

Solder Balling of Lead-Free Solder Pastes

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Solder balling in Sn/Ag/Cu solder pastes was studied in this work. Three different solder pastes, several different reflow profiles and conditions, and two stencil thicknesses were used in the investigation. During the first phase, called the verification phase, the solder pastes were checked to ensure they met the minimum requirements. In the process-screening phase, the reflow profile was varied. Results show that besides flux chemistry, reflow atmosphere plays the major role in solder balling. The average number of solder balls with the best paste was one fifth of that with the worst paste. Furthermore, with all the pastes, the number of solder balls dropped close to zero when nitrogen atmosphere was used. Another finding during the reflow process screening was the influence of the stencil thickness on the solder-balling result. With a thinner stencil, two of the pastes exhibited significant solder balling. This is assumed to be caused by the different ability of fluxes to withstand oxidation during the preheating in the reflow process. In the last phase, the effect of the solder-paste particle size on solder balling was studied more closely. The flux chemistry was kept unchanged, and the solder particle size was varied between type 3 and type 4. The results show that, with type 4 paste, significantly more solder balls are formed compared to type 3 paste. It was also confirmed that, regarding the reflow profile, the ramp-up rate from 150°C to 217°C and the reflow atmosphere were the most significant factors that determine the solder-ball formation for both types of paste.

Key words: Lead-free, solder paste, solder ball, Sn/Ag/Cu, reflow atmosphere

INTRODUCTION

The electronics industry faces new challenges brought along with the environmental requirements. The first step toward more environmentally friendly products and assemblies is to make them lead-free. Generally, in the first phase, lead will be eliminated from the solder. Afterward, it will be phased out from the components and substrates.

From the contract electronics manufacturer's point of view, transition to lead-free will introduce many new challenges for the production. Higher reflow temperatures will impose new requirements on reflow processes and equipment. Process windows need to be optimized again to keep the yield at a

high level. The ability of components and substrates to tolerate higher reflow temperatures is not obvious, and therefore, changes in component and substrate technologies are necessary. New flux systems are needed for solder pastes to comply with the new solder alloys and higher reflow temperatures. Altogether, transition to lead-free will introduce new manufacturing challenges; therefore, a good understanding of the process and materials is a prerequisite for high assembly yields.

In the past, the existence of solder balls has not been a significant problem because of the larger insulating distances and the use of water-soluble fluxes, whose residues are washed away after the soldering process. Surface-mount technology (SMT) uses fine-pitch components, ball-grid array (BGA) types, and chip-scale package (CSP) types of pack-

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ages, where solder balls having a size of 125 μm or more are critical and, if trapped between conductors, may lead to short circuiting.² Mechanical cleaning (brushing) that could remove the loose solder balls is avoided because it may damage the assembly. It has been reported that no-clean fluxes, being less aggressive, seem to cause increased solder balling.²

The solder-balling phenomenon is relatively complex, and it is being affected by many process and material parameters. Humidity absorbed in solder paste may evaporate during the reflow and cause some splattering of the paste.² The amount of humidity absorbed in the paste depends on the chemical composition of the paste, the humidity in the production area, and the time the solder paste has been exposed to air in the opened jar, on the stencil, or on the board.² Humidity may also be absorbed in the solder mask of the substrate. Regarding SMT, it has been stated that absorbed humidity will take some solder paste with it when it evaporates in the reflow oven, resulting in solder balling.²

The occurrence of solder balls depends also on the solder-paste particle size. If the paste contains many ultrafine particles ($<25 \mu\text{m}$), these fine particles can be carried away from the solder and, in this way, cause solder balling.⁵ This may be due to the increased amount of oxidized-metallic surface area in the solder paste, which cannot be cleaned effectively by the flux.

The solder mask has been reported to be one of the most important factors affecting the generation of solder balls.^{5,4,1} A rougher surface has been found to reduce solder-ball formation.^{1,5} It is assumed that a rougher surface increases the surface energy, which seems to reduce the adhesion of the solder to the solder mask.^{1,5} The roughness of the solder mask can be increased by various mechanical and chemical treatments.¹ Also, the chemical cleanliness of the printed circuit board (PCB) influences the solder balling.¹ Some studies state that a light-colored solder mask tends to decrease solder balling.⁵ Light colors do not absorb thermal energy as fast as darker ones and, therefore, do not get as hot on the surface, which means they are less likely to retain free solder.⁵ Besides the solder mask, the surface-finish type of the PCB has been found to be an important factor to influence solder balling.⁴

The solder-paste amount influences the formation of so-called connected solder balls, which typically occur close to passive components. Solder paste flows easily under the component because of the flattening of the solder paste during the placement of the component and because of slump.⁴ Connected solder balls can be reduced by reducing the amount of solder paste within the limits of reliability requirements.⁴

In some experiments, the most important factor that determines the rate of solder balling has been found to be the interaction of the solder paste and the reflow profile. This interaction affects the

amount of both connected and loose solder balls. Besides reflow profile, reflow atmosphere has found to have some influence on the solder balling.⁴

EXPERIMENTAL

The objective of this study was to gain information about the solder-balling behavior of some of the commercially available Sn/Ag/Cu solder pastes under different reflow conditions. First, a verification test was performed to check that the solder pastes met the minimum requirements per the IPC-TM-650- 2.4.43 standard.³ After that, the influence of preheating profile, reflow peak temperature, and reflow atmosphere on the solder-ball formation was studied. This allows for a deeper understanding of the cause and effect of the solder-ball phenomenon.

