Studies of Tin Whisker Growth under High External Pressure

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ABSTRACT

In this study, a series of factors that may affect whisker growth on electroplated tin coatings under high external pressure were studied by an indentation method, including storage time, coating thickness, loading and ball diameter. The indentation test results showed that longer storage time, thicker coating (< 3 µm), heavier loading and smaller inert ball could accelerate whisker growth. In addition, the insertion force, retention force and whisker behavior of compliant press-fit pins inserted into the same design of plated through holes with three different types of final finishes (Immersion tin, ENIG and OSP) were investigated.

INTRODUCTION

Tin whiskers are recognized as a much more serious reliability threat to lead-free electronic components or products due to the implementation of the European Directive on restrictions of hazardous substances (RoHS) legislation in July 2006. This position is exacerbated by the trend for increased sophistication and miniaturization in electronics. Common failure modes attributed to tin whiskers are transient/permanent short circuits, metal vapor (plasma) arcing in vacuum and debris/contaminations [1]. Significant research work in the literature focused mainly on understanding of the whisker formation as a consequence of inner surface stress relief. However, little theoretical or systematic work has been carried out to understand the formation of whiskers driven by external mechanical stress, such as the high external mechanical stress in press-fit applications.

In press-fit technology[2, 3], an oversized compliant pin featuring an elastic behavior is inserted into a plated-through hole in a printed circuit board. The compliant pin deforms during insertion and sustains a permanent contact normal force to establish cold welded interconnections autonomously without using solder, especially when tin plating is used for at least one of both contact partners (pin/hole). The external pressure applied by the compliant press-fit zones during and after performing the press-in process increases the propensity for whisker formation in the coating and significantly shortens the time scale to grow whiskers compared to the stress introduced by intermetallic phase growth or CTE mismatch. Furthermore, the technology trend towards higher density connector solutions (tighter pin to pin/hole to hole pitch, much higher external pressure) further increases the risk of electrical short-circuits due to the formation of tin whiskers.

In this study, some factors that may affect whisker growth under high external pressure were studied using an indentation method at ambient temperature, such as storage time, coating thickness, loading and ball diameter. The indentation tests were designed to simulate the high external pressure applied by the compliant press-fit zones to test the whisker performance of tin coatings. Furthermore, some studies in press-fit systems were conducted, aiming to verify and correlate indentation test results. The insertion force, retention force and whisker growth of compliant press-fit pins inserted into the same design of plated through holes with three different types of final finishes (Immersion tin, ENIG and OSP) were investigated.

EXPERIMENTAL

Indentation Tests

The samples were prepared by electroplating a Ni barrier layer (1-2 µm) and Sn surface finish (0.5-3 µm) on a 3 x 3 cm^2 substrate by a laboratory electrodeposition setup. Brass (Hull Cell Plate) was used as the substrate. The plating current density was 5 A/dm^2 for Ni and 10 A/dm^2 for Sn. Detailed information on the electrolytes and the resulting deposit properties were summarized in TABLE1.

TABLE1. INFORMATION ON NICKEL AND TIN PROCESS

Process	Electrolyte	Deposit
Pure Ni	Sulfate basis	Bright, pure Ni
Pure Sn	MSA basis	Matte, pure Sn

After plating, the coating thickness at five points in the central 1 x 1 cm^2 area of the plated coupons was measured using an x-ray fluorescence apparatus (HITACHI FT9500X) and an average value was taken. After thickness measurement, the central 1 x 1 cm^2 area of all plated coupons were cut and used for other characterization and whisker tests. The cross-section samples were prepared using a cross-polishing apparatus (Cross-section polisher/CP-09010, JEOL). The Ni-Sn intermetallic compounds (IMC) were investigated in cross-sectional view by employing a focused ion beam (FIB) microscope (FEI/Quanta 3D FEG) with an acceleration voltage of 30 kV and beam current of 0.1 nA. The Ni-Sn IMC was also exposed by selectively etching away free Sn using o-nitrophenol+NaOH solution and observed from the top using a Scanning Electronic Microscope (SEM, FEI/Quanta 3D FEG) with an acceleration voltage of 5 kV and beam current of 20 pA. Influence of factors on whisker growth were studied by an indentation method as illustrated in FIGURE 1. Basically, a constant pressure was applied on a tin plated coating for a certain time and then the coating was taken out to observe and measure the real length of the whiskers formed around the indentation using the same SEM conditions. It should be mentioned here that, in our studies, all whiskers shorter than 5 µm weren't counted for ease of comparison.

