Accelerated Tin Whisker Growth. Identification of Significant Factors for Design of Experiment

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Abstract: The first notes about whisker growth phenomenon are dated on the 40s of the last century. During the last 60 years major consortia and research centres were involved in whisker phenomena that contributed to wide literature base. Although expenditures, kinematics of whisker growth hasn't been clearly understood yet. Nowadays tin whiskers become a crucial problem of electronic equipment manufacturers because of replace lead solders with lead-free solders as well as increase of packaging scale integration. According to the EU WEEE and RoHS directives eutectic and near-eutectic solders should be substituted with lead-free solders by August 2005 and July 2006 respectively. Subsequent evaluations are needed in order to comprehend basis of whisker growth physics This paper contains design of experiment, which allows embracing the phenomena of whiskers growth in complex way. Basis of this experimental design are results of experiments described up to now in literature. Published findings and our way of proceed eliminate randomness of future experiment results and keep focus only on the most significant factors stimulating whisker growth.

Key words: whisker growth, experiment design, stimulating, factors, accelerated

1. INTRODUCTION TO WHISKER GROWTH

Whiskers are crucial problem which is connected with reliability of consumer electronic products. Whiskers are single crystals of Cd, Sn, Zn, Au or Ag which grow spontaneously from the surface of pure metal. Whiskers grow from the bottom not from the tip [1]. They can take various shapes. They can grow as kinked, bent or striated needles or may take odd shapes. Whiskers are typically few μm in diameter but can grow from few μm up to few *mm* length. The phenomena of whisker growth are probably an effect of dislocation in the interfacial and multilayer structure of joint.

Whiskers decrease reliability of electronic devices in two different ways. Firstly whiskers can cause electric or mechanical failure. Whiskers are electrically conductive and may trigger transient or permanent short circuits between adjacent patches, lead frames, wires and bond pads. Character of short circuit depends on conducted current. If current is less than *10 mA* the short circuit is permanent, unless it is transient. Secondly whiskers can cause mechanic failures Whiskers can generate debris and contaminate that can interfere with Sensitive Optics or MEMS and affect failures [2].

1.1. Literature review

Long-term investigations brought a lot of experiments, results, analysis and probable factors that stimulate or mitigate whisker growth and theories concerning mechanics of the growth. The world literature is full of proposed or performed experiments. Results of the experiments in some cases confirm each others in some cases contradict each others. Large quantity of information from different sources about the phenomena of whisker growth complicates making distinctions between appropriate and inappropriate experiments, their analysis or conclusions.

Electronic manufacturing industry, research centers, scientific associations and other units are involved in electronic assembly prevention against Sn whisker growth. Prevention can be considered after thorough analysis mechanics of whisker growth. Knowledge about factors stimulating whisker growth and phenomena

that occur in the interfacial structure and adjacent areas in solder joint may result in creating proper model of whisker. The knowledge may be gained in specific experiments. Mostly experiments are expensive and time-consuming. Experiments should be designed before they are performed to eliminate risk of waste of time and money and should be based on the theoretical knowledge about whisker growth. This step of investigations is presented in the paper. The statistic analysis should clarify the group of factors that ought to be concerned during design of experiments. This kind of investigation may confirm our predictions or reject them showing factors that hasn't been considered as crucial and worth of attention yet.

1.2. Probable factors affecting in whisker growth

On the basis of the literature review, accelerated tests of whisker growth may be divided into three groups because of duration. The first group includes long term tests, an example is room temperature storage test. The second group includes medium term tests, dry oven storage test for instance. The third group includes short term tests, this group includes humidity and temperature cycles, thermal and mechanical shocks, vibration tests, bias and electromigration tests [5].

Before the proper statistic analysis probable factors were chosen on the basis of literature review. The crucial factor are internal stresses. Internal stresses may be caused by CTE mismatch between deposited layers, substrate and intermetallic compound (IMC) during thermal shocks, temperature cycles or heating The next reason of internal stresses may be irregular and discontinuous film of the IMC that generates stresses in the way of recrystallization. Other reason may be discontinuous layers of oxidation products from the surface.

