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Progress in Developing Industry Standard Test Requirements for Pb-Free Solder Alloys

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Abstract
Recently, the industry has seen the development of a wide range of new Pb-free alloys. A significant element of uncertainty within the industry regarding these new alloys is the lack of defined data requirements for alloy acceptance.

This paper describes the progress of recent efforts to standardize Pb-free solder alloy testing requirements. Hewlett-Packard, the iNEMI consortium, the Solder Products Value Council, and the IPC are working together to create such standards. To facilitate the standardization of alloy testing, the required tests are divided into three major areas, each of which may be covered by a separate standard.

- Material properties
- Solder joint reliability
- Impact to manufacturing processes

This paper presents the status of standardization efforts in each of these three areas.

Key Words: Lead-free, Pb-free, solder alloys, material testing, industry standards

Introduction

Due to the documented limitations of near-eutectic Sn-Ag-Cu (SAC) solders, the industry has seen the development of a wide range of new Pb-free alloys [1, 2]. The increasing number of Pb-free alloys available provides opportunities to address the limitations of SAC305, SAC405, and similar materials. The development of improved Pb-free solders is expected as Pb-free technology matures, and may provide improvements in solder joint reliability as well as decreased costs over the long run. At the same time, having the choice of so many alloys presents challenges in managing the supply chain, and introduces a variety of technical risks. For example, the high melting point of low Ag alloys will shrink an already small reflow process window. Low Ag alloys may also decrease thermal fatigue resistance in some circumstances [3–5].

One situation regarding new alloys that creates uncertainty within the industry, and which may slow the adoption of improved materials, is the lack of defined information requirements for alloy acceptance. A significant obstacle to useful, data-driven assessments of alternate Pb-free alloys has been the inconsistent testing performed on new materials. The data from experiments conducted, while valid on their own, are often not comparable to data from other equally valid experiments, due to differences in the choice of test conditions, controls, or other parameters. Also, alloys formulated to meet specific goals, such as improved mechanical shock resistance or reduced Cu dissolution, have not been consistently tested to determine suitability for general use by assessing other performance aspects, such as thermal fatigue life.

This paper describes the progress of recent efforts to standardize Pb-free solder alloy testing requirements, thereby facilitating acceptance of new alloys that meet varying company and product requirements. Hewlett-Packard, the iNEMI consortium, the Solder Products Value Council, and the IPC are working together to create such standards. The key to this standardization is the assumption that, while the acceptability of any alloy may vary from product class to product class, and possibly from company to company, the testing methodology and data requirements should be largely the same. In this case, standard testing could be done *once*, and the data then could be used across the industry as companies make specific alloy acceptability assessments. To facilitate the standardization of alloy testing, the required tests are divided into three major areas, each of which may be covered by a separate standard.

- Material properties
- Solder joint reliability
- Impact to manufacturing processes

The status of standardization efforts in each of these three areas is presented in this paper. First, efforts at Hewlett-Packard Co. (HP) are described, followed by a description of activities within the iNEMI consortium, collaboration with the Solder Products Value Council (SPVC), and the IPC.

HP Approach and Status

As described in detail elsewhere [6], HP has been developing company specifications to define test data requirements for new alloys. The tests defined in these specifications are driven by the reliability concerns related to solders, including the impact on the manufacturing process window.

Each specification is broken up into 3 areas: basic material properties, reliability testing, and the impact to the manufacturing process. The required tests in each area depend on the risks associated with the various solder forms, so there are three specifications, one for each of the three different solder forms: wave/miniwave, reflow solder paste, and BGA/CSP ball alloys. For example, the concerns for wave soldered through-hole joints are very different from those for reflowed BGA solder joints, so the required testing differs for the different alloy forms. Therefore, the miniwave/wave specification requires testing against a maximum Cu dissolution level within the HP process window (as Cu dissolution is a concern for through-hole joints), but the only solder joint reliability test required is pin pull testing. In contrast, BGA solder ball alloys require thermal cycle and drop/shock testing to address concerns with these failure modes for BGA joints. Another reason for having separate specifications for the different solder forms is that the target users of the documents (for qualifying alloys) are likely to be different for the different solder forms.

