Matte Tin (Sn) Plating Of Semiconductor Devices – Whisker Growth Study

Anocha Sriyarunya
Spansion (Thailand) Limited
Pakkerd, Nonthaburi, Thailand

Dhiraj Bansal
Spansion LLC (US)
Sunnyvale, CA, USA

Abstract
In the industry's drive towards becoming lead free (Pb-free) by July 1, 2006, as dictated by the WEEE Directive, several Pb-free terminal finishes have been proposed and evaluated. Some of them were rejected as soon as evaluations began. Others have been dropped along the way due to problems with either manufacturability or reliability. However, a few alternatives are becoming increasingly popular and seem to be the "chosen ones". SnAgCu alloys, for example, have emerged as the clear choice for Pb-free solder. In contrast, there is no clear winner yet in the area of Pb-free plating alternatives. Even though 100% matte Tin (Sn) seems to be the most popular, its widespread acceptance is impeded by whisker growth concerns based on long-past issues with pure Tin lead finishes.

This paper present the findings of a series of whisker growth studies performed on 100% matte Sn plating on Copper (Cu) leadframes. Studies were done on different package types, assembled at different locations at different times, with and without mitigation techniques and on samples at a component level and as mounted on PWBs. Since these studies started when no Pb-free or whisker definitions or standards were available, best known methods were employed in the studies. However, results from a new study done using NEMI's recommended Sn whisker test methods and failure criteria are also included.

Based on the results from this wide variety of samples and references from other similar published data, we demonstrate that 100% matte Sn finish on Cu leadframe is resistant to whisker growth under a variety of stress test conditions, and can be expected to produce whisker free assemblies in virtually all expected applications.

Introduction

Several Pb-free plating options have been under discussion and evaluations in the industry. Some of the more common ones are 100% matte Sn, Sn/2.5Bi, Sn/0.7Cu, Sn/3.5Ag and preplated leadframes (PPF). Some of the alloys above are constrained by high cost while others are limited by difficulty in maintaining the plating chemical concentration, wastewater management, narrow manufacturing process windows, ease of cracking etc.

100% matte Sn is fast becoming the "chosen one" amongst suppliers and customers alike. Its advantages include compatibility with existing SnPb solders, lower conversion cost as compared to other alternatives, good solderability and wetting properties, abundant availability, ease of processing and a long history of past use experience. The most important concern with the use of 100% matte Sn plating is its susceptibility to whisker, which has proven to be a reliability concern in the past.

Sn Whiskers – Growth Mechanism and Mitigation Techniques

Even though the subject of Sn whiskers is very old, there is a renewed interest in this field due to the emergence of 100% matte Sn as the most viable Pb-free plating alternative. Numerous individuals and consortiums have conducted a lot of research, in the recent past, to understand the whisker growth mechanism. Industry consensus has been reached and it is now believed that the compressive stress is the driving force for Sn whiskers and that the whisker growth is a stress relief phenomenon[1]-[4]. Some of the important factors that affect whisker growth are the found to be the plating chemistry, plating process and the leadframe material.

Several methods to mitigate whisker growth are being recommended[5]-[7],[11].

- Use of matte Sn instead of bright Sn.
- Use of a thick (approx. 10 um) Sn plating.
- Reduction in induced stress during assembly and storage by
    - Annealing after plating (150°C for 1 hour within 1 hour of plating)
    - Use of a Ni barrier under-plate

- Reduction in internal stresses during plating by
  - Controlling grain size and shape
  - Controlling Crystal Orientation

Even though there is general agreement to the benefits of annealing, conflicting results are available in the literature about the benefits of Ni barrier underplate[8],[9]. Apart from being a cost-adder, tight controls are needed in the assembly process to maintain the integrity of the Ni layer during lead formation.

Spansion LLC started its study on 100% matte Sn plating process somewhere around September 2001. Since then, several DOEs have been run to identify a plating chemistry and develop an optimal plating process that can resist whisker growth in electronic components under a variety of field conditions. Its current plating chemistry and process has proven to resist whisker growth even after 27 months of ambient storage. Some of the initial work has been presented in several conferences including IPC/JEDEC International Conference on Lead-Free Electronic Components and Assemblies, December 2002 and April 2003[10], [11]. This paper presents an update on the results from previously reported and ongoing experiments.

Experimental Study Results and Discussions

The objective of this paper is to present a summary of the previously presented results along with newly obtained results for whisker growth studies using 100% matte Sn finish on C194 copper leadframes. Table 1 summarizes the various studies performed. No Pass/Fail criteria were used in the study. Observations were reported as-is. Approximate maximum whisker lengths are reported in cases where any whisker growth was observed. If absolutely no whiskers were observed, it is reported as "No whiskers".

Table 1: Matrix of various studies done on Sn whisker growth

Study	Package Type	Annealing (150°C, 1hr) - Yes/No	Plating Chemistry	Assby Location	Test Location	Component/Board Level
1	TS048	No	Mixed-Acid	In-House	In-House	Component
	SO044	No	Mixed-Acid	In-House	In-House	Component
2	TS048	Yes	Mixed-Acid	In-House	In-House	Component
	SO044	Yes	Mixed-Acid	In-House	In-House	Component
3	SO044	No	Mixed-Acid	In-House	In-House	Board-Level
4	TS048	No	Mixed-Acid	In-House	In-House	Component
	SO044	No	Mixed-Acid	In-House	In-House	Component
5	T2044	Yes	MSA	Subcon A	In-House	Component
6	TS048	Yes	Mixed-Acid	In-House	In-House	Component
	SO044	Yes	Mixed-Acid	In-House	In-House	Component

Study 1

100% matte Sn plated parts were stressed at various conditions to induce whisker growth. Refer to Table 2 for the various whisker growth storage conditions.

Table 2: Whisker Growth Storage Conditions

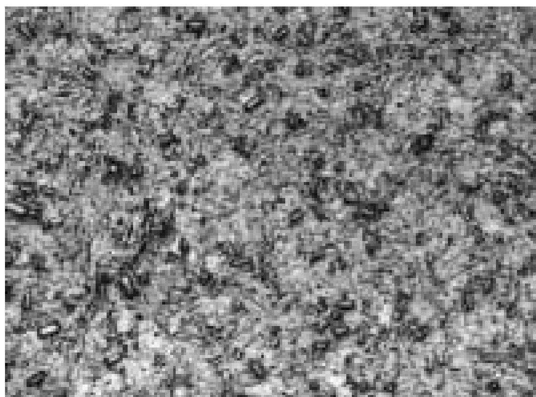
Condition	Storage Condition
1	Temp. cycle (-65 to 150°C) 1000 cycles
2	SPP (121°C, 2 atm, 100%RH) 168 hrs.
3	SPP (121°C, 2 atm, 100%RH) 500 hrs.
4	Storage at 50-55°C, high % RH, 6 months
5	Leave in 20-25°C, 40-65% RH, 2 months
6	Leave in 20-25°C, 40-65% RH, 4 months
7	Leave in 20-25°C, 40-65% RH, 6 months
8	Leave in 20-25°C, 40-65% RH, 8 months
9	Leave in 20-25°C, 40-65% RH, 12 months
10	Leave in 20-25°C, 40-65% RH, 15 months
11	Leave in 20-25°C, 40-65% RH, 24 months
12	Leave in 20-25°C, 40-65% RH, 27 months
13	Store in dry pack, 6 months
14	50°C dry baking, 15 months

