Influence of soldering and aging processes on the structure of lead-free solder joints

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Abstract: Mechanical strength of a solder joint is closely connected with its structure. The presence of defects such as Kirkendall's voids or any other empty spaces, dislocations, discontinuous films of intermetallic compounds (IMCs) or metallic layers within the structure of connection can significantly decrease its resistance to external stress loading. Within the frame of this study three solder alloys and three pad coatings were taken into the careful consideration. The selection was based on the author's previous wide experimental investigations. The test specimens were subjected to aging processes in specific conditions. The evaluations were based on microscope inspections of cross-sections. The authors focused on analysis of the solder joint structure in respect to visible defects after reflow soldering and after consecutive thermal aging processes.

Key words: intermetallic compound, reliability, lead-free solder, aging, defect

1. INTRODUCTION

The reliability of solder joints depends on many factors such as soldering process, metallization of printed circuit board (PCB), coating of solder pads, solder alloy etc. All the factors determine solder joint structure. The structure of solder joint looks alike crystalline. The fracture precursors like dislocations, voids and other defects can decrease mechanical strength of the solder joint significantly. Most problems of lead-free solder joints are directly connected with intermetallic compounds that are formed during the soldering process [1].

Within the frame of reliability investigations, the author focused on most controllable parameters such as different commercial solder pastes, pad coatings and aging processes. The materials were chosen on the base of previous investigations and the literature review. Both component metallization and pad coatings have a great impact on intermetallic compounds (IMCs) and reliability of solder joint in the consequence [1,2]. Aging processes influence on the formation of IMC structure, its shape, thickness and the defect occurrence [3-6]. Kirkendall voids that are formed along boundary interface are the main cause for the joint strength degradation during thermal aging. The voiding process is activated at as low as 100 ºC [7]. The strength of the lead-free solder joint decreases after aging process [8]. It can be influenced by Kirkendall effect. In order to force changes of investigated solder joints structure, especially thickness and shape of IMCs, researchers subject solder joints to multiple aging processes in temperatures that varies between 100 and 150 ºC for several hundred hours [4-8]. The time of storage and the temperature are not accidental, the rate of IMCs growth is determined by activation energy of reactions [3,9-10].

The influence of aging processes and thermal cycles on both structure and reliability of solder joint is evaluated by many researchers. In most cases researchers are focused on changes of microstructure (formation of IMCs, Kirkendall voids etc.) and evaluate specified alloy or metallization [3-7]. Their investigations are based mostly on scanning electron microscopy, X-ray fluorescence analysis of micro-sections or micro-computed tomography that produces detailed three- dimensional images of solder joint structure. In the opposite to considerable works which has been done in this topic, current investigations were focused on wide range of materials (three various solder pastes and three various pad coatings were taken into the consideration). Such investigations enabled to compare different configurations that are commercially applied in electrical and electronic equipment. The author evaluated the influence of aging processes on presence of the macroscopic defects such as voids, empty spaces, cracks. In order to evaluate the micro-sections of the solder joints, an optical metallurgical microscope was used. The solder joints were evaluated in respect of observed defects. In order to determine factors that influence the defects, the results were subjected to analysis of variance (Anova). Application of the Anova was the novelty in this topic. The aging time and the temperature were based on the literature review.

The main aim of this study was to precise experimentally the influence of used materials, soldering and aging processes on changes of the joint structure. The presented study is a crucial part of wide investigations that are performed by the author and are focused on increasing the reliability of solder joints on PCBs.

2. TEST SPECIMEN AND EVALUATION PROCEDURE

In order to evaluate properties of solder joints the author uses 0 Ohm SMD resistors soldered on test printed circuit boards (PCBs). 0 Ohm resistors and daisy chains are commonly used by researchers to investigate solder joints. Under the scope of investigations were three commercial solder pastes and pad coatings. The test PCBs were designed in respect to complex reliability tests, multiple measurements of resistance in static conditions, measurements during accelerated reliability tests [11], evaluation of shear force and visual inspection. The PCBs varied in pad coatings. Example of the test PCB used in this investigations and climatic chamber are presented in fig. 1

