International Journal of Integrated Engineering: Special issue 2018: Mechanical Engineering, Vol. 10 No. 5 (2018) p. 26-31
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DOI: https://doi.org/10.30880/ijie.2018.10.05.005

Structural Assessment of Lead Free Solder Joint of Miniaturized Electronics Assembly

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Received 19 April 2018; accepted 11 August 2018, available online 30 October 2018

Abstract: This paper presents a study on structural assessment of ultra-fine package assembly with nano-composites lead free solder joint after reflow soldering process. In this work, various nanoparticles (i.e. TiO_2, Fe_2O_3 and NiO) with different weight percentage (i.e., 0.01, 0.05 and 0.15 wt.%) were successfully incorporated into SAC305 solder paste using a mechanical solder paste mixer to synthesize novel lead-free composite solders. Effects of the nanoparticles addition on quality of joining and fillet height between various weightage (wt.%) for the ultra-fine package assembly in the reflow soldering process have been investigated by using a scanning electron microscope (SEM) system equipped with an energy dispersive X-ray spectroscopy (EDS) and XTV 160 x-ray inspection system. Experimental results show the addition of TiO_2, Fe_2O_3 and NiO nanoparticles with 0.15wt.%, 0.05wt.% and 0.01wt.%, respectively, produce the best fillet height of each composition of nanoparticles solder paste. Among all these new composition of nanoparticles solder paste, NiO nanoparticles reinforced solder paste with 0.01wt.% yielded the highest fillet height. The miniaturized solder joints do not cause any problem in terms of solder voids. The findings show the capability of the reflow soldering process in assembling miniaturized electronics assembly and expected to provide a reference in electronic package industry.

Keywords: Titanium dioxide (TiO_2) nanoparticle, Ferum oxide (Fe_2O_3) nanoparticle, Nickel oxide (NiO) nanoparticle, SAC305, Composite solder, Ultra-fine package

1. Introduction

Lead free solder is extensively used in the electronics industry for joining purpose in integrated circuit (IC) packaging applications. The current trend of the IC packaging are miniaturizing IC package and passive component (e.g., capacitor and transistor) that demands reliable solder joint to sustain the performance and overall product reliability. Numerous studies had been carried out to improve solder joint reliability of lead free solders. Various types of ceramic or metal based nanoparticles are often added to the lead free solder to reinforce the solder joint during the electronic assembly process [1]. Several lead free solder materials such as Sn-3.5Ag-0.7Cu (SAC), SnAg, SnCu, and SnZn are commonly used to blend with various types of nanoparticles.

The presence of the nanoparticles, such as aluminum oxide (Al_2O_3) [2], zirconia (ZrO_3) [3] and rhodium [4] in the lead free solder content slightly altered the melting temperature. TiO_2 [5], Fe_2NiO_4 [6] and NiO [7] nanoparticles were also used to reinforce the microstructure and mechanical properties of lead free solder. The addition of TiO_2 nanoparticles into SAC solder improved the hardness value up to 34% [5] while the addition of Fe_2NiO_4 nanoparticles improved the hardness value up to 44.07% [6] compared to pure SAC305 and slightly improved the tensile properties. Moreover, the average size and spacing of the intermetallic compound (IMC) layer were reduced by the presence of nanoparticles in the SAC solder content. Over addition of the nanoparticles will decrease the beneficial effect of the nanoparticles to the solder materials and it might create unexpected features to the solder characteristic. The application of nanoparticles in strengthening a structure can also be found in many applications [8]. However, a real application of nano-reinforced solder paste for ultra-fine package assembly via reflow soldering process is still limited in the literature. The investigation of nanoparticle reinforced solder paste on actual electronic component still remains a wide research gap.

Thus, real electronic component (i.e., capacitor) was considered in this study using the new form of TiO_2, Fe_2O_3 and NiO nano-reinforced solder paste for assembly process. Different weighted percentages of each nanoparticles were reinforced into lead free solder paste

(SAC305) to assemble the ultra-fine solder joint during the reflow soldering process. The assessments on the quality of joining process and structural quality of the solder were conducted through microscopy and x-ray investigations.

