在无铅回流和返再加工过程序中所观察到的是什么样的新温度窗口呢？升温对元件和电路主板有什么影响呢？无铅返再加工温度同无铅SMT回流曲线相比又是如何呢？“NEMI”团队仍在评价其长期可靠性，但已发现，由有经验的人员使用优化工具和过程序执行时，无铅回流过程序将对于“锡金铜”合金的熔化温度提升到引起34ºC的温升，建议将焊点的回流和返再加工过程序温度在焊接点定为230º~245ºC，以获得可靠的无铅焊接点（与等相同的锡/-铅过程序的200º~220ºC相比）。

Pb-Free Reflow and Rework

Matt Kelly, Quyen Chu and Jasbir Bath

Key findings of NEMI experiments on process differences – and changes required – for lead-free reflow and rework.

How many heat cycles does an assembly see during lead-free primary attach and rework? What new temperature windows are observed in lead-free reflow and rework processes? What effect does elevated temperature have on components and boards? How do lead-free rework temperatures compare with lead-free SMT reflow profiles? Over the past three years, the National Electronics Manufacturing Initiative's Lead-Free Assembly and Rework team has been busy trying to answer these and other questions.

In early 2000, NEMI's original lead-free project recommended the SnAgCu alloy to replace SnPb solder, and then conducted extensive evaluations of this alloy to determine its reliability for reflow soldering on standard (i.e., 0.062" thick) boards. The first project team's results pointed to the need for evaluations of more complex assemblies with thicker boards and consideration of the special challenges of lead-free rework. A follow-up effort – the NEMI Lead-Free Assembly and Rework Project – was organized to evaluate thicker boards (0.093" and 0.135") and the ability to rework a representative mix of components on such boards.

Temperatures used in lead-free reflow and rework processes are much higher than those required for standard tin-lead processes, dictated by the 34°C increase in solder-melt temperature required by the SnAgCu alloy. This difference exacerbates reflow and hot-gas rework processing. Tin-lead reflow process temperatures are up to 210°C at solder joints and up to 220°C at the package body and board, while lead-free reflow process temperatures often reach 245°C at solder joints and up to 250°C at the package body and board.

The Lead-Free Assembly and Rework Project team designed a test vehicle – named Payette – that represents boards used in mid- to high-level system applications (**Figure 1**). Test vehicles were constructed of high-temperature laminate FR4-like boards (Tg: 170°C and T_d >325°C) with two different surface finishes (immersion silver and electrolytic nickel-gold) and two board thicknesses (0.093" and 0.135"), all with 14 copper layers. A variety of surface-mount components, from chip passives to large ceramic area array packages, were employed to evaluate surface-mount/rework tools and processes.

The project team first developed a reflow profile for the thicker boards and a component mix to evaluate J-STD-020B maximum component body temperature specifications. These profiles

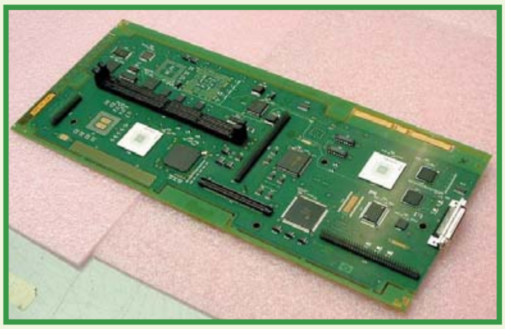

FIGURE 1: The NEMI Payette test vehicle used for lead-free reflow and rework testing. TVs were either 0.093" or 0.135" thick and had 14 copper layers.

were then used to build test boards for rework and as-assembled reliability testing. Test boards assigned for rework had pre-selected components that underwent the full rework operation, which included removal, site redressing and part replacement using hot-air convection rework equipment.

Through a cooperative process, the NEMI team worked with leading equipment manufacturers to optimize rework tools for the new higher temperatures, and then worked to optimize the process using the improved tools.

