Thermal Process Optimization and Monitoring for Long-Term Product Reliability

by Charles R. Delott

Issues that can arise when an electronic assembly is exposed to solder reflow outside its specified process window include reduced solder joint quality and reliability, which can cause failures in the field. While many PCB and hybrid assemblies can pass the standard in-circuit test even though their reflow specs are well outside the recommended process window, growing evidence suggests that in-circuit testing is not an adequate indicator of field reliability and that a primary cause of field failures is an out-of-spec solder process.

Long-term solder joint reliability should be a source of concern to both OEMs and CMCs. Whether an assembly is outsourced or done in-house, it is the OEM's name that is on the final product, and the OEM's reputation that is on the line. In the highly competitive CMC market, the loss of a major customer due to unreliable product assemblies can be the difference between profitability and Chapter 11.

The problem of diminished solder joint reliability is obviously difficult to document, but there is growing anecdotal evidence that it is significant. Defects resulting from screen printing or placement are almost always caught by quality control, but weak solder joints caused by an out-of-spec reflow process often are not. An overview of the issues currently facing OEMs and CMCs establishes the cause-and-effect relationship between thermal management and solder joint field failures.

Long-Term Reliability Problems: Examples

Four examples of solder joint failures represent a cross-section of problems typical in the electronics assembly industry (some specifics have been altered to honor confidentiality agreements).

1. An FR4 PCB telecom transceiver logic board experienced a high percentage of both internal returns and long-term returns that involved shields coming back from the field separated from the board. The shields, made from tin-plated steel, were placed over portions of the circuit to eliminate noise. Internal QA found multiple cases of shields warped in the corners of the boards. Solder was found wicked all around the shields, indicating that they had been subjected to excess heat during the reflow process, causing solder to be drawn away from the joint. This is a major circuit issue, especially at high frequencies in the mega-hertz range.
   This problem was traced to the reflow profile, which allowed too much time over liquidus. This caused excess grain growth, leading to a weak joint. The suspect joint was pull-tested to confirm that it was not up to spec, and then excess grain growth was detected by cross-sectioning.
2. A hybrid alumina substrate on a carbon heat sink power amplifier assembly experienced long-term field returns. Component leads had broken away from the solder pads, causing electrical failure. Again, it was determined that excess grain growth had caused a weak solder joint. The problem was traced to a reflow profile that allowed too much time over liquidus.
3. A telecommunications PCB experienced long-term field returns. Component leads were found to be poorly wet-out, causing electrical failure. The problem was traced to component leads being overly rich in tin, causing poor wetting out of the joints. In this case, it was determined that the reflow profile had too low a peak temperature to wet the tin-rich leads. The solder joints looked good and the defect was not caught by in-circuit testing, but failed in the field from either thermal cycling or vibration. Once the problem was identified, it was remedied by raising the profile's peak temperature.
4. A gold-plated PCB experienced returns from the field due to broken leads. Investigation revealed that the reflow profile had too high a peak temperature, which caused delamination of the gold circuits from the base material. This problem was extremely difficult to detect visually and was undetected by the in-circuit test.

In each of these examples, the reflow profile was inappropriate and directly responsible for the solder joint failures. These failures, once detected, could have been tracked down quickly and then eliminated with proper thermal profiling and monitoring procedures.

Elements of the Reflow Profile

In the reflow process, a PCB or hybrid assembly with solder paste and components placed on it is exposed to a heating process. The solder paste is heated to a point where it becomes liquid and then forms solder joints between the components and the board. The critical statistics in a reflow profile are Preheat Time, Preheat Temperature, Time Above Liquidus (TAL), Peak Temperature and Ramp Rate (Figure 1).

Preheat time and temperature precede the reflow zone of the profile and are critical for heating the assembly evenly and activating the flux. TAL is the period in the profile during which the solder is fluid and the joint is created. Peak temperature is the highest temperature reached by any point on the assembly. Ramp rate is the rate (expressed as temperature/time) at which the assembly is heated and cooled.