2. Materials and methods

2.1 Preparation of the surface mount package with the nano-reinforced lead free solder assembly

The ultra-fine package assembly investigated in this study was 01005 capacitor with dimension of 0.4 × 0.2 mm as shown in Fig. 1. There are three types of nanoparticles used in this study such as TiO_2, Fe_2O_3 and NiO with the average particle size of 10nm. The average particle size of the 96.5Sn-3.0Ag-0.5Cu as received is 15-25µm (Type 5, -500/+635 mesh designation as per ASTM B214). Each type of nanoparticles were used with three different contents of 0.01%, 0.05% and 0.15% by weight which then mixed with the 96.5Sn –3.0Ag–0.5Cu solder paste (SAC305; Alpha OM-353) by using a mechanical stirrer (Fritsch Planetary Mill PULVERISETTE 5) for approximately 10 minutes (300 rpm) to achieve homogeneity prior to assembly. Thus, there are nine mixtures of nano-reinforced lead free solder produced with different type and content of nanoparticles.

The ultra-fine package was mounted on printed circuit board (PCB) with a thickness of 2.0 mm (PCB organic solderable preservative surface finish) using nano-reinforced lead free solder (Fig. 2) through reflow soldering process [9, 10]. Fig. 3 illustrates the general process flow of an ultra-fine package assembly which is used in a reflow oven to heat the mounted boards to a suitable temperature for specified period to achieve the desired heating temperature [10]. A component's peak temperature of 239.7^{o}C was recorded during reflow soldering process.

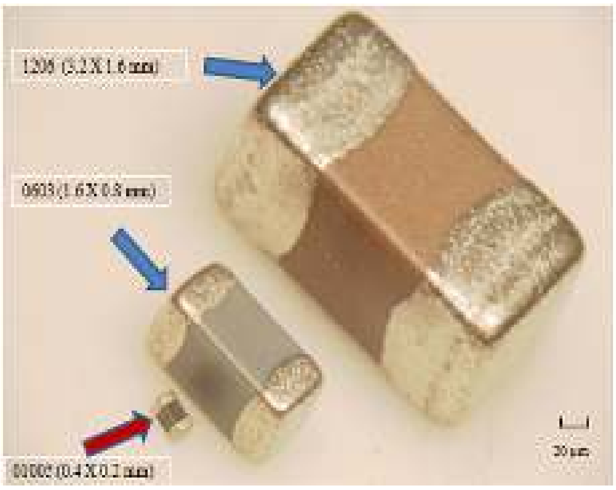

Fig. 1 The size of ultra-fine package (01005 capacitor)

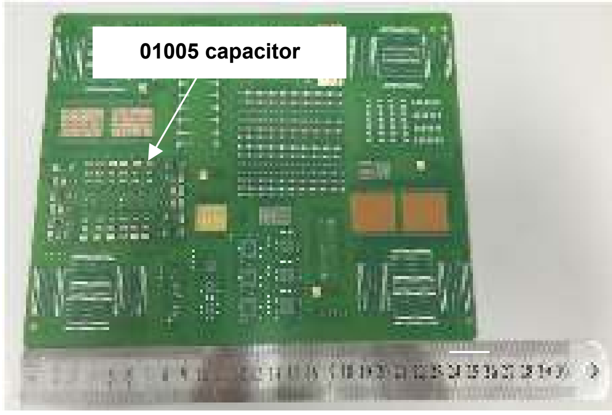

Fig. 2 Ultra-fine package (01005 capacitor) mounted on printed circuit board (PCB).

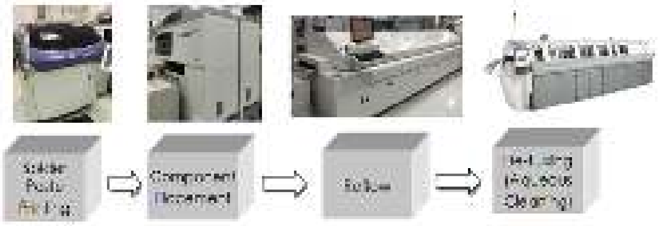

Fig. 3 The general process flow of the ultra-fine package assembly

2.2 Nano-reinforced lead free solder joint characterization

Scanning electron microscopy was used to inspect the solder fillet height. A minimum fillet height should be more than 25% of termination height [6]. Fig. 4 illustrates the measurement of the fillet height for 01005 capacitor after reflow soldering process. It was measured from the bottom of solder joint at printed circuit board up to the last point of solder joint at the termination.

