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Component Candidacy of Second Side Reflow with Lead-Free Solder

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For double-sided assemblies, the solder joints on the topside of the board are inverted and reflowed again. During the second reflow, the components are held in place by the surface tension, which may prevent the components from falling off under the gravitational force. A method is needed to determine a component's candidacy for bottom-side attachment based on the component weight and total pad area.

In this paper, a theoretical model was introduced to determine the critical value for component fall-off during the second reflow. Design of Experiments (DOE) and ANOVA analysis for lead-free solder boards were performed to examine the main process factors which have different effects on the component fall-off for different components, and comparison was made between lead-free and SnPb solders. Optical inspection and cross-sectioning were carried out for further investigation. The test results indicated no significant difference of C_g/P_a value between SnPb and lead-free solders. [doi:10.2320/matertrans.47.1577]

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1. Introduction

Double-sided boards are becoming more popular and increasingly complex. The main advantages of double-sided assembly are PCB real estate savings and lower product costs. There are several methods to complete double-sided reflow soldering to prevent component fall-off.[1)] The first method is to glue the first-side components so that they could still remain in place for the second pass, but this method needs additional process steps, equipment and cost. The second method is based on a hierarchical alloy system using different alloys with different melting points for the top and bottom sides, with the second pass material having a lower melting point. This method also has some serious issues for many applications. The melting points of the low melting point alloys may be too low for the service temperature of the end product, whereas the high melting point alloys may require a higher reflow temperature that could damage the components or the substrate during reflow. The third method is to blow cool gas across the bottom side of the assembly to maintain the solder joints on the bottom side below the liquidus temperature during the second reflow. One disadvantage of this method is the potential stresses introduced due to the temperature differences between the top and bottom surfaces.

Actually for many components, the surface tension of the molten solder is sufficient to hold the parts on the bottom side in place with high reliability. In order to determine which components were candidates for bottom side attachment and second reflow, a ratio for the second side mounting with SnPb solder can be evaluated using a popular "rule of the thumb": $C_g/P_a \leq 30$ (g/in^2), where C_g is the weight of the component, and P_a is the total pad area.[1–3)] This formula has been embedded in PCB design standard, so the designer of the board can complete the calculation and choose the appropriate components for the top and bottom sides during the initial design layout.[4)] For lead-free soldering, due to the differences in the material properties and reflow profiles between SnPb and lead-free solders, the component's candidacy for second side reflow with the lead-free solder needs to be determined.

In this paper, a theoretical model for the components during second side reflow was introduced to determine the critical value for component fall-off. DOE and ANOVA analysis for lead-free solder boards were performed to examine the main process factors, which have different effects on the component fall-off for different components, and comparison was made with the SnPb solder. Optical inspection and cross-sectioning were carried out for further investigation and explanation of the test results. Finally, the critical value for component fall-off was determined based on the test and analysis results.

2. Theoretical Model

2.1 Surface tension

As shown in Fig. 1, a molecule in the interior of a liquid is under attractive forces in all directions and the vector sum of these forces is zero. A molecule at the surface of a liquid is acted on by a net inward cohesive force that is perpendicular to the surface. The intermolecular bonds or cohesive forces between the molecules of a liquid cause surface tension.[5)] Surface tension is the tendency of the surface of a liquid to behave like a stretched elastic membrane. There is a natural tendency for liquids to minimize their surface area.

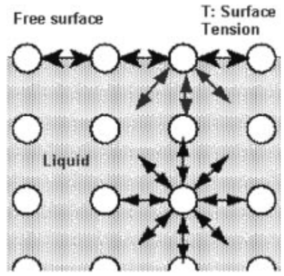

Fig. 1 Surface Tension.

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(a) Wetting (b) Non-wetting

Fig. 2 Contact Angle.

