Field Reliability Estimation of Tin Whiskers Generated by Thermal-Cycling Stress

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[Abstract]

This paper summarizes our approach to product reliability assurance in relation to tin whisker growth. Especially, we implemented stress analyses and field reliability estimation of tin whiskers generated by thermal cycling stress, of which growth is recognized on tin plated electrode with nickel under-layer, using electrodes of our major surface mount components. These tin whiskers grow most rapidly under the stress condition of "–40ºC↔85ºC" cycling with exposure time each 30 minutes and the growth rate slowdowns in any other temperature condition. The reliability estimation using Eyring model tells that 3.66×10^5 cycles (more than 100 years) are necessary for tin whiskers to reach 50μm length even assuming a comparatively severe use condition of "0ºC↔85ºC". Also, we confirmed that reflow soldering heat (240ºC or higher) suppressed whisker growth, and that the whisker growth stopped after 2200 cycles, giving the maximum length of 85μm in our experiment. These results lead us to the conclusion that those whiskers do not grow to a length that may result in reliability problem of electronics components within their lifetime of use. Also, we analyzed the growth mechanism of tin whiskers generated by thermal-cycling stress and clarified that the tin whiskers grow in the high-side temperature cycle step by compression stress in tin plating film generated by thermal expansion coefficient difference between under-layer metal and tin plating film. In addition, we studied the possibility that the diffusion of under-layer nickel into tin plating film suppresses the tin whisker growth.

1. Preface

With the recent promotion of lead-free solder, the application of tin or its alloy plating is becoming popular. However, as there is concern about whisker generation in the use of tin or tin alloy plating, many manufactures are implementing reliability evaluation in relation to the whisker growth, and the national standardization organization of each country such as JEITA (Japan Electronics and Information Technology industries Association) or NEMI (National Electronics Manufacturing Initiative) is promoting the standardization of whisker test methods.
JEIA Subcommittee for Whisker Test Method Standardization has taken up three types of major forces that drive tin whisker growth.
The first is a stress generated by thermal diffusion of under metal copper into tin plating film. The second is a stress generated by thermal oxidation, and the last is a stress coming from the difference of thermal expansion coefficient between under-layer metal and tin plating film under thermal-cycling stress [1]. Although the details of these mechanisms are left for future research, it has been known from experience that there are three types of environmental stresses effecting the tin whisker growth; temperature, humidity and thermal-cycling stresses [2].

As our company has been widely using tin-plated electrode heretofore for our typical products, i.e. chip type electronics components, we have been taking special care for the reliability issue relating to tin whisker and checking the reliability by performing evaluations based on the abovementioned mechanisms.
It has been reported that needle-like tin whiskers, which may cause short-circuit failure in the market place, are most likely to grow generally in 50ºC or room temperature environment [2]. In order to contain the tin whisker growth mechanism generated by thermal diffusion of base metal (copper) into tin plating film, we have been using nickel under-layer plating as a barrier against the base metal diffusion. We confirmed that no tin whiskers were generated on the tin plated electrode with nickel under-layer after 18 years of 50ºC constant temperature storage test, considering there is no practical problem in respect of this whisker generation mechanism [3].
Also, for tin whiskers generated by the thermal oxidation, although we have been implementing various damp tests such as 40ºC93%RH, 60ºC93%RH and 85ºC85%RH tests, etc., no significant tin whisker growth has been experienced until now. Therefore, we consider that the current tin plating film technology secures necessary reliability level in respect of tin whisker due to the thermal oxidation.
As stated above, we consider that there is no problem in our products concerning tin whiskers generated by the diffusion of base metal or thermal oxidation. However, it is known that whiskers grow on tin or tin-alloy plated electrode with nickel under-layer when a thermal cycle stress is inflicted on this type electrode [4] [5] [6]. If tin whiskers generated by the thermal cycle stress (hereinafter referred to as thermal-cycling whiskers in order to differ from those whiskers generated in the conventional constant temperature environmental test) could become problem in the actual use environment of electronics components, they would largely affect future electrode designs, and prompt actions would be required to improve the reliability of products with tin-plated electrode currently placed in the market.
We partially reported our approach to these thermal-cycling whiskers in the previous paper [7] and also

reported that there is no reliability problem in relation to these whiskers.

We have recently summed up our approach to the thermal-cycling whiskers and examined field product reliability by applying the rule of 100μm parts mounting space.

We report the results of these activities in this paper.

The contents are outlined as follows :

(1) Grasp of the trend of thermal-cycling whisker growth on the electrodes of our current major surface mount components.

(2) Estimation of market lifetime calculated using Eyring model.

(3) Consideration of thermal-cycling whiskers growth mechanism and their suppression mechanism.

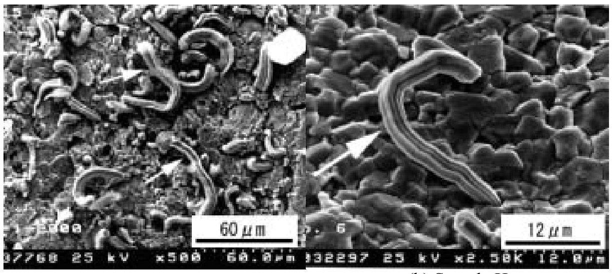
2.States of Thermal-Cycling Whisker Growth on Electrodes of Our Major Surface Mount Components

Various electrode types were selected from our major surface mount component product lines, for which 800 cycles of "–40ºC↔85ºC" thermal-cycling test (exposure time each 30 minutes, air-phase method) was implemented to examine thermal-cycling whisker growth trend. The results are shown in Table 1 below. As it had been known by our preparatory evaluation that the growth of thermal-cycling whiskers is unlikely to reach several millimeters, the evaluation of leaded components, which have large electrode distance, was omitted.

Among these samples, electrodes on which thermal-cycling whisker growth was observed were only those having tin or solder (Sn / Pb) outer-layer. Under-layer of these electrodes were mostly nickel but the whiskers were generated also on an electrode having copper under-layer. Therefore, it is deemed that thermal-cycling whiskers were generated on electrodes of which outer-layer contains tin regardless of under-layer.

Examples of Scanning Electron Microscope (SEM) images of thermal-cycling whiskers generated are shown in Fig. 1.

Although a little difference is observed among the shapes of these thermal-cycling whiskers, they have a common lint-like curving pattern, and characterized by the growth creeping along electrode surface.



(a) Sample D (b) Sample H

Fig. 1 SEM Image of Thermal-Cycling Whiskers
(Test condition: – 40ºC↔85ºC, after 800 cycles)

These experiment results have shown that the thermal-cycling whiskers are generated only on the electrode of which outer-layer contains tin or its alloy. Because no whiskers were observed on Ag, Au or copper outer-layer electrode in this experiment, it is assessed that no thermal-cycling whiskers will be generated on these metal electrodes also in the field use.

