FUNDAMENTALS OF BGA BALL ATTACH REFLOW PROCESS

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ABSTRACT
The fundamentals of reflowing solder balls for the BGA ball attach process is discussed. The content is divided into three major sections: modes of heat transfer, convection technologies used in reflow ovens and mechanics of temperature profiles.

There are three basic modes of heat transfer: conduction, convection and radiation. All three modes are utilized in achieving desired temperature profiles. For most of the reflow ovens in the industry, forced convection is the dominant mode of heat transfer. Understanding the modes of heat transfer assists process engineers in troubleshooting reflow applications.

In the reflow oven industry, there are two basic methods of achieving forced convection: fans and pressure sources. Typically, fans are used to achieve convection and recirculate process gas. Examples of pressure sources are compressors and nitrogen tanks. Benefits of both methods are discussed. In convection heat transfer, temperature and speed of the gas provide quantitatively different effect in heating the product. Adjusting the temperature difference between the process gas and the product is a more effective method of controlling heat transfer. In general, higher gas speed or volumetric flow rate improves the temperature uniformity across products.

There are four different elements in reflow profiling: preheat, dryout, reflow and cooling. Profiling is no longer a 'shoot in the dark' task. There is a definite procedure in performing temperature profiling. Understanding the relationship among heater set point temperatures, desired profile temperature, gas speed and conveyor speed, one can achieve desired temperature profiles with improved efficiency and accuracy.

Understanding and practicing the fundamentals of the reflow process for the BGA packaging can enhance the productivity and lower operational cost.

Key words: BGA, reflow oven, temperature profile, heat transfer

INTRODUCTION

In both the SMT [Surface Mount Technology] and BGA packaging industry, reflow ovens are often considered as 'black boxes'. Many process engineers use reflow ovens for many different applications without fully understanding the science behind the heat control technology. Especially in the semiconductor industry, many engineers are faced with using conveyorized ovens or furnaces for the first time. Others have used conveyorized ovens, but only to the extent of duplicating old processes or steps outline by their predecessors.

The paper's goals are to explain the principles behind the heat transfer in convection ovens and to outline the science of proper temperature profiling.

Many process and quality issues in BGA ball attach process can be improved by following the basic steps of ball attach reflow profiling.

MODES OF HEAT TRANSFER

There are three different modes of heat transfer in reflow ovens. They are conduction, convection and infrared radiation. In most of the convection ovens the predominant heat transfer method is convection, but other modes contribute in transferring heat to the product. For heat to be transferred there must be a temperature difference. In general, the greater the temperature difference, the higher the heat transfer rate. The heat always transfers from a body with higher temperature to one with lower temperature.

Conduction heat Transfer

Conduction heat transfer occurs when bodies of different temperature are in physical contact. The rate of heat transfer depends on thermal conductivity of the materials and geometric factors such as the thickness and contact area. In conduction, the most important factor in determining the heat transfer efficiency is the quality of surface contact. The surfaces must be in 'perfect' contact for efficient conduction heat transfer. In general, the conduction heat transfer equation is

$$Q = \frac{K A (T1 - T2)}{\Delta X}$$

where
Q = Conduction heat transfer [W]
A = Cross sectional area [cm^2]
K = Thermal conductivity [W/cm-°C]
T1 = Temperature at location 1 [°C]
T2 = Temperature at location 2[°C]
ΔX= Thickness between locations 1 and 2.

Another item to consider is the path of conduction. An effect called contriction reduces the quantity of the heat transferred via conduction because of the geometric factor. This can be seen easily on the FEA [Finite Element Analysis] result of the cooling fin analysis. If the conduction heat transfer path is very small the efficiency is decreased. As an example, to conduct heat away from a surface using thin cooling fins the constriction effect needs to be minimized by optimizing the fin shape, dimension, spacing and etc.

Convection heat transfer

In most reflow ovens, convection is the major heat transfer mode. In general, convection heat transfer occurs when a fluid contacts a body of different temperature. The important fact is that the fluid is in motion and makes contact with the body of different temperature. In all three modes of heat transfer, convection is the only mode where motion is essential. The rate of convection heat transfer depends on the convection coefficient, temperature difference and area. The general equation for convection heat transfer is

$$Q = h\,A\,(T_a - T_t)$$

where

Q = Convection heat transfer [W]

h = Convection coefficient [W/(cm^2 °C)]

T_a = Fluid temperature [°C]

T_t = Target temperature [°C].