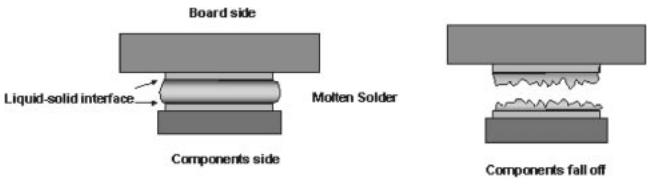


Fig. 3 Components Fall Off During the Second Side Reflow.

2.2 Contact angle

At the liquid-solid interface, if the molecules of the liquid have a stronger attraction to the molecules of the solid surface than to each other (*i.e.* the adhesive forces are stronger than the cohesive forces), then wetting of the surface occurs, see Fig. 2(a). If the liquid molecules are more strongly attracted to each other than to the molecules of the solid surface (*i.e.* the cohesive forces are stronger than the adhesive forces), then the liquid beads up and does not wet the solid surface, see Fig. 2(b). In soldering, the molten solder is required to wet the pad, which means that the adhesive force (between the molten solder and the pad) has to be stronger than the cohesive force (inter-molecule attraction within the molten solder).

2.3 The formula for second side reflow

When reflowing the second side of a double-sided assembly, it can be seen from Fig. 3 that once the solder is molten, the component may fall off from the weakest of three locations: (1) interface between the molten solder and the pad on the board side; (2) interface between the molten solder and the pad on the component side; (3) within the molten solder. As discussed above, if the molten solder should wet the pad, the adhesive force at the liquid–solid interface is stronger than the cohesive force (within the molten solder), so the molten solder should be the weakest location and the component may fall off within the molten solder during the second reflow pass.

When $C_g \leq \sigma \bullet P_a$, the component will remain on the bottom side during the second side reflow, and when $C_g > \sigma \bullet P_a$, the component will fall off when the solder is completely molten, where C_g is the weight of the component, σ is the tensile strength of the molten solder, and P_a is the cross section area of the molten solder. Usually the total pad area is used in the calculation as an approximation because it is too time-consuming to get the accurate cross section area. The tensile strength σ of the molten solder is the maximum tension (force per unit area) that the molten solder can withstand before it breaks. σ is proportional to the cohesive force or the surface tension of the molten solder, and it depends on the material properties of the molten solder at a certain temperature. $\sigma = C_g/P_a$ is the critical value to evaluate if the component would fall off or not.

3. Test Vehicle

The Flextronics lead-free test vehicle was used in this study. The overall size of the vehicle was $21.5\,\text{cm} \times 15.1\,\text{cm} \times 0.16\,\text{cm}$. The test vehicle with six copper layers is a double-sided Printed Circuit Board (PCB) having conventional FR-4 glass epoxy as the laminate base material. Some of the test components were assembled on electroless Ni immersion gold (Ni/Au, or ENIG) finished PCBs and others on organic solderability preservative (OSP) finished PCBs. The test vehicle contains 75 different components. However, only five components were included in this study. The description and original C_g/P_a of the test components are shown in Table 1.

4. Taguchi Design and Experimental Procedure

The fishbone diagram shown in Fig. 4 summarizes the factors affecting secondary reflow in the SMT process. Based on the fishbone diagram, four main process factors were investigated in this study: solder paste type, stencil thickness, surface finish and reflow atmosphere. The Taguchi method adopts the fundamental idea of DOE but simplifies and standardizes the factorial and fractional designs so that the

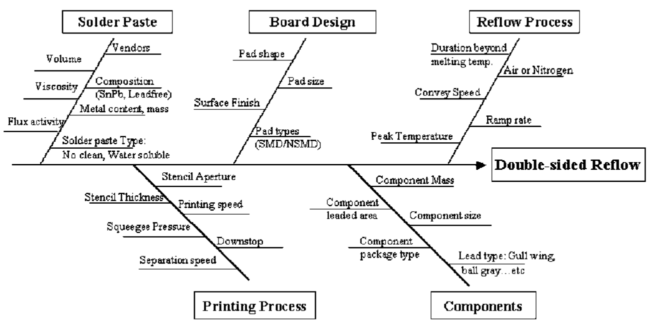


Fig. 4 Fish Bone Diagram for Second Side Reflow.

