iNEMI Lead-Free Alloy Alternatives Project Report: Thermal Fatigue Experiments and Alloy Test Requirements

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ABSTRACT

The original motivation for initiating an iNEMI project on “alternative” lead-free solders was to help the electronics industry manage the introduction of new solder alloys by assessing the industry knowledge and identifying key gaps. Upon completion of this effort, the iNEMI team is now

focused on addressing some of these gaps. Of particular concern is the performance of new solders in thermal cycling and having standard test data from which to evaluate alloy suitability for various product types.

Thus, one direction the project is taking is to perform experiments that will provide the industry with a clearer indication of the effect of alloy composition on the reliability performance of alloys in thermal cycling, including acceleration behavior. The other direction is the identification of a suite of test methods that companies can use to determine the suitability of a particular solder for their application.

This paper describes the experimental program devised for evaluating the performance of a range of alternative alloys in thermal cycling. Also discussed is the team's progress toward establishing standard test methods that could provide the industry with a basis for evaluating any lead-free solder from among the increasing number being offered.

Key words: Lead-free alloys, alternative alloys, low silver alloys, microalloying, reliability

INTRODUCTION

Significant innovations in Pb-free solder alloy compositions are being driven by volume manufacturing and field experiences. As a result, the industry has seen an increase in the number of Pb-free solder alloy choices beyond the common near-eutectic Sn-Ag-Cu (SAC) alloys first established as replacements for Sn-Pb. The increasing number of Pb-free alloys provides opportunities to address shortcomings of near-eutectic SAC, such as the poor mechanical shock performance, alloy cost, copper dissolution of plated through holes, and poor mechanical behavior of joints during board bending. At the same time, the increase in alloy choice presents challenges in managing the supply chain and introduces a variety of technical and logistical risks, such as a potential decrease in thermal fatigue resistance and the complexity of managing manufacturing process parameters (such as peak reflow temperature) given the variability of alloy compositions [1-4]. Thus, the wide variety of Pb-free alloy choices is both an opportunity and a risk for the electronics industry.

One major trend in solder alloy formulation has been the evolution of solder alloys with a low silver content (less than 3%) or no silver at all, and the increasing use of what have become known as microalloying additions to the tin-silver-copper or tin-copper based alloys. This trend has prompted a continuation of the iNEMI Alloy Alternatives project in two directions. One direction is the design of an experiment intended to provide the industry with a clearer indication of the effect of varying silver content and microalloying additions on the reliability performance of alloys in thermal cycling. The other direction is the identification of a suite of test methods that companies can use to determine the suitability of a particular solder for their application. In this latter part of the project, the iNEMI team has opened up communications with solder manufacturers via IPC's Solder Product Value Council (SPVC), and with IPC directly. The iNEMI lead-free alloy alternatives team is currently considering modifications to the test regime developed by one member company as a possible basis for the development of an industry-wide standard on test methods for solder alloys.

This paper describes the experimental program devised for evaluating the reliability performance of a range of alternative alloys in thermal cycling. A key component of the experiment is to assess how acceleration behavior is affected by alloy composition. Also discussed is the team's progress toward establishing standard test methods that could provide the industry with a basis for evaluating any lead-free solder from among the increasing number of alloys being offered.

iNEMI CHARACTERIZATION OF PB-FREE ALLOY ALTERNATIVES PROJECT

Phase 1 efforts of the iNEMI Alloy Alternatives team were focused on establishing and communicating the industry state of knowledge regarding new Pb-free solder alloys. Table 1 summarizes the high priority knowledge gaps identified in the earlier work [1-4]. Those being addressed in the current Alloy Alternatives Characterization Project are highlighted. Essentially, these fall into two categories. The first two items highlighted regard standardizing information requirements and test methods for alloy acceptability assessments. The second two have to do with assuring long term thermal fatigue reliability. The need to fill these high priority knowledge gaps drove the choice of focus for the second phase of the iNEMI work.

Continuing from previous efforts [1-4], iNEMI has recently established the, "Characterization of Pb-free Alloy Alternatives Project" to address these gaps. This project is being executed by a team comprised of representatives from 18 companies spanning the entire supply chain: solder suppliers, component suppliers, EMS providers, and OEMs.

