FACILITATING THE REDUCTION OF HEAD-IN-PILLOW DEFECTS AND IMPROVING ASSEMBLY RELIABILITY & IN-LINE PRODUCTIVITY USING NITROGEN REFLOW

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ABSTRACT
With unprecedented market and technological challenges associated with RoHS compliance and increased assembly functionality and miniaturization, many solder joint issues in ball-grid array (BGA), chip-scale package (CSP), and package-on-package (PoP) have led to assembly defects in the electronic manufacturing industry, such as head-in-pillow (HIP) defects. HIP defects are typically occurring due to poor wetting (random HIP defects) and/or warping (edge or center HIP defects) of the component. As a result of using devices with finer pitch and size and in some cases finer powder size in solder pastes, higher oxidation level will occur at the solder ball surface and within the solder paste due to the higher surface to volume ratio of the solder balls and particles, and decreased flux activity. Formulating the appropriate solder paste rheology and flux chemistry along with using proper component and materials storage to reduce oxidation and suitable assembly processes (printing, placement, and reflow) are necessary to reduce and prevent solder joint defects. While current industry trends tend to prioritize solder paste/flux dipping processes and the use of solder paste flux formulations with a higher metal oxide reducing potential, a straightforward reflow technique that uses a nitrogen inert reflow atmosphere during the heating stage can be employed to improve assembly reliability by 1) preventing the oxidation of the metal surfaces and 2) alleviating the need for aggressive flux chemistry (cleaner and more corrosion-resistant joints). In this paper, we will show evidence of the benefit of reflowing 0.8 mm pitch BGA and 0.5 mm pitch CSP components under a reduced oxygen environment (~1400 ppm O_2 level) by capturing air vs. nitrogen live recordings of the reflow process. The comparative videos and snapshot pictures show that N_2 reflow resulted in faster formation of cleaner solder joints with reduced tendency of forming HIP defects, providing improved assembly reliability and in-line productivity, and facilitating the self-alignment of poorly aligned components upon reflow.

Key words: head-in-pillow, defects, oven reflow, nitrogen reflow, inert nitrogen, electronics reliability

INTRODUCTION
With the miniaturization of personal electronic devices, such as mobile devices, the use of smaller and more complex active and passive components has brought along additional challenges and concerns as the electronics assembly industry converts to RoHS compliant lead-free assemblies. Printing and flux technology challenges associated with the lead-free solder implementation for the electronics industry have led to increased solder joint issues, such as the head-in-pillow (HIP) defects.[1-3]

HEAD-IN-PILLOW (HIP) DEFECTS
What is an HIP Defect?
As shown in Figure 1, a HIP defect is an incomplete coalescence between a solder ball on a component (head) and its solder coated land (pillow) during reflow, which is frequently encountered in assembling ball-grid array (BGA), chip-scale package (CSP), or package-on-package (PoP). This issue typically arises when an oxide film has formed on the surface of the molten solder paste and/or balls (note: this study is only focused on oxidation related to HIP).[3] As the solder melts, the oxide film will remain as a solid, thus resulting in the incomplete coalescence.

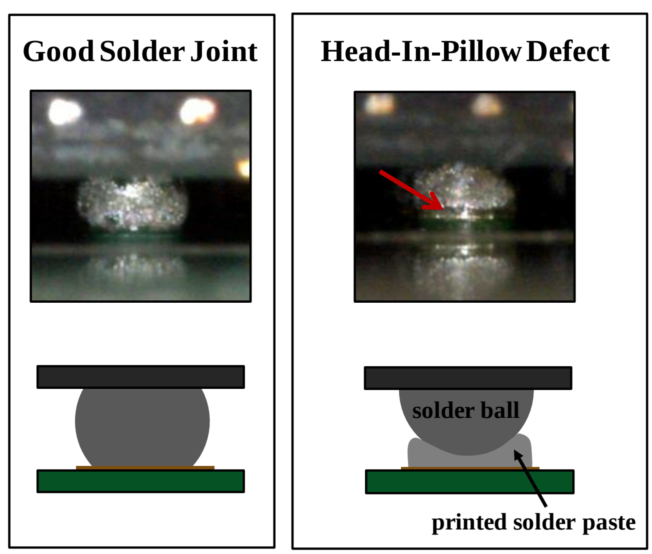

Figure 1. Example of a head-in-pillow (HIP) defect

How to Prevent HIP Defects?