Table 1 Description and Original C_g/P_a of Test Components.

Package Type	Ref. Des.	Lead Pitch (mm)	Solder Ball Dia. (mm)	Ball/pad material	Body Size (mm × mm)	Total Pad Area, P_a, (in^2)	Part Mass (g)	C_g/P_a, (g/in^2)
PBGA196	U1	1	0.51	Lead free	15 × 15	0.1207	0.57	4.72
QFP208	U3	0.5	N/A	Lead free	28 × 28	0.1597	5.48	34.31
QFP208	U4	0.5	N/A	Lead free	28 × 28	0.1597	5.48	34.31
QFP100	U20	0.5	N/A	Lead free	14 × 14	0.0769	0.66	8.58
PLCC44	U54	1.27	N/A	Lead free	16.6 × 16.6	0.0880	2.44	27.73

Table 2 Factors and Levels for DOE.

Factors	Level 1	Level 2
A: Solder Paste Types	LF No clean	LF Water soluble
B: Stencil Thickness	Thin (4 mil)	Thick (6 mil)
C: Surface Finish	OSP	Ni/Au
D: Reflow Atmosphere	Air reflow	Nitrogen reflow

Table 3 Taguchi L8 OA.

Run No.	Solder Paste	Stencil Thickness	Surface Finish	Reflow Atmosphere
1	LF no clean	4 mil	OSP	Air
2	LF no clean	4 mil	Ni/Au	Nitrogen
3	LF no clean	6 mil	OSP	Nitrogen
4	LF no clean	6 mil	Ni/Au	Air
5	LF water soluble	4 mil	OSP	Air
6	LF water soluble	4 mil	Ni/Au	Nitrogen
7	LF water soluble	6 mil	OSP	Nitrogen
8	LF water soluble	6 mil	Ni/Au	Air

Table 4 DOE Run for SnPb Solder Paste.

Run No.	Solder Paste	Stencil Thickness	Surface Finish	Reflow Atmosphere
1	SnPb no clean	4 mil	OSP	Air
4	SnPb no clean	6 mil	Ni/Au	Air

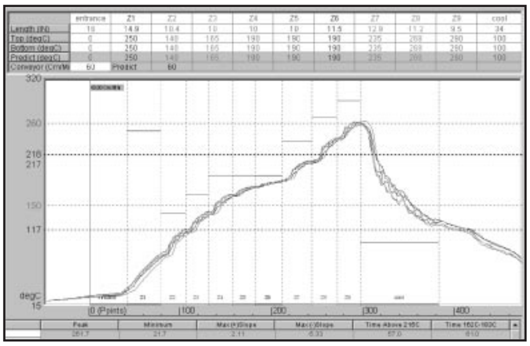


Fig. 5 Reflow Profile for Lead-free Assembly.

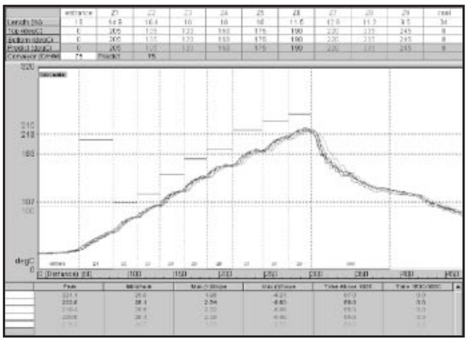


Fig. 6 Reflow Profile for SnPb Assembly.

Table 5 Predicted Weight Value.