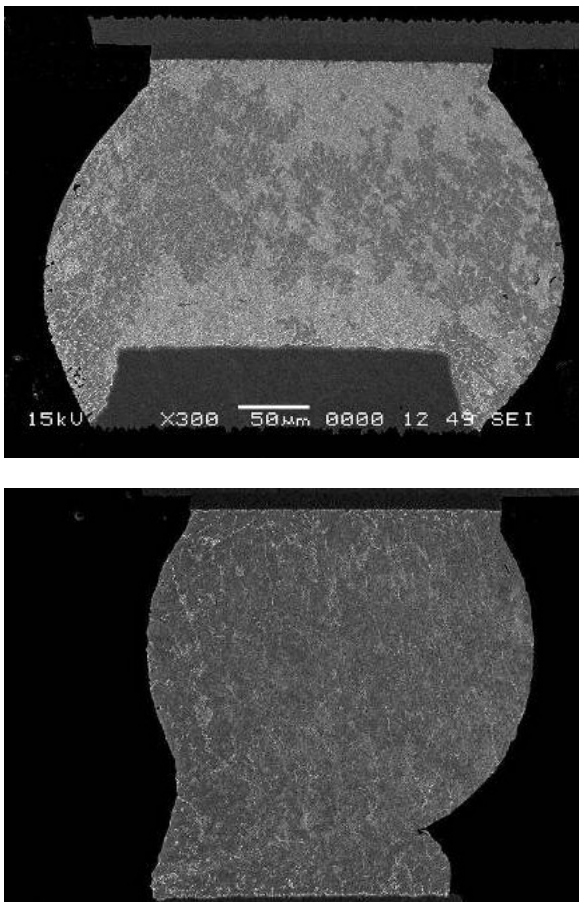

Figure 1 – Proper solder joint formation (top) is possible with current solder technologies. Changes in alloy composition can make it impossible to form good solder joints (bottom) within HP's process window, thereby failing HP's requirements.

An important aspect of the HP specifications for alloy testing is to address potential impacts of alloy composition on manufacturing processes that can affect reliability of the printed circuit assembly (PCA). Figure 1 illustrates one such concern, where an alloy's high liquidus temperature may result in poor solder joint formation within the limits of HP's current Pb-free solder process window. As shown schematically in Figure 2, the manufacturing tests to address such concerns are not intended for process optimization. The objective is to understand the effective processing window for the new alloys and to quantify the risks of damage to other materials in the systems from the time and temperature requirements. This requires assessing conditions beyond the normal process window in order to locate the process "cliffs."

A summary of the tests required for each solder form is as follows. (Note: other tests, particularly for basic material properties, are defined as optional.)

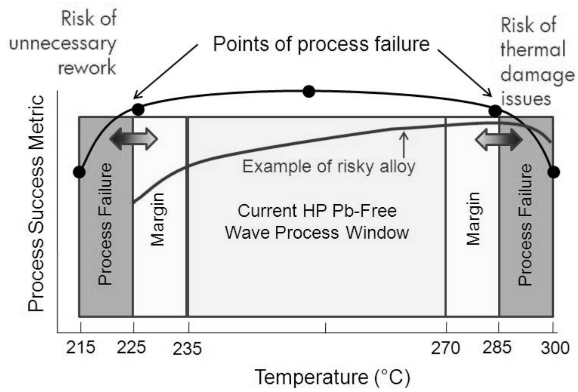

Figure 2 – Schematic representation of solder process effectiveness as a function of temperature. Current solder technologies have high process success across the entire HP Pb-Free process window (black line). A new solder alloy may have decreased process performance (red line), leading to the risk of unnecessary rework or thermal damage to laminates and components.