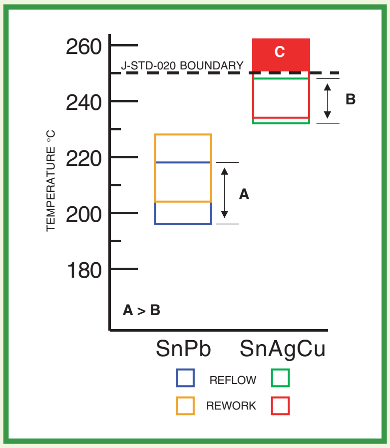

FIGURE 2: Lead-free temperature windows for reflow and hot-gas rework processes vs. tin-lead processes. The lead-free SMT reflow process window is much smaller than the tin-lead process window, primarily because of the maximum package body temperature limits imposed by J-STD-020B.

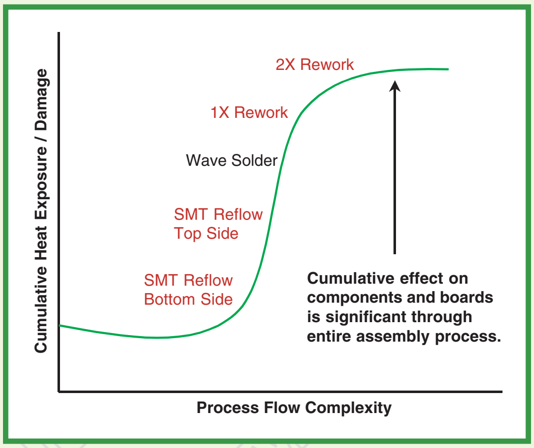

FIGURE 3: The cumulative effect of reflow and rework heat cycles on a single assembly.

Process Variables

Several parameters must be controlled within SMT reflow and hot-gas rework processes. Design and material effects generally include 1) board thickness/number of layers, 2) x/y dimensions and board size and 3) component complexity. Process effects normally include 1) ΔT across components, 2) ΔT across assemblies, 3) time above liquidus (TAL) ranges, 4) cycle time and 5) minimum/maximum temperature boundaries for components and boards.

A common perception is that a single reflow process temperature exists over the entire board surface. It does not. The temperature at any point on the assembly is a function of the thermal mass of the board and components. Temperatures underneath large thermal mass components (such as the ceramic BGAs used on the Payette boards) will be near minimum reflow-process temperatures, whereas areas with small components, particularly along the leading edge of the board, will be subject to the highest temperatures. The term "ΔT across assemblies" refers to the difference between the coolest solder joint and the hottest. NEMI measurements indicate that ΔT can range from 5° to 20°C for reflow processing.

Board thickness is a major variable in controlling process temperature. Thicker boards require more heat, have greater ΔT spread across the board and may require a slower reflow oven line speed. As overall board size increases, process windows tend to shrink. The key to reliable SMT reflow as well as hot-gas rework processing is to understand the effect temperature has on components and PCBs, while controlling the manufacturing line to newly specified operating windows.

Figure 2 shows the effects of elevated lead-free processing temperatures when compared with current tin-lead reflow and hot-gas rework processes. The lead-free SnAgCu-based alloy has a near-eutectic melting point approximately 34°C higher than the tin-lead eutectic. Maximum lead-free surface-mount package body temperature limits, which are set by the newly revised J-STD-020C specification for components, are 245°, 250° or 260°C, depending on package volume and thickness. (Because lead-free rework presents unique issues in terms of reducing peak component temperature, J-STD-020C indicates that any lead-free component not rated to 260°C based on its package volume and thickness must be tested by the component supplier to one additional reflow pass at 260°C peak, to account for lead-free rework.)