THERMAL FATIGUE RELIABILITY

The combination of thermal fatigue and solder joint creep is considered a major source of failure of surface mount (SMT) components [5]. The standard technique for assessing susceptibility to low cycle fatigue failure commonly is referred to as thermal cycling or accelerated thermal cycling (ATC). The thermal fatigue reliability of eutectic Sn-Pb solder has received thorough treatment in the literature and generally is well understood. Reliability of Pb-free solders, however, continues to be a topic of intense study and debate as the conversion to Pb-free solder and processes proceeds throughout the electronics industry [6-10].

One of the most detailed studies on a commercial area array component was by Kang et al. [11]. Their results suggest that a low Ag alloy will have better thermal fatigue reliability than a high Ag alloy. However, a systematic and consistent impact of Ag content on ATC life across all test conditions was not established [1,2]. In contrast to Kang's results, a study by Terashima et al. [12] found that increasing Ag content increases the thermal fatigue resistance of SAC solder. Similar to the findings of Terashima et al., the more recent data of Henshall et al. shown in Figure 1 for a 676 PBGA package suggest that low Ag alloys perform worse in accelerated thermal cycling than alloys with high Ag content [13]. The data from a recent thermal fatigue study of a ceramic chip resistor by Coyle et al. shown in Figure 2 also show a systematic decrease of characteristic lifetime with decreasing Ag content [14].

Table 1. Industry knowledge gaps.

High Priority Knowledge Gaps
Advantages and disadvantages of specific alloys
Composition limits for microalloy additions; ranges of effectiveness
Standard method to assess new alloys; standard data requirements
Consistency of testing methods, including test vehicles & assembly, test parameters, etc.
Establish the microstructural characteristics of specific alloys
Long term reliability data for new alloys, particularly low Ag & microalloyed
Lack of thermal cycle data for evaluating new alloys; benchmark to Sn-Pb and SAC 305/405

To date, there are very limited published studies regarding the impact of microalloy additions on thermal fatigue performance. Recently, solder suppliers have begun generating such data. Pandher et al. recently published data that suggest the addition of bismuth (Bi) to low Ag alloys significantly improves temperature cycling performance, while other additives such as nickel have little to no effect in improving temperature cycling performance [15]. Still, a full understanding of how microalloy additions affect thermal fatigue performance represents a major gap in our knowledge as an industry.

Finally, the impact of significant alloy changes on the acceleration factor that relates field life to accelerated test life is unknown. Darveaux and Reichman [16] performed hysteresis loop predictions for various Pb-free alloys based on measured mechanical property data. The shape and area of the loops, and their dependence on thermal cycle parameters, varied significantly for different alloys. This led the authors to suggest that the acceleration factor will also vary by alloy. However, direct measurements of the acceleration factors from accelerated thermal cycle testing have yet to be published for any of the new alloys.

The lack of information on the thermal fatigue performance for many new Pb-free alloys has motivated the iNEMI Alloy Alternatives team to plan accelerated thermal cycle experiments. The project team has considered many possible sets of experiments in order to answer a variety of questions. In the end, the team has decided to:

- Validate the impact of Ag concentration in the range of 0 to 4% on thermal fatigue resistance.
- Evaluate the impact of commercially common dopants, such as Ni, on thermal fatigue performance.
- Assess how alloy composition affects the acceleration behavior.
- Provide basic thermal fatigue data for several of the most common alternate alloys on the market today, benchmarking them against eutectic Sn-Pb and SAC305.
- Perform preliminary assessments of the thermal fatigue performance of some new commercial and experimental alloys relative to some common performance benchmarks.

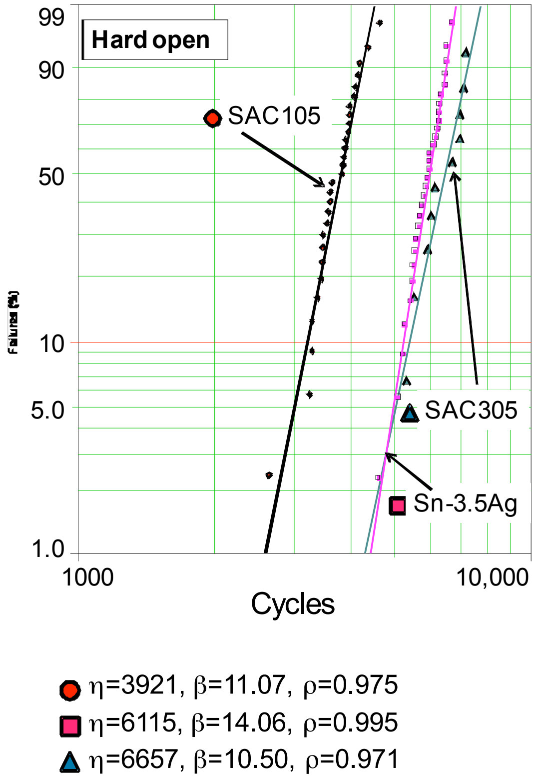

Figure 1. Weibull plots of failure life for three different ball alloy joints using an electrical failure criterion of a hard open. Data of Henshall et al. [13].