Leadframe Material: C194
Grain Size: 3-5 um
Thickness: Minimum10 uinches

Study Sample size: 30 units of each package type tested

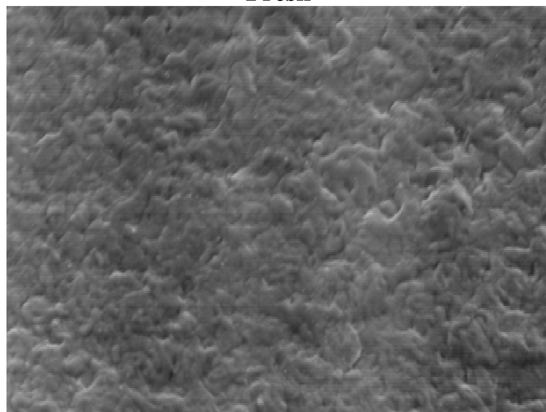
Inspection Method:

- 100% units inspected visually at 50X for whisker growth and grain structure.
- Min. 2000X SEM inspection on minimum 3 units, 3 leads per unit. Refer to Figure 1 for SEM images showing the grain structure after various conditions.



Fresh

Condition #1



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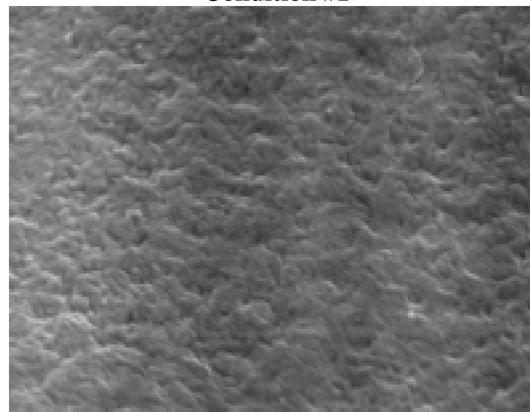

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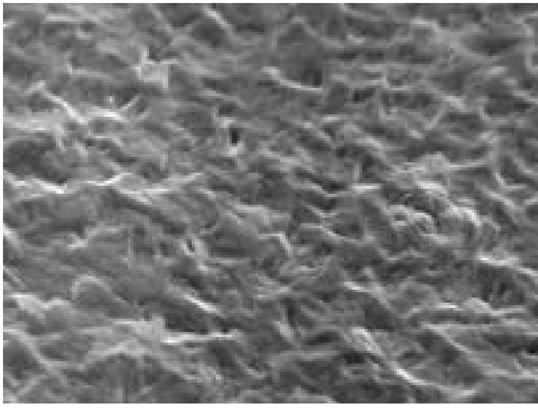
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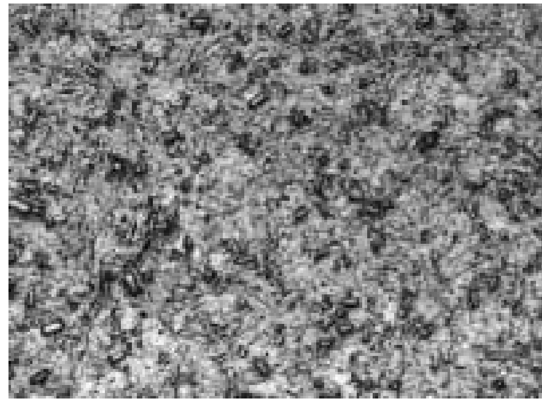
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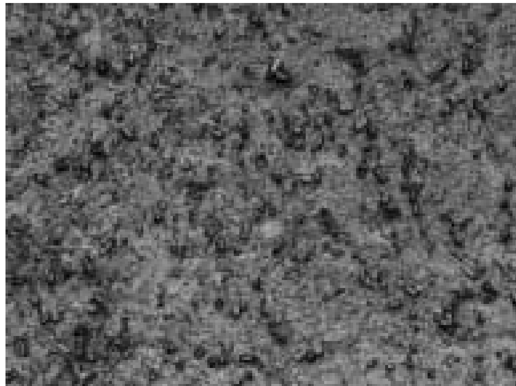
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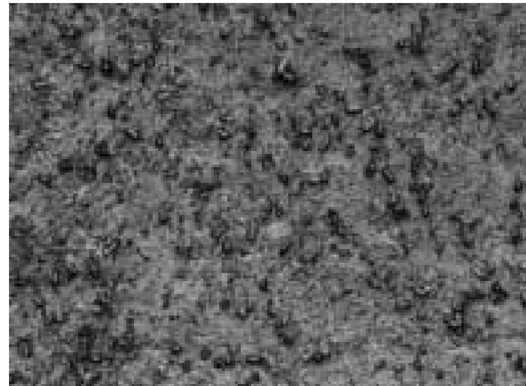
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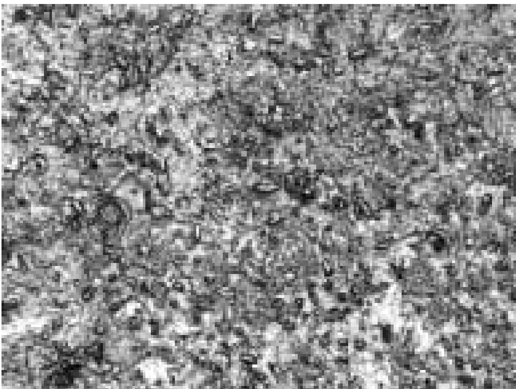
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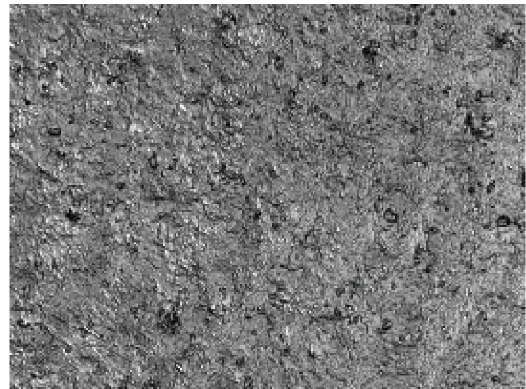
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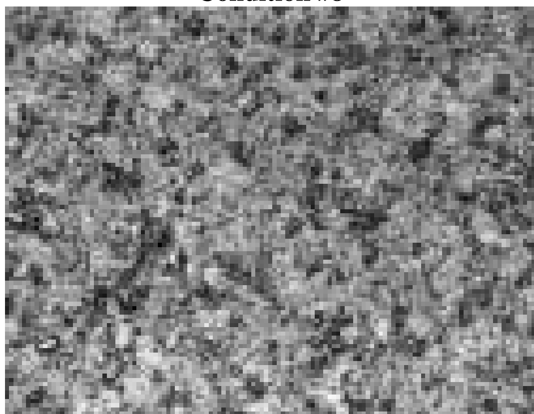
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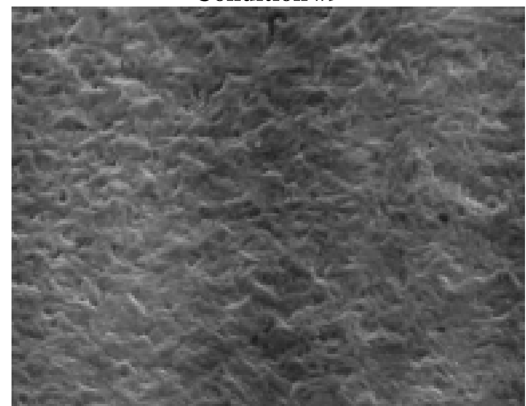
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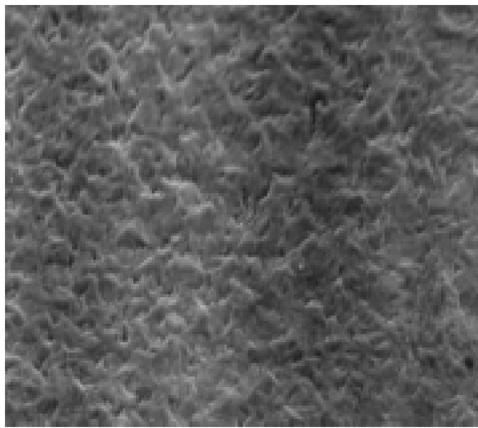