In general, the higher the fluid speed, the higher the convection coefficient. There are two kinds of the convection: natural and forced. Natural convection occurs as the buoyancy of the fluid causes vertical movement because of the temperature difference. Forced convection is caused by some mechanical means such as fan blades or pressure forces which causes the fluid to move.

Infrared radiation heat transfer

Infrared radiation heat transfer occurs when any object is above –273 °C. [absolute zero]. Again, for any heat transfer to occur there must be a temperature difference. While conduction and convection modes of heat transfer are linear function of temperatures, the infrared radiation mode is exponential to the fourth power. This is why infrared [IR] heat transfer is so efficient in heat transfer. The general equation for IR heat transfer is

$$Q = F_v\,\varepsilon_s\,\alpha_t\,\sigma\,A\,[T_s^4 - T_t^4]$$

where

Q = Radiation heat transfer [W]

F_v = View factor

ε_s = Emissivity of the source

α_t = Absorptivity of the target

σ = Stefan-Boltzmann Constant (5.67 x 10^{-12} W/(cm^2 K^4)]

A = Cross sectional area [cm^2]

T_s = Temperature at source [K]

T_t = Temperature at target [K].

Because infrared radiation depends on the line of sight for heat transfer, the geometry of the objects plays a major role. In BGA ball attach process, the IR view factor is very high because of the direct line of sight between the heater panels and products.

In most convection reflow ovens used for BGA ball attach process, heat transfer via conduction is minimal compared to convection and IR. In all convection ovens, IR heat transfer contributes a high percentage to the overall heat transfer. As a rough estimate, the ratio between convection and IR is about 70 to 30. This fact can be explained fairly simply. If the set point temperature of the oven for a particular heating zone is at 250°C., the gas temperature and the heater panel with the array of holes are at around 250°C. In some convection oven designs, the heater panel can be at a higher temperature than the gas by design. The heater panel radiates IR at 250°C, but the IR energy is exponential to the fourth power of 250°C. In BGA ball attach process, the strips are flat and in direct line of sight with the heater panels contributing to very efficient IR heat transfer.

CONVECTION TECHNOLOGIES USED IN REFLOW OVENS

There are many different methods in achieving convection. For the scope of this paper, there are basically two different means: mechanical or utilizing pressure difference. The mechanical method is similar to using a regular household fan. The fan blades exert a mechanical force causing the gas to move or travel; it can be thought as 'hitting' the gas to move.

The pressure difference causes the gas to move because the gas wants to travel to a lower pressure area. The speed of the gas depends on the magnitude of the pressure difference. In convection ovens, the pressure difference is between the heater cavity or the heater box and the chamber. The chamber is defined as the volume where the products are heated during transport on a conveyor system.

Higher pressure in heater cavity is created by one of two methods. One method utilizes a fan to blow gas into the cavity thus creating pressure. The other method utilizes a pressurized source such as nitrogen tanks or compressors. Because the speed of gas depends on the force caused by pressure difference, increasing the pressure inside a heater cavity increases the gas speed as it comes out from the holes in the heater cavity. The pressure inside a heater cavity can be controlled by either modulating the RPM of a fan or a flow meter.

The benefits of using fans are lower cost of operation and the ability to move high volume of gas. The benefits of compressed source are easier control of the gas speed and maintenance of the atmospheric purity inside the oven. On ovens using fans to achieve convection, the pressure and volume of gas movement depends on the fan curves and the system curve. Both curves are not linear: the effect of gas speed is not linear to the RPM of the fan. On ovens using a compressed source, the pressure in heater cavities is controlled via flow meters. The relationship between the gas speed and flow meter setting is linear and thus provides better control of gas speed.

The two control variables in convection heat transfer are convection coefficient and fluid temperature. In convection ovens, the convection coefficient can be modified by either changing the RPM of fans or flow meters. In general, the convection coefficient is proportional to the gas speed. The fluid temperature can be modified by changing the set point temperature of a heater zone. Hence, in convection ovens the two control variables of convection heat transfer are settings of fans or flow meters and set point temperatures.