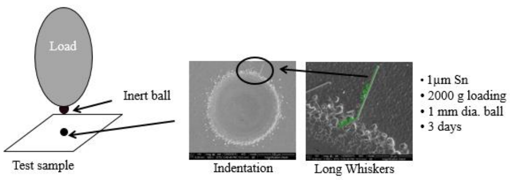


FIGURE 1. SCHEMATIC DIAGRAM OF THE INDENTATION METHOD FOR EXTERNAL PRESSURE INDUCED WHISKER GROWTH

The whisker test setup as shown in FIGURE 2 is designed to minimize equipment variation. There are a total of 12 sets of whisker test setups used for this study. Statistical analysis using JMP confirmed that there is no significant difference among the 12 units. The inert ball used in this study was silicon nitride (Si_3N_4). The newly designed setup ensures absolute vertical positioning and can be leveled by adjusting the four leveling feet. Moreover, the loading and ball size can be changed from 500 g to 2000 g and 0.8 mm to 6.35 mm, respectively. For each test condition, at least 3 samples plated under the identical conditions were tested at the same time to improve data accuracy. Except for the samples used for storage time study, which were stored at room temperature in a dry box with 23% relative humidity for certain periods of time, all samples were tested within 48 hours of being plated (denoted as fresh in this paper). 1 µm Sn plated at 10 ASD and whisker test conditions of 2000 g loading combined with 1 mm diameter ceramic ball for 3 days were set as the control in this study. Storage time, coating thickness and parameters of the indentation method were varied because they are considered important factors that may affect whisker growth. In particular, the external pressure applied on the coating is actually decided by the loading and ball size adopted, hence variation of pressure by changing loading or ball size were investigated. The indentation diameter was measured using the same SEM and the indentation depth was measured by an optical profiler (Wyko NT1100) using VSI measurement mode. The lowest Rv (the maximum valley depth) value in either X profile or Y profile was collected as the indentation depth.

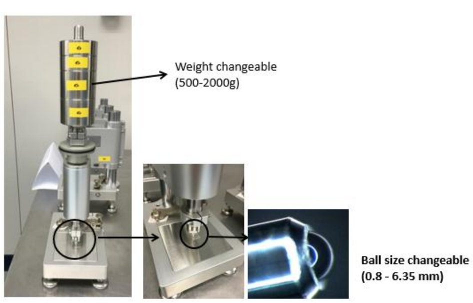


FIGURE 2. PHOTOS OF THE NEWLY DESIGNED WHISKER TEST SETUP

Press-fit Tests

Compliant press-fit pins for press-fit studies were plated with a Ni barrier layer (1.8-2.2 µm) and Sn surface finish (1.4-1.6 µm) using a lab-scale overflow plater which was designed to simulate reel to reel plating mode of a production line. The plating current density was 25 A/dm^2 for Ni and 30 A/dm^2 for Sn. Water circulation and moderate agitation of the substrate (stamped C7025) were applied during electroplating. After plating, the coating thickness at three points on the pins as shown in FIGURE 3a was measured using the same XRF instrument. Comparison of the pins in terms of coating thickness (both Ni and Sn) using JMP confirmed that there was no significant difference among all the pins used.

The PCB board (epoxy laminate, 0.8 mm thick) was specially designed and manufactured for better observation of whiskers. The pin insertion, and the measurement of insertion and retention force were conducted in the Huawei industrial base. Twenty samples were prepared for each type of final finish: half for retention force measurement and half for whisker observation. Insertion force on all the twenty samples was measured and retention force was measured right after the insertion process was completed. For whisker observation, after sample build-up, the press-fit samples were stored in a dry box at room temperature with 23% relative humidity for 5 weeks. Then, both the entry side and exit side of the press-fit samples were observed using a metallurgical microscope under 50X-200X magnification. Observation of the whiskers inside the PTHs was conducted by illuminating from the bottom. An example of the observation is shown in FIGURE 3b. The number of whiskers and the length of the longest whisker per press-fit sample were recorded. The final hole diameter was measured by microsection method and three samples were prepared for each final finish.