Based on the experiment results, a field reliability has been estimated in respect of thermal-cycling whisker generation by using data from the product with tin-plated electrode with nickel under-layer that showed most conspicuous thermal-cycling whisker growth (No. D in Table 1).

3. Field Reliability Estimation

The abovementioned experiment has demonstrated that thermal-cycling whiskers are easily generated on our current surface mount components. The length of the most grown thermal-cycling whisker observed in the experiment was about 35μm (test condition: – 40ºC↔85ºC, 800 cycles).

If minimum gap between two electrodes of mounted devices used in contemporary surface mounting technology is assumed to be 100μm, "50μm whisker growth" from each side electrode can bring a short-circuit risk, which is considered "risk-significant whisker length". Thermal-cycling whiskers might grow to this length or even longer depending on environmental condition and/or time duration. Therefore, it is necessary to estimate further whisker growth trend that may occur in the actual

Table 1 States of Thermal-Cycling Whisker Growth on Electrodes of Our Major Surface-Mount Components

Component No.	Size (mm)	Electrode Matrix	Under-plating Metal Thickness (μm)	Outer Layer Plating Thickness (μm)	Whisker Generating Condition
A	2.0×1.25×0.85	Ag	Ni plating 1.3	Sn plating 1.5	generated
B	6.9×2.9×1.5	Monel	Ni plating 2.9	Sn plating 2.6	generated
C	7.0×2.8×2.5	Fe-42Ni alloy	Cu plating 2.2	Ag plating 0.8	not generated
D	3.7×3.1×1.2	Ag	Ni plating 2.1	Sn plating 1.8	generated
E	11.0×5.3×4.4	Brass	Cu plating 2.2	Solder plating 1.6	generated
F	5.0×5.0×1.7	Tungsten	Ni plating 3.3	Au plating 0.4	not generated
G	4.3×3.8×2.0	–	–	Cu plating 1.6	not generated
H	2.0×1.25×0.5	Ni-Cr	Ni-Cu sputter 1.0 / Ni plating	Sn plating 1.3	generated
I	3.2×1.6×1.15	Ag	Ni plating 1.5	Solder plating 1.0 (Sn : Pb = 9 : 1)	generated
J	2.0×1.25×1.0	Ag / Ag-Pd	Ag firing 21	Solder plating 11 (Sn : Pb = 6 : 4)	not generated
K	2.0×1.25×0.6	Ag	Ni plating 1.7	Sn plating 1.4	generated
L	2.0×1.25×0.6	Cu	Ni plating 1.8	Sn plating 0.9	generated
M	4.5×3.8×1.75	Ag	Ag firing 5.3	Solder dipping 13 (Sn : Pb = 6 : 4)	not generated
N	2.0×1.25×0.9	Cr	Ni-Cu sputter 1.2	Solder dipping 15 (Sn : Pb = 6 : 4)	generated
O	2.0×1.25×1.0	Ni	Ag firing 22	Solder dipping 2.2 (Sn : Pb = 6 : 4)	not generated

using environment and determine whether the estimated whisker growth trend can result in reliability problem.

In order to determine the above whisker growth risk in the field, we implemented stress analyses to evaluate acceleration factors and to determine relation between each stress factor and whisker growth speed, then we have estimated the growing trend of thermal-cycling whiskers in the actual use environmental condition.

3.1 Investigation of Relation between Stress Factor and Whisker Growth

As conceivable thermal-cycling stress factors, there are temperature-difference, temperature level (high and low side temperature levels), transition time and temperature exposure time. Therefore, the effect of each of these factors on the growth of thermal-cycling whiskers was investigated.

3.1.1 Experiment Method

An air-phase thermal cycling test chamber (TSA-70H, Manufacturer: Tabai Espec) was used for the above test. Also, High Stress Chamber (HC-120, Manufacturer: Tabai Espec) was used for the experiment of transition time change. As test sample preparation, products to be tested were soldered onto Ag-Pd electrodes formed on alumina substrates using hot-plate heat soldering method. The sample products were tested in this mounted condition for thermal-cycling stress. After the test, the morphological observation of "observation areas" shown in Fig. 2 was implemented using an optical microscope, a laser microscope and a scanning electron microscope. The length of generated thermal-cycling whiskers were two dimensionally measured using the laser microscope (OLS1000, Manufacturer: Olympus). The observable maximum vision of the laser microscope is 260μm × 195μm. The worst ten whiskers counted from the longest one in each test group were measured and their average value was calculated and used for evaluation (average growth length).

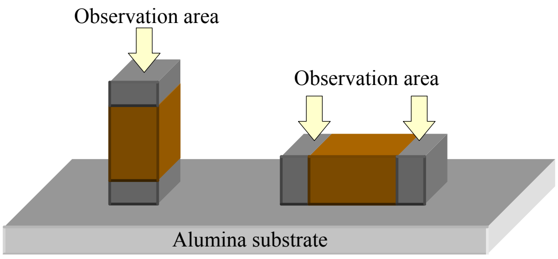


Fig.2 Thermal-Cycling Whisker Observation Area

3.1.2 Relation between Temperature-Difference and Whisker Growth

500 cycles thermal-cycling tests were implemented for each of changed temperature-differences, and thermal-cycling whisker growth lengths of samples from those different temperature-differences were compared, of which results are shown in Fig. 3. The comparison of average whisker growth lengths among those temperature-difference conditions, i.e. 125ºC, 165ºC and 185ºC, tells that the smallest temperature-difference, "–40ºC↔85ºC", has shown the largest average whisker length of 34μm, against the smallest average of about half size 15μm for the largest temperature-difference, 185ºC of "–55ºC↔125ºC" condition. As it has been generally discussed that tin whisker growth is generated by stress inside tin layer, it had been expected that these thermal-cycling whiskers grow more proportionally to the increase of the temperature-difference because of increased compressive stress force in the layer coming from increased temperature-difference. However, the above experiment has shown a reverse relation. Further, it is interesting that two test conditions with the same temperature-difference, "–40ºC↔85ºC" and "0ºC↔125ºC", have shown much different results; thermal-cycling whiskers in the former much more grew than those in the later. This fact has shown that the actual temperature level is an important factor for the growth of thermal-cycling whiskers.

The concept of Eyring model for product lifetime estimation is that severer stress promotes more rapid degradation of tested product, making its lifetime shorter. However, in this case of thermal-cycling whisker growth, the whisker growth was not proportionate to the increase of temperature-difference, which seemingly made it difficult to apply Eyring model to this stress factor. In order to overcome this problem, more detailed stress analysis was implemented in order to examine the Eyring model applicability to this experiment.