Currently, we are in the process of finalizing the accelerated thermal cycle test plan, including determination of: (1) which alloys to test, (2) the test vehicle design, and (3) which thermal cycle profiles to investigate such that meaningful acceleration factor data will result. If we are successful in executing these plans, the data could be of major benefit to the industry, especially since such large studies are nearly impossible for a single company to undertake.

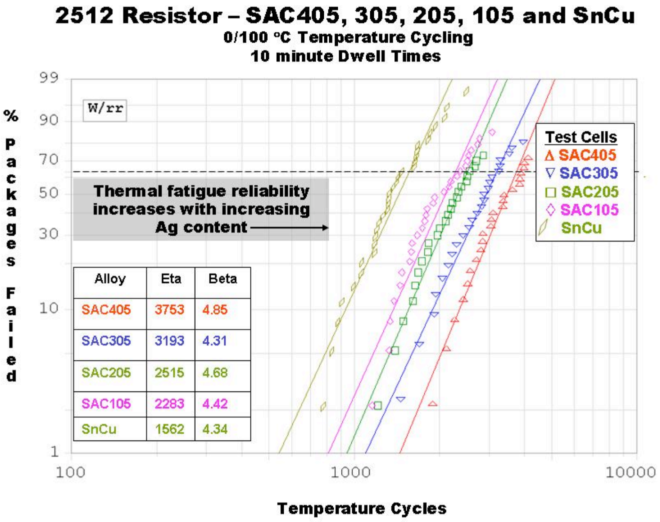

Figure 2. Weibull plot showing the beneficial effect of Ag content on thermal fatigue life of various Pb-free alloys. Data of Coyle et al. [14].

An approximate timeline for execution of this test plan is given in Table 2. Assuming successful completion, the team ultimately will report on the Weibull failure curves for each alloy under each test condition so that modelers can use these data to develop appropriate acceleration models for each alloy.

Table 2. Currently planned ATC project milestones. Subject to change during final planning and execution.

Target Date	Milestone
1-Aug-09	Project start
31-Oct-09	Final test plan complete
31-Dec-09	Materials Procured
28-Feb-10	Test vehicles assembled
1-Apr-10	ATC testing begins
1-Jul-10 to 1-Oct-10	Testing complete (will vary by profile)
31-Oct-10	Data analysis complete
31-Dec-10	Final report published

While planning is not yet complete as of 31 July 2009, the current test plan provides a view into the team's direction. Changes from what is described here are possible as plans are finalized.

Currently, we are planning to test 14 Pb-free alloys plus a eutectic Sn-37Pb control, as shown in Table 3. Table 3 lists the ball alloy composition (to the extent that has been published), the trade name, and the main purpose for including the alloy in the experiment. Note that some alloys have been included to systematically investigate the impact of Ag content, some to investigate the impact of common dopants, such as Ni, and some because they are becoming fairly common in practice. The team also plans to test a new experimental alloy from AMES lab, which has a significantly lower melting point than SAC alloys. Consistent with common industry practice, the alloy used in the solder paste will be SAC305, with two exceptions. The Sn-Pb control will use eutectic Sn-Pb and one leg of the experiment will use SN100C paste with SN100C solder balls to create completely silver-free joints. Of course, in cases where SAC305 paste is used with a ball of another composition, the overall composition of the joint will be a combination of the two alloys. As has been done elsewhere [13], estimates of final alloy composition will be made using the composition calculator of J. Pan [17].

Table 3. Currently planned ATC test alloys. Subject to change during final planning.

