Process and Material Selection for zero defects and superior adhesion Lead Free SMT soldering

Dr. Sammy Shina
Hemant Belbase
Department of Mechanical Engineering
University of Massachusetts Lowell
Lowell, MA
Sammy_shina@uml.edu
Karen Walters
BTU International
North Billerica, MA
KWalters@btu.com
Tom Bresnan
Sanmina (formerly Hadco) Corporation; Tech Center East
Ward Hill MA
tbresnan@hadco.com
Peter Biocca
Tim Skidmore
Multicore Solders
Richardson, Texas
Peter.Biocca@multicoresolders.com
Tim.Skidmore@multicoresolders.com
David Pinsky
Raytheon Corporation
Lexington, MA
David_A_Pinsky@raytheon.com
Phil Provencal
Solectron Massachusetts Corporation
Westborough, MA
PhilProvencal@ma.slr.com
Don Abbott
Texas Instruments
Attleboro, MA
d-abbott1@email.mc.ti.com

Abstract

Researchers on this project formed an industry-led "UMASS Lead-Free Consortium" to evaluate various emerging alternatives to lead-based Solders and finishes. The consortium members donated expertise, time, materials and equipment to this lead free project. The various alternatives of lead free materials, surface finishes and manufacturing processes were evaluated as factors in a set of designed experiments and analyzed, in comparison to a baseline of standard leaded processes, using the quality characteristics of visual, mechanical and thermal testing criteria. The Manufacturing Research Laboratory facilities at UMASS Lowell were utilized to test and analyze the performance of alternatives based on the principles of Design of Experiments. Results were analyzed using statistical techniques resulting in determining whether a particular factor was significant to the quality characteristic being measured.

This paper discusses the mechanical reliability tests of the lead free process, outlines the testing decisions made and the techniques used. Results show that the reliability of the lead free joints as measured after 2000 thermal cycles by pull tests have been shown to be of equivalent quality to the lead based solder joints baseline. Additional testing and cross-sectioning of the lead free solder joints are yet to be performed at the time of authoring this paper.

Key words: lead-free, design of experiments, PWB soldering; solder joint reliability

EXPERIMENTAL DESIGN, INCLUDING FACTOR AND LEVEL SELECTION

A design of experiment matrix was selected by the consortium members based on their collective experience and the available resources and materials. The factors and levels selected were as follows:

1. Solder Pastes: these were selected based published performance and actual use in consumer products
- 96.5/3.8 Tin/Silver (SnAg)
- 95.5/3.8/0.7 Tin/Silver/Copper (SnAgCu)
- 57/43 Tin/Bismuth (Sn/Bi)

2. Printed Wiring Board Surface Finishes: These were selected based on low price and wide use:
- Organic Solder Preservative (OSP)
- Electroless Nickel/Immersion Gold (ENIG)

3. Reflow Atmospheres: Nitrogen was selected as well as air to understand its possible effect on the process
- Air
- Nitrogen (20 PPM Oxygen)

4. Reflow Process: In order to fully understand the impact of the reflow process, 2 factors were selected, one for Time above Liquidus (TAL) and the Reflow profile. Levels were selected to examine the impact of lessening the thermal shock to the electronic components by trading off the lengthening of the reflow time (TAL) versus a lower peak temperature or applying a longer preheat exposure time to the reflow process (a linear or a cash register reflow profile).
- TAL: 60, 90 or 120 seconds
- Profile: linear (soak) or Cash register profile

5. Selected experimental conditions. These include the components, test vehicle, and base-line Tin/lead process

Test Vehicle

The test vehicle was a 4" x 5.5" FR4 board (Figure 1). A total of 66 boards were assembled and tested. 54 printed circuit boards were assembled 100% lead-free and 12 boards were assembled utilizing a controlled 63/37 tin/lead process. A no clean, high residue, high activity flux was used with all four alloys. This was based on optimal flux results from a past study3.

Components

The control boards were built with devices that had a tin/lead component finish and the experimental test boards were assembled with parts that had lead-free finishes. The lead-free passive chips were tin-plated and the lead-free integrated circuit devices were plated with nickel palladium. Components loaded on each board included: (24) 0805s, (18) 0402s, (21) 1206s, (1) LQFP100s - .01977 pitch, (1) LQFP120s - .0157 pitch, (3) SO14s, (3) SO14s

Experiment Layout

Twenty-seven lead-free experiments were run examining the 3 alloys, 2 printed circuit board (PWB) surface finishes, 3 different times above the melting point, soak versus no-soak and nitrogen versus air (reference previous section). For each experiment a sample size of 2 boards was chosen. On each PWB there were 1,279 visual defect opportunities. In addition 12 PWB's were assembled using tin/Lead solder, tin/lead finish components, and a typical conventional tin/lead profile. The Design of Experiment test plans and a set of lead based baseline material and processes matrices are presented in Tables 1 and 2.