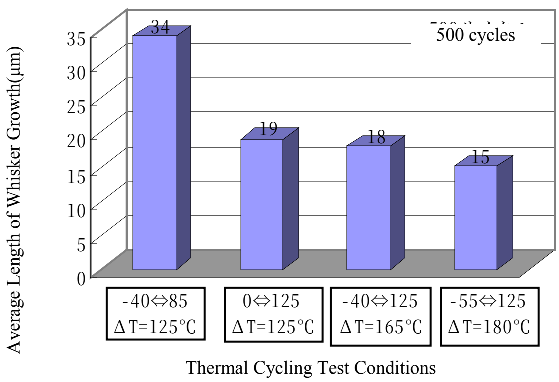


Fig.3 Relation between Temperature difference and Thermal-Cycling Whisker Growth

First, assuming that an optimum temperature for thermal-cycling whisker growth exists in "high side temperature", we implemented 300 cycles thermal-cycling tests, fixing low side temperature at –40ºC and selecting three temperatures, 65ºC, 85ºC and 105ºC for high side temperature, and compared thermal-cycling whisker growth levels among those test conditions, of which results are shown in Fig. 4. Again in this test, the thermal-cycling whisker growth was not proportional to the temperature-difference level, with showing the results that the average length of whisker growth in the condition of high side temperature at 85ºC was the largest 24μm, leaving those in 65ºC and 105ºC conditions to low 17μm each.

From this test, it has been learnt that the high side temperature most promoting thermal-cycling whisker growth is 85ºC.

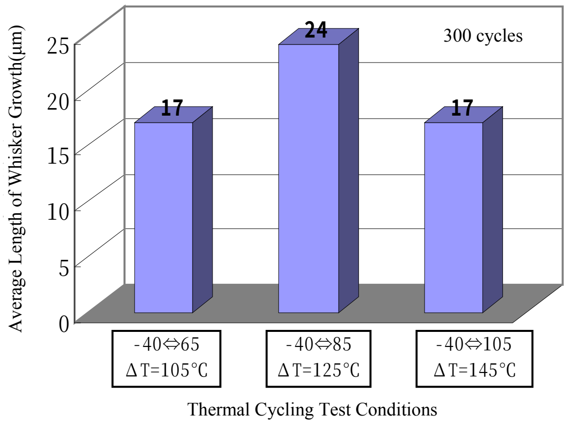


Fig.4 Relation between High Side Temperature and Thermal-Cycling Whisker Growth

Next, in order to find an optimum low side temperature, we implemented 300 cycles thermal-cycling tests, fixing high side temperature at 85ºC and selecting three low side temperatures, –40ºC, 0ºC and 25ºC, of which results are shown in Fig. 5.

Thermal-cycling whiskers in the test condition with –40ºC low side temperature showed the largest growth of 24μm followed by 11μm in 0ºC low side temperature and 9μm in 25ºC. showing a trend that the higher the temperature, the slower the growth speed.

This test has indicated a trend that the whisker growth is more reduced in the higher “low side temperature”. This means that, in the condition in which the high side temperature is fixed at 85ºC, the whisker growth is more accelerated when the low side temperature is more lowered i.e. temperature-difference is more enlarged. Thus it has been demonstrated that Eyring model can be applied to the estimation of field lifetime in respect of thermal-cycling whisker if the high side temperature of thermal-cycling test is fixed at 85ºC. The temperature of 85ºC is a highly severe using condition but sometimes actually existing in the field use [8], which is, therefore, considered reasonable temperature for this type of thermal cycling test.

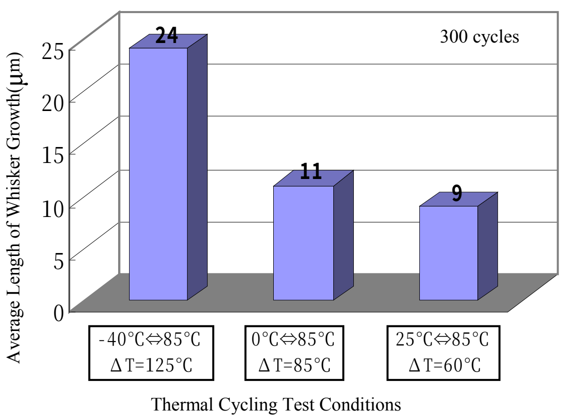


Fig.5 Relation between Low Side Temperature and Thermal-Cycling Whisker Growth

3.1.3 Relation between Transition Time and Thermal-Cycling Whisker Growth

“Thermal cycle stress” charged on electronics devices in actual use environment is generally internal heat up and down of equipment due to power switching on and off, of which temperature shift-time is reported to be 10 to 20 minutes [9], while temperature transition time in laboratory thermal-cycling test is generally three minutes or less. As the shift-time in the actual use is much slower compared to the transition time in the laboratory test, there is a possibility that “compression stress” generated inside tin plating film is smaller in the actual use than in the laboratory test, thus thermal-cycling whiskers grow more slowly in the actual use than in the laboratory test. In order to confirm this possibility, we compared whisker growth speeds in the two transition time conditions, a usual laboratory test condition, two minutes, and 15 times of this usual transition time, 30 minutes assumed as actual shift-time, using High Stress Chamber, of which results are shown in Fig. 6.

The comparison of the two transition time conditions tells a trend that the shorter transition time generates the larger thermal-cycling whiskers as expected, showing the average of 22μm in two minutes condition and 18μm in 30 minutes condition. However, as the thermal-cycling whiskers were also generated in the slower transition time condition without so much difference from those in the laboratory test condition, it is apparent that thermal-cycling whiskers can grow by the temperature “shift-time” in the actual field use. The test also has demonstrated that there is no big difference between short and long transition times, and therefore, it has suggested less necessity to take up transition time factor for our Eyring model.

