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MEASUREMENT TECHNIQUES OF CONVECTION REFLOW OVENS AND THERMAL MODELING OF THE REFLOW SOLDERING

PHD THESIS

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Motivations and aims of the research

Usually a soldering technology is applied during the production of electronics circuits. Nowadays, this technology is manly the reflow soldering due to the strong evolution of the surface mount technology (SMT). The reflow soldering process is applied to enable the attachment of surface mount devices (SMDs) to printed wiring boards (PWBs). The preparatory steps of the process are the solder paste printing to the contact surfaces (pads) of the PWB, and the component placement onto the solder paste deposit. The reflow oven then heats the entire assembly to a temperature beyond the melting point (reflow temperature) of the solder alloy. This allows the melting of the individual solder particles in the paste into a single volume which can wet the soldering surfaces and form the solder joints.

The development of the SMT has brought the widening of the assortment of the surface mounted devices (SMD). Nowadays, not only the small chip components but lots of big power components are also assembled by reflow soldering technology. In addition in the past few years the soldering devices have been also developed. The infrared reflow ovens have been changed to pure convection ovens in which the temperature distribution can be accurately controlled. After 1st of July in 2006 the lead-free solders with the higher melting point and their new aide materials are also caused problems. Due to these effects, in the case of the new type SMD components the formerly eliminated soldering failures are occurred again such as skewing the component during the soldering or the “tomb stone” effect. The tomb stone effect means that one of the contact surfaces is lifted form the PWB. Formerly this type of failure was typical only in the case of chip components. Most of the component displacements are caused by the wrong component topology. The modification of this is very expensive in the production phase. Therefore in the case of this type of failures, the failure analysis by modeling is one of the most important steps during the development of the circuits.

According to the literature I have recognized that the soldering technologies and devices applied in the mass production pass the level of the currently existed modeling and measuring methods. My conclusions are the followings:

- Most of the reflow models deal with the infrared and the mixed heated (means infrared heating with air mixing in the oven) reflow ovens. We can find some significant works between these, however these models are outworn due to the autarchy of the convection reflow ovens. Therefore the former reflow models can be used with limitations or not at all. Up this day only some works has been published in the issue of the pure convection reflow ovens.

- From the component-level thermal models only some models investigate the soldering process and only some of these deals with convection heating. Most of them study the thermal effects of the electronics components (mainly in power ICs) during the operation. The main issues are the heat dissipation and the cooling. Usually these models are unsuitable for the simulation of the soldering process.

- In the case of the reflow models I have observed the largest defect in the field of the determination of the model parameters. I have found only in the 15% of the studied work any kind of ambition to determine or at least to attune the necessary parameters (ex. heater temperature, emission rate, heat transfer coefficient,…) to the given soldering environment. Usually the authors use estimated data form the literature or apply each others results according to false analogies between the examined reflow ovens or circuits. This phenomena has not caused such a big problem during the modeling of infrared or mixed heated reflow ovens, because we have had a lot of information form the parameters of the infrared heating. However the problem is more serious in the case of the convection reflow ovens because we have much less experiences about the parameters of the convection heating.

Consequently the former reflow models and measurement methods can be used with limitations or not at all. Therefore it is especially current to search and develop new modeling methods for failure analysis and new measurement methods for convection reflow ovens. According to these I have chosen the followings to the main issues of my work:

- Investigate the operation of the convection reflow ovens and study the thermal and gas flow effects in the oven.

- Invent measurement methods for convection reflow ovens which can determine the heating parameters of the oven (heater temperature and heat transfer coefficient) and characterize these parameters not only with average values but with distribution.

- Build three dimensional component-level thermal models to study, simulate and presage soldering failures of the convection reflow soldering process.

Applied observation techniques

For the suitable investigation of a reflow soldering failure we need the exact knowledge of the thermal and gas flow processes which happen in the applied reflow oven and we need to know the physical parameters of these processes. Therefore the mile stones of my work were the followings: at the beginning of my research I have had to learn and understand the operation of the convection reflow ovens; then I have invented new measurement methods which can determine the thermal parameters of the ovens and after it I have created new modeling methods to study the soldering failures effectively.

The first aim of my work was to do a measurement method for convection reflow ovens which can determine the heat transfer coefficient of the blow in vertical gas streams in the finest resolution as it is possible under production circumstances. The vertical heater gas streams from the nozzle-matrix can consider to be vertical only until a given distance above the board, form this distance the streams reach an transaction phase and join into a continuous radial flow layer above the board. This radial flow layer affects also significantly to the formation of the thermal profile in the oven, so it is also important to determine the heat transfer coefficient in the radial flow layer. Moreover most reflow ovens are designed to use double conveyor lines, although in many cases the manufacturers use only one of these conveyor lines which is located in an asymmetric position to the walls of the oven. One of the basic questions was during my research how the asymmetrical conveyer position affects on the formation of the radial flow layer and on the heating ability of the oven.