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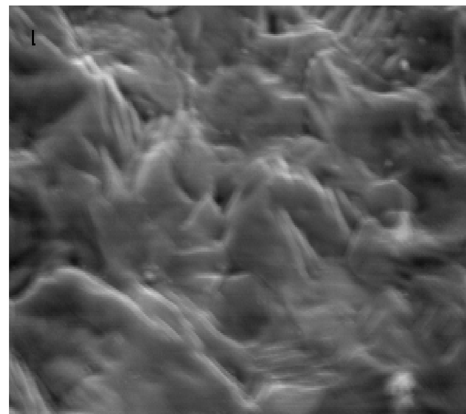

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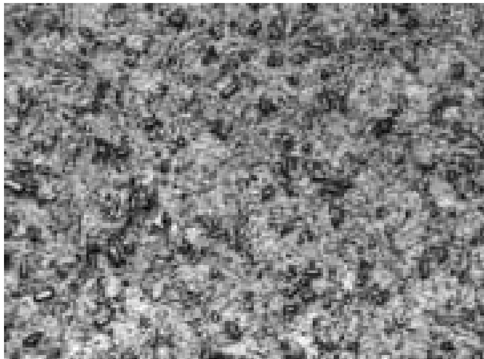


Condition #14

Figure 1: Grain structure after various storage conditions (2000X, Non-annealed parts)

Results: No whiskers or significant grain structure changes were observed on any of the samples stored at all conditions.

Study 2

Post Annealing Whisker Growth Study

Annealing after plating has become a widely accepted whisker mitigation technique. As a result, annealing at 150°C for 1 hour within 1 hour of plating was introduced in our Pb-free assembly process even though our internal studies showed no whiskers for samples without annealing (Refer to Study 1).

This study was, therefore, done to assess the impact of annealing on whisker growth. Refer to Table 3 for the various whisker growth storage conditions.

Table 3: Whisker Growth Storage Conditions for Annealed parts

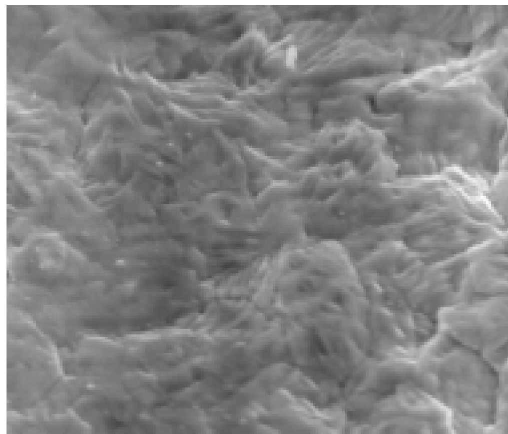
Condition	Storage Condition
1	Leave in 20-25°C, 40-65% RH, 6 months
2	Leave in 20-25°C, 40-65% RH, 12 months
3	Leave in 20-25°C, 40-65% RH, 24 months
4	Leave in 20-25°C, 40-65% RH, 27 months

Leadframe Material: C194
Grain Size: 3-5 um
Thickness: Minimum 10 uinches

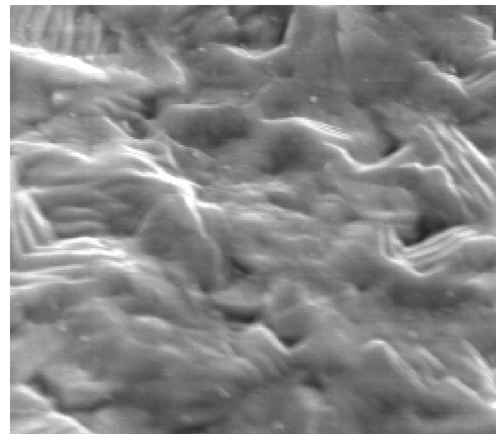
Study Sample size: 10 units of each package type tested

Inspection Method:

– 100% units inspected visually at 50X for whisker growth and grain structure.
– Min. 2000X SEM inspection on minimum 3 units, 3 leads per unit. Refer to Figure 2 for SEM images showing the grain structure after various conditions.



Condition #1



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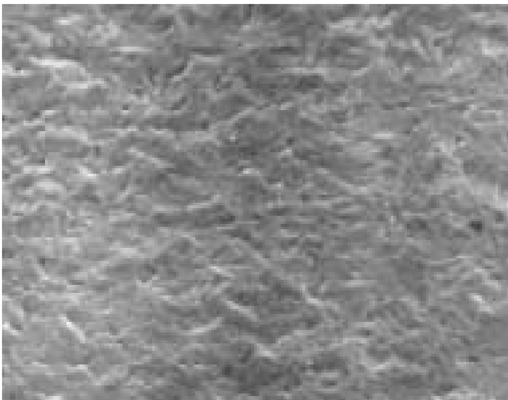
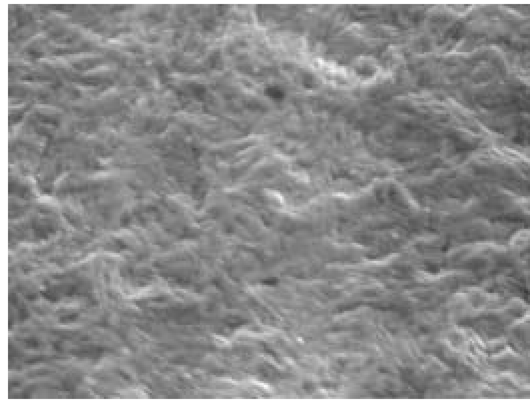


Condition #3



Condition #4

Figure 2: Grain structure after various storage conditions (2000X, Annealed parts)

Results: No whiskers or significant grains structure changes were observed on any of the samples stored at all conditions.