Test Procedure

All the tests were carried out in a production environment having an air temperature of $\sim 20^\circ\text{C}$ and a humidity of 45–50% relative humidity. A Heller 1800 reflow oven was used in the tests. The oven had eight heating zones and two cooling zones. There was also a nitrogen purge option in the oven used during some of the trial runs. When the nitrogen purge was on, the oxygen level in the oven was 140 ppm (0.014%). For solder-paste printing, a high-speed screen printer with metal squeegees was used.

Verification Test

The verification test procedure followed mainly the IPC standard.³ Solder paste was printed with a 200- μm -thick stencil through an aperture diameter of 6.5 mm. Instead of the standard ceramic substrate, a normal PCB with solder-mask coating was used. This was expected to give results that can be easily connected and compared with the real production processes. All the samples were reflowed immediately after printing. The reflow profile for each paste was slightly different because the manufacturers' recommendations were carefully followed. Solder pastes were required to pass the acceptance criteria presented in the IPC specification.

Process Screening

During the process-screening phase, the influence of different reflow parameters was investigated. A stencil thickness of 100 μm instead of 200 μm was chosen because some fine-pitch components were mounted on the same boards.

The "basic" profile, shown as profile 1 in Fig. 1 and Table I, was created by combining the recommended profiles from each solder-paste vendor. Thermocouples for the measurement were attached on the solder mask of the PCB close to the solder-paste deposit. The basic profile was then varied regarding the peak temperature, preheating profile type, the time from 150 $^\circ\text{C}$ to the melting temperature of 217 $^\circ\text{C}$, and reflow atmosphere. Only one parameter was varied at a time, and the other parameters were

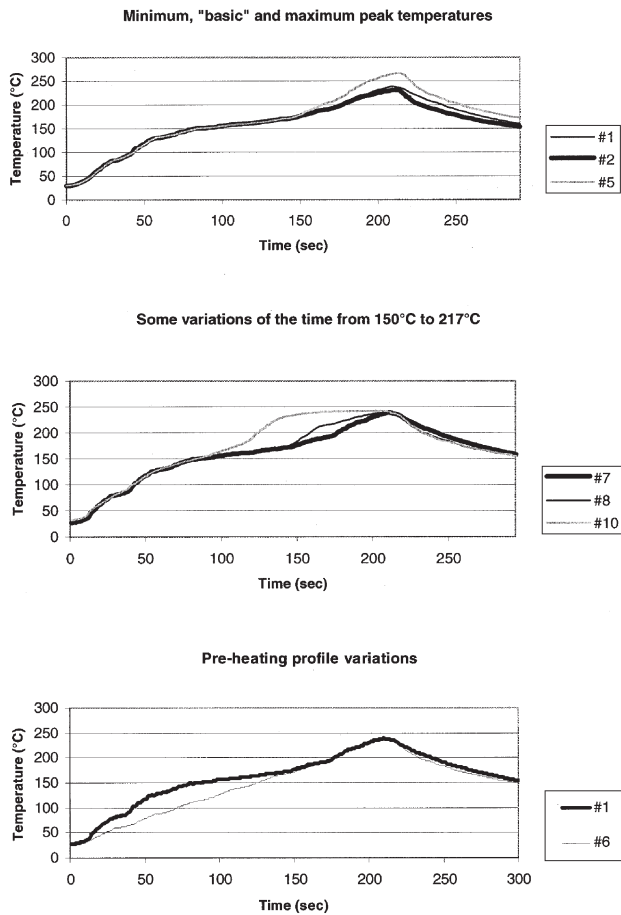


Fig. 1. Some of the reflow profiles used in the study.

kept unchanged as far as possible. Reflow conditions out of normal recommendations were purposely included to address the process window and to observe the typical phenomena in case the recommended limits were exceeded. The characteristics of the basic profile and the test profiles are presented in Fig. 1 and Table I.

The amount of solder balling was inspected after reflow with an optical stereomicroscope, and the results were categorized using the standard.³ In addition, solder balls were counted. Sixteen samples

were inspected for each solder paste/reflow profile combination. Furthermore, the particle size in the solder-paste samples was measured.

Solder Pastes and Printed Circuit Boards

Three different commercial solder pastes were selected for the study. Compositions, metal contents, and flux types are listed in Table II. All the pastes belonged to the Sn/Ag/Cu family; and, in terms of solder particle size, pastes A and C were categorized by the vendor as type 3 and paste B was categorized as between type 3 and 4.

The PCB was a two-layer, PCB with a high T_g FR-4-180 epoxy as the laminate-base material. The solder-ball test area was coated with a solder mask.

RESULTS AND DISCUSSION

It is essential to understand the mechanism of the solder-ball formation during this test method. When the solder paste reaches the temperature of 217°C, the solder starts to melt. Because of the surface tension of the molten solder, the solder rapidly accumulates to one location and forms a large solder ball. While the molten solder moves from the perimeter toward the main ball, the edges of the moving material oxidize if the flux is not strong enough to compensate for the oxide formation. It is assumed that if oxides are not removed effectively, some satellite balls are separated from the contracting molten solder. These small, satellite solder balls were investigated during this study.

