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Resistance changes of lead-free solder joints induced by defects of their structure

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Abstract: Within the frame of this study three solder pastes and three pad coatings were taken into the careful consideration. The selection was based on author's previous wide experimental investigations. Selected soldering alloys as well as pad coatings are commonly used by producers of electrical and electronic equipment that makes results of the study easier to introduce to the market. Test specimens were subjected to aging processes. The evaluations were based on measurements of resistance and microscopic inspections of cross-sections. Investigations were focused on finding correlation between detected changes of solder joint resistance and occurrence of defects or changes within the structure.

Key words: inspection, reliability, lead-free solder, aging, resistance, measurement

1. INTRODUCTION

Producers of electrical and electronic equipment are forced by local legislation as well as ecological and economical aspects to eliminate hazardous substances from products. Higher temperature of lead-free soldering as well as application of new materials lead to occurrence of reliability problems. Main problems of lead-free solder joints are cracks, electromigration and whisker growth. The cracks can cause temporary or permanent openings of electrical circuits, while whisker that grow from pure metal layer can cause shorts between adjacent pads and conductive patches. The problems are mainly connected with defects of solder joint structure such as Kirkendall voids, empty spaces, processes and phenomena such as diffusion, doping, dislocations, recrystallizaton, spalling or re-distribution of intermetallic compounds (IMCs) [1]. Cracks, inhomogeneous thin films of IMCs, wrong solderability or wetting during soldering process have an influence on mechanical strength of solder joint and its resistance [2-4]. Many researchers perform evaluations that are focused on IMC growth, solder joint properties, increasing reliability of lead-free joints. Experimental study such as reliability tests followed by inspections are very time-consuming and expensive.

Standard inspection of solder joints requires expensive equipment such as acoustic microscope or computed tomography, therefore author focuses on developing alternative, cheaper method of solder joint condition evaluation. Proposed method bases on the resistance measurement of solder joints. The main aim of this study was to evaluate the resistance changes induced by the changes of solder joint structure and to confirm or refuse proposed inspection method. The presented study is a crucial part of wide investigations that were performed by the author and focused on increasing reliability of solder joints.

2. TEST SPECIMEN AND EVALUATION PROCEDURE

The most common way to evaluate the solder joints is examination of soldered daisy chains or 0 Ohm SMD resistors. The author evaluates 0 Ohm resistors within the frame of his study. Under the scope of main investigations were three different solder pastes and three different pad coatings. Commercial pastes such as SN100C, Sn96.5Ag3.0Cu0.5 and SnPb (as a reference to others) were used to solder the resistors on designed test printed circuit boards (PCBs) during reflow process (each test board includes 20 pcs of 1206 and 20 pcs of 0805 0 Ohm SMD resistors). The test FR-4 boards varied in pad coatings. The pads were plated by Electroless Nickel Immersion Gold (ENIG), chemical tin or Hot Air Solder Leveling (HASL) lead-free solder coating. The test PCBs were designed in respect to multiple measurements of resistance using 4-probe Kelvin method. Example of the test PCB used in this investigations is presented in fig. 1. In order to force changes of solder joints structure, some PCBs were subjected to two consecutive aging processes (300 h at 150 ºC) [5-6]. In respect to find the correlation between the resistance and defects of the solder joint structure, the PCBs were subjected to multiple measurements of solder joint resistance before they were polished. Obtained cross-sections were subjected to optical evaluations using metallurgical microscope.

