There are over 60 companies worldwide that manufacture IR ovens with an increasing array of options. Although advancements and options are important, the bottom line remains how reliably the PCB assembly can be soldered. Most IR reflow systems, regardless of their mechanics, can handle many types of applications. The question becomes how to optimize the results with respect to the operating parameters. How efficiently, repeatably, safely and easily can a product be processed?

The heating of the PCB assembly must be a controlled process, able to accommodate components and materials. Although many factors governing the reflow soldering process are critical, the process itself is quite flexible. There are four sections of the reflow profile and these sections consist of: preheat, preflow, reflow and cooldown (Fig 1).

**Preheat**

When the PCB assembly enters the oven tunnel at ambient temperature, the heat transfer process begins and energy is gradually introduced to the assembly, reaching 100 to 125°C. IR reflow, whether radiant, convection or forced convection, is not an equilibrium heating process. PCB material, mass and surface area, as well as component mass and layout, will affect heat transfer to the PCB assembly. Some larger assemblies may require a soak portion, known as a plateau, which brings all portions of the PCB assembly within the same temperature range with as little transboard gradient as possible, making the profile a continual, gradual heating. The rate of rise is considered most critical here.

Several important solder-paste steps take place at this time. “Water white” and “tall oil” rosin will melt and solvent evaporation begins. Also, some of the activators that are contained in certain solder-paste fluxes will begin to reduce metal oxides.

**Preflow**

Observing an equal rate of heating, the assembly is heated from 100 to 125°C to between 150 and 170°C. During the soak plateau, the solder spheres in the paste begin melting. When the temperature is brought to just below full liquidous (eutectic), additional activators react and wetting begins. The processed rosin melts. As important as low gradients are, most solder paste manufacturers suggest limiting the 150 to 170°C soak plateau to less than 1 min.

**Reflow**

Assembly temperatures during reflow begin at 150 to 170°C and rise to peak temperature. Reflow takes place after PCB assembly temperatures are raised above the melting point of the solder. All solderable portions of the PCB assembly reach their desired peak temperature while internal and external components are kept within their specified thermal tolerances.

The portion of the profile above the melting point of the solder is called dwell at liquidous. Dwell at liquidous consists of the total amount of time any portion of the PCB assembly is above the melting point. Since these are the highest temperatures seen during the reflow cycle, the time spent in this section should be limited to reduce thermal damage. In almost all cases, the 4-sec minimum duration time to reflow solder at 200°C will be exceeded. This is the most critical part of the reflow cycle. Solder paste goes to a full liquidous state, completes melting and the flux reaches full activation.

The temperature at activation is the minimum temperature that solderable portions of the PCB assembly need to reach. This temperature, averaging around 200°C, should be specified by the solder-paste manufacturer. It typically falls between 195 and 220°C. This temperature differential across the PCB assembly is important. While heating all solderable portions of the board to the desired minimum temperature, other portions of the
The objective is to bring the PCB assembly through cooldown.

Cooldown

In the cooldown section, the assembly cools from the peak temperature through post liquidous. The PCB assembly begins to cool after it moves beyond the last emitter and the end of the heated tunnel. The bigger the assembly, the longer it will retain heat. Since the liquidous dwell time includes both sides of the profile peak, it will continue while any solderable portion of the PCB is above the melting point of solder. Cooling can be aided by fans, blowers, inert gas curtains, refrigeration or exposure to ambient air. The objective is to bring the PCB assembly to a temperature accommodating the processes to follow, such as cleaning or manual handling.

As the molten solder cools, the fillet forms. Considerable attention has been given to speeding up the cooling portion of the reflow cycle, in particular the portion from peak temperature through solidification. Besides reducing the overall dwell at liquidous, this would reduce grain size, thus improving the integrity of the solder joint. However, the same precautions used against thermal shock should be used throughout profile and cooling. The slope attained during cooling should not exceed 5°C/sec. However, this factor, like the heating rate, should be application driven.

System Variables

All IR reflow systems depend on two variables to get the proper transfer of heat to the PCB assembly: emitter temperature and conveyor speed. A profile can be derived from these two factors. In the majority of ovens, the conveyor speed is constant throughout the system, but the emitters are varied throughout the length of the tunnel.

Great emphasis has been placed on accuracy of temperature control and emitter response time. Most manufacturers specify control of emitter temperatures within ±1°C. While accuracy is important, unintentional fluctuations in conveyor speed can adversely affect soldering quality.