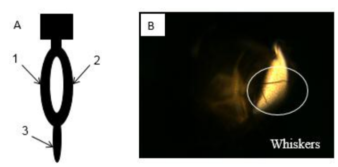


FIGURE 3. (A) ILLUSTRATION OF THE POSITION ON THE PINS FOR THICKNESS MEASUREMENT AND (B) TIN WHISKERS INSIDE THE HOLE WITH ENIG FINISH

RESULTS AND DISCUSSION

Storage Time after Plating

FIGURE 4 shows the effect of storage time on whisker growth. In this study, the same samples were tested three times. The first tests were conducted within 24 hours of the samples being plated, which were labelled as fresh. After whisker observation using SEM, the same samples were stored in the dry box at room temperature for 3 months and then taken out for whisker tests using the same method and under the same test conditions at a position near to the first indentation. The third tests were conducted in the same way after the samples were stored in the dry box at room temperature for half a year. As shown in FIGURE 4, the length of the longest whiskers increased with increasing storage time and much more whiskers grew on the same coatings after being stored for more than 3 months.

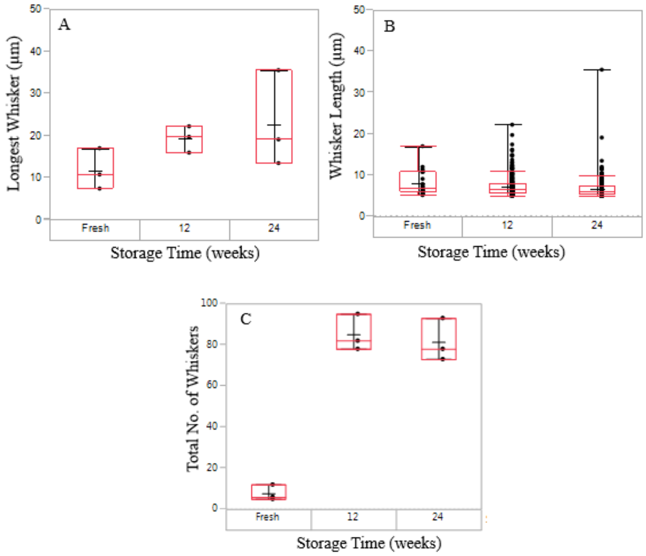


FIGURE 4 COMPARISON OF (A) THE LENGTH OF THE LONGEST WHISKERS, (B) THE WHISKER DISTRIBUTION AND (C) THE TOTAL NO. OF WHISKERS ON THE SAME SAMPLE STORED AT ROOM TEMPERATURE FOR DIFFERENT TIME (WHISKER TEST CONDITIONS: 1 µm TIN @10 ASD, 2000 g LOADING, 1mm DIA. BALL, 3 DAYS)

The IMC formed between Ni and Sn layers after the sample was stored at room temperature for 7 months was exposed using both chemical etching & cross-section methods as shown in FIGURE 5. Top view and cross-section view confirmed that plate like $NiSn_3$ IMC [4] formed after long time storage at room temperature. It is suspected that the formation of irregular NiSn IMC at room temperature may introduce compressive stress to the coating, resulting in the deterioration of whisker performance. More studies are needed to better understand the mechanism behind. Panashchenko and Osterman [5] spent four years to compare the whisker performance of samples with and without Ni underlayer. They found that the samples with Ni underlayer gave lower whisker density but still gave long whiskers comparable to the samples without Ni underlayer.