Parts	Part Mass (g)	Total Pad Area P_a, (in^2)	C_g/P_a, (g/in^2)	Total mass C_g, (g)	Pred. Added Weight, (g)	Test Result
PBGA196	0.57	0.1207	30	3.621	3.051	Not fall
QFP208	5.48	0.1597	30	4.7910	−0.6890	Not fall
QFP208	5.48	0.1597	30	4.7910	−0.6890	Not fall
QFP100	0.66	0.0769	30	2.3070	1.6470	Not fall
PLCC44	2.44	0.0588	30	1.7640	−0.6760	Not fall

experiments conducted will produce more consistent results. As only four factors are evaluated in this study, four of the seven columns of L8 OA are employed. As a result, the experiments can be conducted with a smaller number of experimental runs.

The four factors and levels are shown in Table 2. The corresponding Taguchi L8 OA is shown in Table 3. There are 5 boards for each experimental run. Two additional runs (run 1 and run 4) in Table 4 for SnPb no-clean solder paste were included in this study for comparison with the lead-free solder. Lead-free no-clean solder paste and water soluble solder paste (Sn3.9Ag0.6Cu) and no-clean solder paste (63Sn37Pb) were used for the assembly. Solder paste was printed onto the boards using 4 mil or 6 mil laser-cut stencil. Reflow soldering was carried out in air or nitrogen reflow oven with 9 heating zones and one cooling zone. The reflow profiles for lead-free and SnPb assembly are shown in Figs. 5 and 6, respectively.

Based on the formula for second-side mounting for SnPb solder ($C_g/P_a \leq 30$), the predicted weight, which may cause the components to fall off, was estimated in Table 5. However, none of the test components without added weight fell off during second side reflow, which indicates that the formula $C_g/P_a \leq 30$ for SnPb is conservative in practice.

In order to make the components fall off during second side reflow, small pieces of PCB was glued together and attached onto the topside of the components. Using this method, the size and weight can be easily controlled and adjusted. But the reflow profile would be changed due to the additional PCB thermal mass. The PCB weight and the corresponding profile with the same oven setting are shown in Fig. 7.

Considering the thermal mass of the added PCB weight, the profiles for the second side reflow of the lead-free and SnPb test vehicles with PCB weight were developed and shown in Fig. 8. For the lead-free solder, the highest zone temperature setting was 320°C, the peak temperature was about 260°C, and time above the melting point was about 100 seconds, which assures enough time for the components to fall off. For SnPb, the highest zone temperature setting was 265°C, the peak temperature was about 225°C and the time above the melting point was 95 seconds.

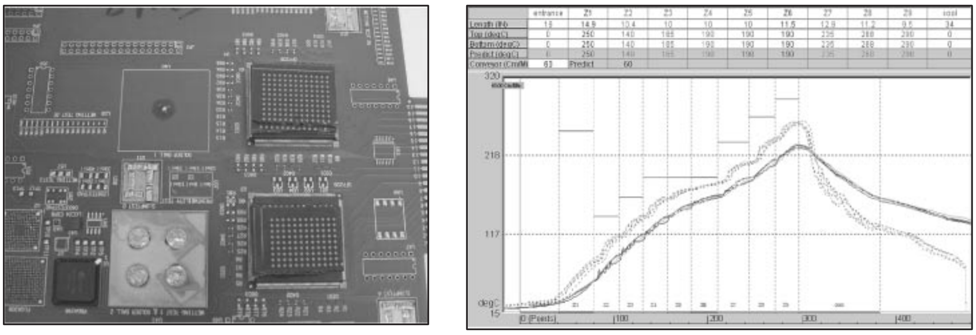
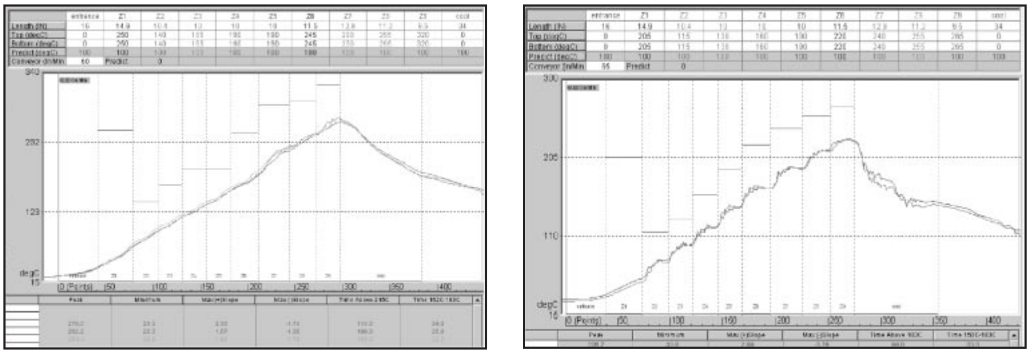