Wave/miniwave specification:

- Required material properties information:
  - Liquidus and solidus temperatures
- Solder joint reliability:
  - pin pull
- Manufacturing:
  - Wetting balance
  - Wave alloy manufacturing DoE (evaluating TH fill, proper solder joint formation, and Cu dissolution)
  - Miniwave alloy manufacturing DoE (evaluating TH fill, proper solder joint formation, and Cu dissolution)

BGA ball alloy specification:

- Required materials properties info:
  - Liquidus and solidus temperatures
  - Elastic constants (dynamic)
  - Stress-strain relationship
- Reliability:
  - Accelerated thermal cycling
  - Mechanical shock
- Manufacturing:
  - Wetting balance
  - Manufacturing DoE for BGA components (evaluating IMC thickness, proper solder joint formation,, and Cu dissolution)

Solder paste alloy specification:

- Required testing is the same as in the BGA ball alloy spec, with the addition of:
  - Manufacturing DoE for leaded components (proper solder joint formation)

Since the previous progress report [6], HP has completed, or nearly completed, the first revision of the solder alloy material requirements for all three solder forms. The status of each specification is as follows.

- Released 15 July 2009. Wave and mini-pot wave solders: HP specification EL-MF-862-09, "HP Sn-Ag-Cu Solder Alloy Material Requirements–Wave and Miniwave."
- Released 15 December 2009. BGA ball alloys: HP specification EL-MF-862-10, "HP Sn-Ag-Cu Solder Alloy Material Requirements – BGA/CSP Solder Ball Alloys."
- Expected release February 2010. Reflow solder paste alloys: HP specification EL-MF-862-11, "HP Sn-Ag-Cu Solder Alloy Material Requirements – Reflow Solder Paste Alloys."

As stated in the earlier report [6], these three specifications emphasize standard testing, including the use of appropriate controls. An example of how controls are used to set pass/fail requirements is shown in Figure 1 for the case of accelerated thermal cycle testing. In this case, performance that equals or exceeds that of the historical and presumably "lower bound" Sn-Pb alloy constitutes acceptable thermal fatigue properties for the new alloy under test. Thus, in this example, New Alloy #1 performs better than eutectic Sn-Pb and meets HP's requirements, while New Alloy #2 fails HP's requirements because performance is below that of eutectic Sn-Pb.

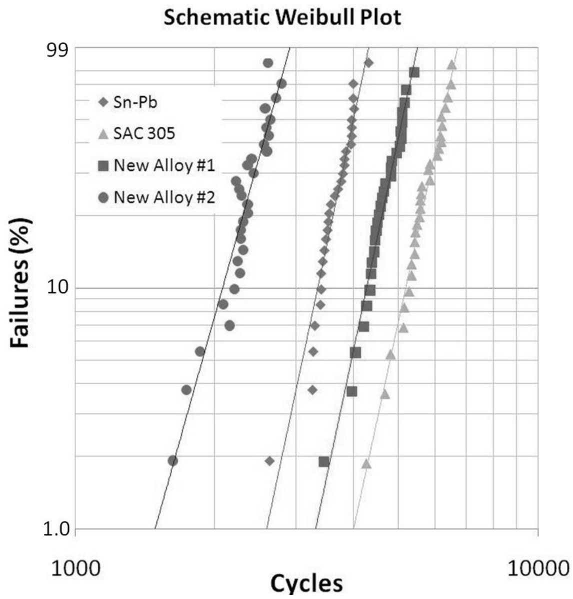

Figure 1 – Schematic Weibull plot of ATC data, including Sn-Pb and SAC 305 controls. The requirement for a passing alloy in ATC is equal or better performance than Sn-Pb. In this example, New Alloy #1 passes but #2 fails to meet these requirements.

As stated earlier, the focus of the selected tests is on providing data that address HP's reliability concerns. Since our earlier report in 2008 [6], however, the authors determined that PCA-level tests were not practical for two areas of potential concern: transient bending and vibration.