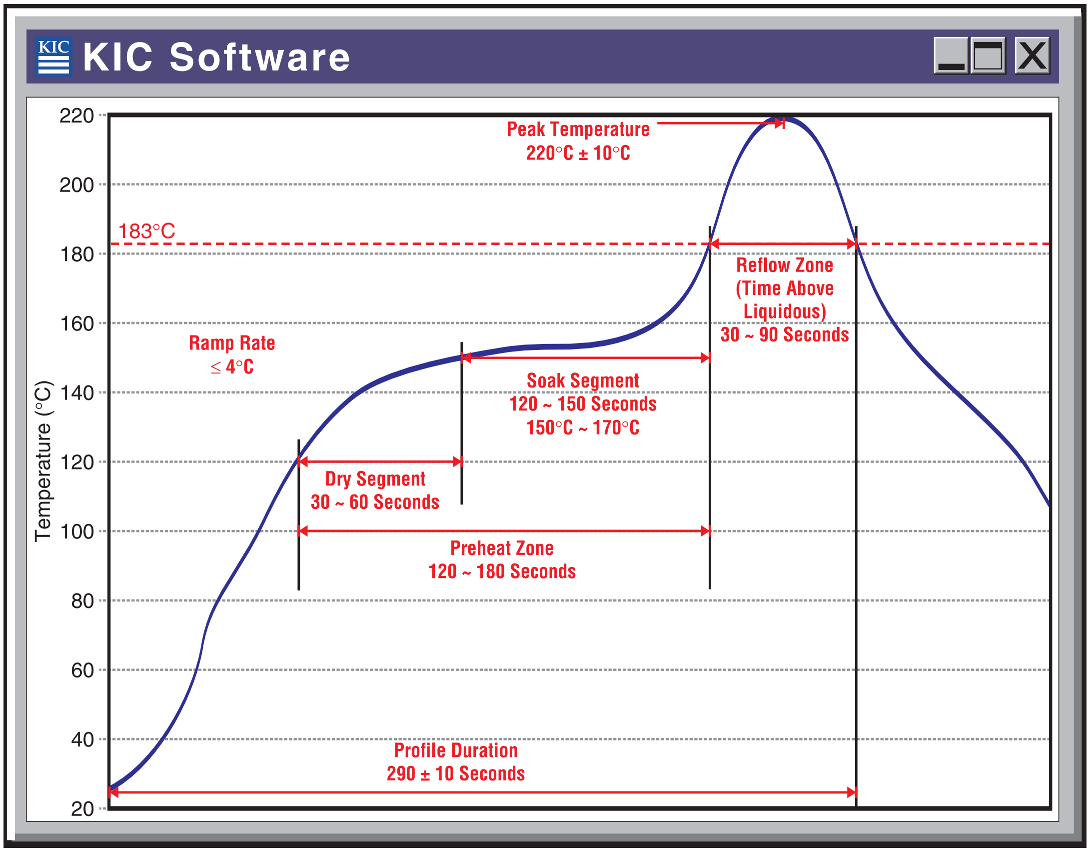


Figure 1: Typical reflow profile.

The reflow oven thermal profile depends on the versatility and capacity of the oven. Factors that influence the profile are the temperature controllers, the mass of the product going through the oven, the efficiency of the reflow oven heat supply and heat transfer mechanism, as well as the speed at which the product passes through the oven. The reflow profile has a direct bearing on process yield, solder joint integrity, microstructure and reliability of the assembly.

Effects on Long-Term Reliability

A solder joint is a metallurgical bond between two metallic surfaces. They are joined by heating a solder alloy which forms an intermediate metallurgical bonding layer between them. Precise control of the heating and cooling zones of the reflow oven (the thermal profile) is critical for developing a reliable bond.

Characteristics and Consequences of Inadequate Reflow Profiles

Preheat time and temperature:

These are critical to flux activation. With too little time or temperature, the flux is unable to clean the joints to be soldered. Too much time or temperature causes the flux to evaporate, resulting in oxidation of the joint. Preheat is also critical to ensure that all components on a board are heated evenly. Large temperature differences across a hybrid or PCB can result in the failure of portions of the board to reach reflow temperature, causing uneven soldering. These temperature differences and their resultant problems can impair long-term solder joint integrity.

