A TEST COMPARISON OF SAC AND NON-SAC LEAD FREE SOLDERS

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BACKGROUND

SAC305 (Sn96.5/Ag3.0/Cu0.5) has become the de-facto choice for lead-free solder in the electronics industry for both SMT and through-hole applications. However, silver is expensive and the price is very volatile, causing sharp fluctuations in alloy cost. The alloy exhibits significantly more solder voiding than Sn63 and has a dull and grainy joint structure. SAC305 is a tertiary alloy, making it more difficult to control than a binary alloy in some soldering processes.

Several years ago, the IPC Solder Products Value Council undertook a study of lead free pastes. They selected four SAC (tin/silver/copper) alloys to test. Six testing protocols showed no significant differences in performance between the alloys. The Council stated, "In conclusion, based upon the results of this study, it is the recommendation of the IPC SPVC that, due to lower cost and equivalent performance, the 96.5/3.0/0.5 SAC alloy be the lead free alloy of choice for the electronics industry".[1] They did not perform any test on any non-SAC alloy for SMT applications. Nor did they perform any testing whatsoever on any lead-free alloy for any other soldering process (such as wave soldering or selective soldering). This is how SAC305 evolved into the default choice for lead-free soldering applications. Interestingly enough, iNEMI recommends a tertiary SAC alloy for SMT applications and a binary alloy for wave soldering applications.

But is a SAC alloy the best choice for lead free applications, or do other alloys exist that perform as well as or better than the SAC alloys? How does one evaluate solder joint reliability?

DISCUSSION

The electronics industry literally grew up around Sn63/Pb37. In the beginning, components and devices were large, unwieldy, and hand-soldered. Little emphasis was put on circuit board reliability. Defects were often fixed in the field. Little or no test data was either available or needed for Sn63. As the industry became more sophisticated, so did circuit boards and their components. The "smaller is better" axiom became reality. Wave soldering was introduced to provide reduction in cost and defect rate, and to reduce variables in the soldering process. An effort was made to emphasize reliable circuit boards going out into the field free of defects As time went on, various tests were needed, performed and then accepted by industry because they provided valuable circuit board reliability information. As the industry grew, so did the knowledge base. The same situation is occurring today with the advent of lead-free solders, the difference being that standard tests are both known and accepted. These tests for joint reliability, joint performance, and/or joint integrity for Sn63 include the following:

- Thermal Cycling
- Vibration Testing after Thermal Cycling
- Shock Testing after Thermal Cycling
- Inter-Metallic Layer Testing
- Shear Testing
- Solder Voiding
- Drop Tests
- Red Dye Tests
- Pull Tests
- Temperature/Humidity Tests

Since many of these tests have provided valid and beneficial information for Sn63 data generation, it is not unreasonable to extend the same tests to lead-free alloys. These tests are meant to provide information to electronics manufacturers regarding the strength, reliability, and longevity of a solder joint, with the ultimate objective of minimizing or eliminating joint failure of a lead-free circuit board.

Inexpensive tests regularly referred to and performed by electronics manufacturers might include the following. A pull test may be performed to ascertain at what force level a solder joint system will fail by pulling the component out of the joint, destroying the component without destroying the joint, or pulling the component, joint, and pad off the circuit board. It is a test to failure. The best outcome would be for the component, joint, and pad to pull off the board since then the entire joint assembly would be stronger than the underlying board. The worst outcome would be for the component to pull out of the solder joint. No pass/fail criteria exists for this test so one is left with the theory that the greater the force exerted to cause failure, the stronger the solder joint. Likewise a drop test may be performed to see if joint failure can occur when a circuit board is dropped from a determined height.

Thermal cycling with subsequent tests for shock and vibration are routinely performed on Sn63. Thermal cycling provides accelerated aging information useful in predicting joint reliability. Each solder manufacturer shows their test results on their alloys. 1,000 thermal cycles (accelerated aging) is an acceptable number of cycles, which loosely represents about 3-1/2 years of circuit board service. The boards are then tested for shock and vibration, again to provide joint reliability data.