HIP defects can be prevented using one or a combination of the following commonly used options: 1) using an inert atmosphere during reflow to minimize solder oxidation, 2) printing thicker paste to tolerate the thermal-induced warpage, 3) solder or flux dipping to facilitate interface contacts, 3) reducing reflow temperature to prevent flux exhaustion, 4) using solder paste fluxes with enhanced oxidation barrier and high fluxing capability.[4,5] Among the aforementioned methods, the use of nitrogen (as compared to air) reflow plus solder-dipping method has shown to greatly improve the quality of solder joints on assembling PoP packages[5] In addition, N_2 reflow has the benefits of widening the process-operating window due to minimized oxidation, thus assisting solder wetting and fluxing action.

This paper presents a visual support through comparative videos and snapshot pictures captured in air versus nitrogen reflow to demonstrate the benefits of nitrogen on the reduction of HIP defects and the improved solder joint formation of BGA and CSP components.

EXPERIMENTAL SECTION

Solder Printing Process

The printing process was performed on a custom-made stencil printer using a pre-cut piece of board (dummy board with OSP finish) and a lead-free no-clean solder paste (type 4 SAC305 with ROL0 flux). The components under investigation were 0.8 mm pitch BGA (array of 8 x 8 balls) and 0.5 mm pitch CSP (array of 14 x 14 balls) components with 8 mm square body size and SAC305 solder balls (Figure 2).

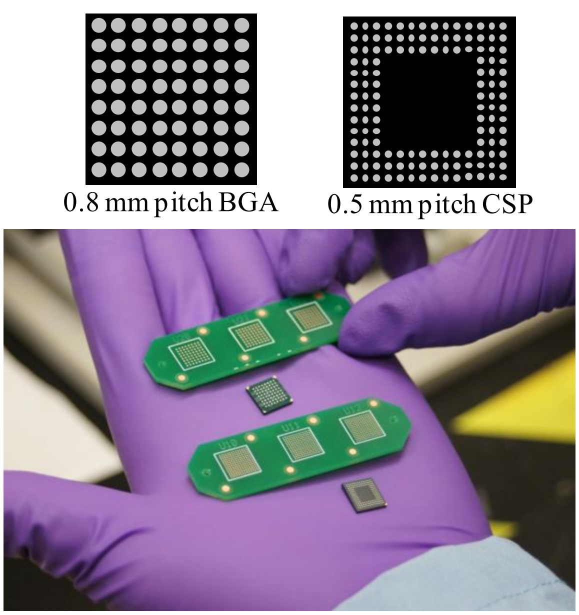

Figure 2. Components under investigation

Air vs. Nitrogen Reflow Experiments

The air- and nitrogen-reflow experiments were conducted using the convection oven of an ARES rheometer. Its inerting capability and straightforward temperature control (Figure 3, top image) can be used to simulate the conditions of a conventional reflow process. A custom-made aluminum sample holder was designed to hold the piece of board and an alignment mask was created to facilitate the alignment of the component balls to the board pads using affixed alignment pins, as seen at the bottom of Figure 3.

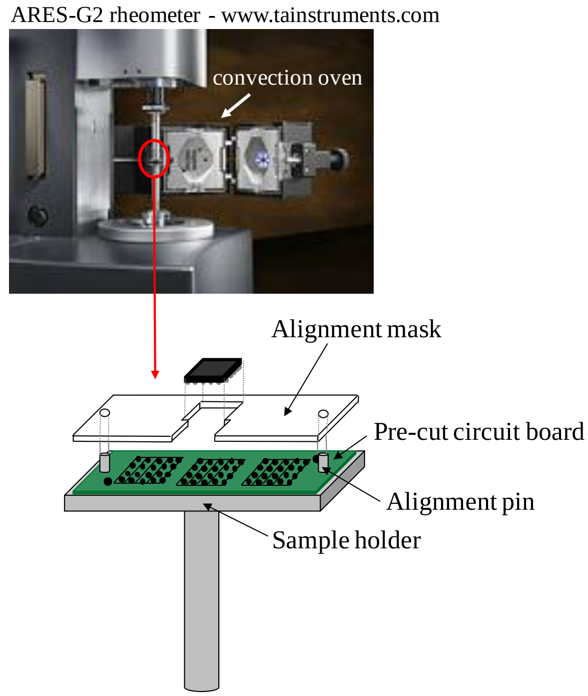

Figure 3. Schematic of experimental setup. ARES-G2 rheometer (top image) and custom-made aluminum sample holder (bottom schematic).