Other process variables of a peripheral nature may also be incorporated into a system. These include air blowers, conveyor rail heaters and edge heater emitters and must be factored into the profile for each application. Improvements gained through these extra variables must be weighed against added complexity in the profile procedure.

Placement in Thermocouples

When profiling, careful thought must be given to the placement of thermocouples (TCs) on the PCB assembly. Since interconnect temperatures are being measured, TCs should be applied to the lead-pad interconnection. A very small amount of conductive epoxy or high-temperature solder (SN 10/90) can be used to attach the TC to metal. Ordinarily, TCs should not be attached to the substrate surface, but representative TCs can be attached to a wide portion of the assembly, including components near the edges and the center of the board. If SOICs, PLCCs or other large-mass, high I/O devices are present, an appropriate interconnect should be sampled (especially one near the center of the assembly.)

In addition to the interconnects, the most vulnerable component (MVC) surface should also be probed on both sides of the PCB. Finally, with heat-sensitive, active components it may be beneficial to observe the internal die temperature cycle during reflow. Depending on the IR emitter and convection technology used, internal component temperatures may run anywhere from a few degrees cooler to over 20 degrees hotter than an interconnect temperature of the same component.

Gradient Across the PCB Assembly

The attainable bounds of temperature gradients are application specific. Accordingly, the tolerance allowed in this area should also be application specific as derived from the reflow specification. A reflow specification with a minimal temperature (full flux activation) of 200°C and a maximal temperature (MVC ceiling) of 225°C has a maximum gradient of 25°C. The smaller the thermal gradient, the smaller the margin and the lower the peak temperature necessary for total reflow.

Controlled Rate of Heating

The rate at which a PCB assembly undergoes heating in the reflow cycle is important. Too steep a slope in
heating could result in thermal shock of some components and cracking of ceramic capacitors. Several component manufacturers recommend limiting the rate of heating to less than 3°C/sec. Some users, however, regularly exceed 5°C/sec with no damage. It has been argued that the rate of heating is critical only for the first 150°C. While some capacitor cracking has been attributed to mechanical forces (such as centering jaws and excessive Z-axis down-force on the pick-and-place system), thermally induced cracking has been shown in soldering processes (mostly wave-soldering). If this is a concern, the 2°C/sec speed limit is usually easy to achieve in a well-controlled IR reflow system.

The Reflow Specification
Any facility using IR reflow should have a reflow specification. This specification mandates what temperatures the PCB assembly will be exposed to at the peak of the reflow cycle. The bottom limit is defined by the temperature at which the flux becomes fully activated. This is determined through consultation with the solder-paste manufacturer. Typically, this occurs between 195 and 210°C depending on the formulation. The application is performed by applying it to the side (or sides) of the assembly being soldered on the pass through the oven.

The higher temperature is derived from the MVC in the assembly. This is the component that has the lowest thermal threshold and is most likely to be damaged. The MVC might be an inserted component with a low melting point (such as an electrolytic capacitor), a plastic connector or switch or some other heat-sensitive part or material. The lowest common denominator within the assembly will determine the highest temperature that any part of the assembly can handle.

The reflow specification might state that at peak reflow, all solderable interconnections on the PCB assembly shall be no less than 205°C T1 and no portion of the assembly greater than 225°C T2. T1 is the full activation temperature of the flux of the solder paste being used, and T2 is the melting point minus a five-degree safety margin for the MVC.

Component Temperatures
Although the primary focus in profiling is on solderable surfaces and material temperature, all the components on the PCB assembly are exposed to temperature extremes. How much a particular component will be heated depends on factors such as the component's mass and metal content, the body material's absorptivity, and in some cases, the color of the body.

A study by a Japanese firm compared several ovens by measuring the gradient across the populated PCB and the surface temperatures of various components (a 100-pin PLCC, a 64-pin PLCC, an inserted metal-encased capacitor and a connector). Prior to the test, the oven supplier profiled the board for optimum performance (Table 1). This type of emitter/convection technique clearly made a difference.

Process engineers have compared the internal die temperature of components to the solder interconnect temperature. Recently, a PLCC-68 toward the center of a moderately populated PCB was tested. A 0.050-in. hole was drilled (from the top) into the body and a TC attached with conductive epoxy to the exposed die. A similar TC was attached to one of the leads of the same PLCC. The die temperature in a natural convection/IR system was 5°C cooler than the solder-joint temperature. In a system using different emitter technology, the die temperature was 30°C higher than the solder-joint temperature.