Testing of the inter-metallic layer is beneficial, since an inadequate inter-metallic thickness may indicate insufficient bond formation between the component lead and the solder, and the solder and the board pad. An either very thin or excessively thick inter-metallic layer connotes greater solder attachment failure potential. A desired inter-metallic thickness is 1 to 5 microns. Over time, the inter-metallic layer may grow. Thermal cycling should show accelerated aging growth of the inter-metallic thickness. Too great an inter-metallic thickness is detrimental to joint reliability since the joint may become more brittle.

Shear testing may be performed to see at what force a joint component can be "sheared", thus indicating joint strength. It is thought that the harder the solder alloy, the greater the shear force necessary to shear the component. Since lead is malleable and tin/lead solder is softer than lead-free solder, it stands to reason lead-free solders would have higher shear strength than tin/lead solders. Other studies have confirmed this fact.[2] However, an examination of the IPC standards (IPC-610 and the J-STD's) failed to turn up any performance standards (or pass/fail criteria) for pull testing, drop testing, or shear testing. The most that can be said about a shear test is that the greater the force required to shear the component, in theory, at least, the better and stronger the solder joint.

Much industry discussion regarding solder voiding and joint reliability has recently occurred. Solder voiding tests might be performed. The only IPC reference found regarding solder voiding is in IPC-610 with regard to BGA's, where a defect is classified as "more than 25% voiding in the ball x-ray image area".[4] The Solder Value Products Council recently addressed this issue, and stated that, "Nine separate methods of statistical analysis comparing cycles to failure looking at both voids greater than 25% of the interconnection area and total voids have been done. Absolutely no correlation between voids and failures under thermal cycling has been demonstrated….there is no evidence that the type of solder joint voiding observed in the SAC alloy solder joints has any significant impact on solder joint reliability."[6] Yet voiding remains an issue often discussed.

A red dye test may indicate the potential for joint failure, and may be performed to visibly show micro cracking in solder joint surfaces before and after thermal cycling. It is believed that micro cracks are the point source for additional cracking, which may lead to joint failure.

Temperature/Humidity tests can be performed to see if an alloy is susceptible to the formation of tin whiskers. The formation of tin whiskers, and/or dendrytic growth, may cause circuit board failure by causing short circuits at an undetermined time after the circuit board has been placed in use. iNEMI recently published their recommendations to mitigate the potential for whisker formation. They stated that "unalloyed tin electroplating has a long history of whisker formation and growth that has resulted in reliability problems for various types of electronic equipment…It is generally accepted that the driving force for whisker formation is compressive strength on the tin films."[3] Various solutions are promulgated by iNEMI to reduce the possibility of failure.

Metallic Resources contracted with an independent laboratory to conduct an exhaustive test comparison between SAC305 and SC995e™ (a cobalt enhanced binary alloy consisting of Sn99.5/Cu0.5/Co). Because it has become the industry standard, the SAC305 alloy was the control. Thermal cycling (including subsequent shock and vibration), solder voiding quantification, a pull test, and a shear test were performed for both alloys. The inter-metallic thickness and alloy diffusion into the copper was examined both before and after thermal cycling/aging for both alloys. In addition, the cobalt alloy was subjected to a temperature/humidity test.

Boards hot air leveled with the Sn99.5/Cu0.5/Co (SC995e) alloy were manufactured. Half of the boards used SAC305 no clean solder paste for the SMT portion and the same alloy for the through-hole portion. The remaining half used the Sn99.5/Cu0.5/Co alloy in both no clean solder paste for SMT and bar solder for wave soldering. Both pastes were manufactured with the same flux chemistry to reduce potential variables. These boards were then sent to a recognized independent laboratory for testing.

TEST PARAMETERS

Thermal Cycling Parameters: IPC-9701-A protocol. Boards of both SAC305 and the enhanced cobalt alloy were subjected to a thermal range of –10 to +110°C. The number of thermal cycles was 1,000. The temperature rate of change was 10-20°C/minute. The soak time at each temperature extreme was 5 minutes.