Fig. 7 PCB Weight and the Corresponding Profile with the Same Oven Settings.



(a) For lead free (b)For SnPb

Fig. 8 Lead Free and SnPb Profile for the Second Side Reflow with PCB Weight.

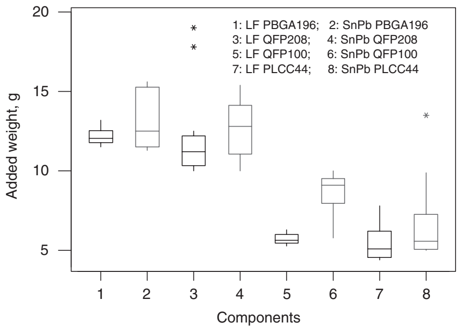


Fig. 9 Added Weight Comparison Between LF and SnPb.

5. Results and Discussion

5.1 C_g/P_a comparison between lead-free and SnPb solders

DOE run 1 and run 4 were carried out to compare the added weight needed for the component falling off between lead-free and SnPb solder (Fig. 9). For different components, the added weight causing components to fall off with the SnPb solder is slightly larger than that with the lead-free solder. The comparison of the mean values for C_g/P_a between lead-free and SnPb solders were given in Table 6. Based on the total pad area, the mean value of C_g/P_a for the SnPb solder is about 13% greater than the lead-free solder. Based on the actual contact area from the cross sections, the mean value of C_g/P_a for the SnPb solder is about 6% greater than the lead-free solder. As is known, the wetting force of SnPb solder is stronger than lead-free solder,[6] leading to better wetting performance and greater tendency to spread, thereby a greater contact area and finally a greater weight to cause component fall-off, for the SnPb solder than the lead-free solder.

Table 6 Comparison of Mean of C_g/P_a for LF and SnPb.

	SnPb	LF	Difference, %
Mean of Weight/total pad area, (g/in^2)	114.30	98.95	13.23
Mean of weight/contact area, (g/in^2)	287.231	269.748	6.09

F-tests were carried out to examine the validity of the equal variance assumption of C_g/P_a for SnPb and lead-free solders. The test for equal variances generates a plot that displays Bonferroni 95% confidence intervals for the response standard deviation at each level.[7]

Figure 10(a) is F-test for C_g/P_a between SnPb and lead-free solders based on the total pad area; and Fig. 10(b) is F-test for C_g/P_a between SnPb and lead-free solders based on the actual contact area obtained from the cross-section samples. The p-values of 0.158 and 0.796 were greater than the significance level $\alpha = 5\%$, so it failed to reject the null hypothesis of the variances being equal;[7] therefore, these data did not provide enough evidence to claim that the populations had unequal variances. That is, there was no statistically significant difference in the C_g/P_a value between SnPb and lead-free solders.