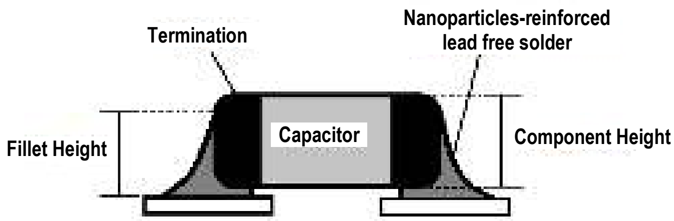

Fig. 4 The measurement illustration of the fillet height for the 01005 capacitor with solder joint.

A relationship between component termination, solder volumes, solder land dimensions, and solder paste flux wetting behaviors are shown below:

$$h = \left(\frac{w_p}{w}\right) \times d \times H_s \times f \qquad (1)$$

where h is the finished solder height, W_p is the width of the stencil which the solder paste is used, W is the width of the printed circuit board solder pad, d is the thickness of the stencil, H_s is the volume fraction of solder in paste and f is the shape factor. Shape factor is the height of the circle segment with cord of W (solder thickness +25% of component termination height divided by the thickness of d of the square with the same area and same length W, which is approximately 1.4).

The ultra-fine package (01005 capacitor) that are investigated uses 0.2 mm printed circuit board solder pad, 0.2 mm width of stencil, 0.127 mm of stencil thickness and volume fraction of solder in paste of 0.5

The calculation is described below:

$$h = \left(\frac{0.2mm}{0.2mm}\right) \times 0.127mm \times 0.5 \times 1.4 \qquad (2)$$

and thus, h = 0.0889mm (Minimum).

Fig. 5 and 6 show the illustration of the main parameters of 01005 capacitor with solder joint and one of the SEM result of fillet height measurement respectively. The dimensions of the fillet height are obtained in the focused area which consists of four columns which are labeled as i, ii, iii and iv. Each column also consists of rows which are labeled as a, b, c, d, e, f, g, h, i and j (Fig. 5). Each ultra-fine package (01005 capacitor) has left and right solder fillet. The dimension readings of the solder fillet height are taken from the 01005 capacitors in the row a and j only. The example of the fillet height measurement using SEM is shown in the Fig. 6.

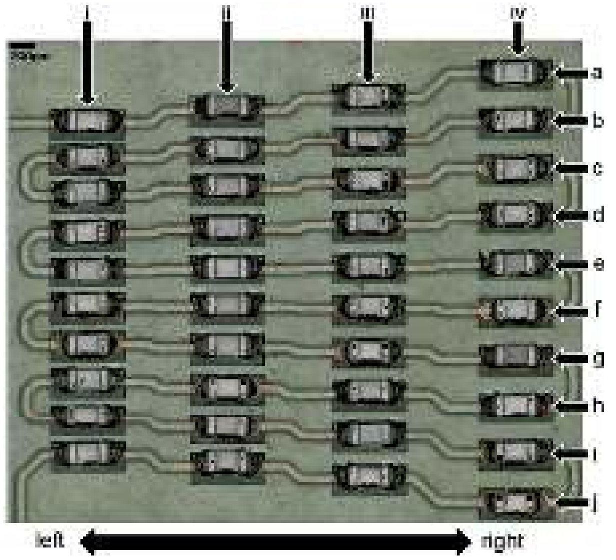

Fig. 5 Fillet height measurement points of ultra-fine packages (01005 capacitors).

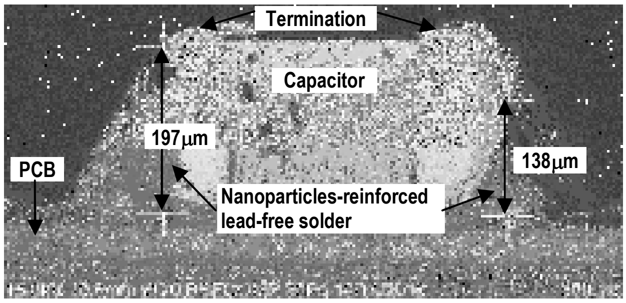

Fig. 6 Fillet height measurement of 01005 capacitor using SEM microscope.