Verification Test

All of the pastes performed very well in the test. Results are shown in Figs. 2–4. All the pastes passed the criteria and belonged to the “preferred” category.³

Process Screening

In Table III, the minimum, average, and maximum solder-ball count per test site, including all the reflow profiles in air atmosphere, are presented for each paste. Paste B resulted in considerably less solder balling than pastes A and C. The average solder-ball count for pastes A and C was very similar. The

Table I. Characteristics of the Reflow Profiles

Profile Name	Peak Temperature (°C)	Time from 150°C to 217°C (sec)	Time to 150°C (sec)	Time above 217°C (sec)
1 (“Basic”)	240	103	84	40
2	230	109	88	30
3	250	99	83	43
4	260	103	89	47
5	270	95	91	57
6	240	68	124	32
7	240	110	92	32
8	240	87	82	56
9	240	70	98	72
10	240	53	97	91
11	240	103	84	40

Table II. Solder-Paste Properties

	Paste A	Paste B	Paste C
Composition (wt. %)	95.8Sn-3.5Ag-0.7Cu	96.9Sn-2.7Ag-0.4Cu	95.5Sn-4.0Ag-0.5Cu
Metal content (wt.%)	89	88	89
Flux classification according to J-STD-004	ROL1	ROL0	ROL0

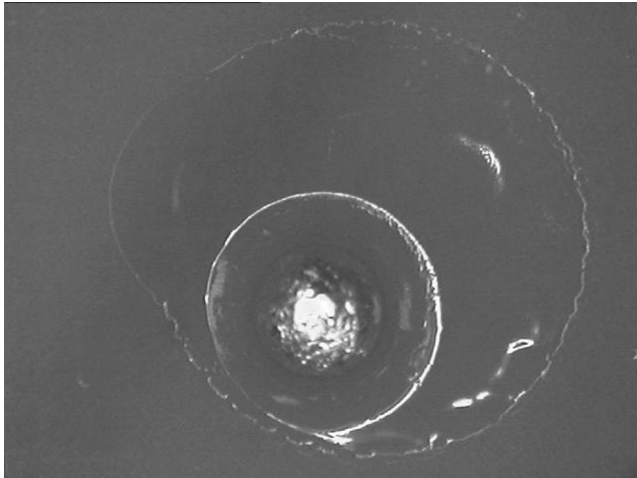


Fig. 2. The solder-paste A after reflow with the recommended profile.

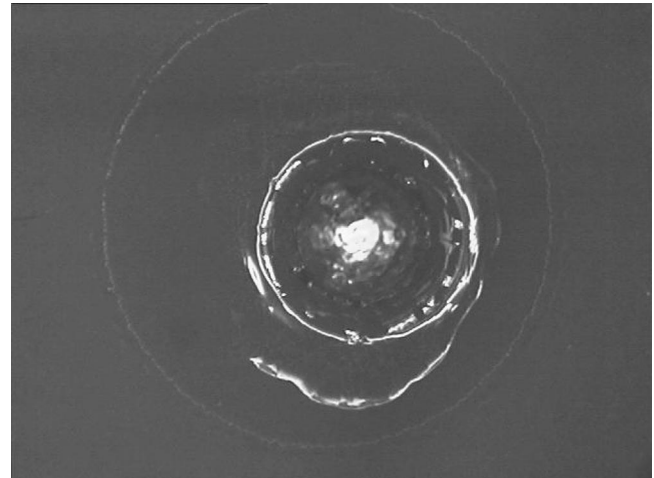


Fig. 4. The solder-paste C after reflow with the recommended profile.

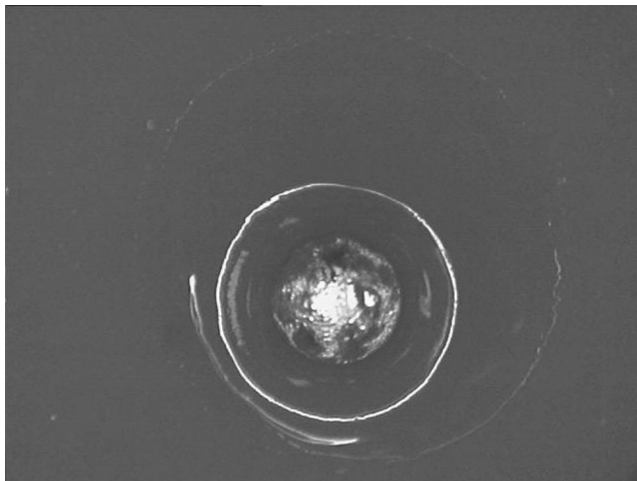


Fig. 3. The solder-paste B after reflow with the recommended profile.

high standard deviation is due to the large variation in the solder-ball count between the different profiles. The average solder-ball counts in air and nitrogen atmospheres are compared in Table IV, and some examples of the test results are presented in Figs. 5–7.

Some common trends were observed for all the pastes.