Monthly Monitor Whisker Growth Study

Starting December 2003, annealing step was added to the ongoing monthly monitor program, which is described below:

- 1-2K units of each package type are plated every week.
- 100% inspection (using 50X magnification) is done after plating.
- All units are stored at 20-25C/40-65%RH storage conditions.
- 300 units are taken out every month to check for any whisker growth. Inspection is done on all leads using 40X magnification.
- 5 units, 3 leads per unit are randomly selected and inspected using 2000X SEM.

Results: Till date, data has been collected for annealed samples up to 6 months of storage. No whiskers have been observed so far. Study will continue up to 24 months of storage.

Study 3

Daisy chain samples of SO044 package were used to perform Board Level reliability test. 1. 5 mm thick double-sided boards with OSP finish were used. Automotive under-hood test condition (-40/125°C, 10 sec transition, 30 mins dwell, 24 cycles/day) was used. Refer to Table 4 for the test matrix.

After the completion of the temperature cycle test, boards were stored at ambient conditions for whisker monitoring.

Leadframe Material: C194
Grain Size: 3-5 um
Thickness: Minimum 10 uinches

Study Sample Size: 32 units per leg

Inspection Method:
- 2000X SEM on 3 units per leg, 3 leads per unit

Results:

- All units passed up to 2000 cycles at which point the test was stopped.
- Whisker inspection was done after completion of temperature cycle. No whiskers were found on any of the legs.
- Whiskers were monitored again after approx. 22 months of ambient storage. Refer to Table 4 for the results of whisker inspection.

Table 4: Test Matrix and Results for Study 3

Leg	Plating	Solder Paste	Stress Test History	Whisker Inspection Result
A	Sn	Sn	2000 TC + 22 months of ambient storage	Whiskers Found. Figure 3. ~ Max. whisker length of 26 um
B	SnPb	SnPb	2000 TC + 22 months of ambient storage	Whiskers Found. Figure 4. ~ Max. whisker length of 10 um
C	Sn	SnPb	2000 TC + 22 months of ambient storage	Whiskers Found. Figure 5. ~ Max. whisker length of 18 um
D	SnPb	Sn	2000 TC + 22 months of ambient storage	Whiskers Found. Figure 6. ~ Max. whisker length of 20 um

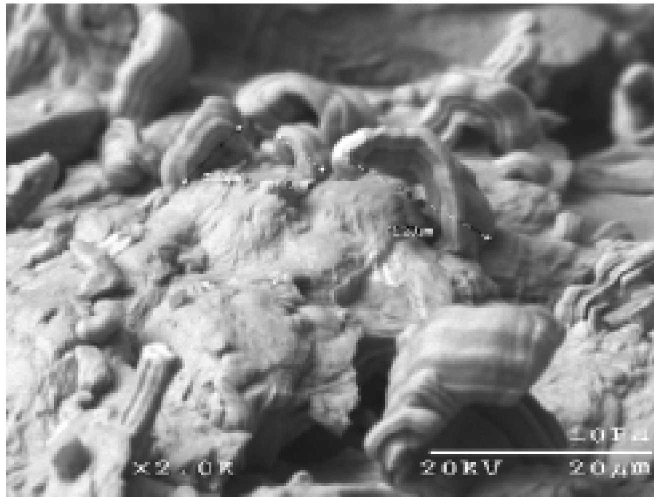


Figure 3 Leg A whisker Inspection Result (~ Max. whisker length seen 26 um)

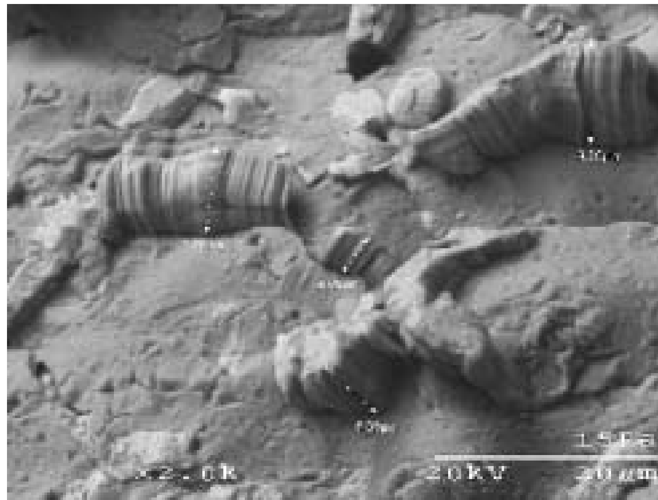


Figure 4 Leg B whisker Inspection Result (~ Max. whisker length seen 10 um)

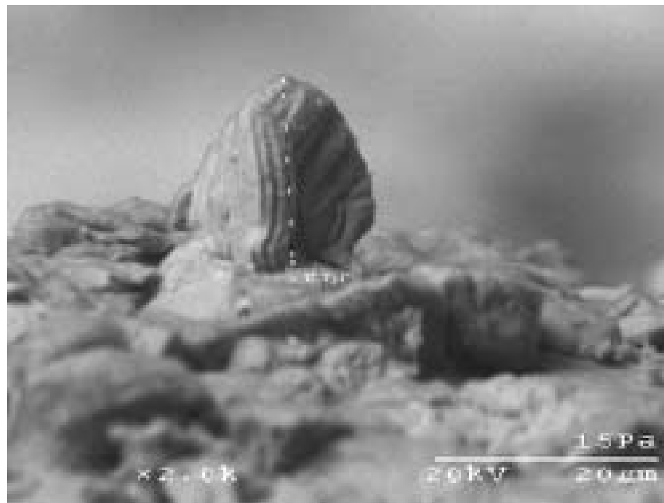


Figure 5 Leg C whisker Inspection Result (~ Max. whisker length seen 18 um)

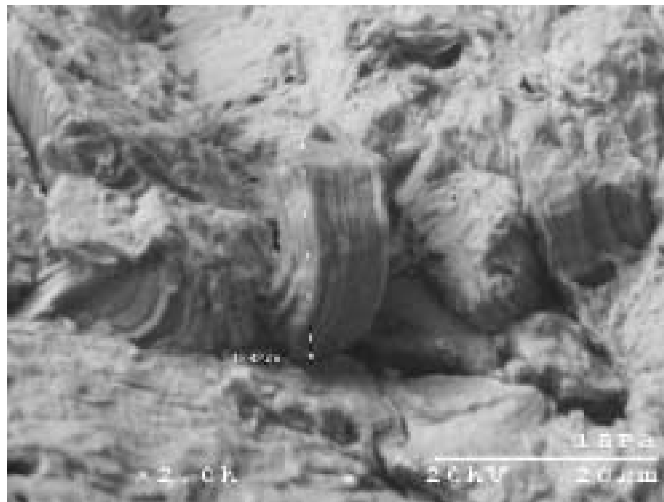


Figure 6 Leg D whisker Inspection Result (~ Max. whisker length seen 20 um)

Both 100% matte Sn and SnPb plated parts with Sn and SnPb solder paste showed the presence of whiskers. As expected, the longest and the maximum number of whiskers were observed in 100% matte Sn plated parts, assembled with Sn solder paste. However, the maximum whisker length found was only approx. 26 um (length/width >2).