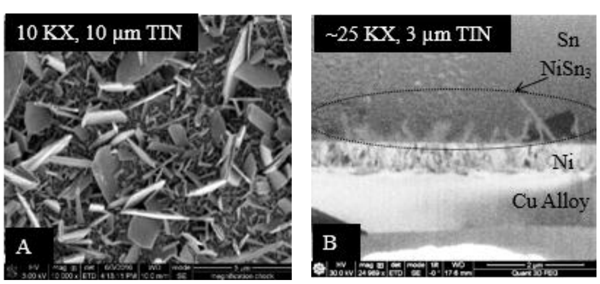


FIGURE 5. (A) TOP VIEW AND (B) CROSS-SECTIOIN VIEW OF THE IMC FORMED BETWEEN NICKEL AND TIN STORED AT ROOM TEMPERATURE FOR 7 MONTHS

Tin Coating Thickness

The whisker performance of 0.5 µm, 1 µm and 3 µm Sn coatings was compared in terms of longest whisker, whisker distribution and total number of whiskers as shown in FIGURE 6. It was found that the length of the whiskers and the numbers of long whiskers increased with increasing coating thickness. The indentation diameter also increased with increasing coating thickness. It was also found that under such harsh test conditions, the indentation depth is larger than the Sn coating thickness itself (TABLE 2). The indentation reached the Ni underlayer and/or the substrate, which makes the whisker growth mechanism more complicated.

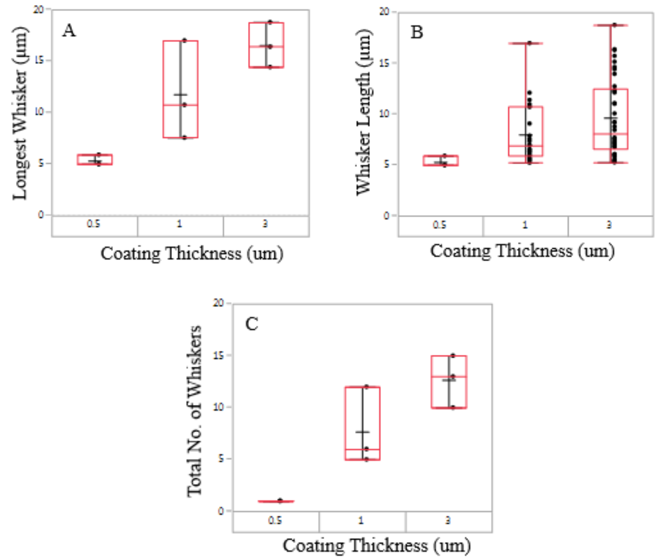


FIGURE 6. COMPARISON OF (A) THE LENGTH OF THE LONGEST WHISKERS, (B) THE WHISKER DISTRIBUTION AND (C) THE TOTAL NO. OF WHISKERS ON THE COATINGS WITH DIFFERENT THICKNESS (WHISKER TEST CONDITIONS: FRESH TIN@10 ASD, 2000 g LOADING, 1 mm DIA. BALL, 3 DAYS)

TABLE 2 INDENTATION DEPTH OF THE COATINGS WITH DIFFERENT THICKNESS

Sn Coating Thickness (µm)	0.5	1	3
Ni Coating Thickness (µm)	1.5	1.6	1.2
Indentation Diameter (µm)	174	184	238
Indentation Depth (µm)	4.0	4.7	5.9

Loading and Ball Size

The whisker performance of the Sn coating is largely dependent on the external pressure it endures, especially when the pressure is very high. For the indentation method, loading is a critical parameter that can change the external pressure applied on the coatings. Therefore, the whisker performance of coatings with similar thickness was tested under three different loadings. As shown in FIGURE 7, the length of the longest whiskers and the number of whiskers increased when increasing the loading. The indentation area and indentation depth showed the same trend. It was also found that on such thin coating of 1 µm, the indentation didn't stay in the tin coating, but reached the Ni underlayer and even the substrate when higher loadings were applied (TABLE 3).

