Study on Influencing Factors and Laws of Temperature Field Distribution of Infrared Hot Air Reflow Soldering

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Abstract. The quality of solder joints formed by reflow soldering is closely related to the temperature profile of solder joint during the hot air reflow soldering process. The temperature profile of solder joint is directly determined by the process parameters of the reflow furnace as the layout of the PCB design remains same. In this paper, the temperature model of the printed board assembly during reflow soldering is numerically built and simulated to obtain the temperature distribution. Furtherly, several process parameters, such as the temperature of each temperature zone, convective heat transfer coefficient and conveyor belt speed of reflow soldering furnace, are selected as the input variables, and the heating factor, time of super liquidus and peak temperature are aimed as the output parameters. The Latin hypercube sampling design is applied to construct the response surface of the output parameters. The influence of these process parameters during the reflow soldering on the temperature profile of PCBA is studied comprehensively. The main influencing process parameters of the reflow soldering are identified and their influence laws are obtained. The research results provide valuable reference and basis for reflow soldering process design.

1. Introduction
Reflow soldering is a key process in SMT production, which directly affects the soldering quality and reliability of electronic products[1]. Soldering defects are more affected by reflow soldering processes than components, solder paste materials, printing, and placement processes. Therefore, the process of reflow soldering must be strictly controlled. The traditional method is solved by adjusting the soldering process constantly. This method not only consumes a lot of manpower, material resources and time cost, but also does not have some optimality; the numerical simulation method especially the finite element method has become an important method for the soldering process due to its advantages of short period and low cost, which solves the limitations of traditional methods; At the same time, The reflow profile directly determines the quality of the reflow soldering process[2], so when setting and adjusting reflow soldering process parameters, it is necessary to understand the influence of reflow furnace process parameters on reflow soldering temperature profile[3]. This paper mainly studies the influence of reflow soldering process parameters on the key indexes of reflow zone temperature profile. Through the numerical modeling of PCB temperature field during reflow soldering, using APDL language, the temperature of 12 furnace zones is simulated and set, and the influence of conveyor belt speed and each furnace temperature is considered, the parameterized
modeling of temperature field is realized. The response surface was fitted by orthogonal experimental design; The main influencing factors and rules of temperature field of infrared hot air reflow soldering are obtained by the method of multi factors influencing the output parameters, which provides guidance for the setting and adjustment of reflow soldering process parameters.

2. Numerical simulation of temperature field during reflow soldering

2.1 The boundary conditions of the temperature field simulated

The reflow process is the heat exchange process between the reflow oven and the PCBA assembly. Normally, there are several individual ovens in a reflow furnace. In each oven, N2 air is preheated and then be send to the PCBA surface using a fan on the top and bottom area of the oven[4]. It can be seen that during the reflow soldering process, the heat transfer between the reflow furnace and the PCBA is mainly performed by heat convection between them and heat radiation between them. In order to facilitate engineering calculation, the heat radiation process is transferred and regarded as an equivalent heat convection process. Correspondingly, the radiative heat transfer coefficient is converted into a form of convective heat transfer coefficient.

Physically, the PCB (printed circuit board) consists of several internal electric layers, substrates and two outside copper foil layers. The PCB is then integrated with BGA, chip components and various ceramic, plastic or metal packaging during the reflow soldering. In this modeling, the PCB with complex structure and multiple material properties is simplified to three layers of structure where the internal electric layers are ignored and only the substrate layers remain with an isotropic material property. Meanwhile, all the chip components and some packages with relative low heat capacity is not considered in the FE model for the temperature simulation. The overall size of PCB is 160mm×100mm×1.63mm see in Fig. 1(a). The PCB substrate size is 160mm×100mm×1.47mm with a fr-4 materials property. The outside copper foil size is 160mm×100mm×0.08mm. Some material properties of the copper pad and FR4 are listed in Table 1 and Table 2 Other attributes of the materials can be found in [6]. The commercial ANSYS code is used to establish the finite element model of PCBA. The whole finite element model consists of 33658 nodes and 4548 elements as shown in Fig. 1(b).

| T /°C | 20 | 80 | 120 | 160 | 200 | 225 | 240 |
|-------|----|----|-----|-----|-----|-----|-----|
| \( K/(W \cdot m^{-1} \cdot C^{-1}) \) | 521.5 | 532 | 539 | 546 | 553.3 | 557.7 | 560 |
| \( c_p / (J \cdot kg^{-1} \cdot C^{-1}) \) | 356.8 | 375.5 | 388 | 400.4 | 412.8 | 420.6 | 425.3 |