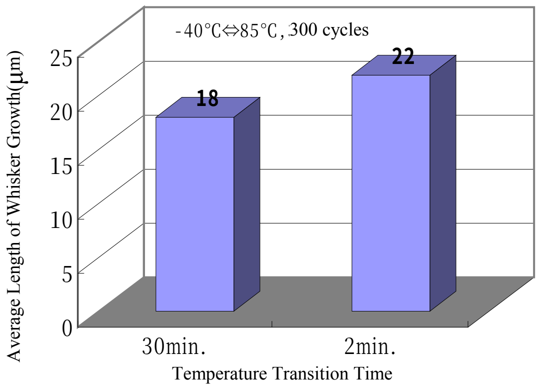


Fig.6 Relation between Temperature Transition Time and Thermal-Cycling Whisker Growth

3.1.4 Relation between Temperature Exposure Time and Thermal-Cycling Whisker Growth

Next, the effect of temperature exposure time to low and high side temperatures was investigated. The thermal-cycling whisker growth was investigated by changing each side exposure time to 10, 30 (monitor) and 120 minutes, of which results are shown in Fig. 7. There was no big difference between the results from 30 minutes and 120 minutes exposure conditions, each generating 22μm and

19µm whisker average length. However, 10 minutes exposure condition generated only 9µm average length, less than a half of the former two levels. These results tell that about 30 minutes exposure time-length to the high side temperature is necessary for sufficient growth of thermal-cycling whiskers. In the actual field use environment, once equipment is powered on, it is usually used for 30 minutes or longer, therefore, the actual use environment provides sufficient time for thermal-cycling whiskers to grow. However, as a trend is observed that the average length of 120 exposure is slightly shorter than that of 30 minutes exposure, there is a possibility that the longer exposure time reduces the whisker growth. Also, as there was no big difference observed in the effects of the test and actual level exposure times on thermal-cycling whisker growth, the introduction of the exposure time factor in the Eyring model was not required.

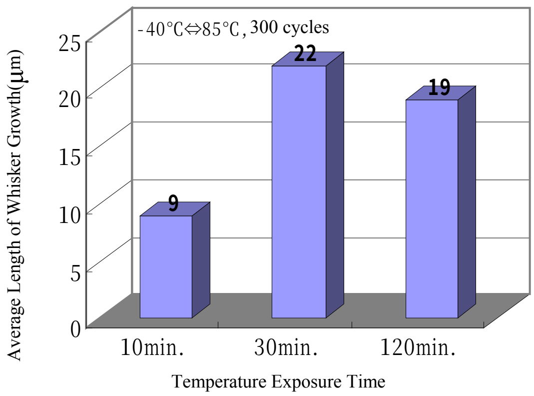


Fig. 7 Relation between Temperature Exposure Time and Thermal-Cycling Whisker Growth

3.1.5 Estimation of Field Lifetime by Eyring Model

From the results in the previous chapters, it has been clarified that the essential acceleration factors for Eyring model to estimate product field lifetime in respect of whisker problem are the difference between high / low side temperatures and the actual temperature level. The transition time and exposure time used in these thermal cycling tests can be considered to be equal level to those used in the actual field.

For the field lifetime estimation, the following conditions were assumed :

(1) The narrowest mounting gap between components on print circuit boards was assumed to be 100µm, and "short circuit" as the worst case was assumed to occur when a thermal-cycling whisker has grown to 50µm. Therefore, a component ends its life at the time one of its whiskers reached 50µm.

(2) The severest thermal cycling condition expected in the field where 100µm component gap is used was assumed to be "0ºC↔85ºC" (85ºC temperature-difference) and that 10 cycles of this thermal cycling per day is charged on each inside component. Target lifetime was determined to 10 years, which give the number of cycles in the total lifetime, 10 years × 365 days × 10cycles = 36500 cycles. These conditions are considered to be very severe assumption compared to actual field use conditions. Although conditions severer than these can be assumed for the engine room inside environment of automobiles used in cold regions like Canada or North Europe, the narrowest gap distance such as 100µm is few applied to devices used in such severe environment, and therefore, the realistic environmental conditions have been adopted for this calculation.

The graph of thermal-cycling whiskers tested in the three test conditions using 85ºC for high side temperature and –40ºC, 0ºC and 25ºC each for low side temperature is shown in Fig. 8. As the thermal-cycling whiskers generated in each of these conditions were growing almost proportionally to the number of cycles charged, regression lines on the graph were drawn and the time when those whiskers reach 50µm were estimated using extrapolation method. The estimated lifetimes are shown in Table 2. These estimated lifetimes were Eyring plotted as shown in Fig. 9, and Eyring model expression was determined as (1) below :

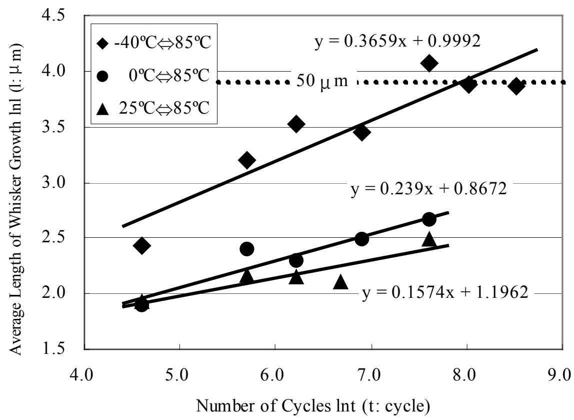


Fig.8 Test Conditions and Thermal-Cycling Whisker Growth

Table 2 Estimated 50µm Growth Lifetime

Test Condition	–40ºC↔85ºC ΔT = 125ºC	0ºC↔85ºC ΔT = 85ºC	25ºC↔85ºC ΔT = 60ºC
Estimated Life	2770 cycles (0.8years)	3.66 × 10^5 cycles (100 years)	3.00× 10^7 cycles (8200 years)

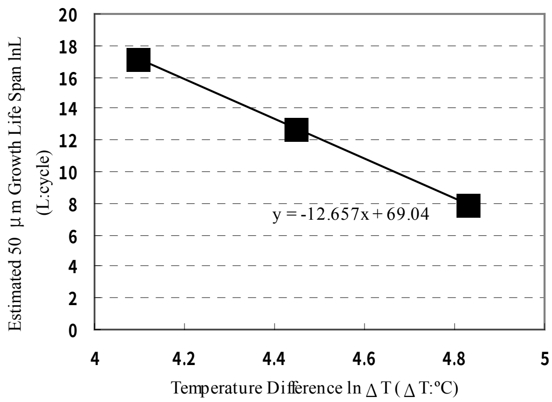


Fig.9 Eyring Plot

$$\ln L = C - \alpha \ln \Delta T$$
$$= 69.04 - 12.657 \cdot \ln \Delta T \quad (1)$$

Where "L" is a lifetime end when thermal-cycling whisker has reached 50μm (unit: the number of cycles), "C" is a constant, "α" is an thermal-cycling acceleration coefficient and "ΔT" is a temperature-difference (ºC) with high side temperature at 85ºC. As the acceleration coefficient, "α = 13", has been obtained, the 13th power rule is to be applied. The calculation of lifetime L using the expression (1) with the condition of temperature difference ΔT = 85ºC has shown lifetime of 3.66×10^5 cycles (longer than 100 years). This calculation result shows that the thermal-cycling whiskers can not grow to a length bringing about reliability problem within a usual lifetime of electronics devices.