No.	BGA Ball Alloy	Trade Name	Solder Paste Alloy	Comments
1	Sn-37Pb	Eutectic Sn-Pb	Sn-37Pb	Control
2	Sn-0.3Ag-0.7Cu	SAC0307	SAC305	Impact of Ag
3	Sn-1.0Ag-0.5Cu	SAC105	SAC305	Impact of Ag
4	Sn-2.0Ag-0.5Cu	SAC205	SAC305	Impact of Ag
5	Sn-3.0Ag-0.5Cu	SAC305	SAC305	Impact of Ag
6	Sn-4.0Ag-0.5Cu	SAC405	SAC305	Impact of Ag
7	Sn-0Ag-0.7Cu + 0.05 Ni + Ge	SN100C	SN100C	0% Ag joint
8	Sn-0Ag-0.7Cu + 0.05 Ni + Ge	SN100C	SAC305	Low Ag joint
9	Sn-1.0Ag-0.5Cu + 0.5Ni	SAC105+Ni	SAC305	Impact of Ni
10	Sn-2.0Ag-0.5Cu + 0.5Ni	SAC205+Ni	SAC305	Impact of Ni
11	Sn-1Ag-0.5Cu + Mn	SAC-Mn	SAC305	Impact of Mn
12	Sn-0.3Ag-0.7Cu + Bi + X	SACX0307	SAC305	Commercial alloy; similar to SAC0307
13	Sn-1.2Ag-0.5Cu + 0.1Ni	LF35	SAC305	Commercial alloy; similar to SAC105+Ni
14	To be Announced	MA3-220	SAC305	Commercial alloy
15	To be Announced	Ames alloy	SAC305	Experimental alloy; Low melting (211C)

In addition to testing a wide range of alloys, the plan is to perform accelerated thermal cycling using a variety of thermal cycle profiles. The choice of profiles is motivated by the desire to provide a systematic set of data from which acceleration models can be derived for the various alloys. Specifically, a full factorial design of experiments approach has been employed in order to fully test the impact of maximum and minimum temperatures, temperature range, and dwell time. Using such an approach, interactions among the three main variables (temperature range, dwell time, and maximum temperature) can be established for each alloy. Table 4 lists the currently proposed thermal cycle profiles. Profile no. 9 is an optional profile to test alloys in a harsh environment, which is of interest in automotive, aerospace, military, and other kinds of electronic products.

The daisy-chain test vehicle for performing thermal cycling of the various alloys has been under discussion for several months and the team is close to making final decisions. Two different package sizes with two different solder ball sizes will be used to determine whether or not these variables affect relative performance among the alloys and to what extent they