A soak temperature profile was utilized, as recommended by the solder paste manufacturer for BGA/CSP components to minimize void formation (Table 1). For the N_2 reflow experiment, the N_2 flow inlet was fed to the chamber using our in-house N_2 source (~4 ppm O_2 level). We note that the oven chamber was not designed to be leak-free. The air and air/N_2 mixtures were allowed to flow out of the chamber with a positive pressure during both the air- and N_2-reflow experiments. Common inerting reflow processes in the electronics assembly industry use nitrogen flows ranging from 500 ppm to 1500 ppm O_2 levels. The selection of O_2 level generally dependents on component/board quality, geometries, configurations and solder paste used. In this study, all N_2-reflow experiments were conducted at ~1400 ppm O_2 content, monitored using a Series 3000 Alpha-Omega O_2 analyzer.

RESULTS AND DISCUSSION

By using the same reflow temperature profile (Table 1), air- and N_2-reflows demonstrate significantly different wetting behaviors. Live videos of the reflow process in both air and nitrogen environments were recorded to provide visual cues on the speed and behavior of solder joint formation throughout the different reflow stages. 0.8 mm pitch BGA and 0.5 mm pitch CSP components were used in the reflow demonstrations. These videos are available online at [insert website link] and on our website at [insert website link].

Zone #	Stage	Temp. range	Rate/Time	Reason
1	initial heating	30 °C to 205 °C	0.5 °C /sec	Flux activation step to remove oxide layers and minimize defects
2	soaking	Hold at 205 °C	2 min	To reduce void formation
3	post-soak heating	205 °C to 235 °C	0.3 °C /sec	-
4	liquidus	Hold at 235 °C	1 min	Soldering step
5	cooling	235 °C to RT	1 °C /sec	The faster the cooling the better for the formation of a fine grain structure

Table 1. Reflow temperature profile for lead free, halide-free, no-clean SAC305 solder

Air- vs. N_2-Reflow of 0.8 mm Pitch BGA Components

Snapshot pictures taken during the reflow temperature stages for 0.8 mm pitch BGA components in both air and N_2 (~1400 ppm O_2 level) atmospheres are shown in Figure 4. As compared to the air-reflowed component (pictures with red borders), component undergoing a soldering process in N_2 (pictures with blue borders) showed no HIP defects and overall cleaner solder joint formation with less flux residues. Additionally, the BGA component reflowed more quickly and at lower temperature (221 °C in N_2 versus 227 °C in air) than the component reflowed under air atmosphere as reflowing in N_2 prevented the in situ formation of oxides and allowed the solder paste flux to be more readily available for cleaning up the existing oxide layers at the metal surfaces. Real time and reflow temperatures at five distinct stages of the reflow process are reported in a summary table and in a graphical representation in Figure 5 for clarity. We note that both air and N_2 reflow experiments were replicated twice and showed reproducible results. Higher-resolution pictures of the four-side-perimeter ball arrays of the BGA components were taken upon reflow in air and N_2 atmospheres to provide clearer visual evidence of the reduction of HIP defects and cleaner solder joints in a N_2 environment (Figure 6).