It has been demonstrated that even 90/10 Sn/Pb deposits will generate growths during thermal cycling. Consumers and industry consortia groups have come to the conclusion that obtaining a "whisker-free" pure tin deposit is simply not feasible particularly given the fact that 90/10 Sn/Pb deposits will form whiskers under certain of the industry-defined whisker test conditions[12]-[15]. Instead the focus has shifted to defining a maximum acceptable whisker length that does not represent a reliability issue, and the specification being proposed most commonly in this regard is 50 microns. The growths observed in the experiment above are well less than 50 microns and even though the growth is classified as a "whisker" (per NEMI criteria[16]), it should not a reliability risk in the field. Moreover, 2000 temperature cycles followed by 22 months of ambient storage is far greater than the expected life of the product.

<u>Study 4</u>

The objective of this study was multifold –

1. To understand the effect of plating additive concentration and plating bath temperature on grain structure and size.
2. To identify a process setting combination which can yield SnPb "work-like" grain structure.
3. To study the effect of the plating parameters on whisker growth.

Refer to Table 5 for the details of the various legs for the experiment with corresponding whisker growth results.

A current density of 124 Amps/Sq. ft. was used for all legs.

Table 5: Study 4 Experiments: Conditions and Results

Leg	Package	Additive Conc.	Temp.	Grain Size	Thickness (uinches)	Visual Inspection after plating	hisker Growth (leave t 20-25C, 40-65%RH for 12 months)	Whisker Growth (leave at 20-25C, 40-65%RH for 24 months)
1	SO 44	0. 00%	80 F	Large	459	Rough deposit, Nodules	No whisker observed	~ Max. whisker length 36um
	TS 48	0. 00%	80 F	Large	477	Rough deposit, Nodules	No whisker observed	~ Max. whisker length 20um
2	SO 44	0. 00%	110 F	Large	529	Rough deposit, Nodules	No whisker observed	~ Max. whisker length 4 um.
	TS 48	0. 00%	110 F	Large	459	Rough deposit, Nodules	No whisker observed	~ Max. whisker length 24um
3	SO 44	2. 00%	80 F	Fine	353	Smooth deposit, Few Nodules	No whisker observed	No whisker observed
	TS 48	2. 00%	80 F	Fine	301	Smooth deposit, Few Nodules	No whisker observed	~ Max. whisker length 28um
4	SO 44	2. 00%	110 F	Fine	446	Smooth deposit	No whisker observed	~ Max. whisker length 13um
	TS 48	2. 00%	110 F	Fine	457	Smooth deposit	No whisker observed	~ Max. whisker length 10um
5	SO 44	4. 00%	80 F	Fine	328	Smooth deposit	No whisker observed	~ Max. whisker length 16um
	TS 48	4. 00%	80 F	Fine	392	Smooth deposit	No whisker observed	~ Max. whisker length 4um
6	SO 44	4. 00%	110 F	Fine	480	Smooth deposit	No whisker observed	No whisker observed
	TS 48	4. 00%	110 F	Fine	404	Smooth deposit	No whisker observed	No whisker observed

Leadframe Material: C194
Grain Size: 3-5 um
Thickness: Minimum 10 uinches

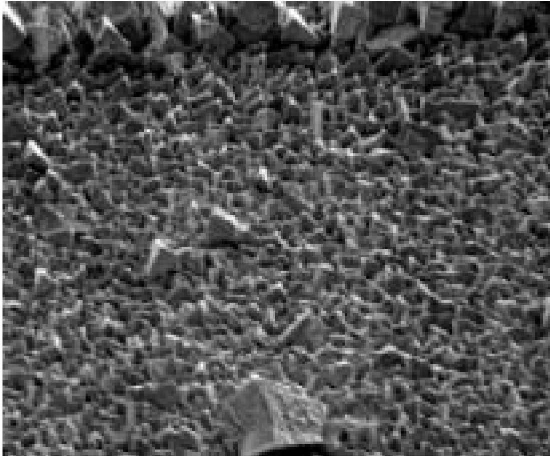
Study Sample size: 10 units of each package type tested

Inspection Method
- 2000X SEM, 10 leads/3 units

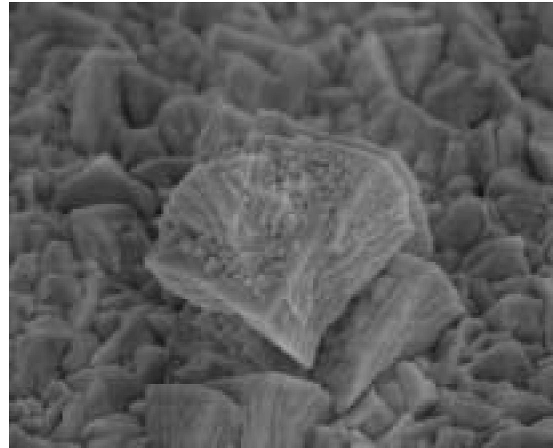
Results:

1) Grain structure and size becomes fine as the additive concentration increases. Plating temperature does not seem to have a significant effect on grain structure or size.
2) Deposited plating becomes smoother and with fewer nodules with increasing additive concentration and plating temperature.
3) None of the process settings tried yielded the "worm-like" SnPb grain structure.
4) Resistance to whisker growth appeared to be proportional to additive concentration and plating temperature. Best whisker growth results were observed with 4% additive concentration at 110F. Refer to Figure 7 for pictures after 24 months of ambient storage.

Leg 1: 0%, 80F

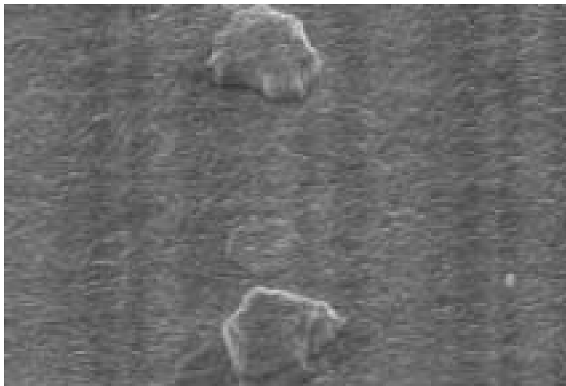


SO044 (Hillocks or Lumps)

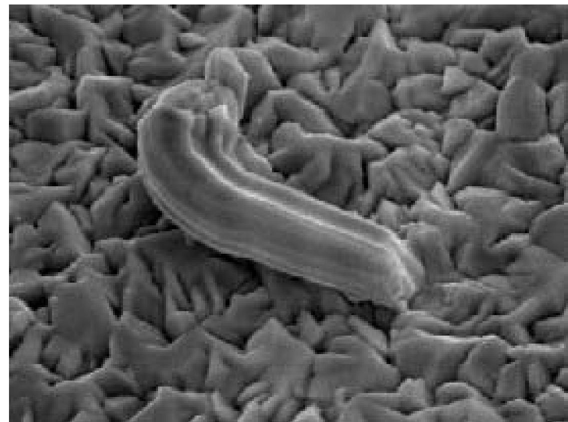


TS048 (Hillocks)