In addition, X-ray inspection system (Nikon XT V 160) was used to examine the structure of joints and the presence of voids in the ultra-fine solder joint.

3. Results and Discussion

The investigation of the capacitor's solder height is important after the reflow soldering process being performed. Insufficient of solder height may cause interconnection failure between capacitor and printed circuit board. There are several factors that could affect the formation of solder height such as wettability and thickness of the printed solder paste. The solder height is required to comply with the acceptance requirement of J-STD-001E-2010 Industrial Standard, Requirements for Soldered Electrical and Electronic Assemblies [11] with at least 0.0889mm solder height for this study. Thus, the analysis of the solder fillet height is crucial for a new composition of nanoparticles solder paste.

Through statistical approach, Fig. 7 shows box plot analysis of solder fillet height for different types of SAC305. The importance of using box plot in the analysis is to compare data set of solder fillet height for different types of SAC305 side-by-side on the same graph. Fig. 7 graphically displays a fillet height and its spread at a glance for pure SAC305 and SAC305 with addition of different types of nanoparticles. It's clearly shown that most of the solder fillet height data in the box plot are above 0.0889mm, fulfilled the acceptance requirement of IPC standard except for SAC305-0.01wt.% TiO_2 composition.

The best formation of SAC305 solder for different composition of nanoparticles can be clearly identified also from the Fig.7. In addition, the mean value can be easily captured from the box plot as shown in Table 1. It also shows standard deviation of solder fillet height for different types of SAC305. The highest mean and the lowest standard deviation indicate the best formation of SAC305 solder for different composition of nanoparticles in terms of fillet height formation.

For TiO_2 nanoparticle reinforced solder paste, SAC305-0.15wt.% TiO_2 has the highest mean (0.180250) and the lowest standard deviation (0.023926) compared to SAC305-0.01wt.% TiO_2 (0.144244; 0.047307) and SAC305-0.05wt.% TiO_2 (0.179450; 0.031228) respectively. Furthermore, SAC305-0.15wt.% TiO_2 has the higher mean than pure SAC305 (0.166187) that shows the best fillet height formation. However, mean value for SAC305-0.05wt.% TiO_2 was almost similar to SAC305-0.15wt.% TiO_2 which both composition yielded the highest fillet height.

On the other hand, SAC305-0.05wt.% Fe_2O_3 has the highest mean (0.172188) and the lowest standard deviation (0.014896) compared to other types of SAC305 with Fe_2O_3 nanoparticles. Furthermore, SAC305-0.05wt.% Fe_2O_3 has the higher mean than pure SAC305 (0.166187) that indicates the best fillet height formation.

Finally, for NiO nanoparticle reinforced solder paste, SAC305-0.01wt.% NiO has the highest mean (0.195222) and the lowest standard deviation (0.012661) compared to SAC305-0.05wt.% NiO (0.166839; 0.033000) and SAC305-0.15wt.% NiO (0.159214; 0.028371) respectively. Moreover, SAC305-0.01wt.% NiO has the higher mean than pure SAC305 (0.166187) that resulted the best fillet height formation. The addition of 0.01wt.% NiO into SAC305 solder significantly improved the fillet height formation compared to SAC305-0.15wt.% TiO_2, SAC305-0.05wt.% Fe_2O_3 and pure SAC305. All the fillet heights fulfilled the acceptance requirement of the IPC standard.

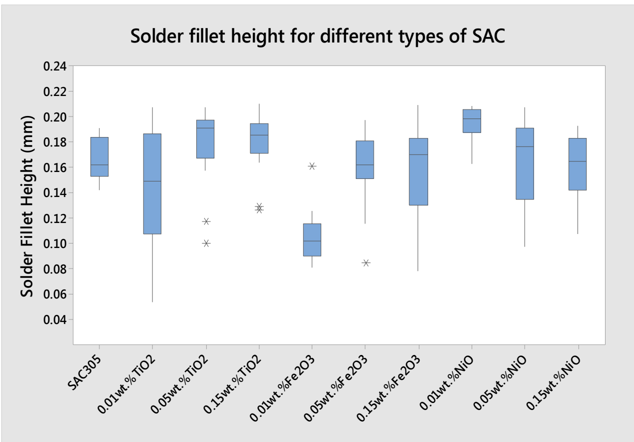

Fig. 7 Box plot analysis of solder fillet height for different types of SAC305

Table 1 Mean and standard deviation of solder fillet height for different types of SAC305