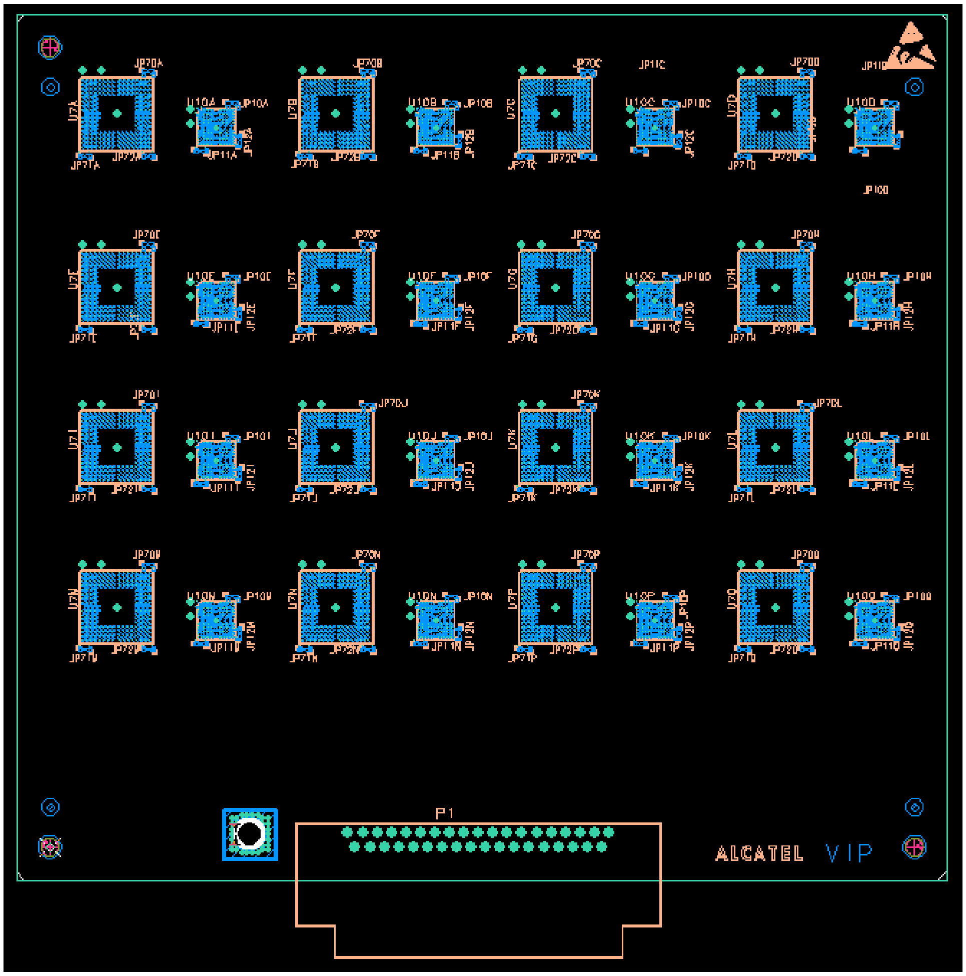

Figure 3. Diagram of the currently planned ATC test vehicle. Subject to change during final planning.

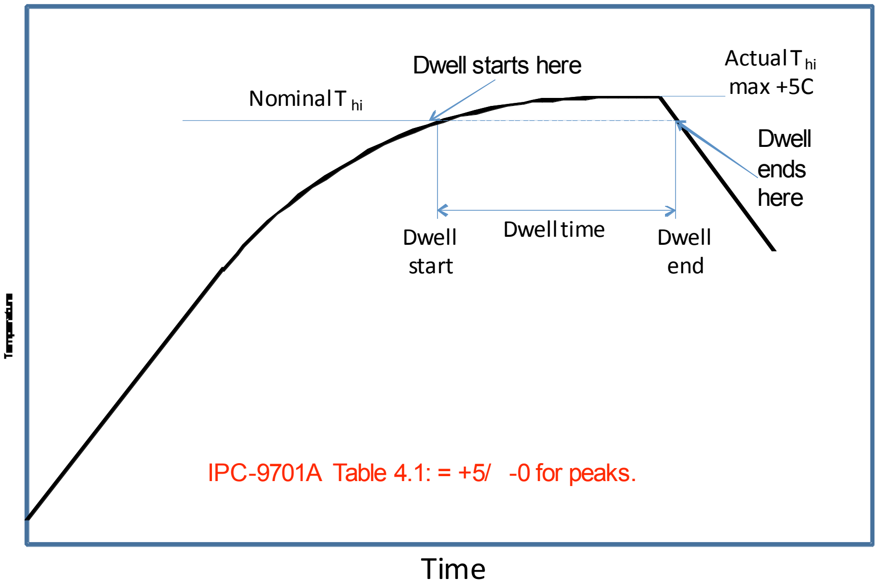

Figure 4. Schematic illustration of the definition of maximum temperature and dwell time in an accelerated thermal cycle.

may impact acceleration behavior. Since many other aspects of the packages are also dissimilar, it will not be possible to evaluate exactly how performance is determined by ball size, pitch, package construction, and so forth. However, the use of two different packages may help to determine how sensitive alloy ranking and acceleration behavior is to package attributes and whether or not further investigations are needed. Table 5 provides a listing of the test vehicle attributes, while Figure 3 shows the overall design. Note that the connector is not populated and is only for wiring purposes. The current plan is to test 16 packages of each type for each ball alloy and ATC profile. This produces an experiment with over 3000 components under test. Since testing will take place at labs of several member companies, the burden will not be too great for any single company yet the amount of data produced will be substantial.

Table 4. Currently planned ATC test profiles. Subject to change during final planning.

No.	Min. Temp. (°C)	Max. Temp. (°C)	Temp. Range (°C)	Dwell Time (min.)
1	0	100	100	10
2	25	125	100	10
3	-40	100	140	10
4	-15	125	140	10
5	0	100	100	60
6	25	125	100	60
7	-40	100	140	60
8	-15	125	140	60
9	-40	125	165	10

Testing will be done using in-situ monitoring of daisy-chain resistances. Since thermal cycling will take place at multiple labs provided by multiple team member companies, details of how to standardize the monitoring and thermal cycling is under discussion. Our preference would be to use one type of monitoring equipment, either event detectors or data loggers. If this is not possible, then a resistance failure criterion with high resistance (e.g. 1000 ohms or full open) will be chosen to minimize the impact of monitoring equipment on the measured number of cycles to failure. Further, standard definitions for terms such as “dwell time,” (that is, when to begin and end each dwell), peak temperature, and so forth must be established. Figure 4 illustrates this point, where the IPC-9701 definition of dwell time is proposed. Final decisions on such definitions will be made prior to execution of testing so that consistency is maintained among labs. The control cells may help to verify that there were no major differences in testing procedures among labs.