- An increase in the peak temperature did not have a major influence on solder-ball formation
- With a shorter time from 150°C to 217°C, fewer solder balls were formed
- The use of a constant preheating profile gave no significant difference

- Nitrogen atmosphere decreased the solder-ball count considerably, by 99% for paste A and by ~80% for pastes B and C

The particle size and the size distribution in the solder pastes were analyzed from scanning electron microscope (SEM) micrographs. The results are shown in Table V. Paste A had the most spherical particles and least variation in particle size as seen in Fig. 8 and Table V. Particles in solder pastes B and C were more distorted than in paste A, as shown in Figs. 9 and 10. There were also smaller particles attached to the larger ones in pastes B and C, as seen in Fig. 11. The size of these small particles varied between 11–19 μm .

Paste B, which had the largest particle-size distribution and the smallest average particle size, performed the best in the solder-balling test. However, in that paste, the surface area of the solder particles is the largest, and hence, there is more oxidized surface. Therefore, from the theoretical point of view, more solder balls would be expected for this paste. This means that the influence of the flux is assumed to be more significant than the particle size. This subject will be discussed further in the next section.

In the verification phase, a 200- μm -thick stencil was used. In process screening, the thickness of the stencil was only 100 μm . Comparison of the results between the verification phase (Figs. 2–4) and the process-screening phase (Figs. 5–7) shows that a thinner paste deposit results in more solder balls. With a thinner solder-paste deposit, the ratio of paste area/paste volume increases. There is greater solder-paste area compared to its volume exposed to

Table III. Minimum, Average, and Maximum Solder-Ball Counts for the Solder Pastes Tested in Air Atmosphere

Paste	Smallest Number of Solder Balls on a Test Site	Average Number of Solder Balls per Test Site	Largest Number of Solder Balls on a Test Site	STDEV from Average
A	0	21	59	13
B	0	4	22	4
C	0	19	62	15

Table IV. Comparison of the Average Solder-Ball Counts for the Solder Pastes Tested in Air and Nitrogen Atmosphere

Paste	Profile 1 (Air)	STDEV	Profile 11 (Nitrogen)	STDEV from Average
A	28	10	0.3	0.6
B	4	2	0.6	1
C	6	2	1	2

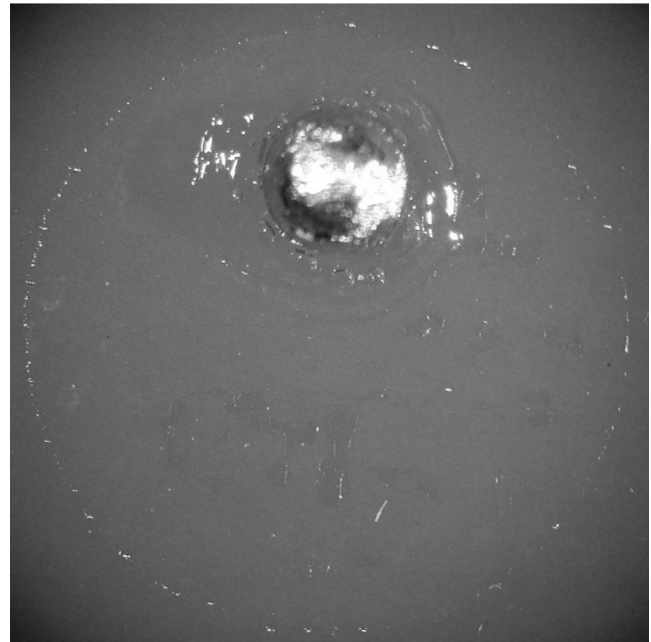
hot air, i.e., oxidative conditions during the preheating phase. A larger part of the activity of the flux is consumed on the surface of the paste deposit. Therefore, more solder balls are observed for thinner deposits.

The beneficial effect of the inert atmosphere can be explained in a similar way. In an inert atmosphere, there is no oxidative attack from the hot air. This allows all the activity of the flux to be consumed to break oxidized layers on the solder particles and on the PCB.

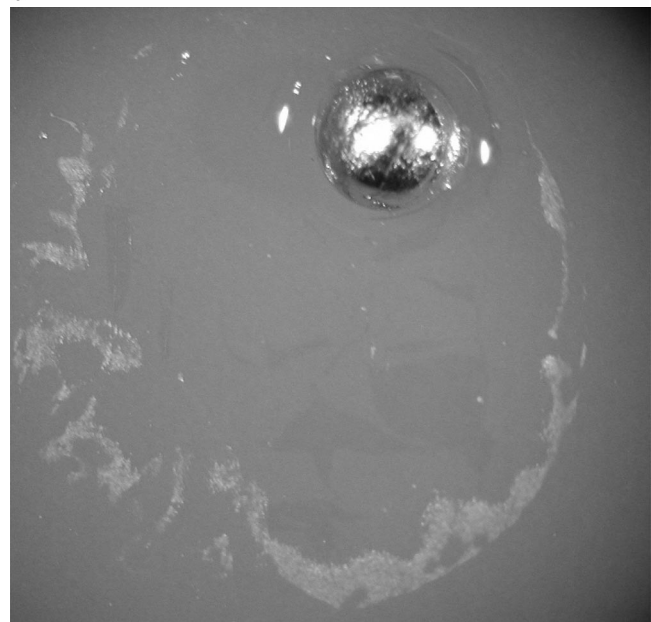
Influence of Solder-Paste Particle Size on Solder Balling

Contrary to the expectations, the paste with the smallest particle size (paste B) resulted in the least amount of solder balls during the process-screening study. Therefore, a third test was run to investigate if the solder particle size can have an effect on solder balling. For this purpose, Paste A with a smaller particle size, of 20–38 μm (type 4), with the same flux system and metal content, was tested. The reason for choosing Paste A was its high solder-ball count in the process-screening phase. This would allow changes in solder balling to be more easily detected. Test runs with the extreme reflow profiles (1, 2, 5, 7, 10, and 11), shown in Table I, were repeated for the new material.