In most reflow ovens, changing the RPM of fans or the flow meter settings have negligible effect to convection heat transfer compared to the effect of changing heater set point temperature. For example, the effect of increasing the convection coefficient from 4 to 8 by increasing the speed of the gas is small compared to increasing the set point temperature from 220 to 260°C. In optimizing the ball attach process or programming the oven for a new product, it is simpler and more efficient if only the set point temperatures are modified. This is based on the assumption that the fans or the flow meters of the oven are already optimized during machine installation.

Temperature uniformity is defined as the temperature difference among products processed in multiple lanes. It describes the capability of an oven to heat products uniformly across the process width of the conveyor belt. Load factor in general is the percentage of process lanes occupied by product. For example, if 50% of the process lanes are occupied by product, the load factor is 50%. This is illustrated in Figure 1. Temperature repeatability is defined as the temperature difference among profiles performed at different time and load factors while the same oven program and product are used. The repeatability of the oven is a design feature. It is a thermal response characteristic of an oven at different load factors and time. Repeatability is the capability of the oven to provide the same temperature profile through out its use as long as the oven program and the product are not changed.

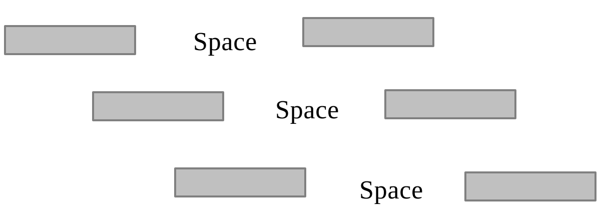

Figure 1. Example of 50% load factor. The length of space is equal to the length of the product.

The importance of temperature repeatability of reflow ovens cannot be stressed enough. It could be the difference in profiling once a week versus several times a day while manufacturing the same lot of product. Even though, repeatability is a design feature of an oven, process engineer must understand what conditions can change the temperature profiles at no fault of the oven. If any of the three variables in the reflow process is changed the profile will change. The steps outlined in this paper can assist process engineers to reduce unintended mistakes. Once the flow meters and fan settings are optimized for the ball attach process, it should not be changed unless there is a dramatic change in the product package type. This leaves the conveyor speed and oven set point temperatures as the only two variables. These two variables make a unique oven program, sometimes called a recipe.

MECHANICS OF TEMPERATURE PROFILES

Typically, a process engineer programs an oven to achieve a particular temperature profile recommended by the flux manufacturer. The basic components of a profile are preheat, dryout, reflow and cooling as illustrated in Figure 2.

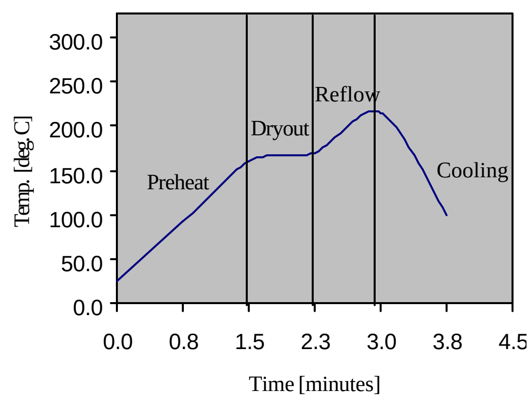

Figure 2. **Temperature Profile**

By understanding the different components of the profile, one can program a reflow oven in less time with greater accuracy.

There are three major steps in programming an oven:

1. Calculating the conveyor speed and oven set point temperatures.
2. Performing a temperature profile or measuring the actual temperature of the product
3. Making minor adjusts to the oven program and re-profiling.