Leg 2: 0%, 110F

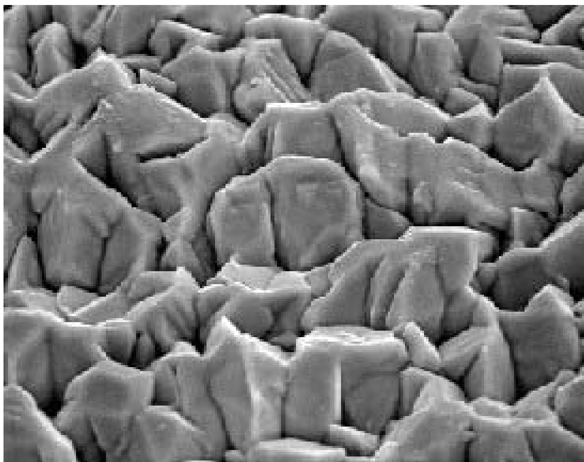


SO044 (Striations Whisker)

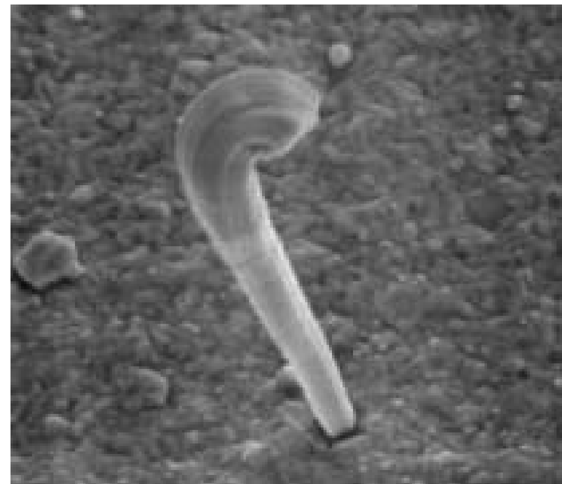


TS048 (Initiating from Hillock)

Leg 3: 2%, 80F

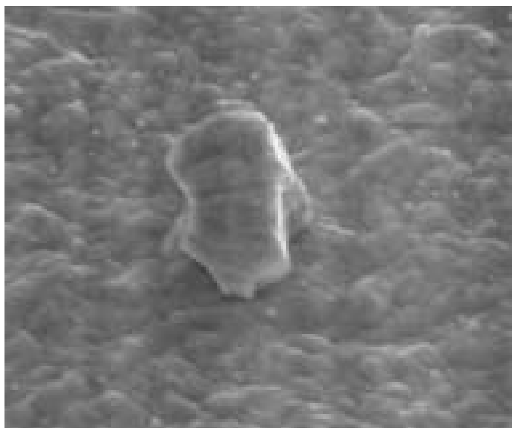


SO044 (No whisker)

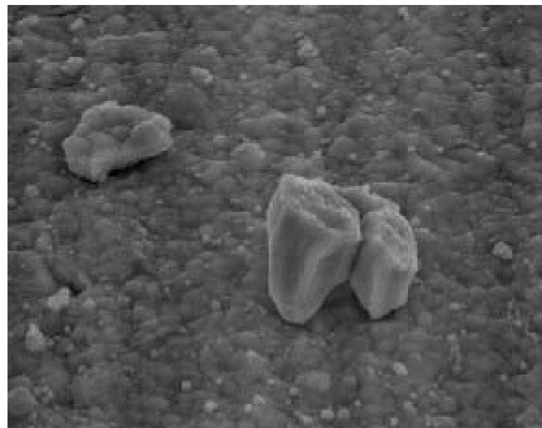


TS048 (Needle Whisker)

Leg 4: 2%, 110F



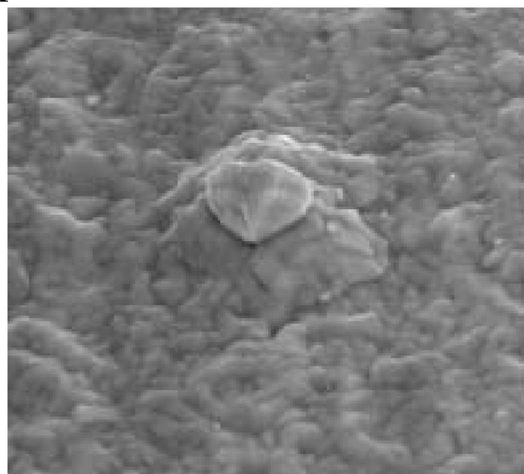
SO044 (Striations Whisker)



TS048 (Striations Whisker)

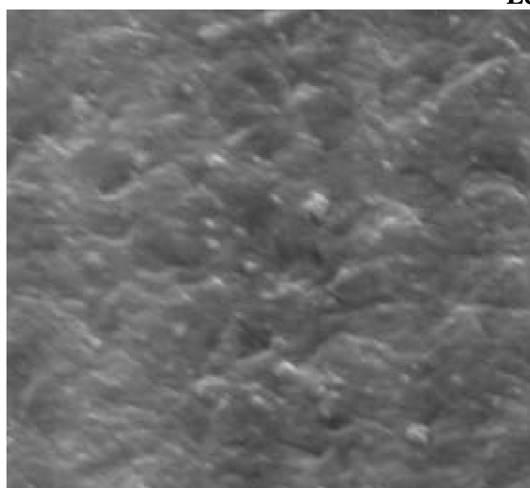
Leg 5: 4%, 80F

SO044 (Rings Whisker)



TS048 (Hillock)

Leg 6: 4%, 110F



SO044 (No whisker)

TS048 (No whisker)

Figure 7: Whisker Growth Inspection Results after 24 months of storage

Study 5

To correlate the subcon provided results with our own internal study, subcon A assembled Type 2 TSOP, T2044, package was stored at 20-25°C, 40-65%RH. 8 months of storage have been completed till now.

Leadframe Material: C7025
Grain Size: 5 to 10 um
Thickness: average 400 uinches

Sample size: 150 units

Inspection Method:
- 3000X SEM for 3 units, 3 leads per unit. Refer to Figure 8 for the typical grain structure observed.

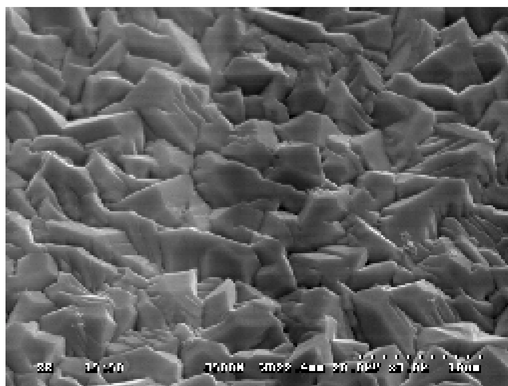


Figure 8: Typical grain structure for Subcon A after 8 months of storage

Result: No whiskers were observed on any of the samples. Further study is ongoing.

Study 6

Since most of the above studies started way before any standards/recommendations existed for accelerated whisker test conditions, a new study was initiated to reconcile the results obtained earlier with NEMI recommended test conditions and inspection criteria[16]. Refer to Table 6 for the experiment matrix.

Samples were assembled using the existing Pb-free assembly process, which includes annealing after plating. A control leg with 85Sn15Pb plating was also run in parallel for comparison.