STANDARD TEST METHODS

One situation that creates uncertainty in the industry regarding new alloys, and which may slow the adoption of improved materials, is the lack of defined information requirements for alloy acceptance. The acceptability of any alloy may vary from product class to product class, and possibly from company to company. However, the methodology and data requirements may be largely the same, regardless of product requirements or company.

Table 5. ATC test vehicle attributes. Subject to change during final planning.

BGA Package		
Designation	192 CABGA	84 CTBGA
Die Size	12 x 12 mm	5 x 5 mm
Pkg. Size	14 x 14 mm	6 x 6 mm
Ball Array	16 x 16 Perimeter	10 x 10 Full Array
Ball Pitch	0.8 mm	0.5 mm
Ball Dia.	0.46 mm	0.3 mm
Pad Finish	Electrolytic Ni/Au	Electrolytic Ni/Au
PCB		
Thickness	2.36 mm (93 mils)	
Surface Finish	High Temp OSP	
No. Cu Layers	6	
Pad Dia.	0.356 mm	0.254 mm
Solder Mask Dia.	0.483 mm	0.381 mm

Development of standard test requirements and methods has begun with a review of the approach being developed by Hewlett-Packard [18]. The iNEMI team is discussing the merits of this approach and possible modifications that may be necessary in order to meet the needs of the broader electronics industry. A dialogue also is taking place between the Alloy Alternatives team, the Solder Products Value Council (SPVC), and the IPC with the ultimate goal of providing a formal starting point for the development of an IPC standard, or set of standards, addressing testing of new Pb-free alloys. In fact, several team members are part of the IPC task group that has begun drafting such standards.

While the team has not yet established a set of recommendations for IPC to consider, some consensus is beginning to build. Listed below are items upon which the team has tentatively agreed, though some changes may yet take place as discussions continue.

- Standard test *methods* should be developed, but not standard pass/fail criteria, since the latter will vary by sector, company, and product.
- Test methods may be divided into three areas:
    - Basic material properties,
    - Impact to PCA reliability,
    - Impact to PCA manufacturing.
- Reliability tests should include at least accelerated thermal cycling and mechanical shock (drop). The viability and utility of other kinds of tests are still being discussed.
- 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.

- For manufacturability, we need to understand the alloy's impact on the process window, not just whether or not a board can be built under a narrow set of specific conditions.

SUMMARY AND CONCLUSIONS

The industry has seen an increase in the number of Pb-free solder alloy choices beyond the common near-eutectic Sn-Ag-Cu (SAC) alloys. The increasing number of Pb-free alloys provides opportunities to address shortcomings of near-eutectic SAC, while at the same time presenting challenges in managing the supply chain and introducing a variety of technical and logistical risks. This paper has described the continuing efforts of the iNEMI consortium to address the challenges and opportunities of increasing choice of Pb-free solder alloys. A summary of progress includes the following.

- Based on our earlier assessment of key knowledge gaps, the iNEMI Characterization of Pb-Free Alloy Alternatives Project is focused in two areas: (1) standardizing information requirements and test methods for alloy acceptability assessments, and (2) experiments to establish the long term thermal fatigue reliability of a wide variety of alloys.
- Thermal cycle experiments are being planned to address five areas of concern.
    - Validate the impact of Ag concentration in the range of 0 to 4% on thermal fatigue resistance.
    - Evaluate the impact of commercially common dopants, such as Ni, on thermal fatigue performance.
    - Assess how alloy composition affects the acceleration behavior.
    - Provide basic thermal fatigue data for several of the most common alternate alloys on the market today, benchmarking them against eutectic Sn-Pb and SAC305.
    - Assess the performance of some new commercial and experimental alloys.
- Current plans include testing of 14 different Pb-free alloys plus a Sn-37Pb control using eight thermal cycle profiles (with an optional ninth) using two different sized organic BGA packages. Publishing of results is planned for the end of 2010.
- Development of standard test requirements and methods has begun. Several areas of consensus appear to be emerging, and formal discussions with the IPC on establishing test standards have begun. Three separate standards appear to be emerging to address:
    - Basic material properties,
    - Impact to PCA reliability,
    - Impact to PCA manufacturing.

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