How critical are these differences? Most active components are subjected to much higher temperatures during fabrication. Although there is not enough data to determine whether future component performance can be adversely affected by the temperatures during IR reflow, many SMT process specifications are taking this possibility into account. The IR system used should be compatible with the specified tolerances of heat-sensitive components.

Atmosphere Containment
Soldering in an atmosphere that is not oxygen-dominated, is an issue that comes up from time to time in IR reflow soldering. That is because oxidation may have an adverse effect on the wetting angle of the solder. With heat acting as a catalyst for oxidation of metals, inerting will prevent further oxidation during the reflow cycle. Typically, nitrogen displaces the purged oxygen in the reflow, many SMT process specifications are taking this possibility into account. The IR system used should be compatible with the specified tolerances of heat-sensitive components.

<table>
<thead>
<tr>
<th>System</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLCC 100</td>
<td>−15(198)</td>
<td>+3(213)</td>
<td>−12(205)</td>
<td>−10(202)</td>
</tr>
<tr>
<td>PLCC 64</td>
<td>−1(214)</td>
<td>+5(225)</td>
<td>−6(214)</td>
<td>−5(222)</td>
</tr>
<tr>
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<td>+15(235)</td>
<td>+11(230)</td>
<td>−1(212)</td>
</tr>
<tr>
<td>Connector</td>
<td>−4(218)</td>
<td>+12(232)</td>
<td>+12(226)</td>
<td>−1(219)</td>
</tr>
<tr>
<td>Profile peak temp.</td>
<td>213-222</td>
<td>210-220</td>
<td>214-220</td>
<td>212-227</td>
</tr>
<tr>
<td>Gradient across PCB</td>
<td>9°</td>
<td>10°</td>
<td>6°</td>
<td>15°</td>
</tr>
</tbody>
</table>

Note: First number indicates difference between solder joint and body temperature. Second number in parenthesis indicates solder joint temperature.

(All temperatures in degrees Celsius.)
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IR Reflow Systems

IR reflow soldering systems fall into four categories: lamp, reflector/lamp, natural convection and forced-air convection.

CLASS I: Lamp IR systems consist of line-source emitters, such as IR lamps or tube-type heaters, in a convectorized furnace. These systems were originally used in high-temperature processes in semiconductor fabrication and in tin-lead soldering of PCBs. Spectral emissions with typically low- to mid-IR as emitters are most efficient at higher temperatures. Applied energy is primarily radiant.

CLASS II: Reflector/lamp IR was developed from Class I lamp IR. Reflectors or walls, ceramic in composition, are heated by the lamps and become secondary emitters of energy in the mid- to far-IR range. Chamber atmosphere is heated, adding convection to applied energy and in turn to the PCB assembly.

CLASS III: Natural convection/IR systems use medium- to high-mass area-source emitters (panel) within a convectorized tunnel. With emissions predominantly in the mid- to far-IR range, oven atmosphere is heated. Energy is transmitted to the PCB assembly by both radiation and convection. Convection is induced thermally or by a natural draw of air through the exhaust stacks (pulling air from the entrance and exit of the chamber)

CLASS IV: Forced air convection/IR is a variation of the Class III convection/IR system. It also uses medium- and high-mass area-source emitters but induces convection by intentionally moving the air within the oven chamber using blowers. Heated air is passed through or around the emitter panels and, in most systems, recirculated. Although PCB assemblies are heated by radiant energy and convection (like Class III), some systems actually emit very little IR and rely mostly on the heated, forced air.

flow chamber. Of course, an inert atmosphere cannot do anything to counteract metal oxidation prior to reflow and is most effective in preventing flux-charring and discoloration of FR4 at temperatures that are above 240°C.

Class I systems (lamp IR), with emissions in the near-IR portion of the spectrum and with very high emitter surface temperatures (400 to 1000°C), benefited from an inert atmosphere. Convection/IR system (Classes III and IV), with predominantly mid- to far-IR and emitter temperatures below 450°C, benefitted less from a nitrogen atmosphere. Manufacturers of Class II systems (reflector/lamp IR) rely more on mid- to far-IR emissions and lower emitter temperatures and do not recommend inerting the oven atmosphere for normal SMT reflow applications.