	Types of SAC305	Mean	Standard Deviation
1	Pure SAC305	0.166187	0.016746
2	0.01wt.% TiO_2	0.144244	0.047307
3	0.05wt.% TiO_2	0.179450	0.031228
4	0.15wt.% TiO_2	0.180250	0.023926
5	0.01wt.% Fe_2O_3	0.105000	0.020601
6	0.05wt.% Fe_2O_3	0.172188	0.014896
7	0.15wt.% Fe_2O_3	0.169000	0.032476
8	0.01wt.% NiO	0.195222	0.012661
9	0.05wt.% NiO	0.166839	0.033000
10	0.15wt.% NiO	0.159214	0.028371

Fig. 8 illustrates samples of laminography x-ray images of electronic joints and its related parts. The voids are indicated by the smaller round white shape located in LEDs joints while the bigger white round shape is a through hole in a typical LED's lead shape [12] as shown in Fig. 8 (a).

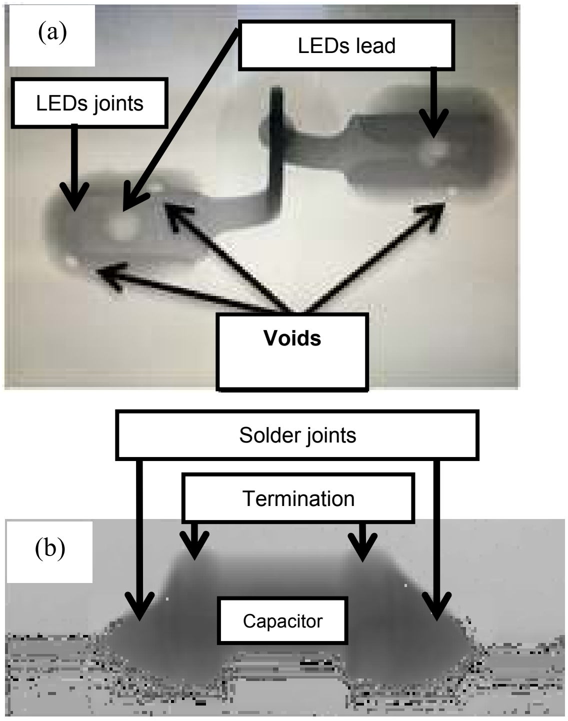

Fig. 8 Example of electronic joints with (a) voids and (b) without voids in laminography x-ray images

Fig. 9-11 (a) – (d) depict the laminography x-ray images of ultra-fine joint that shows a good joint without solder voids appeared in the solder paste. The presence of voids in the solder joint can affect the reliability of the joint. Moreover, the requirement for acceptable level and dimension of non-BGA solder voids depends on the customer conformity based on the IPC Standard [11].

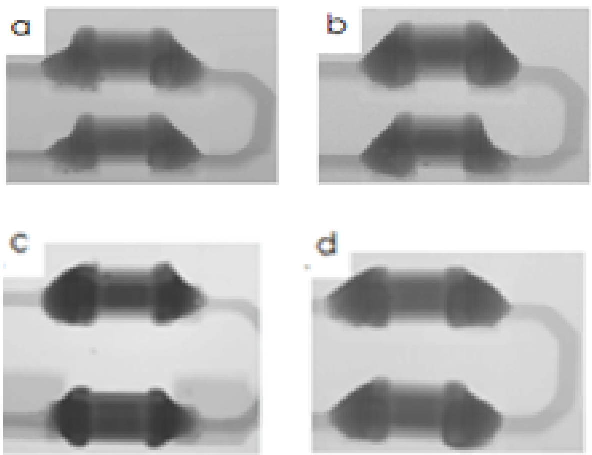

Fig. 9 Laminography X-ray images (400X) of ultra-fine joints in SAC305-xTiO_2: (a) x = 0 wt.% (pure SAC305); (b) x = 0.01 wt.%; (c) x = 0.05 wt.%; (d) x = 0.15 wt.%.