The measured parameters of the reflow ovens are very useful for the calibration and the monitoring of the oven, but they are also necessary for the modeling of thermal processes in the oven. As I mentioned, up to this day there are only a few thermal models which deal with convection reflow ovens in the level of discrete components. Therefore during my Ph.D work the last step was to create new modeling methods which simulate reflow soldering failures under convection environment with the application of my previously measured oven parameters.

In the following section I present my achieved results in the filed of the convection reflow soldering and I also present the application possibilities of my results.

New scientific results

Thesis Group I.

Thesis I/1.: I have invented new measurement method for convection reflow ovens which apply nozzle-matrix blower system. These can determine the distribution of the heat transfer coefficient in the case of the vertical gas streams form the nozzle-matrix in function of the height above the board.

The basic of the method is that I measure the temperate changes under the nozzle-lines in front of the nozzles and at different measuring height. I have developed a calculation method which can determine the heat transfer coefficient and the heater temperature of the gas by the temperature–time curves of the oven and by the heat equation of the measuring probe. The heat transfer coefficient is a constant in the Newton equation which calculates the convection heat flow rate. With the application of my measuring adjustment and my data processing method I have achieved that the necessary measurement steps (in the case of the whole oven measuring) can be reduced to quarter of the data register limit.

Thesis I/2.: With my measurement method (presented in Thesis I/1.) I have proven that in the case of convection reflow ovens applied nozzle-matrix blower system the heat transfer coefficients of the vertical gas streams depend on the height above board. With measurements I have created the typical characteristics of the heat transfer coefficient in the case of the vertical gas streams in function of the height above the board.

The heat transfer coefficient can be considered to be constant from the entrance of the gas streams until to *H/2.5* height; then from *H/2.5* to *H/12* the decline starts and follows a linear shape with 2.9–3.9 $W/m^2K/mm$ gradient, then at H*/12* height there is a cut-off point and the gradient of the decline grows. In a convection reflow oven applied nozzle-matrix blower system it is enough to determine a basic heat transfer coefficient value (α_0) at H/60 height and the other values of the given nozzle-line can be calculated according to my characteristics.

Related publications with Thesis Group I: L1, R1, R2

Thesis Group II.

Thesis II/1.: I have invented new measurement methods for convection reflow ovens which apply nozzle-matrix blower system. These can determine the direction characteristics of the heat transfer coefficient in the case of the radial flow layer on the board in function of the height above the board.

The basic of my method is that I put a measuring gate into the radial flow layer. The measuring gate contains probes at different height and they are positioned in front of flow direction. The front and the rear end of the gate were opened so the radial flow could pass through it, but the roof of the gate protected the probes from the disturbing effect of the entering vertical gas streams. Twelve measuring locations were chosen, each equally located around a circle whose centre aligned with the centre of the test board. The circle had a radius of 30mm. The heat transfer coefficient of the radial flow layer can be calculated from the heat equation of the probes and the measured temperature–time curves.

Thesis II/2.: With my measurement method (presented in Thesis II/1.) I have showed that the construction of the oven affects on the heat transfer coefficients of the radial flow layers. The values were much larger (80–120%) towards the entrance and the exit of the zones than towards the walls of the oven. I have also proven that the asymmetrical position of the conveyor line in the oven affects on the formation of the radial flow layer, this causes 40% difference between the heat transfer coefficients towards the opposite walls of the oven.

Thesis II/3.: With my measurement method (presented in Thesis II/1.) I have proven that in the case of convection reflow ovens applied nozzle-matrix blower system the heat transfer coefficients of the radial flow layer depend on the height above board. With measurements I have created the typical characteristics of the heat transfer coefficient in the case of the radial flow layer in function of the height above the board. I have checked the measured results by an analytical modol.

According to the typical characteristics, from H/2 to H/12 height the rate of growth increases and at H/12 height the heat transfer coefficient reaches the 160% of the base value (α_0 at H/2). From H/12 to H/60 height the heat transfer coefficient decreases substantially and it reaches the α_0 value. With these results it is enough to measure the α_0 value at a given measuring location and the characteristics of the heat transfer coefficient can be determined. So the direction characteristics of α can be defined with a few measurement steps.

Related publications with Thesis Group II: L2, L3, K1, K2, K3

Thesis Group III.

Thesis III/1.*:* I have made a three dimensional component-level thermal model to investigate the displacement of the components during the reflow soldering process such as skewing.

