Section 3:
Reflow Profiling

What is a Temperature or Thermal Profile?

High quality, low defect soldering requires identifying the optimum temperature profile for reflowing the solder paste. Achieving SMT process consistency means repeating this profile over and over. Every solder joint on every board needs to be heated similarly if the desired soldering results are to be accomplished. From the solder's point of view, it does not matter what the heat source to the solder joint is.

What does matter is that the heat is applied to the solder joint in a controlled manner. The heating and cooling rise rates must be compatible with the solder paste and components. The amount of time that the assembly is exposed to certain temperatures must be defined and maintained. In other words, the solder reflow profile must first be defined and then maintained.

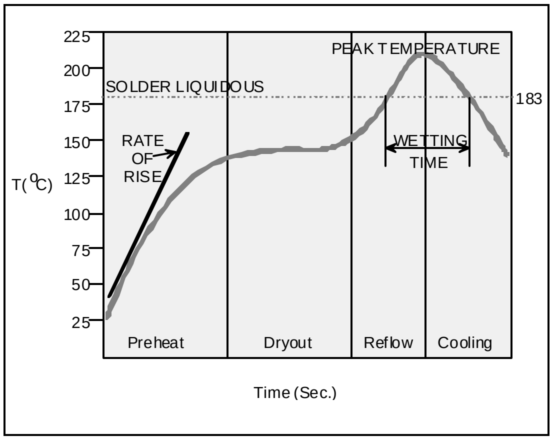


Figure 3-1. A typical thermal profile.

The Typical Profile

The reflow profile is defined by the relationship of temperature versus time during heating. A typical profile consists of three heating slopes (the time vs temperature relationship or rate of temperature rise) defined by Figure 3-1. This "three step" profiling approach has been commonly used since the early days of SMT.

Each solder paste defines the heating slopes and time and temperature limits within each slope. It is best to consult your solder paste supplier to determine the exact heating condition required for the paste you are using. For the purpose of discussion, we will use the traditional three step profile, which is typical of RMA pastes.

The three step heating profile slopes are called preheat, dryout, and reflow.

Preheat
In the preheat section, the goal is to fully preheat the entire SMT assembly to temperatures between 100°C and 150°C. The most critical parameter in the preheat section is to control the rate of rise to between 1-4°C/second.

The main concern is minimizing thermal shock on the components of the assembly. For example, multilayer ceramic chip capacitors can be vulnerable to cracking if heated too fast. In addition, rapid heating can cause the solder paste to spatter.

Dryout

The second heating section, referred to as the dryout, soak, or preflow zone, is used primarily to ensure that the solder paste is fully dried before hitting reflow temperatures. It is characterized by a consistent temperature (often between 150°C - 170°C) for an extensive (60-120 second) time period.

The dryout portion of the profile acts as a flux activation zone for RMA solder pastes. Dryout provides thermal stabilization of large and small components to ensure uniform heating as the SMT assembly enters the reflow zone. Convection ovens have reduced the need for the thermal stabilization, as the entire profile tends to be uniform (referred to as “Delta T” defined as the temperature difference between the warmest and coldest component lead on the board).

Reflow

The reflow section of the profile elevates the solder paste to a temperature greater than the its melting point. For Sn63/Pb37 eutectic solder, the melting temperature is 183°C. This temperature must be exceeded by approximately 20°C to ensure quality reflow for every solder joint lead.

The amount of time the solder joint is above the melting point is referred to as the wetting time or timeover. The wetting time is 30 to 60 seconds for most pastes. If the wetting time is excessive, intermetallic layer may form in the joint, which result in brittle solder joints.

Excessively slow cooldown while the paste is liquidous can also cause the solder joint to consist of a larger grain structure, resulting in a potentially weaker solder joint. Common cooling rates are controlled between 1-2°C/second. Many reflow ovens have water-cooled or refrigerated cooling sections so the timeover and cooling rates can be precisely controlled.

What are the Profile Control Limits?