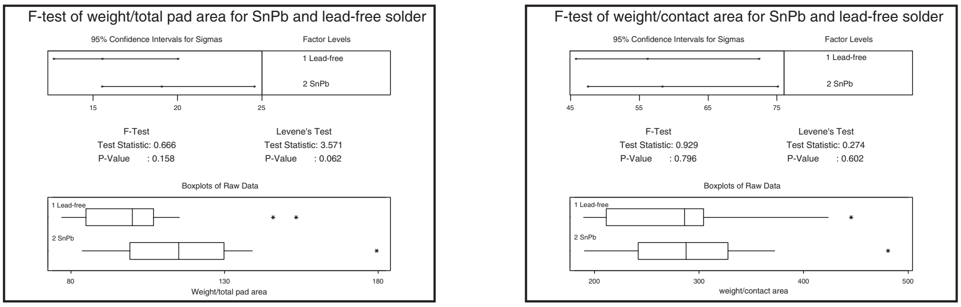


Fig. 10 F-test of Overall C_g/P_a for SnPb and LF Solder.

5.2 ANOVA and Taguchi analysis for lead-free solder

Analysis of variances and Taguchi analysis were performed to investigate the effect of main factors on C_g/P_a for the lead-free solder. The calculated C_g/P_a values were collected and analyzed using Minitab 13.[8)]

For ANOVA analysis, the F-ratio can be used to investigate the confidence in the data collected. If $F < 1$, the control factor is insignificant and indistinguishable from the experimental error; If $F \cong 2$, the control factor has only a moderate effect as compared with the experimental error; while if $F > 4$, the control factor is significant as compared with the experimental error.

As shown in Table 7 and the main effect plot for the mean value of C_g/P_a in Fig. 11, the PCB surface finish had the most significant effect on the C_g/P_a value as $F = 32.27$; The stencil thickness was also a significant factor as $F = 5.05 > 4$, whilst the solder paste type and reflow atmosphere had insignificant effect as $F < 1$. The same conclusion as above can be drawn based on the P value; the factors have significant effect with a level of 95% confidence when $p < 0.05$. For the stencil thickness, the C_g/P_a using 6 mil stencil leads to a larger value than using 4 mil stencil, because the contact area is larger with the 6 mil stencil than the 4 mil stencil.

The C_g/P_a value for different components with the lead-free solder is shown in Fig. 12(a). It was noted that when $C_g/P_a \leq 60$, components with the lead-free solder would not fall off during the second reflow in this study. A safety factor $K = 2$ is introduced for the different components under different process conditions, and $C_g/P_a \leq 30$ was chosen as the threshold value for component candidacy for second side attachment with the lead-free solder.

Similarly, The C_g/P_a value for different components with the SnPb solder is shown in Fig. 12(b). When $C_g/P_a \leq 80$, components with SnPb would not fall off in this study. Again using a safety factor $K = 2$, $C_g/P_a \leq 40$ was chosen as the threshold value for component candidacy for second side attachment with the SnPb solder. The previous critical value $C_g/P_a \leq 30$ for SnPb is rather conservative for current materials and processes in practice.

Table 7 ANOVA Table for DOE.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A: NC/WS	1	29.2	29.2	29.2	0.07	0.798
B: 4 mil/6 mil	1	2239.1	2239.1	2239.1	5.05	0.026
C: OSP/NiAu	1	14299.1	14299.1	14299.1	32.27	0.000
D: Air/N_2	1	174.8	174.8	174.8	0.39	0.531
Error	195	86407.9	86407.9	443.1		

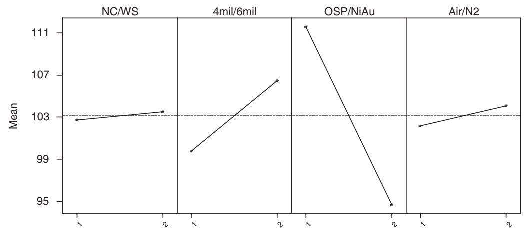
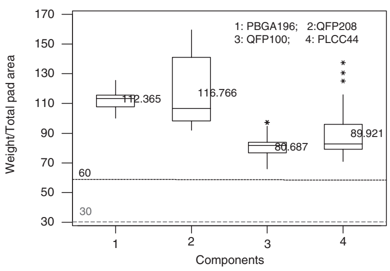