For reference purpose, $\Delta T'$, a temperature-difference required for thermal-cycling whiskers to reach 50μm, has been backwardly calculated, by using 36500 cycles in the expected life of 10 years as L value, which result is shown in the expression (2)

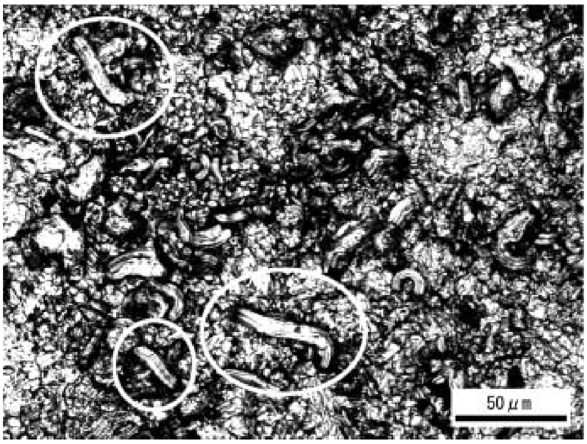
$$\Delta T = \exp\left(\frac{\ln 36500 - 69.04}{-12.657}\right) = 102.0 \ (^{\circ}C) \quad (2)$$

The required temperature-difference is about 102ºC. When high side temperature is set to 85ºC, required thermal-cycling condition is "–17ºC↔85ºC". If electronic components are used in this condition, their thermal-cycling whiskers may grow to 50μm length after 10 years use. However, it is difficult to assume a using environment in which such extreme stress is routinely charged on electronic components used in the contemporary high density mounting technology.

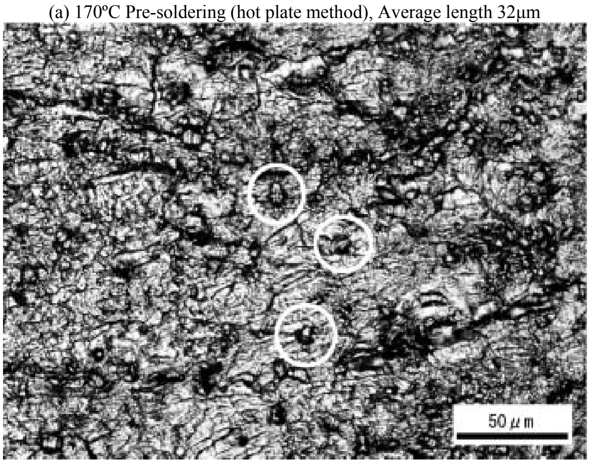
3.2 Investigation of Effect of Reflow Soldering Temperature

Test sample products used in the experiments in the previous chapters were fixed on test substrates by hot-plate soldering method, in which temperature of sample electrode surface before soldering was about 170ºC. As temperature used in actual reflow soldering process is generally set to around 240ºC, above tin melting point (232ºC), there is a possibility that this soldering temperature difference may affect thermal-cycling whisker growth [10].

Therefore, we investigated thermal-cycling whisker growth on samples soldered using a reflow method with a profile of maximum temperature 240ºC. Fig. 10 shows the laser microscope photographs of a hot-plate soldered sample and a reflow soldered sample after "–40ºC↔85ºC", 1000 cycles thermal cycling test. The average whisker length of the hot-plate samples was 32μm, while that of the reflow-soldered samples was mere 9μm, which shows the evident suppression of thermal-cycling whiskers growth effected on the reflow-soldered samples. From this observation, it has been learnt that the reflow soldering method applied in actual soldering processes slowdowns the thermal-cycling whisker growth, further reducing whisker risk in the field.



(a) 170ºC Pre-soldering (hot plate method), Average length 32μm



(b) 240ºC pre-soldering (reflow method), Average length 9μm

○Circled whiskers are typical thermal-cycling whisker in each soldering condition

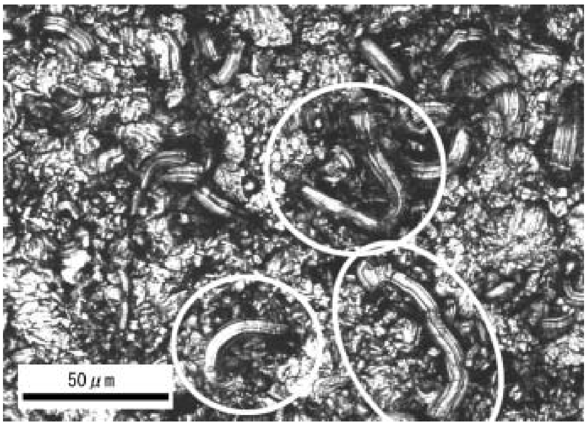
Fig.10 Thermal-Cycling Whisker Suppression Effect of Reflow Soldering

3.3 Investigation of Limit of Thermal-Cycling Whisker Growth

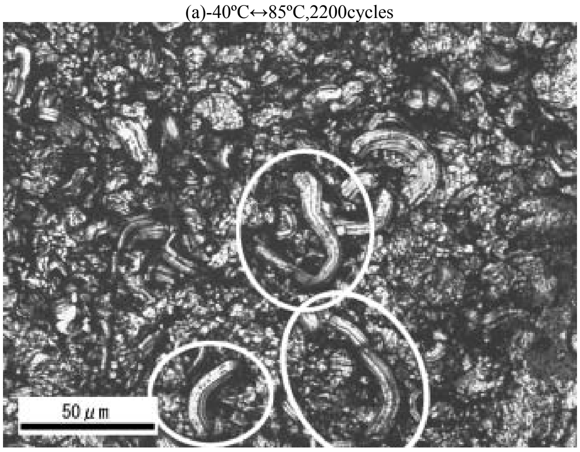
Well, what is the growth limit point of these thermal-cycling whiskers ? There is a report describing tin whiskers growing to several millimeters in the test condition of traditional fixed temperature storage [2]. We observed the progress of thermal-cycling whisker growth by means of continuing test cycles up to 8000 cycles using the condition of "–40ºC↔85ºC", which is the most whisker growth accelerating condition. Fig 11 shows laser microscope photographs of whiskers after 2200 cycles of "–40ºC↔85ºC" test and the same whiskers in the same view field after 8021 cycles of the same test continued. The photographs evidently show no progress of thermal-cycling whisker growth taking place after 2200 cycles. Also, because the longest whisker in this test was 85μm with no whisker exceeding 100μm being observed and their shapes are all convoluted, there is few possibility that they reach 100μm or longer straight line distance.

3.4 Investigation of Resistance against Vibration and Mechanical Shock Stress

Although the risk possibility of thermal-cycling whiskers growing to 50μm length has been proven to be extremely small in the previous discussions, if a generated thermal-cycling whisker falls off from electrode by vibration or mechanical shock stress, it may cause an



(a)-40ºC↔85ºC,2200cycles



(b) -40ºC↔85ºC,8021 cycles

It is apparent from the photographs that the thermal-Cycling whiskers (circled whiskers) were not growing after 2200 cycles.