In some applications, soldering in an inert atmosphere is an integral part of the process. SMCs are soldered to bare copper PCBs in one example. Instead of being coated with tin-lead, the bare copper boards are sealed in a shellac-like coating at the end of the fabrication process. The SMT assembly process remains the same, except the IR oven atmosphere is inerted to prevent oxidation when the coating evaporates as the PCB assembly is heated. This method is used by some manufacturers due to coplanarity issues and because the tolerances that are obtained with hot-air leveling may not be compatible with fine-pitch requirements.

Some initial work has been done with reactive atmospheres. This solder-paste formulation differs from others because it contains only some of the activators. The activating vehicle in the reactive atmosphere never has the chance to form a residue because it is in gaseous form rather than conventional liquid or solid. Experimental compounds in IR reflow soldering, though proprietary in nature, use a formic acid as a key component.

No-clean fluxes have rekindled interest in the role of atmosphere containment in the IR reflow system. This does not mean atmosphere containment will be required to use no-clean flux technology. Solder pastes with such materials are currently being beta-site tested in IR ovens using normal atmospheres.

Applied Conveyor Oscillation

During reflow, the mechanics of surface tension take place as the solder completely melts. Assuming coplanarity and wettable surfaces, the molten solder will bridge between the lead and the pad to form the interconnect. As the component floats in the molten solder, the surface tension may pull the component into better alignment. The probability of this happening affects the relationship between lead-to-pad surface area. High-pin-count devices seem to fare well with this type of phenomenon.

Attempts have been made to enhance this effect by vibrating the conveyor mechanism to induce component movement during the reflow stage. The oscillations transmit through the PCB and aid the surface-tension effect. In most cases, a variable frequency oscillator is attached to the conveyor so peak attenuation is realized in the last vertical heat zone of the oven. (Vibration from an audio source has also been used). One process engineer warns that this system applies only to components with low centers of gravity. Oscillation has the opposite effect on taller components.

The idea that this effect is reliable runs contrary to good process control practices. None of the major manufacturers of IR reflow equipment offer such a device on its ovens. Vibration may not be necessary since current generation placement equipment can properly align components upon placement. There is also concern over the integrity of the solder joint since vibration is also being applied during both the cooldown stage
and fillet formation.

**Process Control in IR Reflow**

Temperature control in an IR reflow oven is typically a closed-loop arrangement between strategically located thermocouples and a controller. In some systems, the TCs are located near emitter, and in others, suspended TCs monitor air temperature in a given region of the oven. Neither system relates to the PCB assembly temperature. It is impractical in a normal, high-volume SMT process to frequently pass an instrumented board through an oven, making sure the profile remains on track. A more practical solution is to use a noncontact temperature-sensing method to continuously monitor WIP without disrupting product flow.

This type of continuous monitoring system has been developed and is currently used. An IR pyrometer is located at two points within the IR oven—one past the preheat zone and another past the last emitter in the reflow zone. A cooling medium is not required since the pyrometers are mounted below the track of the edge conveyor (looking up at the bottom-side of the assembly). As the assembly passes over the sensor, the sensor scans the board using emissivity detection. The readings are converted to corresponding temperatures and an average of the scans posted as the temperature for that board. As the sensor is always seeing the same path of a particular board, the relative temperature of each board is compared to a presampled calibrated value. The readings are logged to a history file that can be recorded and accessed.

In the monitor mode, three user-set warning levels correspond to PCB temperature deviations above or below the set value. In the control mode, user-assigned emitters corresponding to any vertical heat zones in the oven are automatically regulated by the system. Here, temperature deviation is detected, and the oven adjusted before the deviation becomes great enough to affect the process. By regulating the emitters rather than the other variables (such as conveyor speed), product flow to and from other machines is not disturbed.

**Fine-Pitch Device Reflow**

The advent of fine-pitch devices (FPDs) has put greater demands on SMT assembly equipment and rendered some older systems obsolete. Two-camera vision, for example, is required for substantial yield on placement equipment handling components with lead centers below 0.035 in. Screen printers are also being equipped with high-accuracy peripherals as well. The anomaly in the process is the IR reflow system. With 0.025-in. pitch devices and 0.020-in. pitch components being widely used, IR reflow has yet to meet any obstacles. Preliminary work being conducted on 0.016-in. pitch products indicates that IR will be an acceptable method of reflow soldering.

Processes, components and materials leading up to reflow must be carefully monitored. Controlling the deposition of solder paste as well as the coplanarity and colinearity of component leads are all issues that must be dealt with. If they can be maintained within the rigid tolerances, IR reflow will continue to be a viable process. ☑

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