Shock Test Parameters: IPC-9701-A protocol. The shock amplitude and duration was 1500G, 0.5mSec. The number of shocks was 5. The direction of shocks was normal to the surface of the printed wiring board (Z-axis).

Vibration Test Parameters: IPC 9701-A protocol. The frequency range was 20 to 20,000Hz. The vibration amplitude and duration was 15Grms for one hour and 20Grms for one hour. The direction of vibration was all axis simultaneously + 3 rotational displacements (6 degrees of freedom).

Shear Test Parameters: a crosshead speed of 0.1mm/minute with various target components using an Instron 3343 tester. A section of the circuit board was placed on a shear test fixture with an immovable edge to hold the target component in place. The crosshead of the Instron was lowered at a rate of 0.1mm/minute until the device sheared from the circuit board. Three resistors and five capacitors were sheared from each assembly (SAC305 and enhanced cobalt).

Inter-metallic Examination and X-Ray Mapping of the Inter-metallic: measurements were made and photographs taken of the inter-metallic thickness before and after thermal cycling of the cobalt alloy.

Pull Test Parameters: A metal threaded stud was fixed to the top of the IC package and placed in a fixture to hold down the edges of the board while tensile force was exerted. The force was directly normal to the surface of the board to provide equally distributed force. An Instron 3343 tensile tester pulled the stud at a rate of 1 mm/min. until fracture occurred. The maximum force was recorded for both the cobalt enhanced and SAC305 alloys.

Temperature/Humidity Parameters: JEDEC JESD22-A104-B protocol. An assembled circuit board soldered with the enhanced cobalt alloy was subjected to temperature and humidity for 500 hours at temperatures of 85°C +/- 2°C. Relative humidity was at 85% +/-5%. The total test duration was 500 hours. No bias was applied to the circuit board. No monitoring took place until the completion of 500 hours.

TEST RESULTS

Thermal Cycling: (see Fig. 1) both the SAC305 and cobalt alloys exhibited no deterioration in the integrity of the solder attachment after 1,000 thermal cycles. Minor voiding was observed in the solder attachments and TSOP devices for the SAC305 as well as the Cobalt alloy. Voiding was estimated at between 2% to 12%, well within the range of IPC-610 (25% max) and much below the SPVC’s recommendation noted above.

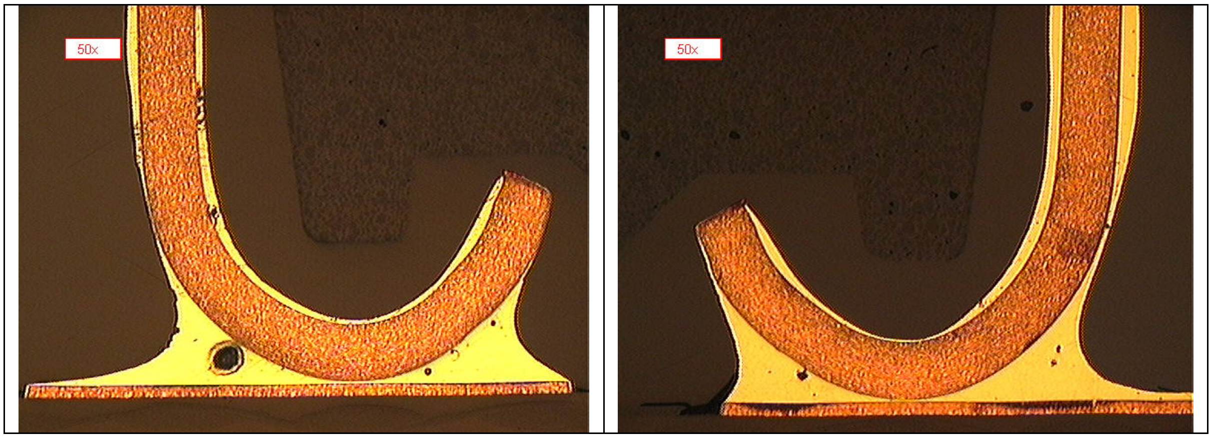

Fig. 1. Micrographs after thermal cycling. Left: SAC305 J-Lead. Right: Cobalt J-Lead.