One of the root causes of displacement is the temperature deviation between the contact surfaces of the components. Therefore, my model calculates the temperature distribution at the level of discrete components. The ability of the model was tested by the examination of a real soldering failure, which was the modeling of a TO-263 component skewing.

According to my results, if 20–30% deviations of the heat transfer coefficients exist between the opposite lateral faces of the component then more than 0.2s time difference can be between the melting time of the solder on the opposite contact surfaces and it can cause the skewing of the component .

I have achieved with my cell partition method (AID – adaptive interpolation and decimation) that the resolution and the accuracy of the model is increased in the investigated areas without increasing the model complexity. With the collective application of the thermal cell method, the AID cell partition and the FDM (Finite Difference Method) calculation method I have achieved that the calculation time of my model is very short compared with the similar FEM (Finite Element Method) models.

Thesis III/2.*:* I have done a new modeling method based on the Dijsktra algorithm to study the heat conduction ability of inhomogeneous material structures. I have presented how the graph theory can be used in the field of thermal study. From a thermal cell model my algorithm builds a directed graph where the thermal nodes are the vertices and the edges are weighted with the time coefficients of the given cell. The graph describes the conduction parameters of the investigated structure therefore the conduction parameters can be studied by graph theory.

The basic of my method is that the heat conduction ability of the different materials can be described with the multiplied value of their heat capacity and conduction resistance as a time coefficient. With the Dysktra algorithm the shortest “conduction paths” between different parts of the component can be find. With this the following effects can be studied during the soldering process: from which points and which paths can the most effective heating of a chosen contact surface be achieved; the differences between the shortest conduction paths; the effect of heat distraction. With application of the AID cell partition method (presented in Thesis III/1.) I have achieved that the step number of the path searching was ~*N/3* instead of N^2 in the function of the cell number (*N*).

Related publications with Thesis Group III: L4, R3, R4, K4

The application of my results

In my Ph.D dissertation I have illustrated the application of my results with several examples. In this section I will summarize these.

The measurement method presented in thesis I/1. is able to determine the necessary parameters of the convection reflow oven for thermal modeling but it is also able to use for the monitoring of the oven operation. We can investigate the effect of the deteriorated parts and the flux residues on the heat transfer coefficient distribution of the vertical gas streams. With the reduction of the measurement steps and with the determination of the typical characteristics function (presented in thesis I/2.) I have achieved that my measurement method can be applied under production circumstances. This condition is indispensable in the electronics industry.

The measurement method (presented in thesis II/1.) and the results of the characteristics measurements (presented in II/3.) are also important about the determination of the oven parameters for reflow process modeling. In addition they are able to examine how the asymmetrical positioned conveyor line affects on the heating ability of the reflow oven. According to my results in thesis II/2., the construction of the reflow oven can cause that the transported convection heat is spatial. This effect together with a wrong component arrangement can cause soldering failures. But, armed with the ability of our oven, effective thermal simulations and failure predictions as well as heating and layout optimizations can be effectively undertaken. Therefore my method is a useful tool for electronics production.

The measurement approaches presented in thesis I/1. and I/2 (after minor development) can be also applicable for optimization of other heater systems applying forced convection heating.

Although in Ph.D dissertation I have only showed results from one investigation of a TO-263 package displacement, but my model (presented in these II/1.) is able to predict most kinds of displacement and movement of SMDs during reflow soldering if they are caused by inhomogeneous thermal properties of the components and/or inhomogeneous convection efficiency. . In addition, my modeling approach is also applicable for simulation and optimization in other thermal processes. For example, where the inhomogeneous convection heating or conduction properties can cause problems, such as the preheating system of wave and selective soldering machines, high temperature surface cleaning and dye-drying process.

The main advantage of my modeling method (presented in thesis III/2) is that we can compare the conduction ability of inhomogeneous material structures easily and fast. These results can be used effectively during the design of circuits or during the design of the components also. Nowadays the optimization of the component assembling ability is becoming more and more important. In addition my modeling method can be useful in other technologies where the heat conduction plays important role, like the optimization of the power circuits cooling.