Leadframe Material: C194
Grain Size: 3-5 um
Thickness: Minimum 10 uinches

Sample size: Refer to Table 6

Inspection Method:
- 40X visual inspection on 100% units after every readpoint.
- SEM inspection - 300X (all leads for 3 units), 1000X and 2000X (3 leads per unit for 3 units) at every readpoint.

Table 6: Sample Size and Inspection Results for various readpoints

Package		TS048			SO044		
Plating		Sn	Sn	SnPb	Sn	Sn	SnPb
Annealing		Yes	No	No	Yes	No	No
JEDEC Level 3 + Temp Cycle (-40C to 150C, 3 cycles/hour)	1000 cycles	320, No	320, No	160, No	320, No	320, No	160, No
JEDEC Level 2A + Temp Cycle (-40C to 150C, 3 cycles/hour)	500 cycles	320, No	320, No	160, No	320, No	320, No	160, No
JEDEC Level 3 + HAST (130C/85%RH, Biased)	96 hours				27, No	30, No	15, No
High Temperature Storage (150C)	500 hours				100, No	100, No	50, No
High Temperature Operating Life (150C, Biased)	500 hours	60, No	60, No	30, No			
NEMI Temp Cycle (-55C to 85C, 3 cycles/hour)	1000 cycles	200, Mounds (Figure 9. 1)	200, Whiskers (Figure 10. 1)	100, No	204, Mounds (Figure 9. 2)	204, Mounds (Figure 10. 2)	102, No (Figure 11)
NEMI Temp Humidity (60C/93%RH)	1000 hours	200, No	200, No	100, No	200, No (Figure 12)	200, No (Figure 13)	100, No (Figure 14)
NEMI Ambient Storage (Air-Conditioned Facility)	3 months (continue upto 24 months)	540, No	542, No	272, No	601, No	597, No	308, No

Note: “No” in the table above denotes “No Whiskers”.

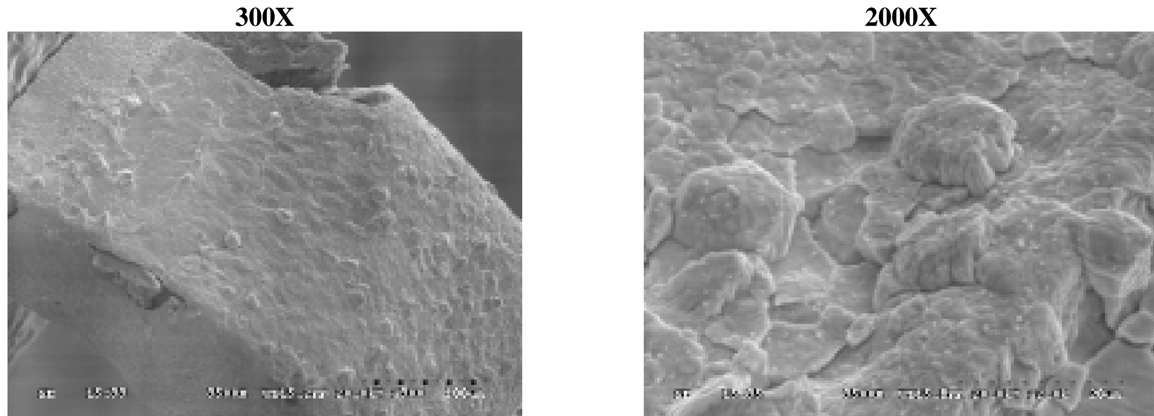
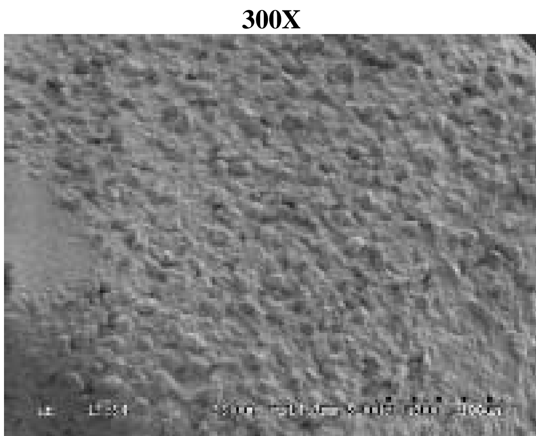


Figure 9. 1: SEM after 1000 TC of NEMI Condition on Pb-free Annealed parts

300X



2000X

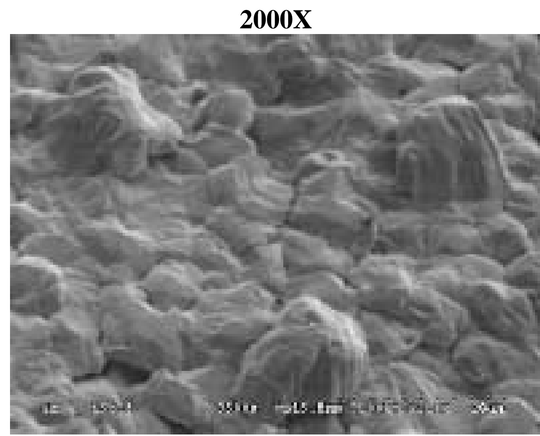
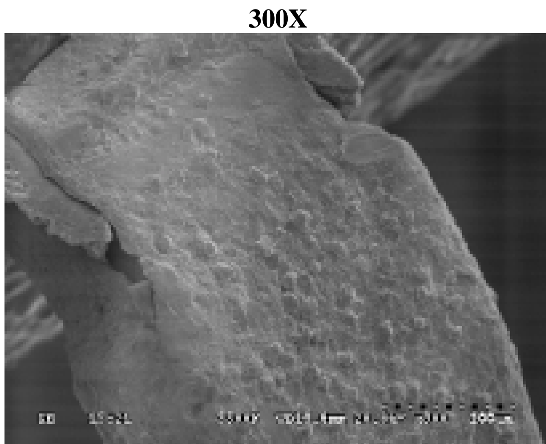


Figure 9. 2: SEM after 1000 TC of NEMI Condition on Pb-free Annealed parts

300X



2000X

Figure 10. 1: SEM after 1000 TC of NEMI Condition on Pb-free Non-Annealed parts (Maximum Whisker Length ~ 20 um)