After reflow, the solder-ball test sites were analyzed with SEM. First, the average number of solder balls per test site was counted. As can be seen from the results presented in Fig. 12, a greater number of solder balls are generally formed with the paste type 4. When the ramp-up time from 150°C to 217°C is shortened from 110 sec to 53 sec (profiles 7 and 10) or when inert atmosphere (profile 11) is used, the number of solder balls with type 4 paste drops dramatically. Solder-ball count for type 3 solder paste is not as highly influenced by the reflow condi-



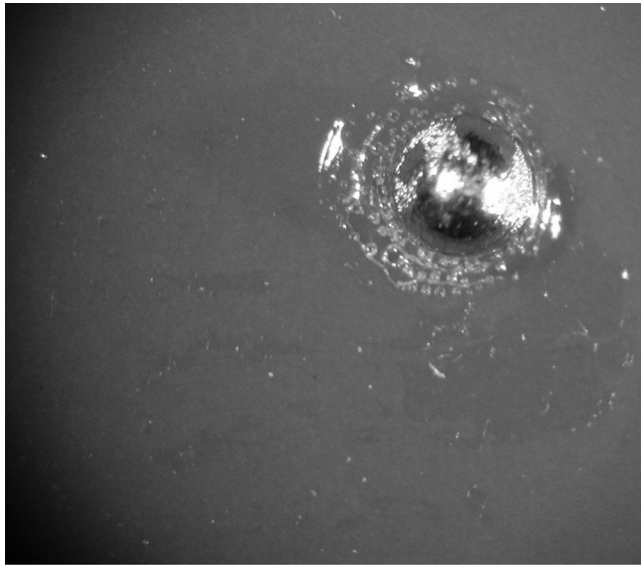
a



b

Fig. 5. An example of solder-paste A after reflow in (a) air and (b) nitrogen atmosphere.

tions as for type 4. The fact that the fast ramp-up rate from 150°C to 217°C is more favorable may be explained by the fact that the paste is exposed for a



a

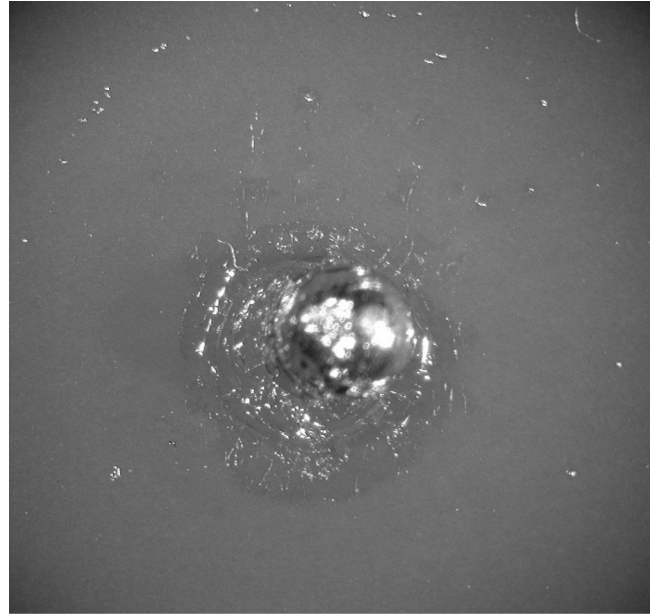


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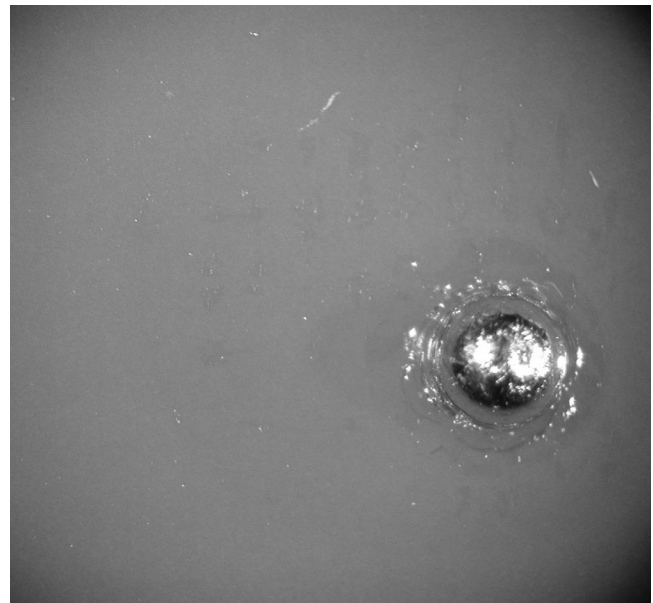
Fig. 6. An example of solder-paste B after reflow in (a) air and (b) nitrogen atmosphere.

shorter time to oxidative conditions before melting occurs.