Thermal Shock: (see Fig. 2) for the SAC305, minor voiding was observed on tested J-leads and no voiding of TSOP devices. For the cobalt alloy, the TSOP devices exhibited minor voiding while no voiding was observed on the J-leads. The cobalt enhanced alloy exhibits a much finer and more uniform grain structure than that of the SAC305. As indicated in the below micrograph on the left, the dark areas are silver enriched pockets of the SAC alloy.

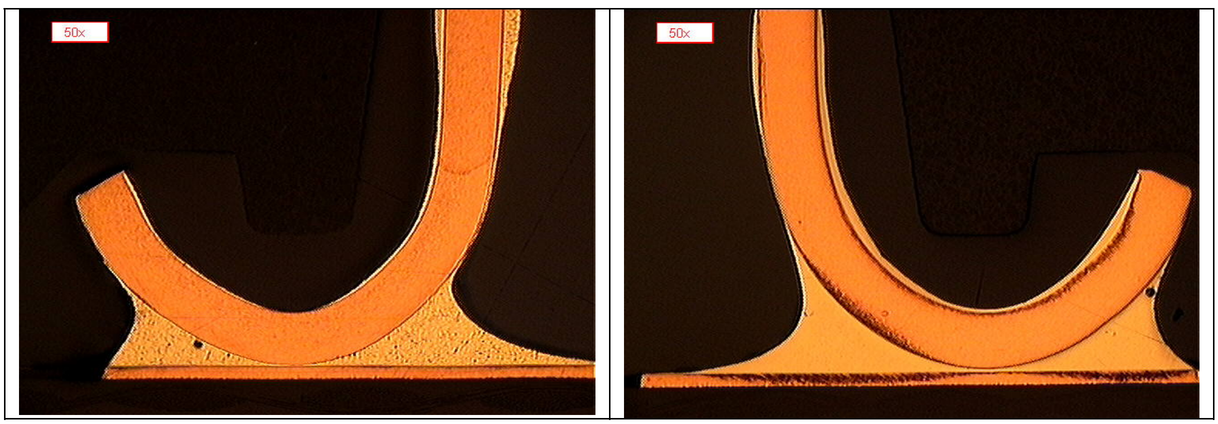

Fig. 2. Shock Test micrographs. Left: SAC305 J-Lead. Right: Cobalt J-Lead

Vibration: (See Fig. 3) for the SAC305 alloy, minor voiding was observed on both the J-leads and TSOP devices as well as minor cracks. The cobalt enhanced alloy performed the same as the SAC305. The grain structure of the cobalt enhanced alloy is much finer and tighter than that of the SAC305, providing a significantly brighter solder joint.

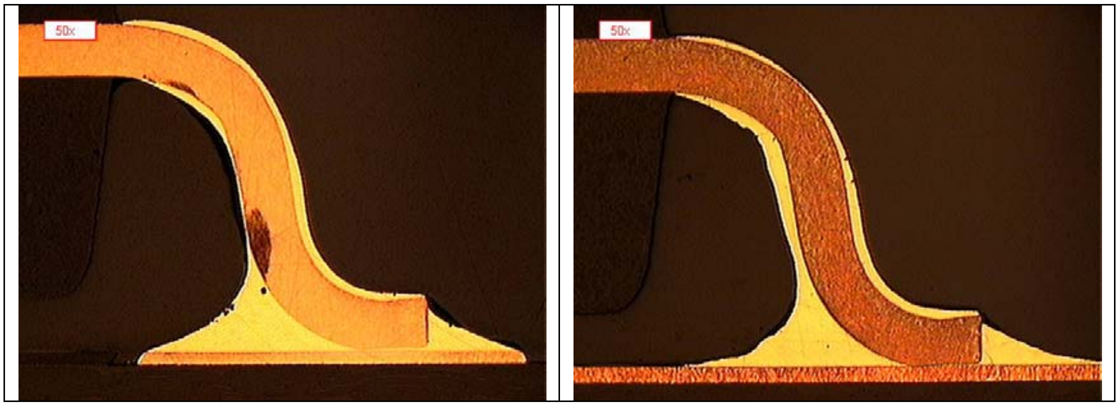

Fig 3. Vibration micrographs. Left: SAC305 TSOP. Right: Cobalt TSOP.