Table 1 The thermal conductivity (K) and specific heat (cp) of copper foil at different temperatures

| T /°C | 20 | 70 | 120 | 240 | 250 |
|-------|----|----|-----|-----|-----|
| \( c_p / (J \cdot kg^{-1} \cdot C^{-1}) \) | 1200 | 1380 | 1500 | 1650 | 1600 |

Table 2 The specific heat (cp) of FR-4 substrate at different temperatures
2.2 boundary condition loading
In this paper, the reflow soldering furnace with infrared forced hot air heating mode is selected. The reflow soldering furnace of Heller is named by 1809 EXL. During the reflow soldering process, the Heller 1809 EXL reflow furnace is divided into 12 temperature zones, and the setup temperature and length of each temperature zone are shown in Table 3. The conveyor belt speed is 80 cm/min. The transient time-varying thermal load (convective heat transfer coefficient \( h \), hot air temperature \( T \)) is loaded on the surface of PCBA finite element model.

| temperature zone | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| \( T \) (°C)     | 125| 150| 160| 170| 175| 175| 200| 240| 227| 180| 150| 140|
| \( L \) (mm)     | 360| 257| 267| 250| 250| 295| 315| 270| 240| 110| 310| 310|

2.3 solution results and post-processing
During reflow soldering, the temperature field distribution of PCBA components at different time, such as 66s, 176s, 242s and in different temperature zones of reflow soldering is shown in Fig. 2 and the temperature profile of solder paste is shown in Fig.3. It can be seen that the maximum temperature of the PCBA component is lower than 245°C, which ensures the reliability of the PCB. The maximum temperature of the Sn63Pb37 solder paste is less than 225°C, which ensures that the solder joint temperature is not too high.

![Fig.2. Temperature field distribution of PCBA components](image)

![Fig.3. Solder paste temperature profile](image)

This paper mainly studies the output of temperature profile in the reflow zone of solder paste. The theoretical basis of data output is the concept of heating factor. Heating factor is defined as the integral of the measured temperature over the dwell time above liquidus (183°C) in the reflow profile[8]. Researches reveal that the heating factor is directly related to thickness of the intermetallic compound (IMC) then thus influences the reliability of the solder joints of PCBA.

The numerical simulation results show that the value of heating factor is: \( Q_{\eta_{max}}=928.69°C \), \( Q_{\eta_{min}}=803.23°C \); The value of heating factor is between 630s°C-1800s°C; the value of super liquidus: \( \Delta T_{max}=82S \), \( \Delta T_{min}=78S \), and the time of super liquidus is between 60-90s, which conforms to the range of Sn63Pb37 characteristics. The simulation results are effective.
3. Influencing factors and laws of temperature field

3.1 experimental design
Taking the temperature $T$ of each temperature zone, the convective heat transfer coefficient $h$ of each temperature zone, and the conveyor speed $v$ as input parameters, the heating factor value, the super liquidus time and the peak temperature of the reflow zone are numerically simulated as output parameters; The parameterized modeling of temperature field is realized. Using the DOE module, the Latin hypercube sampling method is adopted, and 150 experimental designs are carried out[9]. so that the whole experimental design points are evenly distributed in the space.

3.2 response surface fitting
According to the generated experimental design points, the Kriging response surface is fitted by least squares method[10]. Fig. 4 shows the response of conveyor belt speed and reflow zone temperature to peak temperature. The relative error method is used to test the fitness. All the fitting accuracy is above 0.95. The comparison between the target predicted value and the observed value is shown in Fig.5.

![Fig. 4. Response of process parameters to peak temperature](image)

![Fig. 5. Comparison of predicted and observed values](image)

3.3 local sensitivity
In this paper, the temperature of the reflow soldering furnace temperature, convective heat transfer coefficient and conveyor speed and other factors are taken as input variables, and the heating factor, super liquidus time and peak temperature are taken as output parameters. The orthogonal experimental design is used to fit the response surface. The response surface is obtained. The relationship between the single input parameter and the output parameter can be observed through the response surface. The influence degree and influence law of the three main process parameters of the reflow oven on the key indexes of the recirculation zone temperature profile are qualitatively analyzed. Fig.6 is the local sensitivity diagram of input parameters to output parameters.
Fig. 6. Local sensitivity of input parameters to output parameters.