Time Above Liquidus:

TAL influences the metallurgical properties of the solder joint. Too little TAL causes cold solders, poor wetting and incomplete solder joints. Too much TAL causes excessive grain growth and the formation of intermetallics, which both result in a weakened solder joint.

Peak Temperature:

This is critical in two ways. If it is too high, damage to components and boards may occur; if Peak Temperature is too low, cold solders, poor wetting and opens may occur.

Ramp Rate:

This is simply an indication of preheat and cooling time and temperature. The main problem associated with too rapid a Ramp Rate is the cracking of sensitive components.

Most Common Types of Solder Joint Failures and their Causes

Cold Solder Joint:

This is caused when the process temperature is insufficient to melt the solder, resulting in a joint that is only partially reflowed. A cold solder is usually indicated by solder balls and generally fails an in-circuit test or a visual inspection. Cold solders tend to occur when components are not brought up to reflow temperature.

Wetting ability:

This refers to the solder's ability to adhere to the materials being joined by the solder joint. The time and temperature in the reflow oven preheat zone directly affects the solder flux activity and the production of acceptable solder joints. In general, RMA soldering fluxes work best with a rapid rise in preheat temperature to 150°-160°C. No-clean soldering fluxes give their best activity with a slow rise in preheat temperature to 130°-150°C. For no-clean pastes, too rapid a preheat temperature rise causes the solder to oxidize and produces poorly reflowed solder joints.

Solder joint voids:

These are cavities inside the solder joint caused by gases released from the flux during reflow. Solder joint voids are controlled by the flux activity in the preheat zone. In addition, solder joint voids are controlled by having sufficient TAL to ensure full reflow of the solder.

Leaching:

This is often due to a combination of two problems — excess gold or silver plating on component leads, followed by excess liquidus time and temperature. This combination of events causes the formation in the solder joint of gold-tin or silver-tin intermetallic compounds that are very brittle, often resulting in delayed failures.

Microstructure of the solder joints:

The formation of intermetallic compounds is one of the main sources of solder joint failure. Care must be taken to prevent the formation of excess amounts of intermetalics at the solder joints. Intermetallic growth is detrimental to the long-term reliability of the solder joint. In the solder reflow profile, peak temperature and dwell time must meet a balance for good wetting, fine grain growth and minimal intermetalic formation. A minimum peak temperature and short dwell time is best for long-term reliability.

Table 1: Reflow Profile Characteristics and Potential Solder Joint Defects

ZONE	CHARACTER	POTENTIAL SOLDER DEFECT
Ramp	Too rapid rise	Cracked components Solder balls Delamination of PC Board
Preheat time	Too little time	Poor flux activation Poor wet-out of solder Cold solder joints
	Too much time	Flux evaporation Flux deterioration Oxidation of solder
Preheat temperature	Too low temp.	Poor flux activation Poor wet-out of solder
	Too high temp.	Flux evaporation Oxidation of solder
Soak (TAL)	Too little time	Cold solder joint Poor wetting of joint Poor wetting of leads
	Too much time	Excess grain growth Intermetalics Poor strength of bond
Peak temperature	Too low	Cold solder joint Poor wetting of joint
	Too high	Component damage Leaching Delamination of board

The assembly described earlier — an FR4 PCB telecom transceiver logic board that experienced a high percentage of both internal and field returns — provides a case study of the critical role of thermal process monitoring in producing reliable solder joints. The problem concerned shields made from tin-plated steel that were placed over portions of the circuit to eliminate noise. Internal QA found multiple cases of shields warped in the corners of the boards. Long-term returns involved shields coming back from the field separated from the board. This occurred because the solder joints, weakened by excess grain growth, were not capable of withstanding the vibration and thermal cycles of normal service.

Once the problem was determined to be reflow-related, data saved by a continuous automated thermal management system was accessed. These history files included thermal profiles that had been saved automatically during the period that the failed assemblies had been reflowed. Data from the thermal manager was also used for SPC charting of Peak Temperature and TAL. Analysis of the reflow oven profile and the SPC charts for the period during which the parts were made showed a very slow cool-down in the reflow cycle.