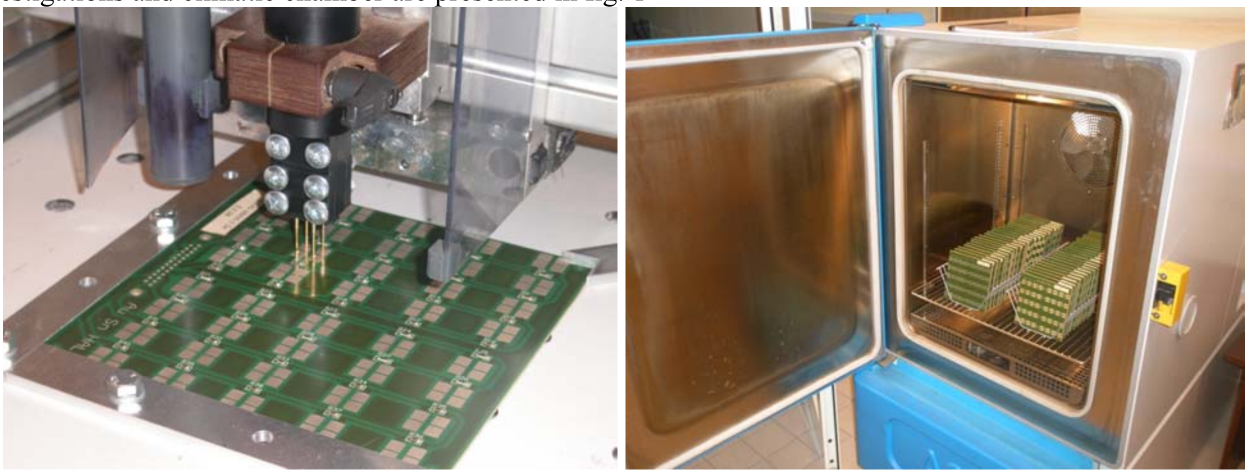

Figure 1. View of the test PCB and the climatic chamber

In case of the first group of the PCBs, the solder pads were plated by chemical tin commonly used because of its relatively low price and its flatness. In case of the second group of the PCBs, pads were plated by Electroless Nickel Immersion Gold (ENIG) thin film that ensures great flatness, but is more expensive than chemical tin. In case of third group of the PCBs, pads were plated by Hot Air Solder Leveling (HASL) film that does not ensure flatness, it is not useful in case of fine pitch electronic assembly, but is much cheaper than the others. Commercial pastes such as SN100C, Sn96.5Ag3.0Cu0.5 and SnPb (as a reference to others) were used to solder resistors on the PCBs during reflow process (each test board includes 20 pcs of 1206 and 20 pcs of 0805 0 Ohm SMD resistors). Test specimens were divided into 9 groups in respect of solder paste constitution and pad coating.

On purpose to force changes within solder joint structure, the test specimens were subjected to two consecutive aging processes at 150 ºC for 300 hours each. After reflow process and after each aging processes six resistors (three 1206 and three 0805) of each group (nine groups of the PCBs) were subjected to micro-sections using polishing machine. The micro-sections were subjected to visual inspection using optical microscope. Simple comparative analysis did not delivered any correlations between aging process duration and changes of solder joint structure. Therefore to find correlation, precise factors that influence structure changes and confirm correctness of realized experiment, analysis of Anova was performed. 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.

3. RESULTS AND ANALYSIS OF VARIANCE (ANOVA)

Micro-sections of the solder joints (soldered resistors) were subjected to optical inspection. At this stage, the author focused just on solder joint structure defects visible under an optical microscope. The solder joints were evaluated in respect to defects such as voids that occur in the region of IMC, in the bulk or under the metallization of the resistor, cracks or losses of the solder. Examples of observed defects are presented in fig. 1. Weights of the defects were assumed in order to perform the analysis. Values of the weights were determined by their credibility and influence on the joint structure. Six solder joints were evaluated for each group of tested PCBs after each process (reflow and two aging processes). The table of assessments (sums of the weights) was the base to three-way Anova analysis. The summary of the Anova results is shown in table 1. There are three controlled parameters in this experimental situation. The A factor is a solder paste, the B factor is a pad coating, and the C factor is an aging process. All the factors are 3 level factors (A1- SnPb, A2- Sn96.5Ag3.0Cu0.5, A3- SN100C, B1- chemical tin, B2- ENIG, B33- HASL, C1- after reflow process, C2- after one aging process for 300 h at 150 ºC, C3- after two aging processes for 600 h at 150 ºC). Correlations between factors are marked as A x B, A x C, B x C, A x B x C.