Maximum peak component body temperatures of 245° to 250°C were consistently measured during lead-free reflow soldering in the NEMI Payette trials. These temperatures were attained on the 7.5 x 19" board using both the 0.093" and 0.135" thickness constructions. The hottest measurements were found on small form-factor components, usually passives, while the coolest temperatures were recorded in center solder joints of BGA-style devices. The lead-free reflow process developed to assemble more than 100 Payette test boards conforms to J-STD-020C specifications for component temperature exposure limits.

Laminate/Via Stressors

The higher lead-free processing temperatures place greater stress on components and boards and amplify the cumulative heat exposure effect. **Figure 3** illustrates the cumulative effect of reflow and rework heat cycles on a single assembly. A typical assembly, such as the NEMI Payette test board shown in Figure 1, would be subjected to 1) bottom-side reflow, 2) top-side reflow, 3) wave solder, 4) first rework and 5) a second rework. Therefore, an assembly could typically be exposed to five thermal heat excursions: two reflow passes, a wave-solder pass and two local hot-gas rework passes.

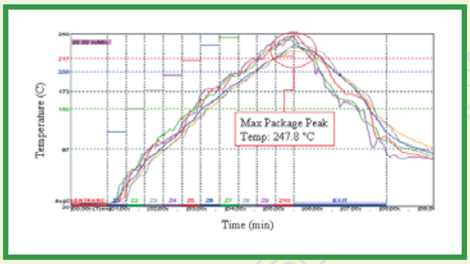

FIGURE 4: NEMI Payette TVs were built using this optimized lead-free reflow profile.

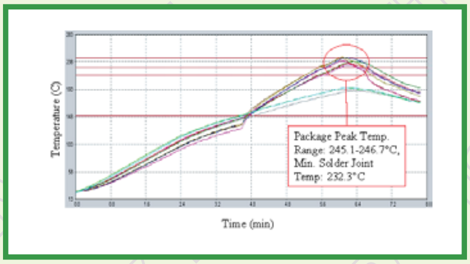

FIGURE 5: A representative lead-free PBGA rework profile on the Payette assembly.

Internal package structures within components and PCBs must survive all processes and still provide long-term reliability. Component effects include increased moisture-sensitivity levels (MSLs) and subsequently a shorter exposed floor life, while PCB laminates must withstand internal-layer delamination, via cracking and board warpage.

The most demanding thermal process in a manufacturing environment is hot-gas rework. The high temperatures required in small, localized areas for long periods of time impact several variables on the assembly that should be monitored, including maximum component body temperatures, PCB laminate survivability and maximum temperatures of both adjacent and bottom-side component solder joints. The objective of the rework process is to mimic, as closely as possible, the primary attachment SMT reflow process to ensure that solder joint formation (and reliability) are similar. Several challenges hinder making reflow and hot-gas rework processes identical. The main difference between the two is that SMT reflow is a full assembly heat excursion while the hot-gas rework process is a local heat excursion. This localized heat during the rework process creates local stresses within the component and PCB.

NEMI findings from trials conducted with lead-free rework processing on both board thicknesses are, notably, the reverse of what was found for lead-free reflow processing. The highest component body temperatures (maximum peak temperatures of 250°C) were recorded on large BGA devices during lead-free rework operations, while the lowest body temperatures were found on smaller form-factor components.

Maintaining temperatures noted in J-STD-020B (245°C or 250°C, depending on package volume and thickness) posed a challenge for the NEMI team. Increasing bottom-side heat through the board was an effective method to reduce the amount of top nozzle heat flowing into the component, which reduced ΔT. However, this may have reliability implications in terms of secondary reflow of adjacent topside and bottom-side components and the board laminate material itself. Also, the rework development profiling of thermocoupled boards was conducted over a period of a few months, whereas, in production, this task would be accomplished in hours or days (and only if thermocoupled profile boards were available). This level of rework profiling optimization to reduce the temperatures encountered on the topside of the component would be difficult to accomplish in a production environment.