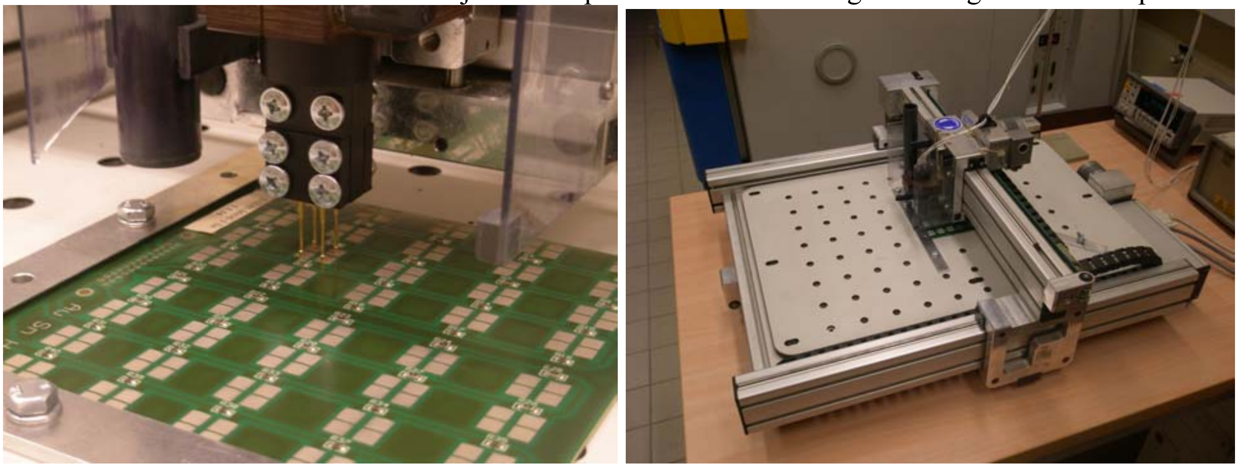

Figure 1. View of the test PCB and measuring system

Measurements of solder joint resistance causes problems because of its low level. It is crucial to avoid measuring errors connected with floating conditions of the measurement, used method, meter circuitry etc. In order to avoid the errors and find correlation between the resistance of solder joint and its structure, statistical evaluations that base on multiple measurements were performed. In purpose to ensure high repeatability of multiple measurements of solder joint resistance the dedicated control stand developed by the author was used. The control stand is presented in fig. 1. The control stand consists of CNC machine tool with designed measuring header, precision multimeter and microcontroller. The measuring header was fitted out with four commercial gold plated test probes with springs (4-probe method measurement of resistance). The header was lowered at the same height during each measurement. Such solutions ensure that all four tips of the test probes press the pads with the same pressure during each measurement. The movement of the header, the settings and the readings of the multimeter were controlled by the microcontroller therefore the measurement procedure was fully automatic (time saving). Before each measurement the control stand was calibrated. In order to calibrate the control stand, standard resistors were used. The results of the measurements collected by the PC computer were used in the final analysis of variance (Anova). The Anova is a statistically based decision tool for detecting any differences in average performance of groups of item tested. It enables to detect factors and correlations that influence on measured object [7].

Performed preliminary evaluations proved that even such small change of solder joint resistance as the change that results from aging processes can be detected using the control stand. During the evaluations test specimens were subjected to aging processes (the same conditions as in present evaluations), after each aging process the resistance of the test specimens were measured using the control stand. The results were subjected to two-way Anova analysis that included two parameters (the resistor and the aging time). The results indicated that the detected resistance changes were caused by the aging and no important factors were omitted from the experiment. Moreover the preliminary evaluations confirmed that resistance of used resistors does not change significantly during aging processes. The facts ensured the author that the control stand would be adequate to find the correlation between resistance of solder joint and the defects within its structure.

3. RESULTS AND ANALYSIS OF VARIANCE (ANOVA)

First round of measurements (before any aging process) indicated that the resistance of measured test specimens (soldered 0 Ohm resistors) strongly depended on the solder paste constitution. In order to avoid incorrect conclusions, the tested PCBs were divided into three groups in respect to the used solder pastes (SN100C, Sn96.5Ag3.0Cu0.5 and SnPb respectively). Eighteen resistors were chosen from each group for the final analysis. The resistance of every resistor was measured nine times during each measurement procedure. In order to avoid deviation the header (of the control stand) with the measuring probes was lowered three times in case of each resistor. Every time the probes touched measuring pads the resistance was measured three times. The results obtained for each group were subjected to three-way Anova analysis. The summary of the Anova results for Sn96.5Ag3.0Cu0.5 is shown in table 1. There are three controlled parameters in this experimental situation. The A factor is a pad coating, the B factor is an aging process and the C factor is a condition of solder joints. Both the A and the B are 3 level factors (A1- chemical tin, A2-ENIG, A3- HASL, B1- after reflow process, B2- after one aging process for 300 h at 150 ºC, B3- after two aging processes for 600 h at 150 ºC) while the C is 2 level factor (C1- proper solder joints, C2-solder joints with visible defects of structure). The C was evaluated on the base of microscopic observation of cross-sections. The defects that were taken into the consideration are presented in fig. 2. Correlations between factors are marked as A x B, A x C, B x C, A x B x C.

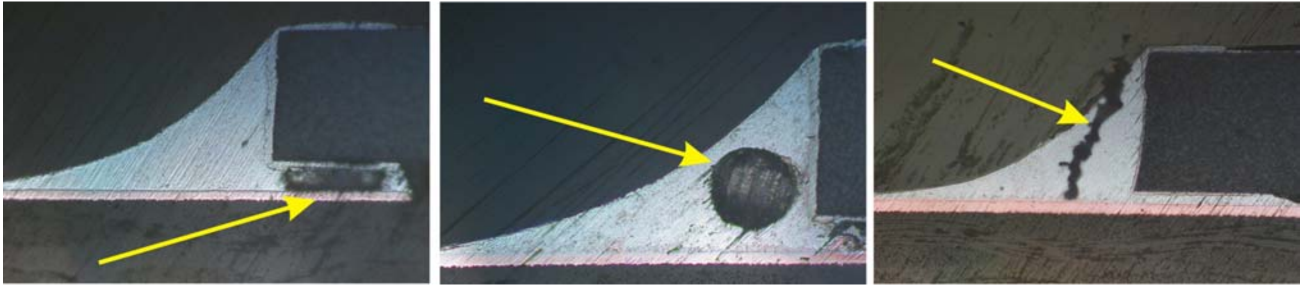

Figure 2. Examples of detected defects of solder joint structures (empty holes and cracks)

Table 1. Results of Anova calculated for the second group of PCBs (Sn96.5Ag3.0Cu0.5)

