

### TABLE 1. Optimization settings.

| Variable | Type         | Value Range     |
|----------|--------------|-----------------|
| Temperature°C | Target function | Minimization |
| Temperature°C of small temperature zones 1 to 5 | Designed variable | 165 to 185 |
| Temperature°C of small temperature zone 6 | Designed variable | 185 to 205 |
| Temperature°C of small temperature zone 7 | Designed variable | 205 to 245 |
| Temperature°C of small temperature zones 8 to 9 | Designed variable | 245 to 265 |
| Velocity over the oven (cm/s) | Designed variable | 1.083 to 1.667 |

In the meantime, MATLAB is used to calculate the area of the parts in the oven temperature curve exceeding 217 °C, and the result is 436.0789 °C·s. FIGURE 15 shows the oven temperature curve of reflow soldering after optimization.

### TABLE 2. Optimization results.

|                | Temperature/°C | Velocity through the oven/cm·s⁻¹ |
|----------------|----------------|---------------------------------|
| Small temperature zones 1 to 5 | 179.1442 | 1.4799 |
| Small temperature zone 6 | 185.0008 | 1.4799 |
| Small temperature zone 7 | 234.5456 | 1.4799 |
| Small temperature zones 8 to 9 | 264.4821 | 1.4799 |

5) ANALYZING THE MODEL SENSITIVITY

1) Impact on the Oven Temperature Curve

In the preceding part of this paper, there are four stages for the value of k. In the third phase, the value is a cubic polynomial function related with the temperature T, and its actuating range is for the soldering zone from the starting point of cooling to fully cooled to the solidity status. This process is relatively short, and the value of k in this stage has small impact on changing the overall oven temperature curve. k1, k2, and k3 are specified as the values of k in the first stage, the second stage, and the fourth stage, respectively. As shown in (14), the values of k are 0.0199, 0.0218, and 0.0100, respectively. In this section, the impact of the deviation of values of k in the three stages on the oven temperature curve and on the area of the parts in the oven temperature curve over 217 °C is analyzed.

A change of −20%, −10%, 0, +10%, and +20% is applied to values of k1, k2, and k3 to fit the corresponding oven temperature curves, as shown in FIGURE 17 to 20. As shown in FIGURE 17, the value of k1 has impact on all sections of the curve. As shown in FIGURE 18, the value of k2 has impact on only the parts of the curve in 200 °C and above. As shown in FIGURE 19, the value of k3 has impact on only the curve in cooling stage.

To evaluate the impact of the deviation of the value of k on the oven temperature curve, the following formula is used for calculation.

$$\text{mae} = \frac{\sum_{i=1}^{n} |T'_i - T_i|}{n}$$

The above formula is used to evaluate the impact from the fluctuation of the value of k on the oven temperature curve. T' is the temperature after the value of k is changed, T is the temperature before the value of k is changed. In this formula, the calculation must be within the impact range of the value of k. Table 3 lists the calculation results. It is shown that the fluctuation of the value of k1 has the greatest impact on the oven temperature curve, the impact of the fluctuation of

4) VERIFICATION OF OPTIMIZATION RESULTS

During the welding process, the time for the temperature in the center of the welding area to exceed 217 °C should not be too long, and the peak temperature should not be too high. The ideal oven temperature curve should minimize the area covered by the part of exceed 217 °C to the peak temperature (the shaded part in FIGURE 2). The area covered by the part of exceed 217 °C to the peak temperature before optimization is 1267.24 °C·S, and the area covered by the part of exceed 217 °C by the part of exceed 217 °C temperature (the shaded part in FIGURE 2). The area covered by the part of exceed 217 °C to the peak temperature before optimization is 1267.24 °C·S, and the area covered by the part of exceed 217 °C temperature (the shaded part in FIGURE 2).
the value of $k_3$ is smaller, and the impact of the fluctuation of the value of $k_2$ is the smallest.

2. Impact on the Area
The sensitivity indicates the dependency relationship of the model resolution results on the observed data or actual information. It is assumed that the expression of the model resolution result is $f = f(x; a, b)$, where $a$ and $b$ are parameters, and the sensitivity of $f$ over $a$ is denoted as $s(f, a)$. Then the change rate of $f$ related with $a$ is defined as follows.

$$s(f, a) = \frac{\Delta f}{\Delta a} \approx \frac{a \Delta f}{f \Delta a}$$  \hspace{1cm} (27)$$

In the formula, $f$ is the area, and $a$ is $k_1$, $k_2$, and $k_3$. The image of $\frac{\Delta f}{f} \sim \frac{\Delta a}{a}$ is calculated, and Table 4 lists the calculated sensitivity. It is show that the sensitivity of area is the highest for $k_1$, and lower for $k_2$, and the change of value of $k_3$ has almost no impact on the area.