2. DESIGN OF EXPERIMENTS (DOE)

The knowledge on a product or process behavior seems to be crucial in engineering applications. Though it can be considered as a black box, there still may be some knowledge collected. The first step can be based on experimental recognition, which goal is to assess, even without a complete understanding of the hidden phenomena, which parameters seem to be the most essential and the same would allow controlling its behavior. In most of the cases, the power of the input variables, expressed as e.g. percentage contribution, on the selected output would be the most interesting factor. The main idea behind the Design of Experiments (DOE) is controlling the input variables and recording the output signal of a product or process. Most often the input variables are referred to as factors while the output variable as a response. Unfortunately, current research was based on literature data and therefore did not fit exactly into any known DOE scheme, as orthogonal, CCD, etc. Therefore it required application of special statistical techniques, partly based on Latin Hypercube scheme and second order polynomials. For that purpose VPT (Virtual Prototyping Tool) was selected, which has been developed by LIPEC laboratory of Wroclaw University of Technology in Poland.

From the wide list of literature positions tens publications were chosen. In the scope of interest were publications which present conditions of performed experiments and their results. The analysis was based on about 30 publications. Factors which influence on whisker growth were assessed. The evaluation was done basin on the assessment of: whisker length and density of its occurrence. In fact fifteen factors were chosen under the scope of our study. Such an amount of the factors caused that specific statistic analysis were applied. The results were averaged in order to give only one number per experiment and factor R:

$$R = w_1 L + w_2 T + w_3 D \tag{1}$$

where: w_i are the assumed weights, L is the length, T is the thickness and D is the density of whiskers.

Actually for the current experiment all the weights w_i were assumed to be equal 1. The input data were collected in a table (Tab. 1), along with estimated values expressing the influence on the whiskers growth. The results of analysis (Tab. 1) allowed for the percentage power estimation of the factors and interactions.

We need directly controllable factors to precede design of experiment. These factors don't have to be proximate causes of tested phenomenon. In the case of whiskers we can't control basic factors which stimulate their growth such as structure of IMC or volume of internal stress. On the other hand we can control and measure the others factors like chemical constitution of layers, grain size, humidity, temperature, etc. The primary factors are the results of indirect agents. That is the reason of the chosen way of factors selection method. Our task is to interpret, basing on physical metallurgy knowledge, their influence on the whiskering.

Tab. 1. The input data and estimated values of the whiskers growth, where F1 stands for thermal cycling, F2 – various solders, F3 – thermal shocks, F4 -storage, F5 – humidity, F6 – heating, F7 - external stresses, F8- thickness of deposited layers, F9 - leadframe material, F10- crystal orientation, F11 – grain size. F12 – deposition conditions, F13-bias, F14- pre-conditions, F15 - reflow temperature [6-45]

Factor	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	Sum
1	5	3.5														**8,5**
2			5													**5**
3	5	5		3											5	**18**
4		1	2													**3**
5						3	3									**6**
6				4	3			4								**11**
7							3				3					**6**
8								2		2		3				**7**
9	3	2	4		3				2							**14**
10	3			3	3					4	1	3				**17**
11				3	3	1		1	1					4		**13**
12							4	3		3	3	4				**17**
13				3			4									**7**
14	2	1		3.5	3.5	3.5							1			**145**
15			3		3.5	3.5		3	4			2		2		**21**
16	3						3					2			3	**11**
17					3	3								1		**7**
18	3				3	3		3	4				3			**19**
19					1	1			1			1			2	**6**
20	4				4	4										**12**
21		3		3	3	3			2							**14**
22										2	1					**3**
23							2									**2**
24	3			1	1	3										**8**
25					2		2			3						**7**
26					3	3	2									**8**
27	3			3	3				3							**12**
28			4			3										**7**
29	2			3			2	4			2					**13**
30					3	3		3			4					**13**
31						3			3					2		**8**
Sum	**36**	**15,5**	**18**	**29,5**	**45**	**40**	**25**	**23**	**20**	**14**	**14**	**15**	**4**	**9**	**10**	**318**

Tab. 2. The results of analysis (more than 3% contribution)

Factor	F11xF12	F4xF6	F2xF3	F4xF11	F2xF9	F9xF14	F1	F2	…	Sum:
[%]	7,7	7,5	6,8	6,4	6,2	5,5	5,3	5,2	…	83,7

According to the achieved results it can be conclude that:

- The greatest impact on whiskers growth have deposition conditions and grain size. These two factors are closely connected because the grain size outcome of conditions during spreading the finish layer. The structure of finish layer has great influence on internal stresses value. Inside amorphous structure occurs huge density of dislocations causing big internal stresses. In literature we can find that the matte Sn is more disposed to whiskering. Matte Sn has bigger grains and more ordered crystal lattice. As we know (def.) the whisker is monocrystal arising because of movement of helical dislocation by the action of compressive stress. Amorphous structure causes that movement of dislocations becomes impossible because their start to block each other. The type of bath used to plate finish layer can also influences on propensity of finish layer surface to oxidation and put into finish layer some impurities (blocks movement of vacancies). The grain size has an effect on structure of IMC, which is forming and increasing along the grains boundaries. In matte Sn boundaries are more distant than in fine. This causes that thickness of IMC is more diversified - there are less places where the same amount of base layer atoms can diffuse. Inhomogenity of IMC thickness inducts bigger internal stress.
- Following factors stimulating whiskers growth are the time of storage and heating. Forming of IMC doesn't have rapid character, it is result of atoms diffuse which need time to move from one crystal lattice to others. Longer storage will cause increase the section thickness of IMC, but it also will make it