Shear: (Table 1 below) the cobalt enhanced alloy outperformed the SAC305 on the resistors while the SAC305 outperformed the cobalt enhanced alloy on the capacitors. Averaging all results, the cobalt enhanced alloy slightly outperformed the SAC305. The smaller deviation of the cobalt enhanced alloy suggests a greater ability to maintain consistency in all soldering processes.

Table 1. Shear Test Results Summary

Device Location	Maximum Shear Force (N)	
	SAC305	Cobalt
R19	76.13	64.93
R21	82.27	85.01
R34	68.83	78.62
C13	103.60	90.43
C14	103.65	92.69
C15	99.16	77.28
C22	74.65	69.03
C34	68.32	72.42
Average Resistor	75.74	76.19
Deviation Resistor	6.73	10.26
Average Capacitor	89.88	80.37
Deviation Capacitor	17.03	10.66
Overall Average	84.58	78.80
Overall Deviation	15.24	9.98

Inter-metallic examination: (See Fig. 4) the cobalt enhanced alloy showed an average inter-metallic layer of 2.18 microns for the unstressed sample, while the average thickness after 1,000 thermal cycles was 2.32 microns. This suggests little or no growth of the inter-metallic layer, which indicates long term solder joint reliability. Both unstressed and stressed samples were well within the 1 to 5 micron desired thickness. (See Fig. 5) the SAC305 alloy showed an average inter-metallic layer of 2.00 microns for the unstressed sample, while the average thickness after 1,000 thermal cycles was 3.43 microns, still within the desired thickness range.

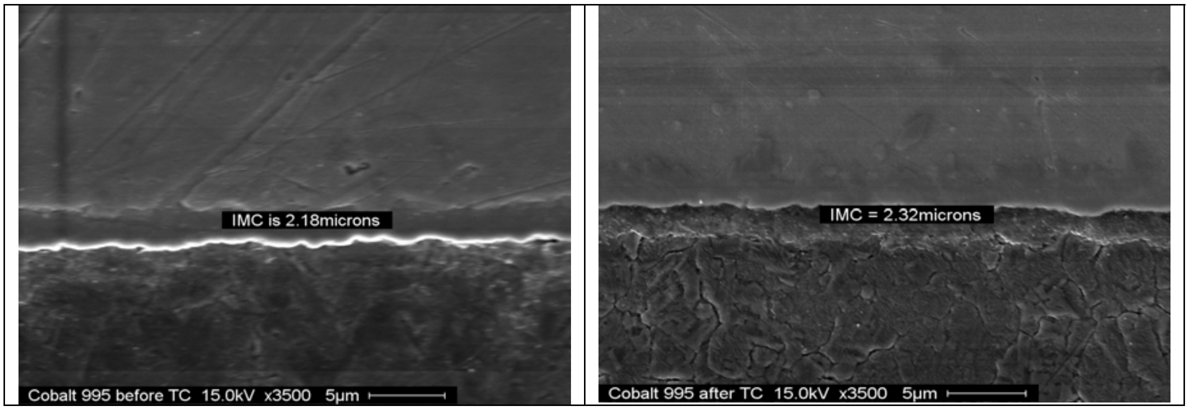

Fig. 4. Micrographs of inter-metallic layer. Left: cobalt enhanced alloy before thermal cycling.. Right: cobalt enhanced alloy after 1,000 cycles.