The diameter of the solder balls was also measured. This information together with the solder-ball count was used to calculate the average total area of the solder balls per test site as seen in Fig. 13. The results show that the total surface area of solder balls is $\sim 20\text{--}220\%$ larger with type 4 than with type 3 paste, depending on the profile. The peak temperature has no clear influence on solder balling. This is expected because solder balls are formed immediately when the solder starts to melt. However, shortening the ramp-up time from 150°C to 217°C reduced solder balling significantly for both type 3 and type 4 pastes. With the profile 10, having the shortest ramp-up time from 150°C to 217°C , only very small solder balls were formed. The introduction of an inert atmosphere had a more pronounced effect,



a



b

Fig. 7. An example of solder-paste C after reflow in (a) air and (b) nitrogen.

resulting in even fewer and smaller solder balls. Switching from air to nitrogen reduced solder balling by 98% for type 3 paste and by 95% for type 4 paste. Some examples of solder balling or absence of solder balling with type 4 paste are shown in Figs. 14–16.

In most of the samples, some hidden solder balls were found on the perimeter of the initial printed-paste area under the flux residue, as shown in Fig. 17. As these balls were very difficult to detect and measure, they were not included in the results presented in Figs. 12 and 13. It was noticed that the number of hidden solder balls was significantly smaller with profiles 10 and 11 than with the other

Table V. Minimum, Average, and Maximum Particle Size of Solder Pastes

Paste	Minimum (μm)	Average (μm)	Maximum (μm)	STDEV (μm)
A	35.5	38.2	41.9	2.32
B	19.4	30.0	38.7	4.80
C	25.8	32.7	45.2	4.11

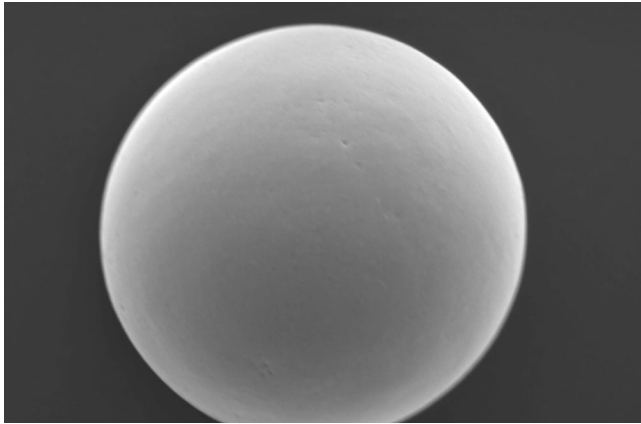


Fig. 8. The solder particles in solder-paste A.

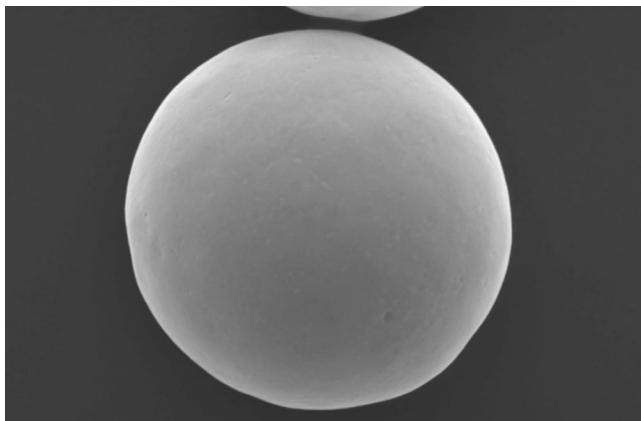


Fig. 9. The solder particles in solder-paste B.

profiles. This correlates very well with the counted number of solder balls.

During this work, the influence of solder-paste particle size on solder balling was studied for one of the pastes. In addition, for data-collection reasons, a paste being very susceptible to solder balling was selected. However, the results obtained may be different for different flux chemistries. It is possible that with a better flux system, the effect of solder particle size is not as remarkable. This assumption is supported by the fact that the impact of nitrogen during the process-screening phase was also very different for different pastes. More work is needed to address the impact of solder particle size for different flux systems.

CONCLUSIONS

In the verification phase, the solder balling in three commercial solder pastes were studied accord-

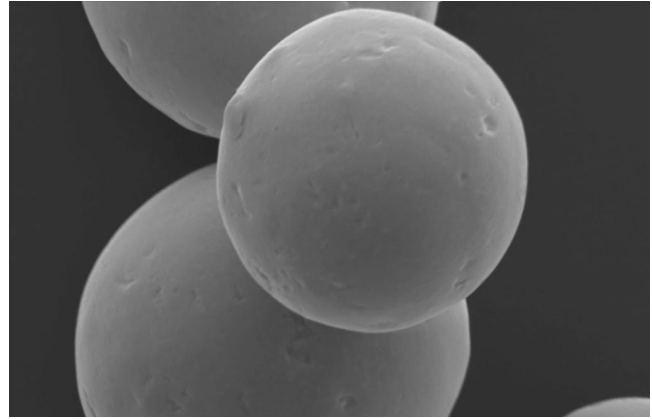


Fig. 10. The solder particles in solder-paste C.