Fig.11 Limit of Thermal-Cycling Whisker Growth

unexpected failure phenomenon. Therefore, we implemented series tests to examine the mechanical strength of generated thermal-cycling whiskers using vibration and mechanical shock stresses in Table 3, in which no deformed or falling-off whisker was observed. Stress conditions applied to these tests were equivalent to vibration stress test condition for aircraft devices [11] and dropping stress test condition for mobile phone devices [12]. The results of these tests have demonstrated that there is almost nil possibility of generated thermal-cycling whiskers falling-off onto print circuit board by vibration or mechanical shock stress, with little possibility of triggering a circuit board failure phenomenon.

Table 3 Vibration and Mechanical-Shock Test Conditions

Vibration Test	Vibration frequency range: 10 to 2000 Hz Maximum acceleration: 20G Maximum amplitude: 3.0 mm 1 octave / minute, two directions, 10 cycles
Mechanical-Shock Test	Maximum acceleration: 3000G Acted time:: 0.3msec., 6 directions, each 3 times

4. Thermal-Cycling Whisker Growth Mechanism

In the next place, the growth mechanism of thermal-cycling whiskers was analyzed.

4.1 Detailed Observation on Thermal-Cycling Whiskers

Fig. 12 shows observational photographs of thermal-cycling whiskers on the same sample after 16 cycles, 57 cycles and 171 cycles of "–40ºC↔85ºC" thermal cycling test. The thermal-cycling whiskers in these photographs were growing as if they push up multiple tin grains on the tin plating film surface. This is a very interesting phenomenon. It seems that tin crystal grains underneath the tin plating film surface have grown to thermal-cycling whiskers and pushed up upper-side multiple tin grains like paring them away across the grain inside.

Fig. 13 shows a SEM image of thermal-cycling whiskers. Stripes in the whisker growing direction are observed, but also fine stripes in the vertical direction to whisker growth can be observed in the magnified image. As the number of these fine stripes corresponds to that of thermal-cycling test cycles, they are considered to be traces like wood growth rings generated by each cycle of thermal-cycling test.

Fig. 14 shows a Scanning Ion Microscope (SIM) images of cross-section surface of a thermal-cycling whisker before and after Focused Ion Beam (FIB) processing. The cross-section surface image after the processing indicates that the thermal-cycling whisker was composed of plural tin crystals. Fig. 15 shows a reflection electron image of a thermal-cycling whisker on solder plating (Sn : Pb = 9 : 1). There are two sections, white part and black part, in the single whisker. We have confirmed that the white part has lead-rich composition and black part has tin-rich composition. Also, from this result, it is reasonably concluded that thermal-cycling whiskers consist of plural crystal grains.

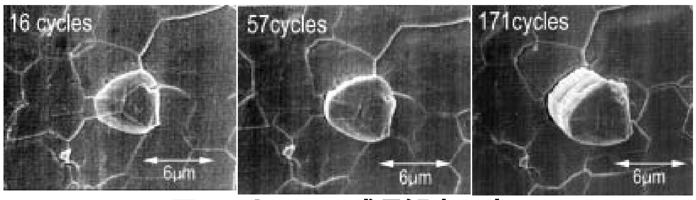


図 12 ウィスカ成長観察写真

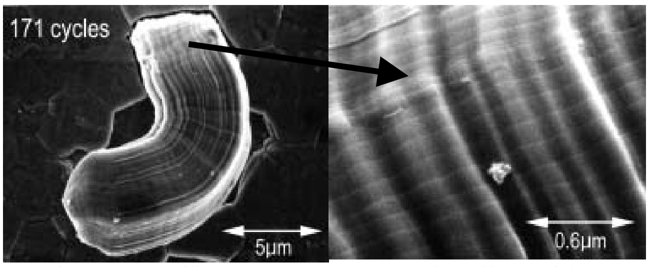


Fig. 13 Magnified SEM Image of Thermal-Cycling Whisker

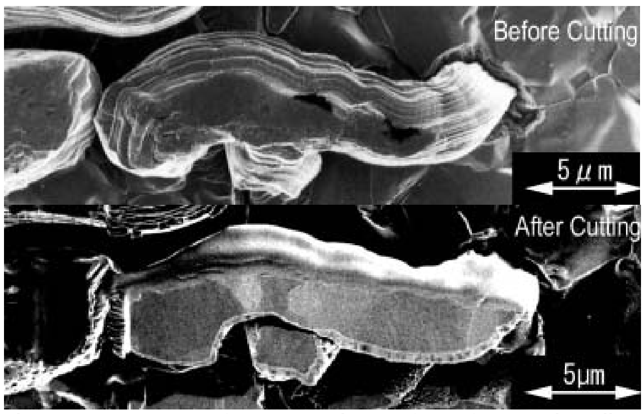


Fig. 14 SIM Images of Cross-Section Surface of Thermal-Cycling Whisker Before and After FIB Processing

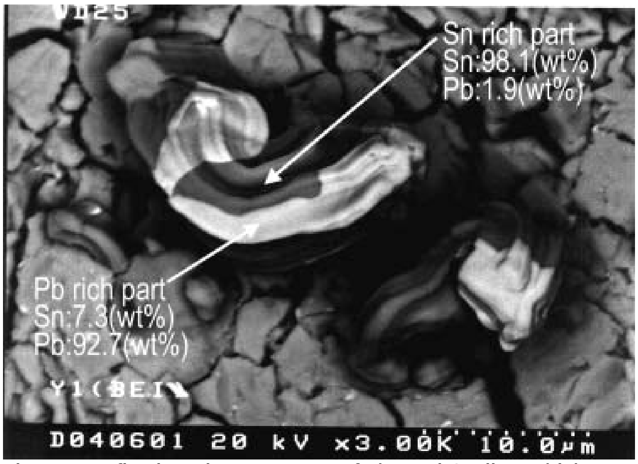


Fig. 15 Reflection Electron Image of Thermal-Cycling Whisker on Solder Plating

4.2 Consideration of Growth Mechanism

It is inferred that thermal-cycling whiskers are generated by compression stress inside tin plating film taking place due to thermal-cycling. In order to verify this inference, we made a bimetal substrate as shown in Fig. 16, on which tin plating film inevitably incurs compression stress.

This bimetal substrate is designed so that it warps upwards in the high side temperature and downwards in the low side temperature of thermal cycling test. Therefore, the compression stress is charged to the top surface tin plating film in the high side temperature and in the low side temperature to the bottom surface tin film.