The profile is not a simple line graph between time and temperature, but rather a band or process window as defined by upper and lower control limits. Heating within the limits will result in high quality solder joints providing all other aspects of the process are in control.

The size of the reflow profile band is defined by the range of temperature deviation (thermal tolerance) that can occur during while yielding high quality solder joints.

In Figure 3-2, the profile band size is indicated as 25°C. The actual limits of the band will vary depending upon solder paste, component type, and circuit board material.

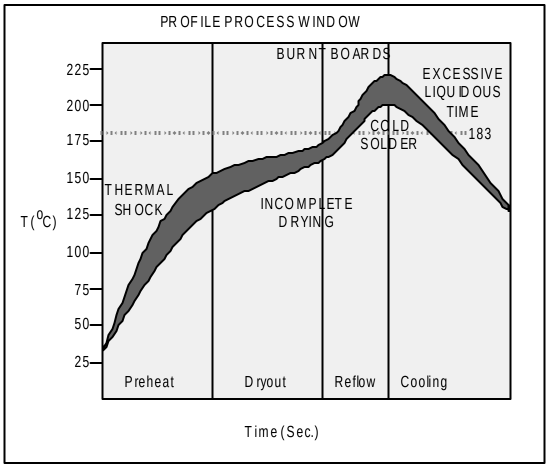


Figure 3-2. A graphical representation of a 25°C reflow profile process band.

It should be noted that the band width is defined by the temperature *and* time axis. If the product temperature profile is not maintained within the control limits, a defect will occur. Figure 3-3 indicates some of the production problems from improper profiling and possible causes.

One should note that these problems may also be caused by non-reflow processes as well.

Figure 3-3. Basic Solder Reflow Troubleshooting.

Problem	Possible Cause (Profile Related)
Cracked chip capacitors	Excessive rise rate in the preheat zone
Solder balls	Incomplete drying before reflow (dryout section too cool and too short a duration) Excessive drying temperature (fluxes skin over) Improper gas atmosphere (nitrogen versus air)
Cold solder joints	Insufficient time over reflow temperature
Solder not wetting to leads	Excessive drying time causing fluxes to deteriorate Excessive reflow temperature/time causing oxidation
Solder not wet on pad	Lead is heating faster than board (too much airflow)
Component/board burning	Excessive reflow temperature

Notes:

Defining the Profile Control Limits

The profile control limits need to be defined for the given SMT assembly. To define these limits, one should be aware of not only the solder paste requirements, but also any specific requirements of components or the circuit board material. The process band width is defined as the total deviation in temperature that can occur and yield reliable results.

To determine the profile control limits, thermocouples are attached to a sample board populated with components.

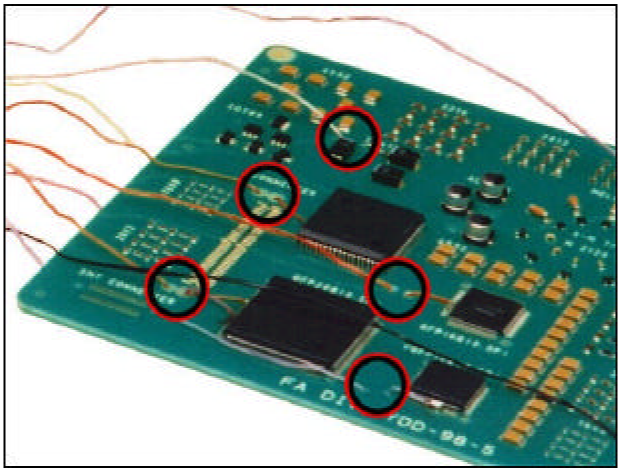
The Thermocouple Attachment Process

NOTE: This section contains information from KIC Application Note #00001, Rev: 98-05. The entire document is found at www.kicthemal.com.

It is strongly recommended to attach TCs with <u>high-temperature solder</u> for best results. An alloy like Indium #228 (88Pb/10Sn/2Ag) with a 267°C solidus temperature is a good solder for TC attachment.