	SS **Sum of squares**	**ν** **Degrees of freedom**	**V** **Variance**	**F** **F ratio**	**SS'** **Expected SS due to factor**	**P** **Percent contribution**
A***	6,71E-007	2	3,35E-007	154,20	6,66E-007	2
B***	**9,38E-006**	**2**	**4,69E-006**	**2156,28**	**9,37E-006**	**22**
C***	**1,01E-005**	**1**	**1,01E-005**	**4663,40**	**1,01E-005**	**23**
AxB***	7,06E-007	4	1,76E-007	81,16	6,97E-007	2
AxC***	1,75E-007	2	8,76E-008	40,30	1,71E-007	0
BxC***	**1,48E-005**	**2**	**7,40E-006**	**3405,00**	**1,48E-005**	**34**
AxBxC***	**7,15E-006**	**4**	**1,79E-006**	**822,03**	**7,14E-006**	**16**
e	3,13E-007	144	2,17E-009		3,50E-007	1
T	3,13E-007	161				100
e*pooled	1,86E-006	152	6,02E-007			4

***at least 99 % confidence **bolded-significant factors**

The results of Anova indicate that aging process, condition of solder joint structure and correlations between factors have significant effect on the resistance of evaluated test specimens. Percent contribution (P) shows the relative power of a factor to reduce variation. Percent contribution indicates that the aging process, defects of the structure and the correlation between them contribute the most toward the variation observed in the experiment. The percent contribution varies between 22 and 34 %. Percent contribution due to error is low, about 1 % (when pooled increases to 4). It is assumed that no important factors were omitted from the experiment. The results of Anova performed for two other groups of PCBs (SnPb, Sn100C) were similar.

The main aim of the study was to confirm correlation between condition of the solder joint structure and the joint resistance. Significant correlation between these two factors and their similar percent contribution forced to exclude the aging process and perform two-way Anova analysis. Moreover the contribution of the B factor could be caused by influence of aging process on solder joint resistance as presented in previous investigations or by deviation of tested resistances (resistances of soldered resistors). After measurement the test specimens were polished therefore other test specimens were measured after each aging process.

In order to perform final analyses, the data were divided into nine groups in the respect to the solder paste and the aging process. The summary of the two-way Anova results for Sn96.5Ag3.0Cu0.5 after two aging processes (600 h at 150 ºC) and Sn100C after reflow process is shown in table 2 and table 3 respectively. There are two controlled parameters in this experimental situation. The A factor is a pad coating while the factor B is a condition of solder joint structure.

Table 2. Results of Anova calculated for Sn96.5Ag3.0Cu0.5 (600 h at 150 ºC)

	SS	**ν**	**V**	**F**	**SS'**	**P**
A***	8,05E-007	2	4,02E-007	217,87	8,01E-007	5
B***	**1,31E-005**	**1**	**1,31E-005**	**7068,47**	**1,31E-005**	**84**
AxB***	1,51E-006	2	7,56E-007	409,24	1,51E-006	10
e	8,87E-008	48	1,85E-009		9,79E-008	1
T	1,55E-005	53				100
e*pooled	2,41E-006	52	1,16E-006			16

***at least 99 % confidence **bolded-significant factors**

Table 3. Results of Anova calculated for Sn100C after reflow process

	SS	ν	V	F	SS'	P
A***	**1,52E-006**	**2**	**7,60E-007**	**352,68**	**1,52E-006**	**27**
B***	**3,85E-006**	**1**	**3,85E-006**	**1788,58**	**3,85E-006**	**69**
AxB***	6,88E-008	2	3,44E-008	15,96	6,45E-008	1
e	1,03E-007	48	2,15E-009		1,14E-007	2
T	5,55E-006	53				100
e*pooled	1,72E-007	50	3,65E-008			3

***at least 99 % confidence **bolded-significant factors**

In both presented cases the results of Anova indicate that the condition of solder joint structure has the significant effect on the resistance changes of evaluated test specimens. As occurred the structure defects increase the resistance significantly. The percent contribution due to B varies between 69 and 84 % while the percent contribution due to error is low and varies between 1 and 2 % (when pooled increases to 16). It is assumed that no important factors were omitted from the experiment. In the case of other 7 of 9 groups the percent contribution due to error does not exceeds 10 %. In three cases the B factor has a dominant effect, in other three cases it has a significant effect, only in one case it has no effect.

4. CONCLUSIONS

Experimental investigations supported by the analysis of variance (Anova) indicate that condition of the solder joint structure has a significant measurable impact on the resistance. Therefore non-destructive evaluations of the solder joint condition (its structure) that base on resistance measurements seem to be possible. Such evaluations require the control stand that enables high repeatability of measurements and accuracy. It is crucial to ensure the same conditions during measurements. As presented, the method is sensitive to deviation of the resistance caused by other factors such as solder paste (various resistivity), pad coating, aging process, deviation of nominal resistance of tested daisy chains etc. Nevertheless after some modification the proposed method could be implemented, for example, onto the control stand in an assembly room by producers of electronic devices. The solder joints that include voids and other significant defects could be isolated with high possibility if the whole batch of solder joints was evaluated (the same pad coatings, solder paste etc.). Further complex evaluations are advisable.

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