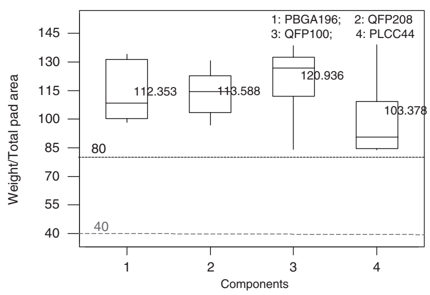
Fig. 11 Main Effects Plot for Means of C_g/P_a.

5.3 Optical inspection

Optical inspection was carried out to examine the pads and pins after component fall-off. As can be seen in Fig. 13, the pads and pins or solder balls after the components had fallen

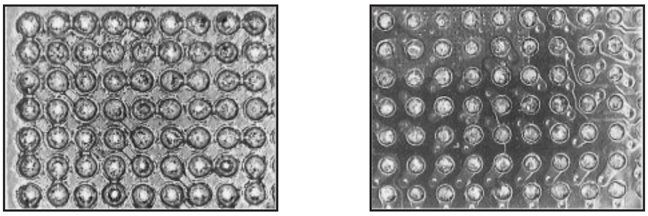


(a) For Lead free

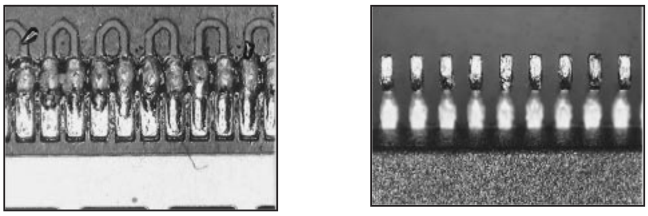


(b) For SnPb

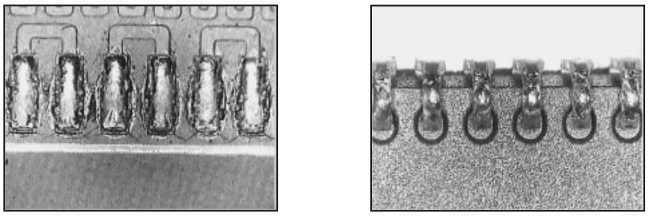
Fig. 12 The C_g/P_a Value for Different Components.



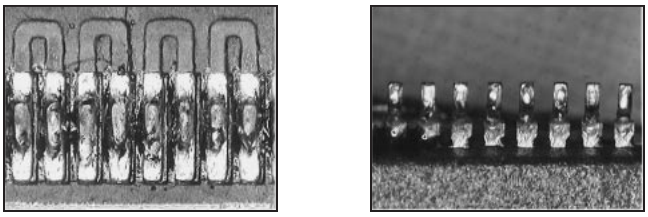
(a) PBGA196



(b) QFP208



(C) PLCC44



(d) QFP100

Fig. 13 Pads and Pin/Solder Balls After Components Fall Off.

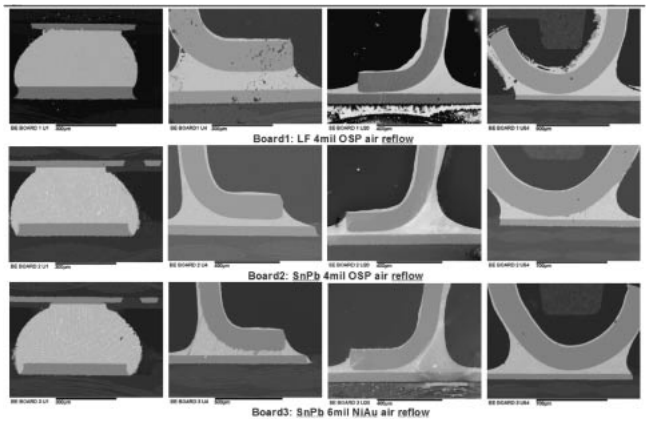


Fig. 14 SEM Pictures of Components Cross-sectioning.