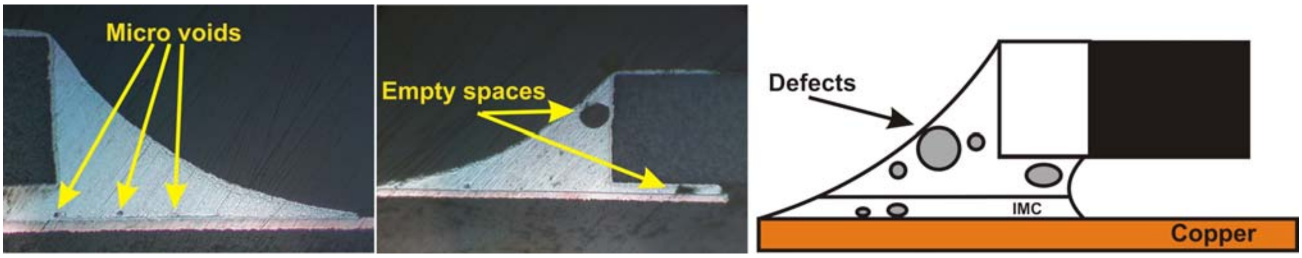

Figure 1. Examples of detected defects of solder joint structures considered during evaluations and Anova analysis

Table 1. Results of Anova analysis

	SS Sum of squares	v Degrees of freedom	V Variance	F F ratio	SS' Expected SS due to factor	P Percent contribution
A*	25	2	12	3	16	3
B	20	2	10	2	11	2
C	21	2	10	2	12	2
AxB*	58	4	14	3	39	7
AxC*	52	4	13	3	34	6
BxC	24	4	6	1	5	1
AxBxC* **	**149**	**8**	**19**	**4**	**112**	**19**
e	**246**	**54**	**5**		**364**	**61**
T	594	80				100

***at least 99 % confidence * at least 90 % confidence **bolded-significant factors**

Percent contribution (P) due to error is much higher than 50% while none of the factors has significant influence (P was less than 15%). It means that some important factors were definitely omitted, the conditions were not precisely controlled or the measurement error was excessive [12]. The evaluation was based on optical verification, conditions were precisely controlled (the factors were precisely determined). Thus it can be concluded that some important factors were omitted. The analysis indicates that the influence of investigated factors on the defects of solder joint structure is not significant or there is other significant factor omitted in the experiment. Only percent contribution of correlation between investigated factors exceeded 15 %, what means that it has some influence on defects of solder joint, but because of the high percent contribution due to error, this result is rather unreliable.

Careful optical analysis of test specimens following previous investigations confirmed the results of Anova analysis. The factors that were omitted could be differences in thickness of the solder paste applied during the assembly procedure, improper reflow curve or the wet solder paste. An inhomogeneous film of the applied solder paste full of gas bubbles could cause the defects during reflow process.

It is difficult to compare obtained results with the results of other researchers because most of them are focused on microstructures such as intermetallic compounds, Kirkendall voids etc. Their evaluations mostly base on measurements of layer thickness or estimations of defects quantity. In most cases the results of the studies showed that the microstructures changes after aging processes, moreover thermal cycling can accelerate rate of changes.

4. CONCLUSIONS

The presented experimental evaluations indicate that multiple aging processes do not cause visible defects in the structure of solder joint on PCBs. The defects were not connected with the used materials. The results of Anova analysis suggest that other factors could cause defects and influence the structure significantly. Careful visual inspection confirmed that the inhomogeneous solder paste full of gas bubbles applied on pads before soldering process could be the reason of most observed defects. Other author's investigations connected with stability of the solder joint resistance suggest that the aging process influence the joint structure. Additional scanning electron microscopy and X-ray fluorescence analysis of cross-sections would confirm that aging processes influence the structure at IMC level. The results are the base for next investigations.

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