For transient bending, or flexure, of lead-free PCAs, HP's experience is that transient bend testing results in pad cratering in almost every case (see Figure 2). PCA-level bend test results, therefore, are highly sensitive to the properties of the laminate, making *alloy* assessment by bend testing extremely problematic. Thus, the released specifications do not include a bend test requirement. Instead, these specifications include the requirement to report the elastic constants and the stress-strain properties of yield strength and ultimate tensile strength (UTS). Acceptance is based on the new alloys having elastic moduli and strength values no larger than those for SAC405. Since the propensity for bend/flex failures increases as the elastic stiffness and plastic strength of the alloy increase [7, 8], these values are limited to those of the strongest SAC alloy accepted today by HP.

For vibration testing, HP's investigations have shown that there are no useful standards on vibration testing, nor do any provide a standard test vehicle specification; vibration test results are highly sensitive to the design of the test vehicle. Furthermore, vibration is not a major issue for most HP products, unlike automotive or aerospace electronics. Thus, HP will address any vibration concerns for new alloys on a case-by-case basis. Standardized vibration testing that provides data on the basic alloy vulnerability to this failure mode is an area for industry attention.

iNEMI Recommendations

Since 2007, the iNEMI consortium has been investigating new Pb-free solder alloys. A team of 18 companies spanning the entire supply chain (solder suppliers, component suppliers, EMS providers, and OEMs) now comprises the Pb-Free Alloy Characterization Project team. The Phase 1 efforts were focused on establishing and communicating the industry state of knowledge regarding new Pb-free solder alloys [1]. The gaps selected for attention in the current project fall into two categories: (1) standardizing information requirements and test methods for alloy acceptability assessments, and (2) long-term thermal fatigue reliability [2].

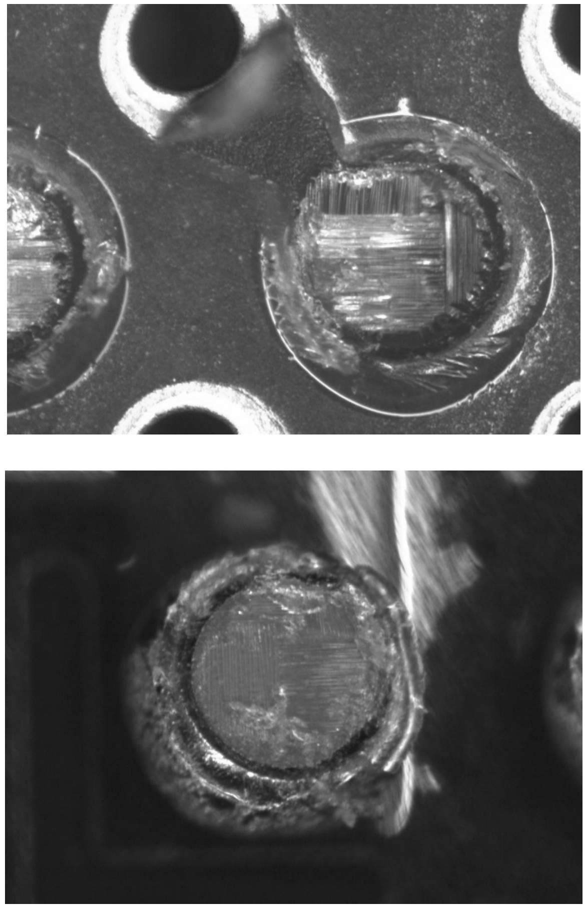

Figure 2 – Pad cratering, revealing glass fibers in the laminate on the PCB side (top) and the solder joint with lifted pad on the BGA substrate (bottom).

The iNEMI team continues to develop a set of recommendations for solder alloy test requirements. So far, the team has tentatively agreed on a number of basics.