It can be seen from Fig. 6 that the factors that have a great influence on the reliability of solder joints ($Q_\eta$) are successively the setting temperature $T_9$ and $T_8$ of the soldering area, the temperature setting $T_6$ of the heat preservation area, the belt speed $s$ of the conveyor belt, and the temperature setting $T_{10}$ of the cooling area; the factors that have a great influence on the peak temperature $T_{\text{max}}$ of the return area are the setting temperature $T_9$ and $T_8$ of the soldering area, the belt speed $s$ of the conveyor belt, and the temperature setting $T_6$ of the heat preservation area; and the super liquid phase time line $\Delta T$ are belt speed $s$, temperature setting $T_{10}$ in cooling area, temperature setting $T_6$ in heat preservation area and temperature setting $T_9$ in soldering area;

From Fig. 6, it can be concluded that the belt speed has a negative correlation with the reflow temperature field. When the belt speed is at low speed, the value of heating factor is larger, and with the increase of belt speed, the value of heating factor decreases. Qualitative analysis of the reason: the belt speed is fast, resulting in a short liquidus time, which affects the heating factor reduction; the belt speed is slow, the super liquidus time increases, and the heating factor increases. And the influence of the convective heat transfer coefficient on the reflow soldering temperature field is positively correlated. When the convective heat transfer coefficient is small, the value of the heating factor is small, and vice versa. Qualitative analysis of the reason: the convective heat transfer coefficient affects the convective heat transfer, and the heat transfer increases the temperature, resulting in a larger heating factor. The effect of reflow zone temperature on reflow temperature field is positive correlation. When the temperature is lower, the value of heating factor is smaller, and vice versa. Qualitative analysis of the cause: the heating factor $Q_\eta$ is the area of the profile on the liquidus. It can be simplified as a triangle. The bottom is $\Delta t = t_2-t_1$, and the height is $\Delta t = T_{\text{max}}-T_m$, which is related to the maximum temperature. Therefore, the higher the temperature is, the greater the value of the heating factor will be.

4. Conclusions

Based on the theoretical analysis of the influence of the main process parameters of the reflow oven on the key parameters of the reflow zone temperature profile, the actual PCBA reflow soldering temperature field simulation was carried out, and the DOE test design was used to analyze the experimental results. The optimal level, excellent combination and main order of each factor under the multi-parameter comprehensive action are obtained, and the factors and laws that have the greatest influence on the key indicators of the reflow zone temperature profile are determined.

1) The factors that have a great influence on the reliability of the solder joint are the set temperature $T_9$ and $T_8$ of the reflow zone, the temperature setting $T_6$ of the heat preservation zone, the belt speed $S$ of the conveyor belt and the temperature setting $T_{10}$ of the cooling zone;

2) The factors that have a greater influence on the peak temperature $T_{\text{max}}$ of the recirculation zone are the set temperatures $T_9$ and $T_8$ of the reflow zone, the belt speed $S$ of the conveyor belt, and the temperature setting $T_6$ of the heat preservation zone;
3) The factors that have a greater influence on the super liquidus time $\Delta t$ are the conveyor belt speed $S$, the temperature of the cooling zone $T_{10}$, the temperature setting of the heat preservation zone $T_6$ and the set temperature $T_9$ of the reflow zone;

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References
[1] Manko, HowardH. Solders and Soldering Materials, design, production, and analysis for reliable bonding[M]. (McGraw-Hill, 1964).
[2] Yubing G. Study on Optimization of Furnace Temperature Profile Under Reflow Soldering[J]. Hot Working Technology, 2013, 45(15):187-190. [In Chinese]
[3] Gang F Z , Wen Y D , He Z Y . Effect of parameters of reflow oven on the Reflow Profile[J]. Electronics Process Technology, 2004 (06):243-246+251. [In Chinese]
[4] Balázs Illés. Measuring heat transfer coefficient in convection reflow ovens[J]. Measurement, 2010, 43(9):1134-1141.
[5] Balázs Illés, István Bakó. Numerical study of the gas flow velocity space in convection reflow oven[J]. International Journal of Heat and Mass Transfer, 2014, 70:185-191.
[6] Piotr Breitkopf, Hakim Naceur, Alain Rassineux, Pierre Villon. Moving least squares response surface approximation: Formulation and metal forming applications[J]. Computers and Structures, 2004, 83(17):1411-1428.
[7] Sun Z L , Guo Y , Pan E S , et al. Reflow Soldering Process Virtual Test Based on BPNN-GA and ANSYS[J]. Applied Mechanics and Materials, 2013, 281:417-421.
[8] Tu P L , Chan Y C , Lai J K L . Effect of intermetallic compounds on vibration fatigue of μBGA solder joint[J]. IEEE Tran on Adv Pack, 2001, 24(2):197-205.
[9] Bing-Yuan H, Gui-Zhen S , Tong-Ling Z . Mathematics Model of Reflow Soldering Temperature Field in SMT[J]. Electronics Process Technology, 2005 (06):26-28. [In Chinese]
[10] S.M. Yang, W. Q. Tao. Heat Transfer[M]. (Higher Education Press, China, 1998). [In Chinese]