300X

2000X

Figure 10. 2: SEM after 1000 TC of NEMI Condition on Pb-free Non-Annealed parts

300X **2000X**

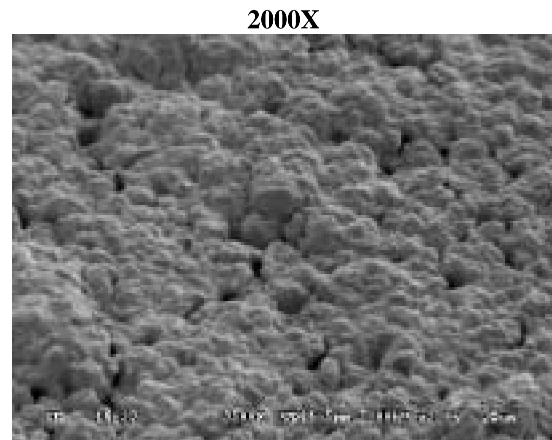


Figure 11: SEM after 1000 TC of NEMI Condition on SnPb Non-Annealed parts

300X **2000X**

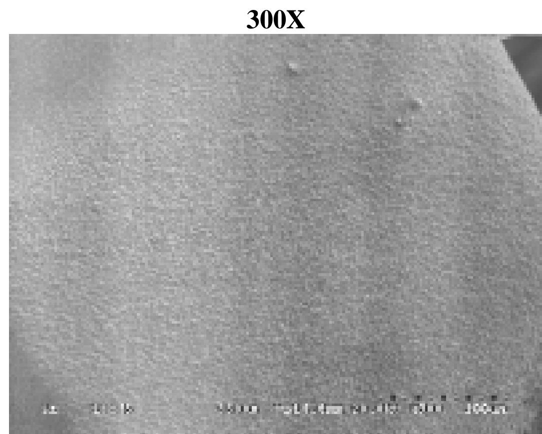
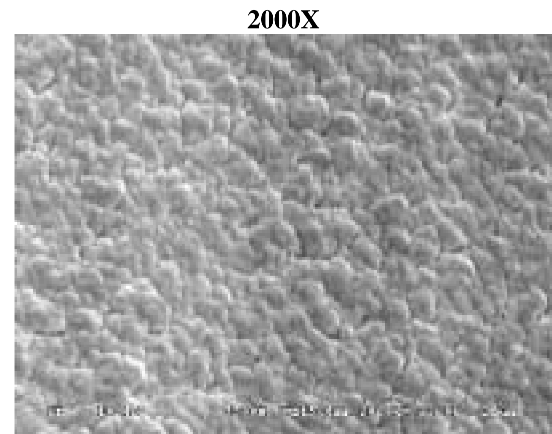



Figure 12: SEM after 1000 TH of NEMI Condition on Pb-free Non-Annealed parts

300X **2000X**

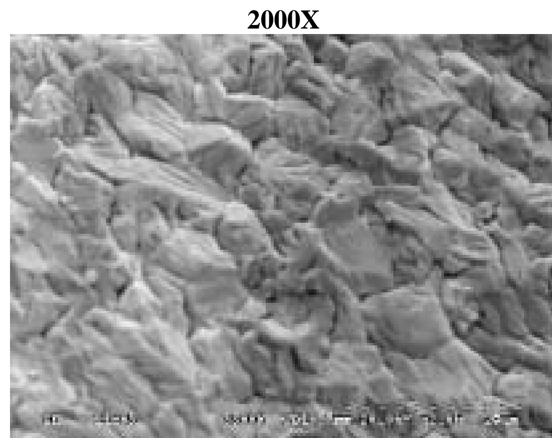


Figure 13: SEM after 1000 TH of NEMI Condition on Pb-free Non-Annealed parts

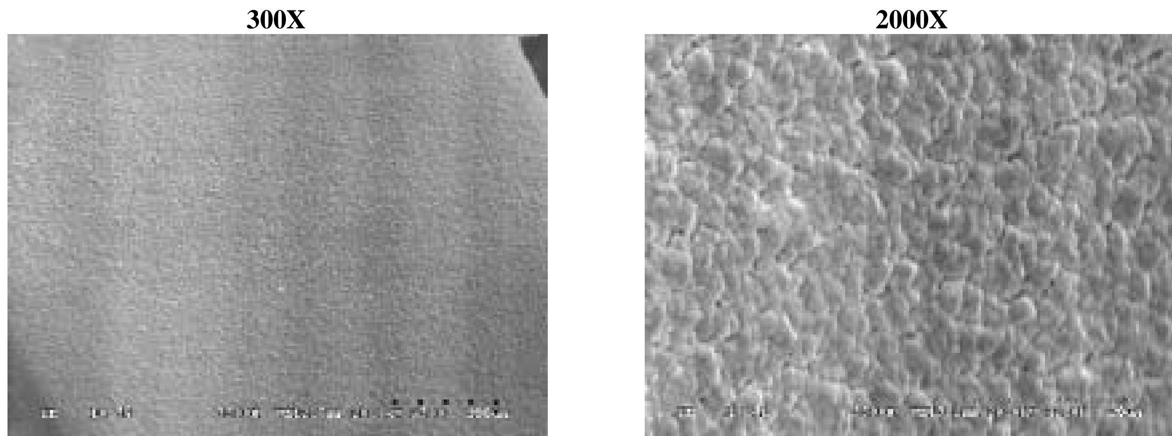


Figure 14: SEM after 1000 TH of NEMI Condition on Pb-free Non-Annealed parts

Results and Discussions:

1. NEMI recommended temperature cycle condition seems to be more effective at accelerating whisker growth. However, it could also be due to the lack of reflow (during preconditioning) prior to NEMI tests as compared to 3 times reflow for the other temperature cycle condition. Reflow could have acted as an annealing step for the samples and hence increased their resistance for whisker growth. NEMI tests with reflow will be conducted in near future.
2. Whiskers were observed on non-annealed parts under NEMI Temperature Cycling test. Short growths were observed in annealed samples that underwent NEMI recommended accelerated temperature cycle condition. The short growths observed are defined as "mounds". They are not Sn whiskers. Mostly, the growths observed were less than 5 microns in length. The compressive stress effect in the tin deposit, which is generated by temperature cycling, is a result of the CTE mismatch between the copper alloy substrate and the Sn deposit, i. e. , 17 vs. 23 ppm/deg K respectively. As the temperature cycling proceeds, the difference in the rates of expansion (during heating) and contraction (during cooling) of the Sn and copper generates the compressive stress that is the driving force for Sn whisker growth. The normal response for a whisker-resistant matte Sn coating when subjected to these types of compressive stresses is the formation of the small mounds observed in the study.
3. Annealing seems to be effective in retarding whisker growth under NEMI recommended accelerated testing conditions.

Conclusions

Most of the subcontractor houses have chosen 100% matte Sn as their Pb-free alternative after their own internal whisker growth studies. In addition, there are numerous references of technical papers and other publications from individual researchers, companies and industry consortiums that show results similar to the ones obtained above with pure Sn on Cu leadframes using different chemistries and plating processes[16]-[20].

From the review of the existing data from other sources and internal results obtained in all the studies so far, it is clear that 100% matte Sn on Cu leadframes can be a whisker resistant Pb-free alternative, if the right plating chemistry and plating process is chosen. 100% matte Sn plated Pb-free parts have proven to be whisker growth resistant under a variety of extensive stress test conditions done up to date and hence can be expected to produce whisker free assemblies in the field.

Ongoing and Future Work

Currently, various studies are ongoing and under planning. Some of the major ones are listed below.

- Perform NEMI recommended accelerated whisker growth tests on samples after 24 months of ambient storage.
- Perform NEMI recommended accelerate whisker growth tests on samples after Preconditioning (JEDEC Level 3 and JEITA Rank 'E').
- Perform NEMI recommended accelerate whisker growth tests on subcon assembled parts.
- Repeat Board Level Reliability studies on Pb-free assemblies.
- Identify an optimal time and temperature for effective annealing post plating.

The results from these studies will be presented as and when available, in future conferences.

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