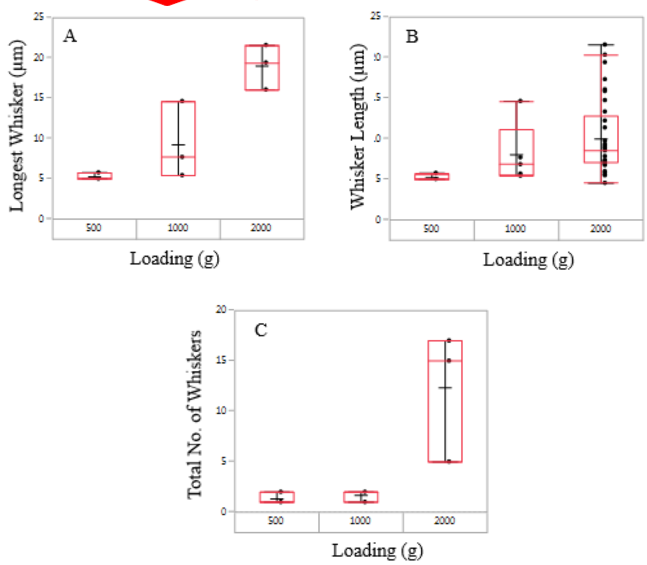
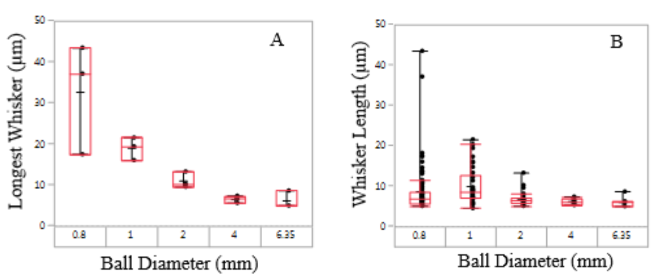


FIGURE 7. COMPARISON OF (A) THE LENGTH OF THE LONGEST WHISKERS. (B) THE WHISKER DISTRIBUTION AND (C) THE TOTAL NO. OF WHISKERS ON COATINGS TESTED WITH DIFFERENT LOADINGS (WHISKER TEST CONDITIONS: 1 µm FRESH TIN@10 ASD, 1mm DIA. BALL, 3 DAYS)

TABLE 3 PRESSURE APPLIED ON THE COATINGS TESTED UNDER DIFFERENT LOADINGS

Loading (g)	500	1000	2000
Indentation Diameter (µm)	136	158	199
Indentation Depth (µm)	2.7	3.0	4.7
Estimated Pressure (MPa)	578	1,040	1,328

Ball size is another factor that can significantly affect external pressure, thus affecting whisker growth. In this study, five ceramic balls with different ball diameter were investigated and the results were summarized in FIGURE 8 and TABLE 4. The results showed that the smallest ball gave the worst whisker performance because it applied the highest pressure on the coating when the loading was kept the same. Upon increasing ball diameter, the whisker performance improved gradually until the ball size was larger than 4 mm, when no significant difference in whisker performance was observed.



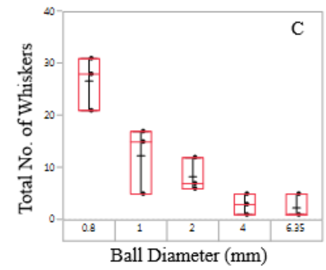


FIGURE 8. CONPARISON OF (A) THE LENGTH OF THE LONGEST WHISKERS, (B) THE WHISKER DISTRIBUTION AND (C) THE TOTAL NO. OF WHISKERS ON COATINGS TESTED WITH DIFFERENT BALL SIZE (WHISKER TEST CONDITIONS: 1 µm FRESH TIN@10 ASD, 2000 g LOADING, 3 DAYS)

TABLE 4 PRESSURE APPLIED ON THE COATINGS TESTED WITH DIFFERENT BALL SIZE

Ball Diameter (mm)	0.8	1	2	4	6.35
Indentation Diameter (µm)	183	199	219	252	278
Indentation Depth (µm)	5.4	4.7	2.8	1.6	1.3
Estimated Pressure (MPa)	1,445	1,328	1,115	975	756

PTH Final Finishes

FIGURE 9 shows the microsection photos of the PTHs with three different final finishes and compared their final hole diameters. It was found that the PTHs with immersion tin and ENIG finish have close final hole diameter, however, the PTH with OSP finish is around 7% larger. In order to eliminate the influence of hole size on insertion/retention force and whisker growth, only the performance of the samples with immersion tin and ENIG finish were compared.