This slow cool-down rate had the effect of extending the TAL, which was believed to be the source of the excessive intermetallic growth. The engineers focused on the cooler because they were aware that intermetallic formation could be avoided only by increasing cooler power. Designed experiments using the thermal manager then showed what the optimal TAL should be.

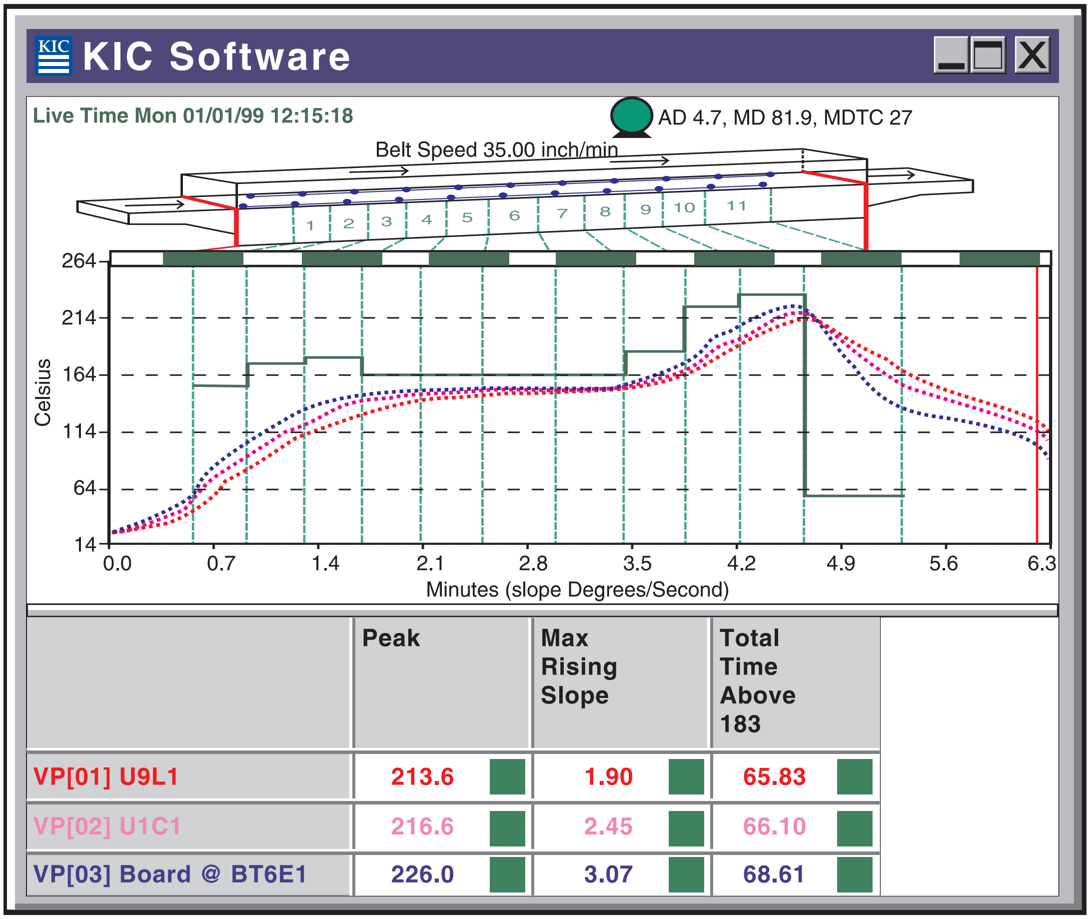
Further investigation revealed that the reflow oven cooler was not being cleaned frequently enough, and the build-up of flux solids was degrading cooler function to the point that the reflow portion of the profile was extended into the cooling section. Readjusting the SPC control of the TAL dwell times eliminated this problem. The performance of the oven and the chiller are now monitored continuously and automatically during production. An added benefit of this continuous monitoring is that cleaning and preventive maintenance are now done on an as-needed basis. SPC data is output in real time and defects have been substantially reduced.