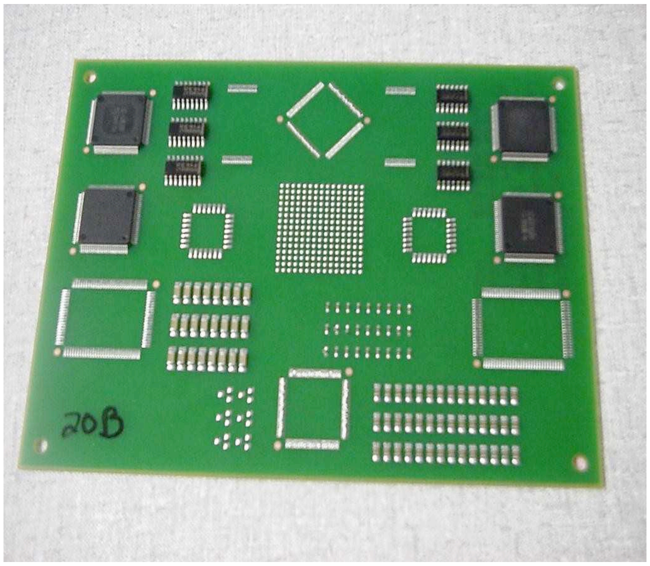


Figure 1: Test Vehicle

VISUAL ANALYSIS RESULTS

Test method and Defect Count: Tests were performed according to industry standards and with specific visual inspection settings. Several defect categories were observed:
- IPC JSTD-001 followed as guideline
- Lens Magnification 0.7 X 10x

Defect count

- Fillet
- Poor wetting
- Bridging
- Solder balls

Lead-free solders do not seem to wet very well as compared to tin-lead solder. Most of the defects encountered were due to poor wetting and fillets. Since the flux used in the experiments is a no clean, high activity, high residue type, most of the boards had high flux residue.

At first glance it could be observed that the solders did not reflow as expected. This could be due to the metallurgical behavior of the materials of solder and surface finish. Since wetting characteristic of the solder will depend upon the metallurgy of component lead and pad surface finish, this was not of a surprise. Indeed this would be more interesting to analyze different lead-free solders behavior with different options.

Visually OSP finished boards seemed to have more defects than the ENIG finished boards. It was also observed that nitrogen did improve the wetting characteristic of the solder.

Tin-lead baseline had no different behavior than the lead-free setup. Although the defect counts was less than the lead free they followed the same behavior for OSP and ENIG surface finish and nitrogen reflow environment

Statistical analysis indicated that the significant factors were lead-free solder paste, PWB surface finish and the reflow environment (Nitrogen). All other factors were not significant in the visual defect performance of the PWB's.

Table 1: Lead Free Solder test plan

Paste	**S. Finish**	**TAL**	**Soak**	**Nitrogen**
Sn/Ag/Cu	OSP	60sec	Yes	Yes
Sn/Ag/Cu	OSP	90sec	No	No
Sn/Ag/Cu	OSP	120sec	No	Yes
Sn/Ag/Cu	ENIG	60sec	No	No
Sn/Ag/Cu	ENIG	90sec	No	Yes
Sn/Ag/Cu	ENIG	120sec	Yes	Yes
Sn/Ag/Cu	OSP	60sec	No	Yes
Sn/Ag/Cu	OSP	90sec	Yes	Yes
Sn/Ag/Cu	OSP	120	No	No
Sn/Bi	OSP	60sec	No	Yes
Sn/Bi	OSP	90sec	No	Yes
Sn/Bi	OSP	120sec	Yes	No
Sn/Bi	ENIG	60sec	No	Yes
Sn/Bi	ENIG	90sec	Yes	No
Sn/Bi	ENIG	120sec	No	Yes
Sn/Bi	OSP	60sec	Yes	No
Sn/Bi	OSP	90sec	No	Yes
Sn/Bi	OSP	120sec	No	Yes
Sn/Ag	OSP	60sec	No	No
Sn/Ag	OSP	90sec	Yes	Yes
Sn/Ag	OSP	120sec	No	Yes
Sn/Ag	ENIG	60sec	Yes	Yes
Sn/Ag	ENIG	90sec	No	Yes
Sn/Ag	ENIG	120sec	No	No
Sn/Ag	OSP	60sec	No	Yes
Sn/Ag	OSP	90sec	No	No
Sn/Ag	OSP	120sec	Yes	Yes