more homogenous. Most intensive whisker growth will be observed in moment when the IMC will have already been along all boundary between layers and there will be the most inhomogeneous thickness. The stress can be relaxed by heating in temperature above which predomination of recrystallisation starts. Heating under this temperature force atoms to diffuse faster but reconstruction of crystal lattice proceeds as a treatment process which is only ordering dislocations. This phenomenon is called traversing and it can be way in which slip planes, along which whiskers grow, are founding.

- Chemical constitution is factor that significantly determinate the structure and thickness of formed IMC. If the finishing layer material contains the atoms of underlayer material the diffusion is less intensive because the concentration between layers is more equal. Additionally very meaningful is which elements are components of finish layer alloy. Literature says that presence of IMC Cu6Sn5 is the most stimulating because it increases into crystal lattice of Sn and its lattice constant is bigger than lattice constant of Sn. This is the reason of internal stress. Opposite effect causes the presence of Ni because it's solubility in Sn is lower than solubility Sn in Ni, and atoms of Sn diffuse to Ni crystal lattice causing stress relaxation.
- Correlation between thermal shocks and various solders affecting in whisker growth may be explained by thermal conductivity of specific solders. Fast heating and cooling cause heterogeneous decay of temperature inside the finish layer. The decay depends on thermal conductivity which is connected with homogeneous of alloy structure significantly. High distinction between low and high temperature cause thermal distortion in the bulk of solder, which provides mechanical stresses.
- Leadframe material is another important stimulating factor which may be controlled. It has crucial influence on IMC layer as well as induct mechanical stress caused by thermal mismatch between materials.
- As preconditioning we mean conditions which samples are exposed on before the main experiment. During this phase surface of finish layer oxidizes. The surface layer of oxides has big impact on internal stress relaxation. It stops dispersion of energy when moving dislocation reaches the surface of finish layer. However the thick layer of oxides can make whiskers growth impossible because it becomes to strong. On the other hand inhomogeneous layer of oxides may provide similar results as inhomogeneous layer of IMC.
- Thermal cycling is the way to sum a few effects together which we mentioned about earlier. Changing of temperature and thermal mismatch cause mechanical stresses. Additionally the influence of high temperature is the same like in the case of heating. Additionally we can change the ramp of heating and refrigerating temperature causing thermal shock effect.

3. CONCLUSIONS

Summarizing whiskers growth intensity depends on many factors. Sometimes the influence of these factors weakens each other and sometimes existence of more than one of them is necessary to create the whisker. Control of factors such as temperature or humidity is simple but it is important to keep their values in range which is the most stimulating. Controlling for example grain size or its structure is more complicated, requires tests before the main experiment in order to make investigator sure about input values used in the final experiment. It is necessary to provide conditions in which whisker growth will be not accidental.

REFERENCES

[1] S.E. Koonce, S.M. Arnold, *"Growth of Metal Whiskers"*, J. Apl. Phys. (letters to the editor), 24(3), pp. 365-366, 1954
[2] http://nepp.nasa.gov/whisker/index.html
[3] H.L. Cobb, "*Cadmium Whiskers*", Monthly Rev. Am. Electroplaters Soc., 33(8), pp. 28-30, January 1946
[4] S.M. Arnold, "The Growth of Metal Whiskers on Electrical Components", Proc. of the IEEE Elec. Comp. Conf., pp. 75-82, 1959
[5] "*NEMI overview and NEMI Pb-free Task Group Activities*", Workshop on Modeling and Data Needs for Lead-free Solders, New Orleans, LA, February 2001
[6] M. Dittes, P. Oberndorff, P. Crema, V. Schroeder, P. Alto, *"The Effect of Temperature Cycling on Tin Whisker Formation*"
[7] T. Ando, M. Shibata, S. Okada, Y. Namasuya, "*Stress Analysis and Accelerated Evaluation of Tin Whisker under Thermal Shock Stress*"

Because of limitation the full list of references [1-44] is available on the web site:
http://www.lipec.info/publications/pdf/DOE_IMAPS2005.pdf