V. RESULTS AND DISCUSSION
(1) From the process of solving the heat transfer model of reflow soldering, it is known that the temperature in the temperature zone 1-5 is stable. Using the experimental data and MATLAB software, the key coefficient $k$ of the temperature differential equation is calculated by traversal search. The key coefficient is related to the phase state of the welding area itself, so $k$ does not change when the temperature is lower than the transformation temperature range, but $k$ will change after the phase change occurs in the welding area and the phase change is completed. The Euler forward method is used.
to establish the difference format of the differential equation of temperature change, and the air temperature distribution in the oven is inversely derived. It is found that the temperature of the gap between the temperature zones of different temperatures changes roughly linearly, and the edge temperature of the temperature zone is also affected. After the mathematical model is solved, the first oven temperature curve simulated by the model is in very good agreement with the actual oven temperature curve.

(2) Considering that the configured temperatures in each temperature zones are different during the reflow soldering, in actual integrated circuit board production, the thickness of the integrated circuit board should be firstly confirmed, then the heat transfer model of reflow soldering is used to conduct simulation on the integrated circuit board to determine the initial temperatures of each temperature zone, and in the end, the genetic algorithm optimizing is used to conduct the process curve's parameter optimization. According to the calculation results in Table 2, the following settings is the recommended as curve parameter settings for integrated circuit boards in this paper: the conveyor belt velocity is 1.4799 cm/s, and the temperatures in each temperature zone are 179 °C for small temperature zones 1 to 5, 185 °C for small temperature zone 6, 235 °C for small temperature zone 7, and 264 °C for small temperature zones 8 to 9.

(3) Based on the process curve parameter settings after researches in this paper, FIGURE 15 shows the area of the peak parts of the curve exceeding 217 °C is 831.1611 °C·s less than that of the actual oven temperature curve, and the curve has a better peak symmetry than the actual oven temperature curve. Therefore, the results show that the process curve optimization should be implemented based on the soldering zone thickness of different integrated circuit boards and the configured temperatures of simulated temperature zones.

(4) Through the sensitivity analysis, the rate of contribution for each design variable to output variable can be calculated, and the impact of each parameter to the output variable can also be analyzed. This facilitates research personnel to learn which design variable has greater impact, and which design variable has smaller impact. In this way, research personnel can focus on sensitive factors and leave out insensitive factors, reducing the blindness in designing the oven temperature curve of reflow soldering of integrated circuit boards.

VI. CONCLUSION

The actual oven temperature curve measured by experiments is used to verify the reliability of the simulation performance of the heat transfer model of the reflow soldering. The results show that the simulated oven temperature curve matches the actual curve well, which proves that the computer can authentically restore the temperature curves in various situations through modifying the materials and the input of data in temperature zones in the heat transfer model of reflow soldering in this paper. Then, in the case of no or less experiments,
whether the input temperature of the temperature zone is suitable for integrated circuit board soldering can be known in advance to reduce experiment or trial production costs, which is beneficial for improving the production level of integrated circuit boards. At the same time, it is derived from the model that the gap temperature between the temperature zones of the reflow oven changes roughly linearly, and the edge temperature of the temperature zone is also affected by the mathematical law, which is conducive to improving the welding quality.

Because simple temperature simulation can hardly improve the reflow soldering performance for integrated circuit boards, and can hardly facilitate operation personnel in quickly spotting the optimal temperature curve, through designing the optimization target, optimization variables, quantitative target, and constraints, and using the genetic algorithm, the optimal oven temperature curve of the reflow soldering of integrated circuit boards have been obtained in this paper. The area of the peak parts in the optimal curve exceeding 217 °C decreases by 831.161 °C·s compared with the actual oven temperature curve, and the curve is much closer to the ideal oven temperature curve and has a better peak symmetry than those of the actual oven temperature curve, which is helpful to improve the reflow soldering performance for integrated circuit boards, and promote the development of key components of intelligent manufacturing equipment.

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