Table 2: Tin/Lead Test plan

Surface Finish	**Reflow Environment**
OSP	Nitrogen
OSP	Nitrogen
OSP	Nitrogen
OSP	Air
OSP	Air
OSP	Air

It was interesting that a combination of 4 material and processing conditions attributed to defect free and lead free soldering processes for SMT technology. These are outlined in Table 3.

Table 3. Conditions for Defect free and lead fee soldering materials and processes

.Paste	**S. Finish**	**TAL**	**Soak**	**Nitrog**
Sn/Ag/Cu	***ENIG***	90sec	**No**	yes
Sn/Ag/Cu	***ENIG***	***120sec***	**Yes**	yes
Sn/Ag	***ENIG***	**60sec**	**Yes**	yes
Sn/Ag	***ENIG***	90sec	**No**	yes

RELIABILITY TESTING FOR LEAD FREE SMT TECHNOLOGY

Mechanical Sources of Materials Failures

Mechanical Reliability of Lead free solder joints is based on several properties of the material being studied. They include the following:

1. Fatigue: this can result in a sudden and catastrophic failure of the solder joint. It is mostly due to fluctuating load or deformation over time. Fatigue begins with a crack, and proceeds to grow until it becomes unstable. Cracks are generated due to slow embrittlement of the solder joint over time. A major source of fatigue is thermal cycling, where load cycling is produced when the product is being subjected to varying temperatures. Many electronic components are designed with flexible leads to reduce the temperature effects of thermal fatigue. There are 2 types of fatigue

    High Cycle Fatigue: is when the thermal load is low, and the strain is in the elastic region, with reversible strain deformation. The number of cycles required is between 10,000 to 100,000

    Low Cycle Fatigue: This occurs with high loads, and the strain cycle is in the plastic region, with deformation occurring since the solder joints does not return to its original geometry. This is developed is less than 10,000 thermal cycles.

2. Creep. This failure is caused by the material being subjected to plastic (unrecoverable) deformation over time, under varying stress and temperature causing geometrical changes of dimensions. This causes the joints to have increased elongation and reduced cross sectional areas. As a result, there might be contact resistance problems over time with creep. Creep strain begins with temperature varying at 35-75% of alloy melting temperature (based on Kelvin). Creep rates change with strain and temperature, and most creep action is short term and occurs in less than 1 hour[4].
3. Impact or Mechanical Chock: This occurs when force or displacement is rapidly applied. The resulting stress deformation is much larger than if the force was applied gradually. This type of behavior is usually simulated by drop tests. Such tests would consist of dropping the product 1meter onto a concrete floor.5 times each face (10 drops) and 5 times each edge which is a

non–connector edge (15 drops). Solder joints rarely fail this test, and therefore, this type of failure was not part of our reliability testing for lead free SMT technology.

4. Reforming of Inter-metallic Boundaries. Temperature cycling would cause migration of certain metals inside the alloy matrix, and therefore would affect some of the mechanical and electrical properties of the solder joints. This behavior would best be investigated with cross-sectioning, and that action was not performed as of this time.

Temperature Cycling Profile.

The thermal profile selected for temperature cycling lead free solder joints will have to be selected depending on these varying parameters.

- Maximum and minimum temperature. 0 and 100’ C
- Ramp rates (up and down) for Min/maximum temperature. Select the fastest possible rates to increase the effects of low cycle fatigue and creep = 10’C/min.
- Dwell Times at high and low temperatures. These are the shortest time for the solder joint system to stabilize prior to reversing the temperature = 20 minutes.
- Number of cycles. This number should be balanced between the reasonable time required to show deterioration of the solder joints versus the possibility of hard failures. It was decided to visually inspect the joints for cracks every 200 hours and to perform another pull test after 2000 cycles.
- No Humidity or Power cycling were performed.

The temperature Profile is shown in Figure 2.