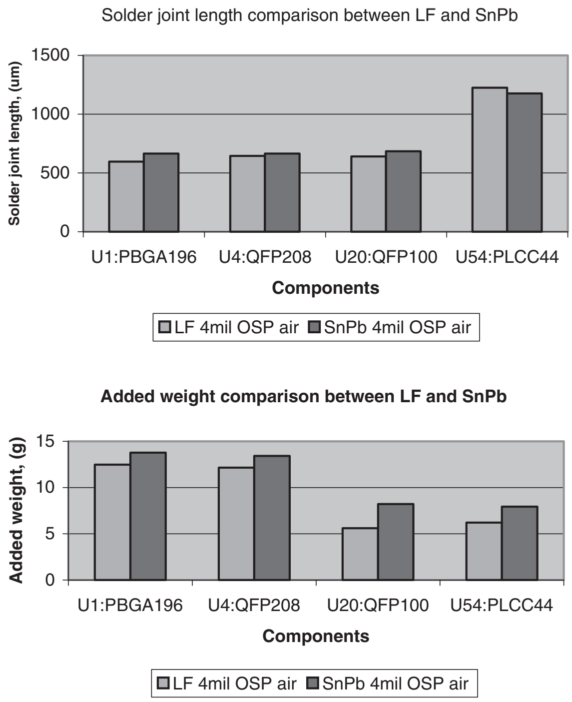


Fig. 15 Solder Joint Length and Added Weight Comparison Between SnPb and LF.

off were shining, and most of the solder was left on the pads on the PCB and only a small part of solder was left on the pins or balls on the components, indicating that the breaking location of components initiated from the smallest contact area within the molten solder. This confirms the assumption of the theoretical model that the molten solder should be the weakest location, and components may fall off within the molten solder during the second reflow.

5.4 Cross-sectioning

Based on $C_g = \sigma \bullet P_a$, the weight of components which could be sustained during the second reflow depends on the tensile strength and the contact area. Here the contact area may change due to the wetting performance difference under the different process conditions. In this study, cross-sectioning analysis was conducted to compare the contact area under the different process conditions. After cross-sectioning, the solder joint length was measured and compared. Figure 14 shows SEM pictures of component cross-sections under different process conditions.

In Fig. 14, comparing board1 (LF 4 mil OSP air reflow) and board2 (SnPb 4 mil OSP air reflow), we can find that the wetting performance of SnPb was better than lead-free. Comparing board2 (SnPb 4 mil OSP air reflow) and board3 (SnPb 6 mil NiAu air reflow), there is no obvious difference for wetting performance between board2 and board3. Figure 15 shows the solder joint length and added weight comparison for component fall-off between SnPb and lead-free solders for board1 and board2. The solder joint length of SnPb was slightly larger than lead-free, and the corresponding added weight for component fall-off for SnPb was slightly larger than for lead-free.

6. Summary

C_g/P_a can be used to determine the candidacy of a component for bottom–side attachment based on component weight and total pad area. No statistically significant difference in the C_g/P_a value between SnPb and lead-free solders has been found. ANOVA analysis has indicated that the PCB surface finish and the stencil thickness had significant effect on C_g/P_a, while the solder paste type (no-clean or water soluble) and reflow atmosphere (Air or N_2) had no significant effect on C_g/P_a. Heavier components could sustain with 6 mil stencil than 4 mil stencil, due to the different contact areas.

Optical inspection indicated that the components were pulled off within the molten solder at the smallest cross section, not from the interface between the solder and the pad. Solder joint length were measured and compared from the cross-sectioning samples. The results indicated that for OSP boards, the wetting performance with the SnPb solder was better than the lead-free solder, and the contact area was larger with the SnPb solder than with the lead-free solder.

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