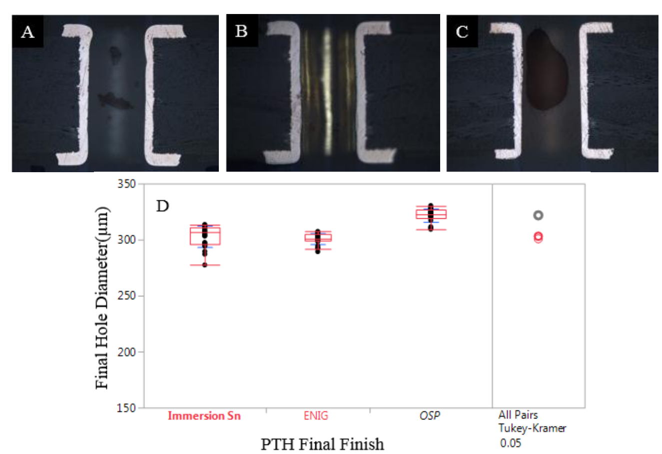


FIGURE 9 VERTICAL CROSS-SECTION VIEW OF THE THROUGH HOLES WITH THREE TYPES OF PTH FINAL FINISHES ((A)IMMERSION TIN, (B) ENIG AND (C) OSP) AND COMPARISON OF THEIR FINAL HOLE DIAMETERS

As shown in FIGURE 10, the pins needed a little bit larger force (~ 4% larger) when being inserted into the PTHs with EING finish than those with immersion tin finish. After insertion, the pins sustained close retention force in the PTHs with the two final finishes. No whiskers were observed outside any of the PTHs after five weeks' storage at room temperature, which means there is not a high risk of short circuit failure. However, when the inside of the PTHs was inspected, the ENIG samples gave more and longer whiskers than the immersion tin samples (FIGURE 11) even though the retention force of the two types of samples was similar. Further studies will be conducted, e.g. observing the press-fit samples by cross-section method, comparing the whisker performance of OSP samples with similar PTH diameters, extending the storage time to see if the whiskers continue to grow, changing the PTH size, testing the whisker performance under harsher environment with high temperature and high relative humidity, etc. to observe the whisker growth in press-fit applications and better understand the underlying whisker growth mechanisms.

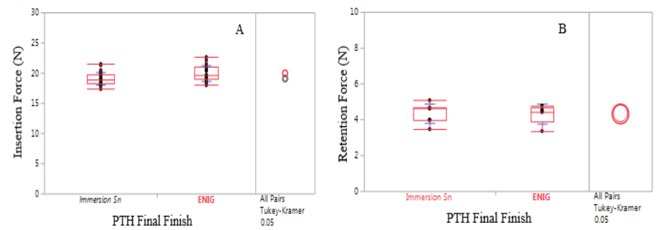


FIGURE 10. COMPARISON OF (A) INSERTION FORCE AND (B) RETENTION FORCE ON PTHS WITH IMMERSION TIN AND ENIG FINAL FINISHES

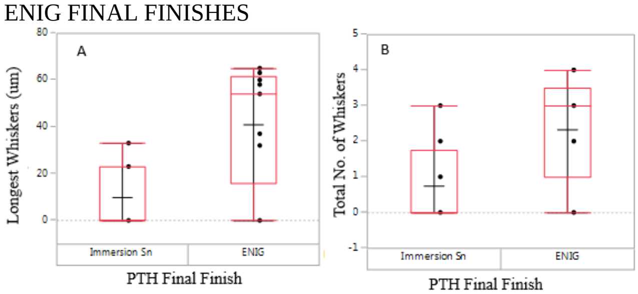


FIGURE 11. COMPARISON OF (A) THE LENGTH OF THE LONGEST WHISKERS AND (B) THE TOTAL NO. OF WHIKSERS ON PTHS WITH IMMERSION TIN AND ENIG FINAL FINISHES

CONCLUSIONS

Indentation and press-fit tests were conducted to study some factors which could affect whisker growth under high external pressure. The following conclusions can be made through this study.

- Whisker performance deteriorates with longer storage time, thicker coating (< 3 μm), higher loading and higher pressure.
- The PTH samples with ENIG finish gave worse whisker performance than those with immersion tin finish.

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