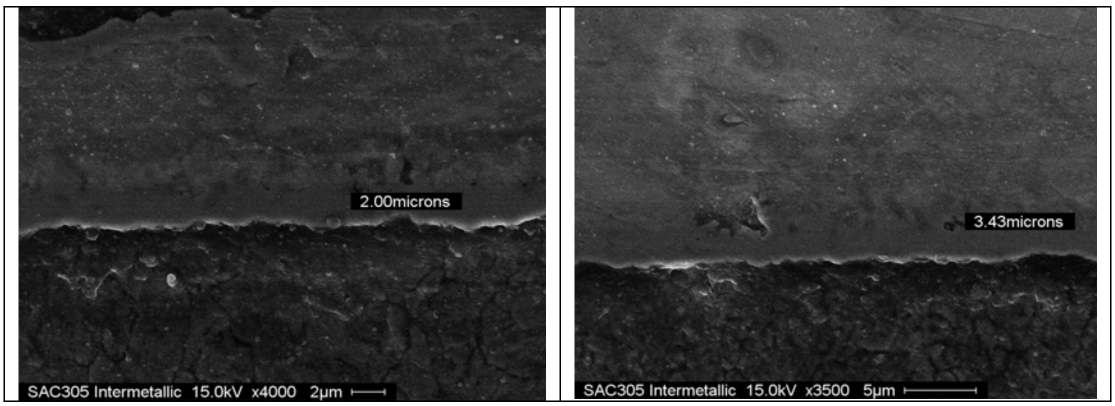

Fig. 5. Micrographs of inter-metallic layer. Left: SAC305 alloy before thermal cycling.. Right: SAC305 alloy after 1,000 cycles.

X-ray inter-metallic mapping: (see Fig 6.) both the cobalt enhanced alloy and SAC305 samples were subjected to X-ray mapping to show copper diffusion at the inter-metallic layer level. Copper diffusion was limited strictly to the inter-metallic layer for the cobalt enhanced alloy, while the SAC305 exhibited more copper diffusion into the bulk solder. The greater the copper diffusion beyond the inter-metallic layer, the more brittle the solder joint can become.

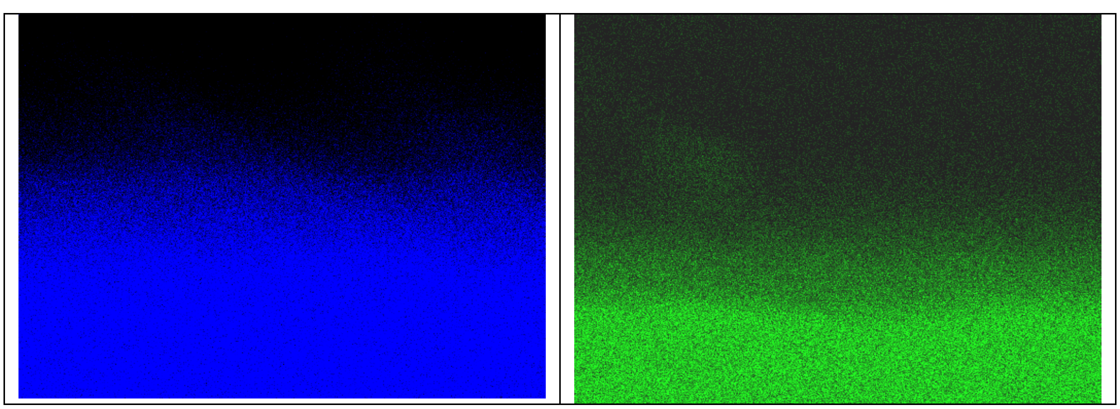

Fig. 6. X-ray map of copper diffusion in cobalt alloy (left) and SAC305 alloy (right).

Pull Test: (See Table 2) the SAC305 alloy slightly outperformed the cobalt enhanced alloy on the three devices pulled with 352.5N for the SAC alloy and 316.5N for the cobalt enhanced alloy. However, the SAC alloy exhibited a larger deviation in the results (41.6N for the SAC alloy and 11.2N for the cobalt enhanced alloy), which suggests that the cobalt enhanced alloy shows a greater ability to maintain consistency in the soldering process. Since no figures exist for pass/fail criteria, and the test is to failure, it is not known if the forces are indicative of real world use.