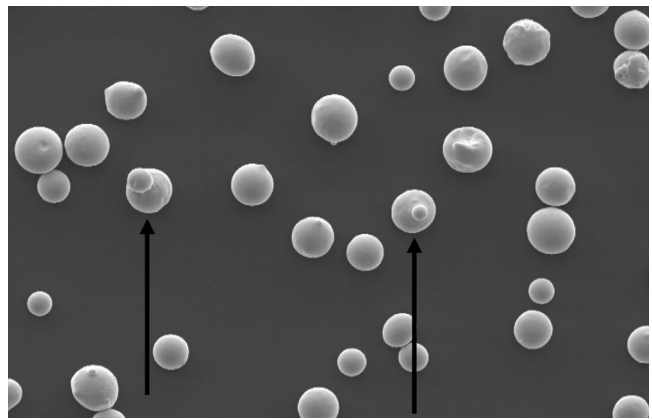


Fig. 11. An example of small solder particles attached to the larger ones.

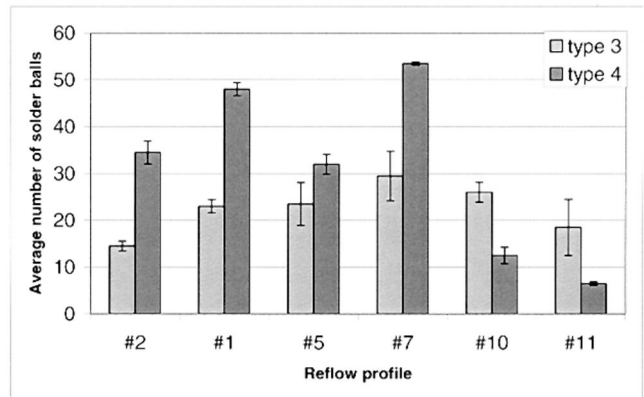


Fig. 12. The average solder-ball count as a function of reflow profile and the solder-paste type.

ing to the IPC-TM-650, 2.4.43 standard. During this work, the IPC test arrangement was modified so that a solder-mask surface and a real reflow profile were used. All the pastes passed the criteria presented in the IPC specification and belonged to the “preferred” category.

In the process-screening phase, the reflow profile was varied. Different preheating profiles, reflow peak temperatures, and reflow atmospheres were tested for all three pastes. Results show that flux chemistry plays a major role in solder-ball forma-

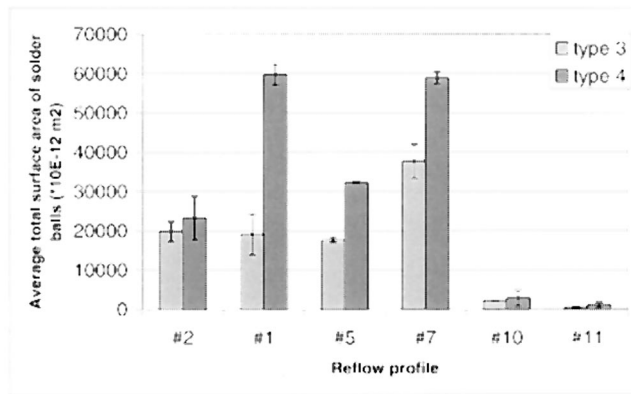


Fig. 13. The total surface area of solder balls as function of reflow profile and the solder-paste type.

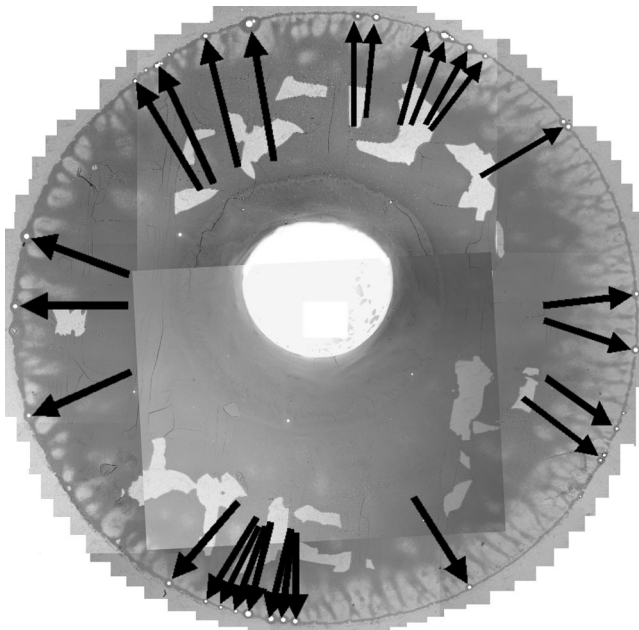


Fig. 14. An example of solder balling for type 4 solder paste reflowed with the profile 1 (basic profile).

tion. The next important factor is the reflow atmosphere. Reflow process times and temperatures were less significant, although the ramp-up time from 150°C to 217°C was found to have a considerable influence. The average number of solder balls with the best paste was one fifth of that with the worst paste. In addition, the best paste had the smallest particle size. This fact strengthens the conclusion on the dominant effect of the flux chemistry over the other factors especially when air atmosphere is used because a paste with a small particle size contains more oxidized-metal surface area and, thus, can be expected to be more prone to solder balling. Furthermore, with all the pastes, the solder-ball count dropped close to zero when an inert atmosphere was used. Therefore, an inert atmosphere can compensate for the bad performance of a flux system.