TC Locations

TC location is usually determined by identifying critical or sensitive components and attaching the TC's to the appropriate pads. Additionally, it is best to place the TC's so that you receive temperature readings from the hottest and coldest points on the board. The measurements received from these three to twelve TC's (depending on the size of the board) will allow you to determine whether the thermal profile is consistent throughout the product, and also to measure the heating and cooling profiles of heat sensitive components. In placing your TC's, it is important to keep in mind that areas that are densely populated or have larger components will take longer to heat up and also will hold heat longer. It is also important to place TC's at the edges of the board and in any areas with small or non-existent components that will heat up faster than the rest of the board.



Thermocouple placement for determining profile control limits. (Photo courtesy of KIC Thermal Profiling.)

Surface Preparation

Thoroughly clean your selected TC locations, taking care to remove any residual low temperature solder and other contaminants that might prevent complete high temperature solder wetting.
Use alcohol or a suitable solvent to scrub the attachment surface. Then place the solder wick on the surface and press the soldering iron into the wick, heating both the wick and the surface to be cleaned. Use as much wick as necessary to remove all free flowing solder droplets. When solder has been completely removed, re-scrub the attachment surface to remove any remaining contaminants.

Attachment

Do not attempt to attach the TC by melting solder into the spot and then shoving in the bead. Place the TC bead on the attachment surface and heat both evenly, then touch the solder to the heated TC bead and let the heat from the TC bead melt the solder. This method gives you superior wetting and a stronger solder attachment to the pad or lead.

Your temperature reading will come from the first point of contact between the two wires leading from the TC. To insure accurate readings, it is critical to carefully separate the two wires all the way up to the TC bead after soldering.

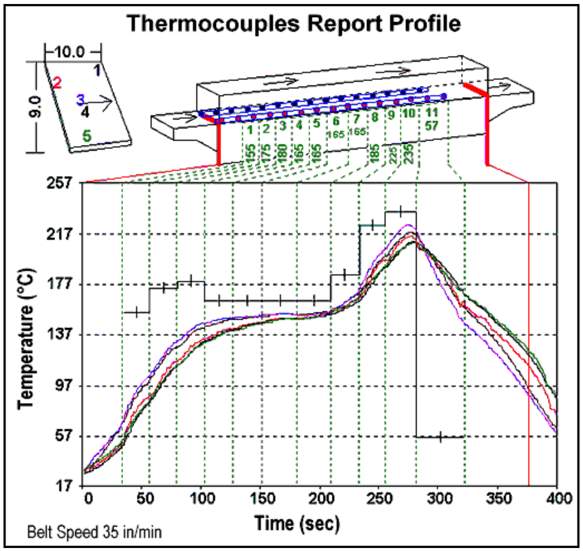
High temperature solder is an efficient heat conductor, so if a tiny bit gets between the TC bead and the lead or pad, you will still get an accurate reading. However, too much solder at the measurement point will increase the heat capacity of the TC and cause your peak temperature measurement to read low.

Oven Setup

Once the thermocouples are placed on the test board, the reflow oven is set up to create a three step thermal profile on the board. Common oven parameters that are adjusted to create the thermal profile are:

- Zone setpoint temperatures
- Conveyor speed
- Fan speed
- Refrigerated cooling rates (if applicable)

Profiling then becomes essentially an iterative process comparing the test board temperature results to the desired profile. If the results differ, oven parameters are adjusted and the test is rerun.



Each of the curved lines is the temperature as sensed by a thermocouple attached to a product as it passes through the oven. (Graph courtesy of KIC Thermal Profiling.)

How Does Oven Performance Relate to the Reflow Profile Control Band?

Once the three step profile is defined and the oven parameters are determined, the reflow oven must be able to produce consistent results within the reflow profile band. The user should be aware of all variables that influence the band. To achieve high quality, low defect soldering results, the sum of all the non-uniformities must fall within the defined reflow profile band. These variables may be defined as product related and oven related.