To better understand the differences between the two processes, examine lead-free SMT reflow. Based on NEMI test results, lead-free SMT reflow processing typically has the following characteristics:

- Four- to six-minute cycle times.
- Temperatures ranging from 230° to 250°C for joints and body temperatures.
- ΔT ranges from 5° to 20°C on a single assembly.
- TAL ranges from 60 to 90 sec.
- Linear ramp to reflow profile shapes (paste vendor recommendation).
- Air reflow is appropriate for some lead-free pastes/applications.

NEMI Payette test vehicles were built using the reflow profile in **Figure 4**. Visual inspection and reliability testing show that the solder joints were properly formed and that second-level assembly solder joints were reliable.

In a normal manufacturing environment, processing errors or early component failures lead to rework. Hot-gas rework processing is carried out on a failed location basis.

Early work with one-time state-of-the-art rework tools did not permit rework processes within J-STD-020B specifications. Substantial effort with rework tool suppliers and extensive rework process profile development resulted in greatly improved tool designs and reduced peak process temperatures. Multiple rework trials were performed before developing satisfactory profiles. A typical rework profile is shown in **Figure 5**.

NEMI experiments showed that the lead-free hot-gas rework process typically has the following characteristics on the relatively thick Payette test vehicle:

- Up to eight-minute cycle time for most packages.
- Temperatures range from 230° to 255°C for joints and body temperatures.
- ΔT ranges up to 25°C.
- TAL ranges from 60 to 90 sec., and more than 90 sec. for a large package on a thick board.
- Linear ramp to rework profile shape to help minimize ΔT across components (from the solder joint to the top of the package).

NEMI's comparison of processes for SMT and hot-gas rework indicated that rework requires longer cycle time (SMT: six minutes; rework: eight minutes), wider temperature range (SMT: 230° to 250°C; rework: 230° to 255°C) and longer time above liquidus (SMT: up to 90 sec.; rework: more than 90 sec.).

As discussed, the hottest temperatures are often recorded in the higher temperature range for BGA rework processes. This is the main reason for recommending a 260°C maximum peak component temperature limit for rework, taking into account the wider process window required for rework as compared to reflow.

Components for rework may require special handling, stocking and pre-process bake-out to withstand the higher process temperatures, a challenge for the industry.

Conclusions

Although long-term reliability evaluations are still ongoing within the NEMI Lead-Free Assembly and Rework Project, the process work is complete. Processes for both reflow and rework were developed that provided for the assembly of large, thick boards with a range of components using the lead-free SnAgCu solder alloy.

The team found that, even when using optimized tools and processes carried out by experienced personnel, the lead-free reflow process pushes component temperatures to the limits of J-STD-020B. The 34°C increase in melt temperature for SnAgCu alloys forces tighter and hotter SMT reflow and rework process windows. Reflow and rework process target temperatures of 230° to 245°C at the solder joint are recommended to achieve reliable lead-free solder joints (compared to 200° to 220°C for the equivalent tin-lead process).

Large BGA devices are the coolest components during SMT reflow, and can be the hottest during rework. Even with optimized rework tools and processes, many BGA package designs need to be able to withstand 260°C maximum peak temperatures. These higher temperatures – for BGAs as well as other components – mean that components are much more thermally stressed. They are hotter for longer periods of time, and thermal stress is greater with the rework process than the SMT reflow process, due to localized heating effects.

Based on its results, the NEMI Lead-Free Assembly and Rework Project team was able to provide manufacturing environment data to IPC and JEDEC to help revise J-STD-020B to the current J-STD-020C. (The newly released J-STD-020C raises the temperature range to 245° to 260°C.) The team also provided data and recommendations to rework equipment suppliers that have resulted in substantial improvement in machines and processes to meet the future challenges of volume manufacturing of lead-free/RoHS-compliant assemblies. Development does not stop here: this is a work in progress. ■

Acknowledgments

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Ed.: For additional information about NEMI's lead-free activities, visit nemi.org/projects/ese/lf_hottopics.html.