The test results are shown in Fig. 17. Thermal-cycling whiskers were generated only on the top surface film and no whiskers were observed on the bottom surface film. This fact tells that thermal-cycling whiskers grow by compression stress charged to tin plating film at the high side temperature step in thermal-cycling test.

From these results, we considered that a base metal having larger difference of thermal expansion coefficient from that of tin plating film more easily generates thermal-cycling whiskers. In order to verify this consideration, thermal cycling tests were implemented for 6 type metal plates (Fe-Ni, Fe, Ni, Cu, Ag and Zn) on which tin was plated.

The results are shown in Fig. 18. The horizontal axis of this graph is graduated in compression stress values determined using FEM simulation method and the vertical axis is graduated in the number of thermal-cycling whiskers generated.

It has been figured out from this graph that a metal substrate having lager difference of thermal expansion coefficient from the tin expansion coefficient, 22.0ppm/°C, gives larger compression stress to tin plating film, and accordingly, generates more thermal-cycling whiskers. If nickel is taken up for example, it is inferred that, in the high side temperature step, tin attempts to expand according to its expansion coefficient but nickel under-layer plating can not follow the tin expansion because nickel's thermal expansion coefficient is 11.8ppm/°C, which produces a compression stress charged state in the tin plating film, and this state drives the growth of thermal-cycling whiskers. Conversely, in the low side temperature step, tin attempts to shrink according to the said coefficient but nickel under-layer plating can not follow the tin shrinkage, which produces a tensile stress charged state in the tin plating film, therefore, thermal-cycling whiskers are not generated. This mechanism supports the above bimetal experiment results.

Also, it is interesting that, although conventional type tin whiskers are more easily generated on copper under-layer than nickel under-layer, as to thermal-cycling whiskers, a trend is observed that copper under-layer generates less whiskers on tin surface-layer than nickel under-layer. These observations tell that thermal-cycling whiskers grow by a different force than that of conventional type whiskers, the force effected by the diffusion of under-layer metal into tin plating film.

From the above discussions, we have concluded that the force driving thermal-cycling whisker growth is the compression stress generated by the difference of thermal expansion coefficient between tin and under-layer metal.

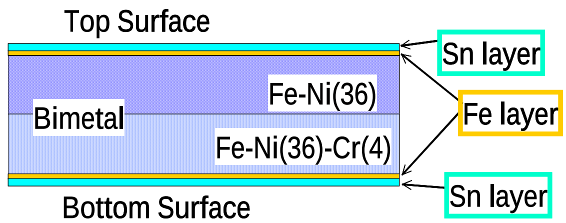


Fig. 16 Bimetal Experiment Substrate

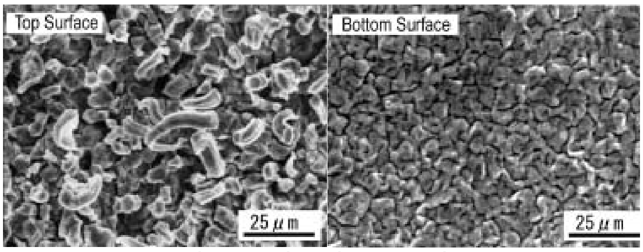


Fig. 17 Bimetal Test Result

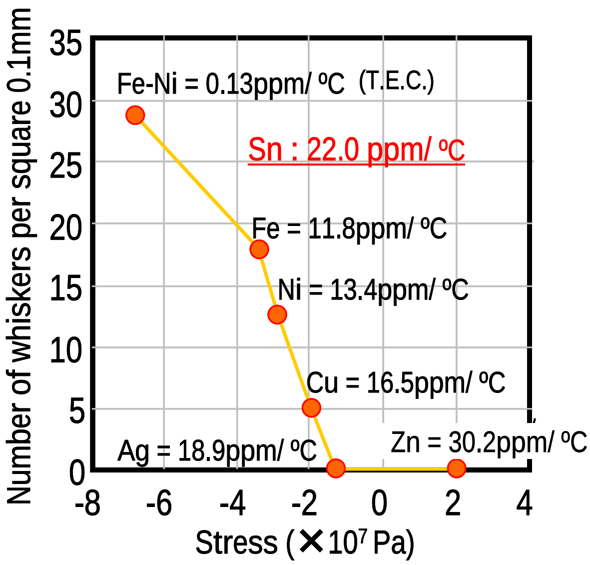


Fig.18 Correlation between Film Stress and Whisker Generation

4.3 Consideration of Suppression Mechanism against Thermal-Cycling Whiskers

In these stress analyses, the phenomenon has been learnt that thermal-cycling whiskers most rapidly grow at the high side temperature step of 85ºC and their growth is suppressed at a temperature higher than this degree. Also, it has been learnt that the growth of thermal-cycling whiskers do not ceaselessly continue but stops at around 2200 cycles of "–40ºC↔55ºC" test.

In order to examine the cause of these suppression mechanisms, the cross-section of thermal-cycling whiskers generated part of tin plating film was analyzed. As its result, nickel element mapping image by EPMA (Electron Probe Micro-Analyzer) is shown in Fig. 19. This mapping image shows nickel diffusion into the grain boundary of tin plating film. In this case, it is conceivable that a compression stress is generated by the intrusion of nickel into tin plating film, which promotes whisker growth. However, if the nickel diffusion could promote thermal-cycling whisker growth, the tin whisker growth should have been observed also in high temperature storage test because the nickel diffusion into tin plating film also occurs in the storage test.

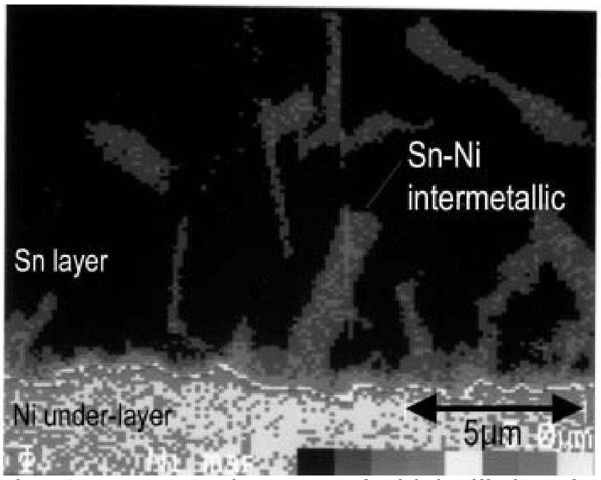


Fig. 19 EPMA Mapping Image of Nickel Diffusion after Thermal Cycling Test

However, no tin whisker growth has been observed on tin plating film with nickel under-layer in the past high temperature storage tests. And also from the mechanism discussed in the above analyses that thermal-cycling whiskers grow by compression stress due to the difference of thermal expansion coefficient between under-layer metal and tin plating film, the nickel diffusion is considered not to be involved in the growth of thermal-cycling whiskers.