Calculating the oven conveyor speed

The conveyor speed is calculated using the formula below:

$$\text{Conveyor Speed} = \frac{\text{Total Heated Length}}{\text{Profile Time}}$$

The Total Heated Length is provided by the oven manufacturer and the Profile Time is recommended by the flux provider. The profile time is defined as the total time the product takes to reach the peak temperature. It most cases this is between 2 and 3 minutes for BGA ball attach process. If the oven's total heated length is 48 inches and the profile time is 3 minutes:

$$\text{Conveyor Speed} = \frac{48 \text{ inches}}{3 \text{ min.}}$$

$$= 16 \text{ IPM } [0.41 \text{ m/min}]$$

Calculating Oven Set Point Temperatures

The next step in programming the oven is to set the individual heater zone temperatures. The layout and lengths of the heater zones in the oven are used to identify which heater zone is used for what purpose. For the sample profile in Figure 3, the first two vertical zones can be used as preheat. The third zone and the fourth zones can be used for dryout and reflow, respectively.

The resident time of the product in each zone is calculated as

$$\text{Resident time} = \frac{\text{Length of Zone}}{\text{Conveyor Speed}}$$

This equation calculates how long the product is resident in a particular zone. For example, if a zone is 12 inches [30cm] long and the conveyor speed is 16 IPM [0.41 m/min], the resident time is 0.75 minute or 45 seconds.

Z 1	Z 2	Z 3	Z 4	Cool
205	210	165	265	

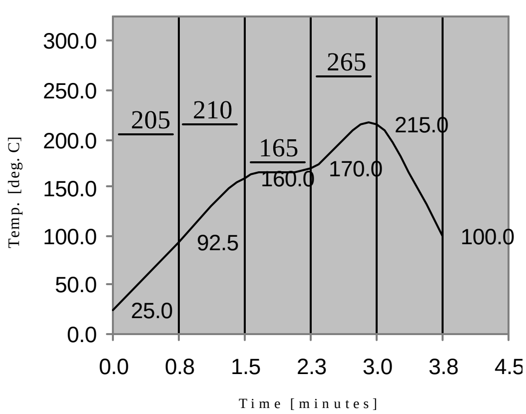

Figure 3. Sample temperature profile

Using this information, different components of the temperature profile can be matched to the heater zones of an oven. After finding out which zone controls which component of the profile, the next step is to calculate the temperatures.

One important item to keep in mind is that because the product travels through the oven, the temperature it reaches at each heater zone is not equal to the zone set point temperature. For example, when the oven set point for reflow zone is 275°C, the peak temperature might be only about 210°C.

Normally, engineers try an oven program from their experience and then profile to compare it to the desired profile shape. This is a 'guessing game'. By analyzing the science of temperature profiling, the task of profiling can be fine-tuned.

The Delta T between the oven set point temperature and measured temperature can be calculated from either previous profile data or can be obtained by profiling 3 times on a new oven. From these data, one can calculate a simple equation for each heater zone that can predict within a reasonable accuracy the set point temperature and final temperature of the product as it leaves each zone.

As an example, let's examine an oven with 4 vertical zones, total of 8 heating zones, with the following set point temperatures. For this example, each oven zone is 12 inches [30cm] long.

In Figure 3, both the zone set point and recorded temperatures are shown. The Delta T's between the zone set point and measured temperatures can be calculated. The Delta T for the reflow zone is calculated below:

$$\text{Delta T} = 265 - 215 = 50°\text{C}$$

By using another profile with a different conveyor speed, a linear equation as a function of conveyor speed can be formulated to predict the profile temperature of each zone.

For each zone, the Delta T's between the zone set and measured temperatures for two different profiles are

Profile #1: $TD1 = TS1 - TM1$
Profile #2: $TD2 = TS2 - TM2$

Where

TS = Set Temperature
TM = Measured Temperature from profile
TD = Temperature difference

Using a simple linear equation, $Y = MX + B$, where M is the slope and B is the Y-intercept, the data from two profiles are used to come up with an equation:

$$M = \frac{TD1 - TD2}{CS1 - CS2}$$

Where

CS = Conveyor Speed.

Hence the equation is

DeltaT = M [Conveyor Speed] + B.

Using this equation, we can calculate the approximate Delta T between the set and measured temperatures. From this value, one can predict the profile temperature from the oven set point temperature and vice versa:

Calculated Temperature = Oven set point T – DeltaT.

This is a very simple, yet effective way of calculating both the profile temperatures and oven set point temperatures. The accuracy can vary from less than 5°C to about 10°C depending on unique characteristics of ovens. With additional profile data points, the equation can be 'fine-tuned' further for greater accuracy.