Product Related Variables

By far the most critical product related non-uniformity is that created by large mass differences on the product. Since it is easier to heat an area that has no components as compared with an area with large components, temperature differentials will exist on the product.

Oven Related Variables

Consistent thermal repeatability under product load (oven temperature changes due to mass variation) and edge-to-center and front-to-back product heating uniformity are the two most common factors that effect the reflow process.

The following sections describe these three main causes of non-uniform heating in the SMT reflow process: board mass differential (product related variables), conveyor and heater edge effects and product loading (oven related variables).

Mass Differential

The amount of temperature rise of a product as it travels through an oven heating zone depends upon a number of variables. The temperature rise of an object subjected to heat is determined by the following equation:

$$\Delta T = Q \times A \times t / (M \times C_p)$$

<u>WHERE:</u>

ΔT = Product Temperature Rise (°C)
Q = Heat Absorbed (W/cm^2)
A = Exposed Area (cm^2)
t = Heating Dwell Time (seconds)
M = Mass of Object (kg)
C_p = Specific Heat (W-sec/kg-°C)

The mass (M) times the specific heat (C_p) is often referred to as thermal mass. Greater thermal mass requires more heat to achieve a given temperature rise.

In Figure 3-4, the area populated with the PLCCs has considerably more thermal mass per unit area than the area with the discrete components.

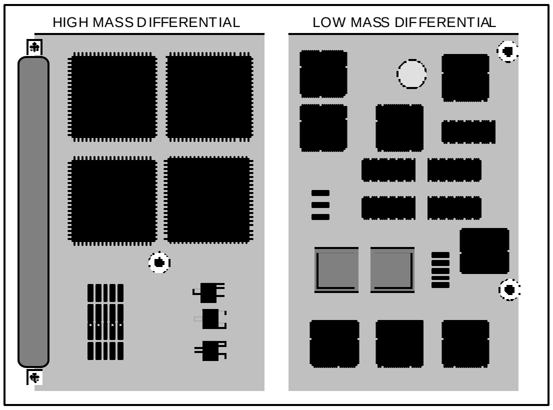


Figure 3-4. Comparison of high mass versus low mass differential boards.

The high mass area will be more difficult to heat. The non-uniformity caused by thermal mass differential may be measured by thermocoupling a lead on the largest and smallest device, and running a profile. (As described previously.)

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Oven Uniformity

A second main cause of non-uniform product heating is the oven heating pattern. This can be caused by edge effects on the heaters (less heat at the end) or by heat sinking of the conveyor system. The edge effect may be caused by insufficient airflow around the edges of the machine, or by non-uniformities that are inherent in the heaters.

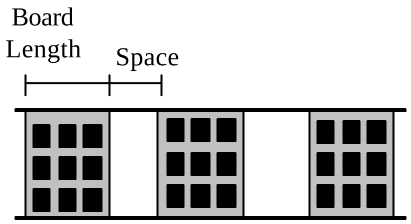
The heat sinking of the conveyor is really a mass effect, similar to the one described above. The oven uniformity may be measured by thermocoupling a bare board over a matrix of points, and running a profile. The matrix should include points on the board edges (front, back, left, and right), and the center of he board.

Oven Repeatability

Repeatability refers to the oven's capability to repeat a given profile. Repeatability is affected by machine loading (number of boards in the oven). Figure 3-5 shows a typical product loading condition. The loading factor is defined in the figure.

The higher the value of the loading factor, the more difficult it is for any oven to give repeatable results. Ovens will generally specify a maximum loading factor (ranging from 0.5 to 0.9).

The loading factor becomes an important consideration when sizing an oven. *(See Section 7 – Choosing Your Reflow Oven.)* The non-uniformity caused by repeatability can be measured by running a profile on a test board, then loading the oven down. Periodically, run the test board within the oven load and compare with the unloaded profile.



$$\text{Load Factor} = \frac{\text{Board Length}}{\text{Board Length + Space}}$$

Figure 3-5: Load factor calculation combines board length and the space between the boards.

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