Table 2. Pull Test Results Summary

Device Location	Maximum Shear Force (N)	
	SAC305	Cobalt
U2	305.2	305.7
U7	368.7	315.8
U11	383.6	328.1
Average	352.5	316.5
Deviation	41.6	11.2

Temperature/Humidity: after the parameters discussed above were completed, the cobalt enhanced solder attachments were examined for defects precipitated by the test. No structural defects on the circuit board were observed at 30x magnification. No tin whiskers were observed.

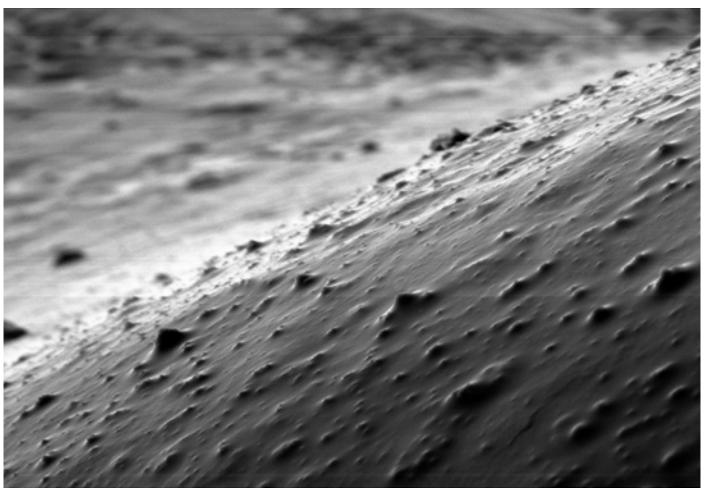

Fig. 7. Magnified solder joint showing no tin whiskers

CONCLUSIONS

Although much industry testing has yet to be accomplished and evaluated, the independent testing performed has shown that an enhanced tin/copper lead-free alloy can provide benefits equal to, and in some cases better than, those of SAC alloys. Since silver has drastically increased in price with additional increases to come, it would seem a non-silver alloy which provides the same or better results would be preferable and much more cost-effective than SAC305. In addition, the cobalt enhanced alloy provides a much brighter and shinier solder joint with a tighter grain structure when compared to SAC305 joints; in fact, the solder joints are virtually indistinguishable from Sn63 joints. When used in through-hole applications, a binary alloy (such as cobalt enhanced) is much easier to maintain operating specifications when compared to a tertiary alloy (such as SAC305): thus less solder pot maintenance becomes necessary. When performance, joint reliability, cost, aesthetics, and ease of process control are all considered, a non-SAC lead-free solder alloy outperforms a SAC alloy. (See Table 3.)

Table 3: Comparative Advantages of a Non-SAC and a SAC alloy (+ equals advantage, - equals disadvantage).

Attribute	Advantages	
	Cobalt enhanced	SAC305
Performance	+	+
Cost	+	-
Appearance	+	-
Availability	+	+
Ease of Control	+	-
Melt Point	+	+

References

1. IPC Solder Products Value Council, "Round Robin Testing and Analysis of Lead Free Solder Pastes with Alloys of tin, Silver and Copper final Report", p. v.

2. Thomas Siewert, Stephen Liu, David R. Smith, Juan Carlos Madeni, "Properties of Lead-Free Solders Release 4.0", p. 21, Table 1.18, Database for Solder Properties with Emphasis on New Lead-free Solders, national Institute of Standards and Technology & Colorado School of Mines, February 11, 2002.

3. iNEMI, "iNEMI Recommendations on Lead-Free Finishes for Components Used in High-Reliability Products, Version 4 ", p. 3-4, 12/1/06.

4. IPC, "IPC-A-610, Revision D", p. 8-83, February 2005.

5. IPC Solder Products Value Council, "The Effect of Voiding in Solder Interconnections formed from Lead Free Solder Pastes with Alloys of Tin, Silver and Copper", p. 5.

6. IPC Solder Products Value Council, "The Effect of Voiding in Solder Interconnections formed from Lead Free Solder Pastes with Alloys of Tin, Silver and Copper", p. 11.

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