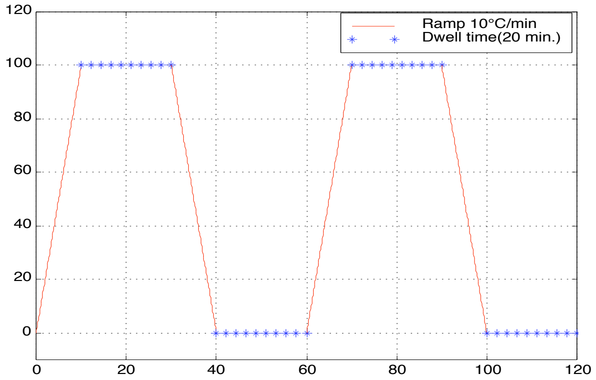


Figure 2. Thermal Profile for Reliability Testing of Lead free Soldering

PULL TEST METHODOLOGY

Some of the issues of the pull test are how to develop a proper test fixture and method of pulling (straight and/or shear pulls) since no systematic method was found in the literature. Mr. Saed Kazan, a graduate student at the University of Massachusetts Lowell developed a good working prototype and methodology for the pull tests. A fixture was developed to lock-in the PWB’s, and allows the pull instrument to align perfectly with the pulling head. The pulling instrument was a set of medical tweezers, which were modified for this test and attached to an Instron machine. The pull test fixture is shown in Figure 3. The pull rate was set at .01” per minute, It was important that the pull test recorded neither a pad pull nor a lead break. For that matter, and to ease the data analysis, several pulls were made for each component, and both the minimum (joints) break point was recorded, as well as the maximum pull at any point on the solder joint system (this maximum pull included pad lifts and broken leads). Only SO14 Palladium components were pulled, with many pulls need to record a single component and include both minimum and maximum pulls. Several lessons learned were discovered during the pull tests.

1. It is probably best to have a 45’ degree pull as opposed to straight pulls. This will record both straight and shear pull forces. This is preferable since the comparison will be made of the lead free versus the tin lead baseline
2. Care should be exercised in monitoring the element(s) that separated. It is important not to confuse pad pulls or lead breakage with solder fracture, and to only record pull values when it is clear that only the solder pad fractured.
3. It is advisable to pull all of the leads in an IC so that a profile of the pull distribution is shown. The minimum value of the various pulls should be recorded, not the average value.

Figure 3. Pull test Fixture

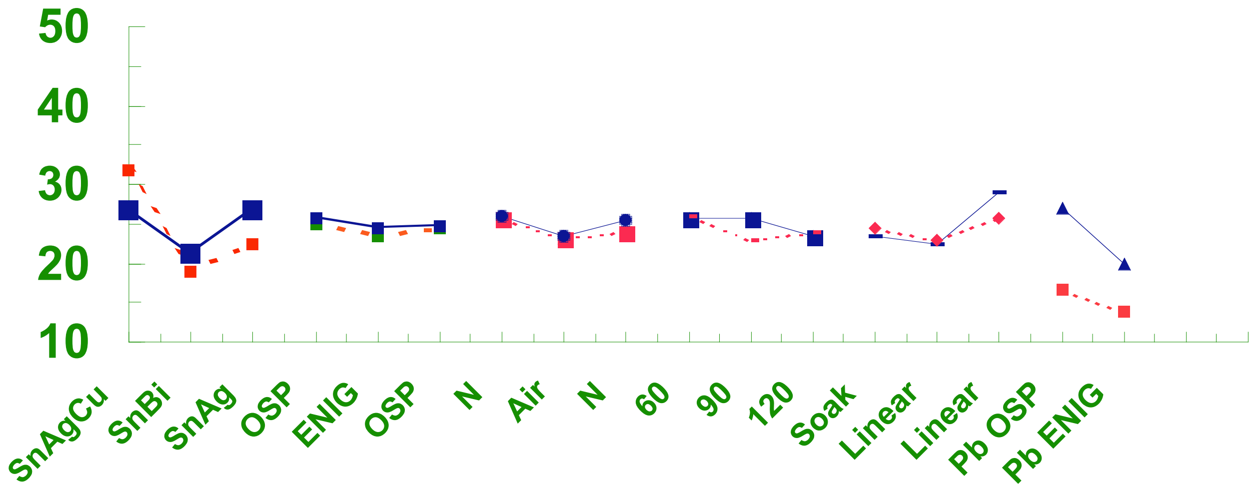
PULL TESTS RESULT SUMMARY

The result of pull test during 2000 cycles of thermal cycling indicated the following:

- Not a single joint has separated, when inspected every 200 cycles during the 2000 total thermal cycle test

Statistical analysis of the minimum-value pull-tests before and after thermal cycling indicated that only the solder material was significant. All other factors did not influence the value of the pull tests. The pull strength of the different solder alloys remained essentially the same, and much higher than the tin/lead baseline. Only the tin/lead pull

Figure 4. Minimum Pull strengths (Newtons) versus factors showing before (solid line) and after cycling (dashed line)



- Strength increased after thermal cycling, as indicated by conventional wisdom, due to changes in the inter-metallic composition of the copper migrating through the alloy towards the components.
- Statistical analysis of the maximum-value pull-tests before and after thermal cycling indicated that only the solder material was significant. All other factors did not influence the value of the pull tests. The pull strength of the different solder alloys increased significantly, probably due to the fact that many of the pulls included those due to pad lifts, which tended to increase in value. This is probably due to better curing of the pad adhesion. Only the Tin Bismuth solder did not increase in value, probably due to the fact that the pull test indicated joint fracture. The temperature cycling did in fact relieve the creep strain on the joints, since the melting temperature of the Tin/Bismuth was close to the thermal cycling maximum (138 versus 100' C). The pull for the Tin Silver alloys were mostly pad pulls. The statistical analysis indicated a slight (7%) effect of the surface finish, mostly due to the fact that the pad pulls influenced this analysis. The data is shown in Figure 4.

CONCLUSION

It has been shown in this paper that it is possible to obtain a Lead Free soldering process that is defect free and exhibits a better reliability profile than that of the baseline Tin Lead.

The selection of the material and processing parameters are very important to the defect free visual performance of the Lead-free soldering. For reliability performance, as expressed by thermal cycling, the Tin silver/alloys have shown to be stronger than the tin lead baseline and performed equally well after 2000 thermal cycles. Additional work is needed to complete the reliability study of this project, especially in studying the inter-metallic structure of the alloys

ACKNOWLEDGMENTS

The project team wishes to acknowledge the following for their knowledge, material and resource contributors to this research as well as the member corporations of the UMASS Lead free Consortium

Liz Harriman. TURI Institute
Charles Pace, STEP Program
Raymond Lizotte, Texas Instruments
BTU Corporation
Multicore Solders
Raytheon Company
Sanmina (formerly Hadco) Corporation, Tech Center East
Solectron Massachusetts Corporation

We would like to thank Solectron Corporation, Westborough, MA site for assisting the project team in completing the final assembly of the boards at their facilities. Special thanks to Phil Provencal and entire staff of Solectron Massachusetts for their technical help and great moral support during the entire assembly process.

We would also like to Sanmina (formerly Hadco) Corporation for their contribution of the PWB's with the specified surface finishes. In particular Dennis Gagne of process engineering and General Manager Paul Nelson

Thanks to Raytheon Corporation Reliability Analysis Laboratory for their use of environmental chambers, and in particular Bill Tice, Manager of the Laboratory.

SPONSORSHIP

This research was sponsored by The University Research in Sustainable Technologies program which is a joint project of the Toxics Use Reduction Institute (TURI) and the Center for Environmentally Appropriate Materials (CEAM) at University of Massachusetts Lowell, with support from the Commonwealth's Strategic Envirotechnology Partnership (STEP) program. The University Research program taps the research capabilities of the University of Massachusetts to advance the investigation, development and evaluation of sustainable technologies that are environmentally, occupationally and economically sound. The program provides research funding to UMass faculty from all campuses, annually, on a competitive basis and encourages faculty/industry partnerships and cross-campus collaboration.

REFERENCES

[1] Shina, S. et al; “Selecting Material and Process Parameters for Lead Free SMT Soldering Using Design of Experiments Techniques”, Proceedings of the APEX Conference, Long Beach, CA, January 2001

[2] Shina, S. et al, “Design Of Experiments For Lead Free Materials, Surface Finishes And Manufacturing Processes Of Printed Wiring Boards”, Proceedings of the SMTA International Conference, Chicago, IL, September 2000.

[3] Skidmore, T. and Walters K., “Lead-Free Research: Optimizing Solder Joint Quality”, Circuits Assembly, April 2000.

[4] Collins, J., Failures of Materials in Mechanical Design, 2nd edition, John Wiley and Sons, NY, 1993

[5] “IPC Roadmap: A Guide for Assembly of lead-free Electronics”, Draft IV, June 2000.