Related publications with my theses

Reviewed journal articles:

L1. **B. Illés**, G. Harsányi: 3D Mapping of Forced Convection Efficiency in Reflow Ovens, Periodica Polytechnica Electrical Engineering (2009) xxx-xxx. (megjelenés alatt)

L2. **B. Illés**, G. Harsányi: Heating Characteristics of Convection Reflow Ovens, Applied Thermal Engineering 29 (2009) 2166–2171

L3. **B. Illés**, G. Harsányi, Investigating Direction Characteristics of the Heat Transfer Coefficient in Forced Convection Reflow Oven, Experimental Thermal and Fluid Science 33 (2009) 642–650

L4. **B. Illés**, G. Harsányi, 3D Thermal Model to Investigate Component Displacement Phenomenon during Reflow Soldering, Microelectronics Reliability 48 (2008) 1062–1068

Referred conference papers:

R1. **B. Illés**, O. Krammer, G. Harsányi, Zs. Illyefalvi-Vitéz, A. Szabó: 3D Investigation of Internal Convection Coefficient and Homogeneity in Reflow Ovens, Proceedings of 30^{th} ISSE, Cluj-Napoca, (2007) 320–325

R2. **B. Illés**, O. Krammer, G. Harsányi, Zs. Illyefalvi-Vitéz**,** Modelling Heat Transfer Efficiency in Forced Convection Reflow Ovens, Proceedings of 29^{th} ISSE, St. Marienthal, (2006) 80-85

R3. **B. Illés**, G. Harsányi, Investigate Heat Conduction Ability of Power Components with Dijsktra Algorithm, Proceedings of 31^{th} ISSE, Budapest, (2008) 426-431

R4. **B. Illés**, O. Krammer, G. Harsányi, Zs. Illyefalvi-Vitéz, A. Szabó: Effect of Component-Level Heat Conduction on Reflow Soldering Failures, Proceedings of 1^{th} ESTC, Dresden, (2006) 1386–1392

Not referred conference papers:

K1. **B. Illés,** Direction Characteristics of the Heat Transfer Coefficient in Convection Reflow Oven Part I: Parameters and Gas Flow Model, Proceedings of 14^{th} SIITME, Brasov, (2008) 60–64.

K2. **B. Illés**, Direction Characteristics of the Heat Transfer Coefficient in Convection Reflow Oven – Part II: Measurements and Discussion, Proceedings of 14^{th} SIITME, Brasov, (2008) 65–69.

K3. **B. Illés**, O. Krammer, Variation of Gas Flow Parameters in Forced Convection Reflow Oven, Proceedings of 13^{th} SIITME, Baia Mare, (2007) 27–31.

K4. **B. Illés**, O. Krammer, G. Harsányi, Zs. Illyefalvi-Vitéz, and A. Szabó: 3D Thermodynamics Analysis Applied for Reflow Soldering Failure Prediction, Proceedings of 4^{th} EMPS, Terme Catez, (2006) 217–222

Not related publications

Referred conference papers:

R5. O. Krammer, B. Sinkovics, **B. Illés**, Studying the Dynamic Behaviour of Chip Components during Reflow Soldering, Proceedings of 30^{th} ISSE, Cluj-Napoca, (2007) 18–23

R6. O. Krammer, B. Sinkovics, **B. Illés,** Predicting Component Self-Alignment in Lead-Free Reflow Soldering Technology by Virtue of Force Model, Proceedings of 1^{th} ESTC, Dresden, (2006) 617–623

R7. O. Krammer, **B. Illés,** Lead-Free Soldering Technology Review – Evaluating Solder Pastes and Stencils, Proceedings of 29^{th} ISSE, St. Marienthal, (2006) 86–91

R8. M. Janóczki, **B. Illés**, Cost Effective Design for Six Sigma in Component Placement, Proceedings of 29th ISSE, St. Marienthal, (2006) 441–446

R9. L. Tersztyánszky, **B. Illés**, Incompatibility Problems in Soldering Technology, Proceedings of 28th ISSE, Wiener Neustadt, (2005) 90–96

R10. Zs. Illyefalvi-Vitéz, J. Pinkola, G. Harsányi, Cs. Dominkovics, **B. Illés**, L. Tersztyánszky, Present Status of Transition to Pb-free Soldering, Proceedings of 28th ISSE, Wiener Neustadt, (2005) 72–77

Not referred conference papers:

K5. O. Krammer, A. Nyakó, **B. Illés**, Measuring Methods of Solder Paste Hole Filling in Pin-in-Paste Technology, Proceedings of 13th SIITME,Baia Mare, (2007) 142–146

K6. O. Krammer, **B. Illés,** Comparative Study of Stencils for Advanced Lead-Free Reflow Soldering Technologies, Proceedings of 12th SIITME, Iasi, (2006) 58–62

K7. O. Krammer, **B. Illés**, Reflow Soldering Optimization in Lead-Free Environment – Immersion silver finishes are an alternative for Electroless Nickel Immersion Gold finishes, Proceedings of 11th SIITME, Cluj-Napoca, (2005) 85–89

Other publications:

E1. **Illés Balázs**: Különböző kontaktusfelület-bevonatok hatása az ólommentes kötések megbízhatóságára, ELEKTROnet (2006) (1) 64–65