Sample calculation

Let us review the process using a set of sample data for the reflow zone.

	Set Point	Peak T.	Conveyor Speed
Profile #1	255°C	210°C	14 IPM [0.35m/min]
Profile #2	270°C	214°C	16 IPM [0.41m/min]

Profile #1: TD1 = 255 – 210 = 45°C

Profile #2: TD2 = 270 – 214 = 56°C

$$M = \frac{56 - 45}{16 - 14} = 5.5$$

$$Y = 5.5\,X + B$$

Setting Y = 45 and X = 14, B is calculated as –32.

Hence the equation is

DeltaT = 5.5 [Conveyor Speed] - 32.

AT 16 IPM,

DeltaT = 5.5 (16) - 32 = 56 °C.

If the set point temperature is 265°C, then

Calculated profile peak temperature = 265 – 56 = 209°C.

As illustrated the only variables are the conveyor speed and the heater zone set point temperature. Because the conveyor speed is dictated by the oven length and the profile time requirement of the flux, the only control variable is the oven set point temperature. Following a method such as this can decrease the time it takes to profile and improve the quality of BGA ball attach process.

Performing a temperature profile

In order to obtain accurate temperature profiles, there are two items that process engineers need to practice caution.

The first item is attaching thermocouples to the sample. The goal is to measure the correct temperature for attaching the solder balls to the pads. The thermocouple must be securely fixed to the desired point on the substrate with a minimum amount of compound. If the volume of the fixing compound is too large, the temperature reading will be artificially lower. The reason is that a preformed solder ball is very small compared to the compound.

The most crucial point is that the thermocouple must be in contact with the pad on the substrate. On a conveyorized convection oven, the gas temperature is higher than the sample temperature during profiling. If the thermocouple is not contacting the pad on the substrate, the measured temperature tends to be higher. The same is true if the thermocouple is not securely fixed. The reason is that the thermocouple might be reading the temperature of the gas, fixing compound or combination of both.

The second caution is for the length of thermocouple wire between the sample and the measuring device. Many commercially available measuring devices or profilers are available for process engineers. They are transported through the oven along with the thermocoupled sample. Compared to a typical BGA strip, a profiler is many times the volume and hundreds times the weight. If the sample BGA strip and the profiler are in the same heating zone as they are transported inside the oven, the profiled temperature will be artificially higher. Because of its weight, a profiler takes away substantially more heat from the oven zones than BGA strips. As the heat is taken away from the zone, the oven compensates the heat loss by increasing the heater output following a PID algorithm. Almost all advanced convection ovens use a PID [Proportional Integral Derivative] method for controlling temperatures inside the oven. The effect is that the measured temperature from the sample could be artificially higher. A good rule of thumb is that the length of the thermocouple wire between the sample and the profiler must be longer than the longest heater zone in the oven. This method allows the profiler to be at least one zone downstream from the sample in the direction of travel and minimizes the interference effect.

After profiling, it is a good practice to critically analyze the profile data. Many profilers provide pre-analyzed data such as slopes of temperature rise and fall, dwell time at designated temperatures, and etc. If the profile is for a product already in production, it should match the previous profile(s) within the oven's repeatability specification.

SUMMARY AND CONCLUSION

In BGA ball attach reflow process, there are three process variables: gas speed, conveyor speed and oven set point temperatures. By eliminating two variables, the task of programming the oven and temperature profiling can be simplified. The gas speeds in heater zones are controlled by either the fan settings or flow meters. Optimizing the fans or flow meters during installation is recommended. The act of changing the gas speed to achieve a certain temperature profile is shown to be negligible compared to modifying the zone set point temperatures. The equation for calculating the conveyor speed is explained.

The 'guess work' of determining the zone set point temperatures can be eliminated by utilizing simple equations that can provide reasonable predictions. The method of formulating prediction equations as a function of conveyor speed is explained.

Items that affect the temperature profile data are explained. The location of the thermocouple junction on the sample, the amount of compound used in attaching the thermocouple, and the length between the sample and profiler can affect the temperature reading.

By understanding the principles of heat transfer inside convection ovens and following the science behind temperature profiling, process engineers can increase the efficiency of profiling and BGA ball attach reflow quality.

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