Another interesting finding during the reflow process screening was the influence of the stencil thickness on the solder-balling result. Process

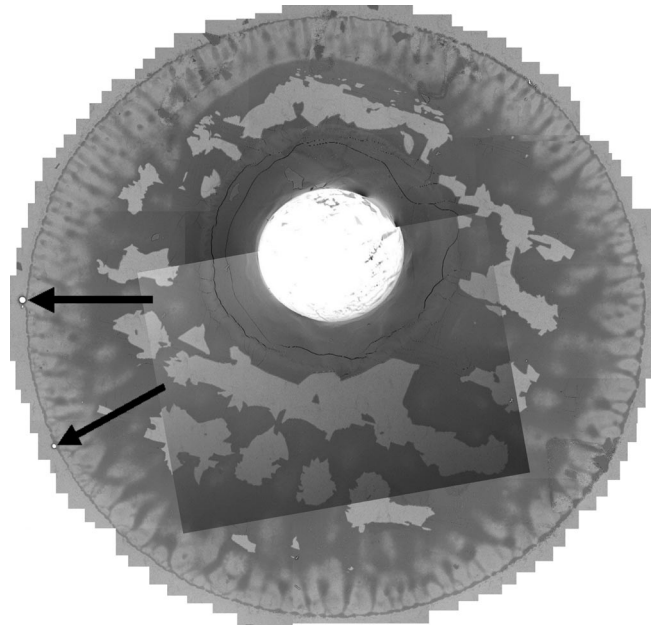


Fig. 15. An example of solder balling for type 4 solder paste reflowed with the profile 10.

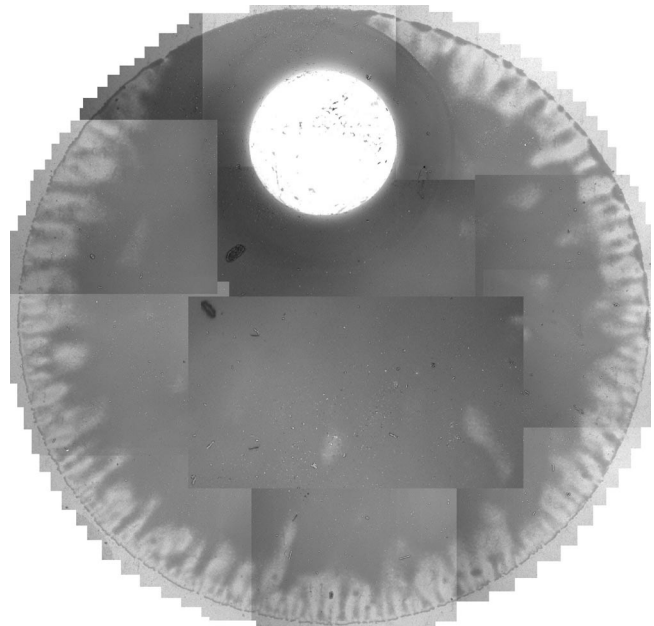


Fig. 16. An example of absence of solder balling for type 4 solder paste reflowed with the profile 11.

screening was carried out with a thinner stencil than the verification test. With the thinner stencil, two of the pastes exhibited significant solder balling, whereas the third paste still performed very well. This is assumed to be due to the different ability of fluxes to withstand oxidation from the hot air during the preheating in the reflow process. As a general conclusion, the use of a thin stencil increases the possibility of solder balling.

In the last phase, the effect of the solder-paste particle size on solder balling was studied. One flux type was selected, and the solder particle size was varied between type 3 and type 4. The reflow profile

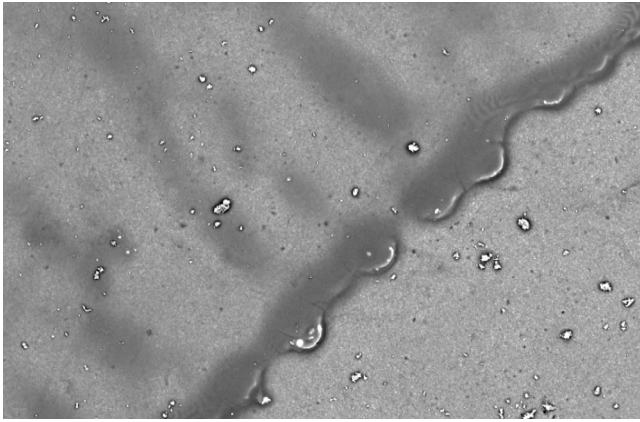


Fig. 17. The hidden solder balls under the flux.

was also varied. The results show that the total surface area of solder balls is $\sim 20\text{--}220\%$ larger with type 4 than with type 3, depending on the reflow profile. Reflow atmosphere and ramp rate from preheating temperature to the melting temperature were confirmed to be the dominant factors determining the level of solder balling for both types of

solder pastes. When the ramp-up rate from 150°C to 217°C was shortened, the amount of solder balls was reduced remarkably. This can be explained through less oxidation before the melting of the solder takes place. However, reflow atmosphere was clearly the dominating factor, reducing the solder-ball surface area by $95\text{--}98\%$. It has to be emphasized that these results are obtained for one flux system. The effect of solder particle size may be different for other flux chemistries.

Finally, it can be concluded that the solder balling of Sn/Ag/Cu pastes on a solder-mask surface is mainly dependent on the flux chemistry, reflow atmosphere, preheating ramp rate, and stencil thickness.

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