On the contrary, we consider that the nickel diffusion into tin film grain boundary effects the suppression of thermal-cycling whiskers. The results of "–40ºC↔85ºC", 1000 cycles test of samples pretreated by 125ºC, 1000 hours storage test are shown in Fig. 20. This figure shows that there was no continuing growth of thermal-cycling whiskers on the samples preheated. It is known that, in a high temperature state, stress relaxation occurs in tin plating film, which suppresses tin whisker growth. However, as to thermal-cycling whiskers, it is difficult to consider that the stress relaxation by heat causes whisker growth suppression because they grow by repeated stress charged from outside, the thermal cycling stress. We infer that the generation of heat stress coming from thermal expansion coefficient difference is relaxed because under-layer nickel diffuses into tin plating film and generates a tin-nickel metal compound in the film grain boundary. Also, there is a high possibility that such nickel diffusion into grain boundary of tin plating film effects the suppressions of thermal-cycling whisker growth by preventing tin atom migration. Therefore, for the purpose of suppressing the growth of thermal-cycling whiskers, it will be effective to diffuse a metal like nickel, etc. into tin plating film. The results of the above experiment demonstrates the effect of this type pretreatment [13].

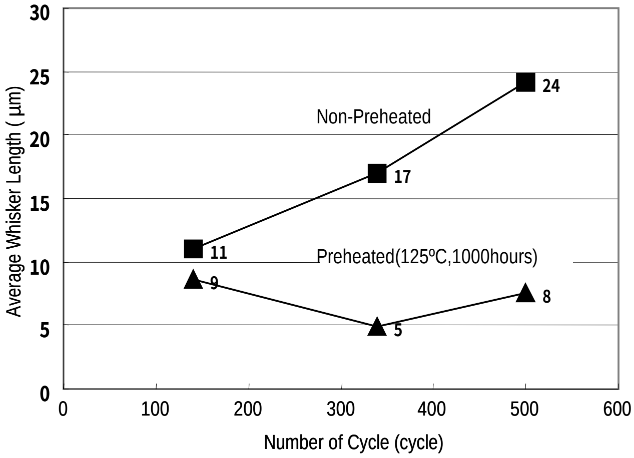


Fig. 20 Influence of Preheated

From the above discussion, it is inferred that the reason for the slowdown of thermal-cycling whisker growth in the above stress analysis test condition with the high side temperature higher than 85ºC is that the higher temperature promotes more speedy nickel diffusion. Also, it is inferred that a temperature around 85ºC is the optimal point for the whiskers to grow in respect of the balance between the growth mechanism by heat stress and the suppression mechanism by nickel diffusion. Further, it is inferred that, when temperature cycling reaching around 2000 cycles, the nickel diffusion has eminently progressed to an extent where the growth of thermal-cycling whiskers is discontinued. The whisker growth suppression effect by reflow soldering heat is probably due to the promotion of nickel diffusion into tin plating film occurring when the tin plating re-melts.

However, although it is certain that high temperature storage effects the suppression of thermal-cycling whisker growth, the details of the suppression mechanism by nickel diffusion are still in the research stage, which should be further studied in the future.

5. Conclusion

We have to estimate the field lifetime of products having inevitable degradation process and assess the risk of such degradation causing quality accident in the field use. In this research, we implemented several experiments to investigate thermal-cycling whisker growth by using stress analysis methods from the view point whether they can be serious reliability problem in the actual use environment of electronic components. We have estimated the expected lifetime of electronic components in respect of the thermal-cycling whisker problem using Eyring model, and examined the risk of field failure occurrence.

The results obtained in this research are outlined as follows:

(1) The thermal-cycling whiskers do not show simple growth proportionate to a given thermal-difference. The growth is also affected by actual (absolute) temperature level, in which the most accelerating high side temperature is 85ºC. The growth of thermal-cycling whiskers is suppressed in the test condition of which high side temperature is set to 105ºC, 125ºC or 65ºC. In the condition of which high side temperature is fixed at 85ºC, the larger the thermal difference is, the more the growth is accelerated; the experiments have shown that the highest whisker growth occurs in "–40ºC↔ 85ºC" condition.

(2) In the conditions of which high side temperature is fixed at 85ºC, the relation between thermal-difference stress and expected lifetime follows Eyring model, in which estimated acceleration coefficient of thermal-difference factor is "13". The field lifetime of products with tin plating electrode estimated in relation to thermal-cycling whiskers by using Eyring model obtained in this research is approximately 100 years in "0ºC↔85ºC" environmental condition, which shows almost nil risk of short-circuit or other accident in the field arising from thermal-cycling whiskers.

By the way, the thermal-cycling acceleration factor, "α = 16", obtained in this research is a very large figure compared to, for example, "α = 2" for solder break lifespan by heat fatigue, which means large dependency of thermal-shock whisker growth on thermal- difference in the condition of the high side temperature fixed at 85ºC.

(3) Grown-up thermal-cycling whiskers did not fall off by the application of vibration and mechanical shock stresses. Also, the phenomena were learnt that re-flow soldering heat suppresses the growth of thermal-cycling whiskers and the whisker growth stops after 2200 cycles in the test condition of "– 40ºC ↔ 85ºC". These findings totally show almost nil risk of thermal-cycling whiskers growing over 50μm in the actual use environment.

(4) We have learnt that, as to the growth mechanism of thermal-cycling whiskers, compression stress arising from the difference of thermal expansion coefficient between tin and under-layer metal is effected on the tin plating film, and the whiskers grow by this repeated stress on one by one cycle basis of high side temperature step in thermal-cycling test.

(5) We have also learnt that the involvement of under-layer nickel diffusion into tin plating film is highly probable as the reason of the suppression mechanism of thermal-cycling whisker growth,.

Although our products with tin plating electrode have been used long time in the actual market, we have no quality trouble experience arising from thermal-cycling whisker. It is reasonably considered that there will be no this type whisker problem also in the future even if tin plating electrode is widely promoted with the increased lead-free electrode application.

When the surface mounting technology has adopted minimum mounting gap narrower than 100μm in the future, further severer test criteria may be required. However, it is unlikely that such minimum gap is applied to an equipment part that suffers from very severe thermal-cycling condition, where two tin electrode components are very close to each other and generated two thermal-cycling whiskers contacted by a pin-point probability.

Although the conclusion has been deducted from these experiments that thermal-cycling whiskers will generate no problem in the market field, when adopting a new type of product, electrode or plating bath, we are verifying product reliability in respect of thermal-cycling whiskers by implementing reliability tests according to the criteria for tin whisker evaluation established based on the experimental results herein.

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