Companies that purchase a new reflow oven but not a “chiller cooler” and a thermal manager are at a distinct disadvantage, as an efficient reflow cooling section and continuous, automated thermal management are critical to long-term solder joint reliability.

Managing the Reflow Profile

The key to resolving the problem of the shields was the installation of a real-time, continuous thermal manager on the reflow ovens at the facility in question. The automated thermal manager made it possible to obtain real-time, live data output from a process that has traditionally been difficult to monitor. Using thirty thermocouples (twice the number found in a typical oven) embedded in two slim stainless steel probes permanently mounted just above or below the conveyor, the thermal manager monitors process temperatures at the belt rather than at the heater element. Readings are taken as frequently as every five seconds.

These temperatures are displayed as “Process Profiles” on the user’s PC screen. The thermal manager provides rapid feedback, based on the setup of the oven, to verify that the process has been set up properly to fall within the parameters established for the reflow profile of a given assembly. During processing, the thermal manager can detect critical process temperature variations that oven control thermocouples cannot, and immediately reveal these temperature drifts and their location on the PC screen. At the same time, all data is recorded permanently to the hard drive, giving users the ability to review process data from any previous production date.



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VP[01] U9L1	213.6	🟩	1.90	🟩	65.83	🟩
VP[02] U1C1	216.6	🟩	2.45	🟩	66.10	🟩
VP[03] Board @ BT6E1	226.0	🟩	3.07	🟩	68.61	🟩

Figure 2: Virtual Profile

The thermal manager provides a product profile for every board processed by creating a mathematical correlation between product profile, as measured by a pass-through profiler, and process temperature, as measured by the thermocouple probes. This “Virtual” product profile is calculated every 30 seconds and statistics such as peak temperature are also calculated and updated continuously (Figure 2). The Virtual Profile gives real-time monitoring above and beyond the simple heater core thermocouple data provided by the oven controller.

An automated prediction tool, available with the thermal manager, allows users to predict how changes to belt speed and oven setpoints will affect a product profile. This is the tool that was used to find the optimal profile for the shielded boards. It also gives users the capability to maintain a permanent record of the thermal profile for every board produced; this data can be fed to an external SPC package for real-time process control. The data may also be distributed to remote locations via either a corporate Intranet or the Internet, allowing the viewing of data from an individual oven or multiple ovens at any given time. The internal distribution of data via an Intranet maximizes the value of scarce engineering resources. Time spent efficiently by engineers means a better bottom-line for any facility.

Conclusions

Several factors affect the long-term reliability of solder joints. Current trends in the electronics industry appear to be leading to an increase in field failures in products that should be trouble-free. Many consumers have had problems with products purchased from major companies with reputations for high quality, and these failures may begin to affect the reputation of both the companies and the industry as a whole. The solution to this problem is for companies running their own production to refocus on the thermal process, and for companies that are outsourcing to investigate the thermal management procedures used at their CMCs.

Many failures can be attributed to complacency with regard to the soldering process. For today's complex assemblies, the optimal reflow profile has the properties of slower heating rate, cooler temperatures and rapid cool-down. Such a profile is rarely used, as production needs often overtake the reflow oven's output. The more common solution to reflow throughput problems is to raise the peak temperature in the reflow section and increase belt speed, greatly increasing the potential for solder joint failures. However, solder joint defects are not inevitable. Currently available technology makes continuous, automated monitoring of the soldering process realistic and affordable and, with full-time monitoring of the process, high levels of product reliability can be achieved.

References

C.F. Coombs, Jr., Printed Circuits Handbook, McGraw-Hill, New York, 1995

J.S. Hwang, Solder Paste in Electronics Packaging, Van Nostrand Reinhold, New York, 1989

P.C. Kazmierowicz, "Reducing Oven Changeover Time by Finding Common Recipes for Mixed Production Lines", Nepcon West 1999

R.R. Lathrop, "No-Clean Solder Paste Benchmarking, Part II," Circuits Assembly, June 1999