- Standardize on tests and methods, not on pass/fail criteria. Pass/fail criteria will depend on the product type, company and industry sector, whereas the test data from which to make those assessments are likely to be independent of these factors.
- Testing should address three areas: basic material properties solder joint reliability, and the impact of alloy composition on manufacturing processes. This approach aligns with HP's.
- Solder joint reliability tests should include at least mechanical shock (drop) and accelerated thermal cycle testing. Bend and vibration are of interest and are still under consideration.
- Material property testing is likely to include at least: measurement of liquidus and solidus temperatures, dynamic elastic constants, tensile testing for yield strength, UTS, elongation to failure, and coefficient of thermal expansion (needed for modeling).
- Concerns that need to be addressed in assessing the impact of alloy composition on manufacturing process window are still under consideration. The team tentatively agrees that the industry needs to understand the impact of alloy composition on the process window, not just whether or not a board can be built under a narrow set of specific conditions. At this point, the team is considering the sensitivity of results to equipment used, PCA characteristics (thermal mass, etc.), and process materials (e.g. fluxes).
- Tests must focus on *alloy* performance and results must not be overwhelmed by other parts of the assembly (laminate properties, board design, etc.).
- Test protocols should avoid creating new test methods – use industry standard test methods wherever possible.

Currently, the iNEMI team is looking in detail at the HP specifications, particularly the BGA ball alloy specification, as a starting point for establishing alloy testing guidelines for the broader industry. These recommendations will be provided to the IPC for consideration in developing industry standards.

SPVC Recommendations

In December of 2008, the SPVC invited representatives from the iNEMI Pb-Free Alloy Characterization team to begin discussions on alloy testing. This initial meeting led to agreement on several points.

- We should begin drafting three separate standards: material properties solder joint reliability, and manufacturing impact. Furthermore, it was agreed that we should start with the most straightforward and move to the more complex, leading to the following prioritization:
  1. Material properties
  2. Solder joint reliability
  3. Impact on manufacturing process
- Data need to be "transferrable" or "portable." That is, data collected at one lab need to be useful for acceptability assessments around the industry.
- Tests must focus on the impact of the *alloy composition* and not on other parts of the system (e.g., solder fluxes, manufacturing equipment, etc.)
- Testing must be economical.

Based on this initial meeting, a group was formed to begin work on the first two standards (material properties and solder joint reliability). This group has been led by Dr. Greg Munie of IPC. Several drafts have been developed and reviewed by the team, representing a significant step forward in the development of industry standards. A draft standard for basic material properties has been sent to IPC for formal development into a standard. Issuance of the standard will be dependent on which committee finally agrees to sponsor the effort, the SPVC being an industry group and not a standards body.

IPC Standards Development

The IPC's role is to develop formal standards for the industry on alloy test requirements. Under the leadership of Dr. Munie, the IPC process is to begin with drafts provided by the SPVC. This has already taken place in the case of the standard for basic material properties. Furthermore, the IPC will consider input from the iNEMI Pb-Free Alloy Characterization team, as well as individual companies.

As of the writing of this paper, the IPC is reviewing the SPVC draft on standard testing for basic material properties. The next step is to establish committee sponsorship. From this point, drafts will work through the normal IPC processes for development and release of standard(s) for alloy testing.

Conclusions and Next Steps

The need has been seen by HP, iNEMI, the SPVC and IPC for standardized methods for testing new Pb-free alloys. These groups agree that input from all segments of industry are needed: solder suppliers, CMs, BGA component manufacturers, OEMs. A consensus is starting to build for the following.

- Standards are needed in three areas: (1) basic material physical and mechanical properties, (2) solder joint reliability, and (3) impact of alloy composition on manufacturing processes.
- Tests are needed that minimize the effects of materials other than the alloys themselves (fluxes, laminates, etc.) or processing equipment, such that the resulting data are portable and useful to OEMs in making acceptability decisions for their products.

HP has taken the lead in driving standardization of alloy testing methods. To date, HP has released test requirements specifications for wave/miniwave solders and BGA ball alloys. Release of a specification for reflow solder paste alloys is expected in February 2010. These specifications are being used as a starting point for the iNEMI Pb-Free Alloy Characterization team in the development of guidelines for the broader industry.

In parallel with iNEMI, the SPVC is helping to lead the development of industry-wide standards. This group has met with the iNEMI Pb-Free Alloy Characterization team and others, has drafted standards for basic material properties and reliability testing, and has submitted a draft of the former document to the IPC. The IPC is considering creation of formal industry standards based on input from the SPVC, iNEMI, and individual companies, such as HP.

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