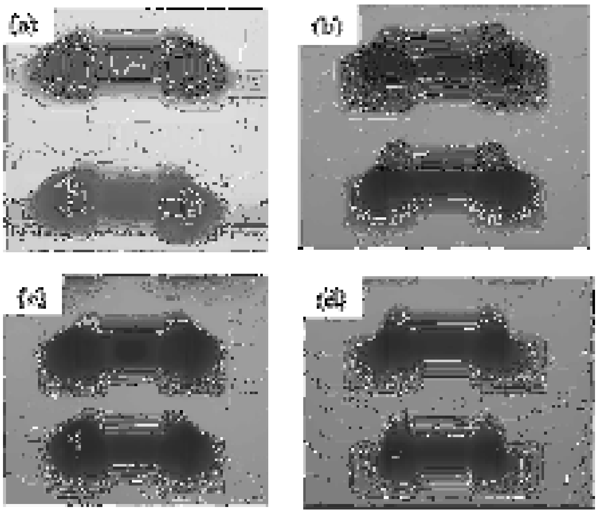

Fig. 10 Laminography X-ray images (400X) of ultra-fine joints in SAC305-xFe_2O_3: (a) x = 0 wt.% (pure SAC305); (b) x = 0.01 wt.%; (c) x = 0.05 wt.%; (d) x = 0.15 wt.%.

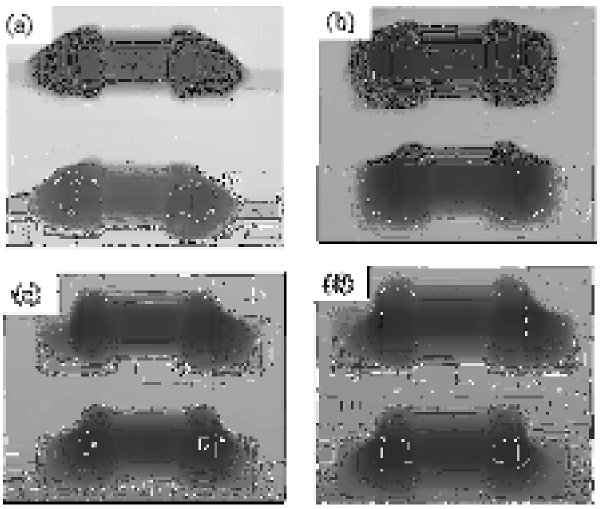

Fig. 11 Laminography X-ray images (400X) of ultra-fine joints in SAC305-xNiO: (a) x = 0 wt.% (pure SAC305); (b) x = 0.01 wt.%; (c) x = 0.05 wt.%; (d) x = 0.15 wt.%.

4. Conclusion

The ultra-fine solder joints were formed successfully with different weight percentages of nanoparticles and fulfilled the IPC standard. The reflow soldering process with modified equipment produces good quality solder joints without solder voids. This study has successfully demonstrated the real manufacturing assemblies of ultra-fine packages with automated production line by using TiO_2, Fe_2O_3 and NiO nanoparticles reinforced solder paste at different weight percentages.

The addition of the nanoparticles at the optimum weight percentage crucially improved the wetting behavior which resulted highest fillet height of the ultra-fine solder joint. The box plot analysis of the fillet height data indicate the addition to 0.15wt.%, 0.05wt.% and 0.01wt.%, of TiO_2, Fe_2O_3 and NiO nanoparticles respectively, produce the best fillet height of each composition of nanoparticles solder paste. Among all these new composition of nanoparticles solder paste, NiO nanoparticles reinforced solder paste with 0.01wt.% yielded highest fillet height. However, the increment of NiO to 0.15 wt.% reduced the wetting behaviour which resulted a lower fillet height for the ultra-fine solder joint.

Acknowledgement

The authors would like to thank the Universiti Sains Malaysia for RUI grant 1001/PMEKANIK/8014607. Also, the authors would like to acknowledge the support from ETS Department of Jabil Penang and Advanced Packaging Unit of USM.

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