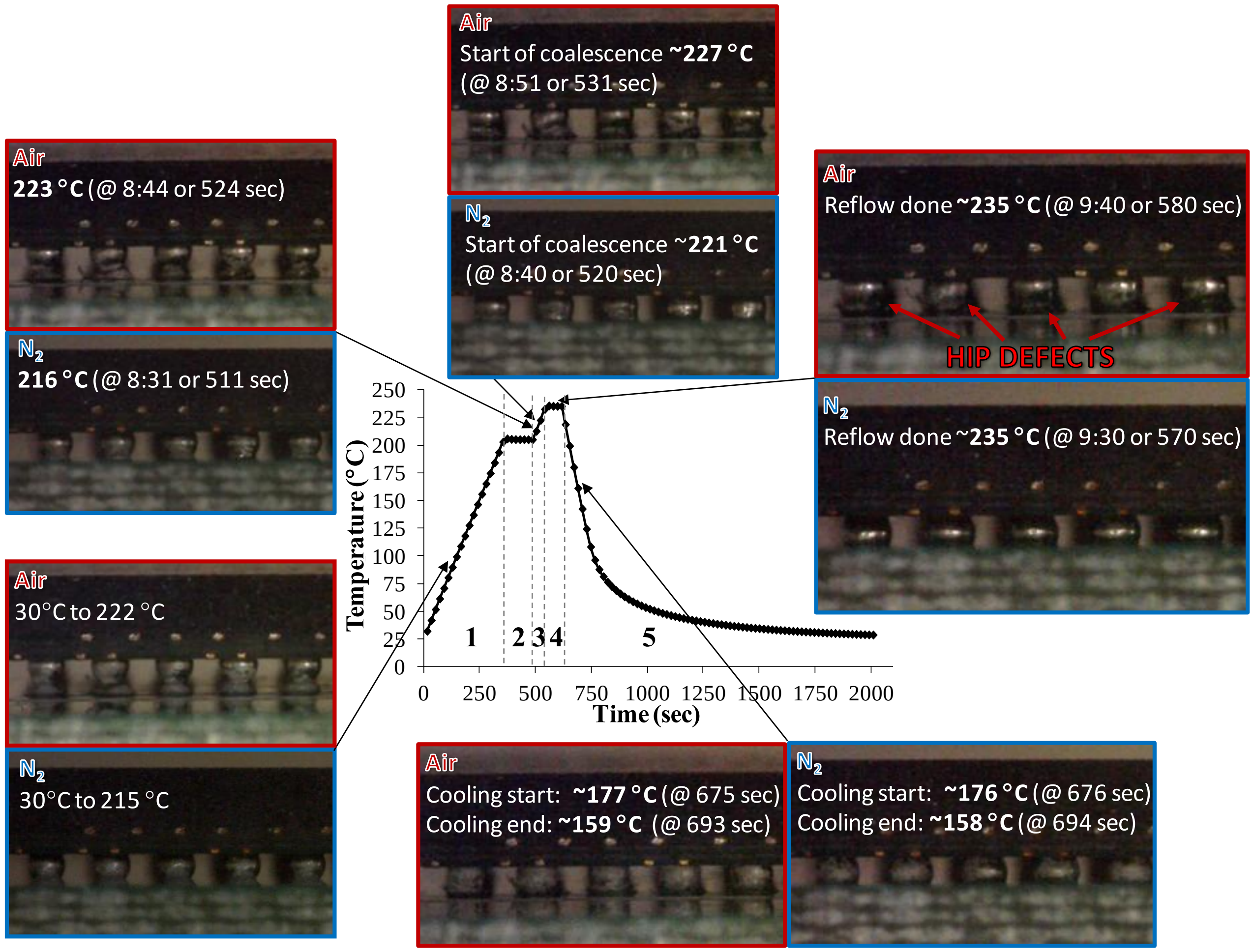

Figure 4. Air vs. N_2 (~1400 ppm O_2 level) reflow process of a 0.8 mm pitch BGA component onto an OSP finished-board. The graph of the reflow temperature profile depicts the different heating stages 1-5, as stated in Table 1. Snapshots of the experimental live footage are taken at different reflow process stages, illustrating the formation of HIP defects upon air reflow.

		N_2		Air	
		Time (min:sec)	Temperature (°C)	Time (min:sec)	Temperature (°C)
1	First sign of activity	8:31	216	8:44	223
2	Start of reflow of 1st balls array	8:40	221	8:51	227
3	End of reflow of 1st balls array	9:25	235	9:40	235
4	First sign of ball cooling	11:16	176	11:15	177
5	Complete cooling of 1st balls array	11:34	158	11:33	159

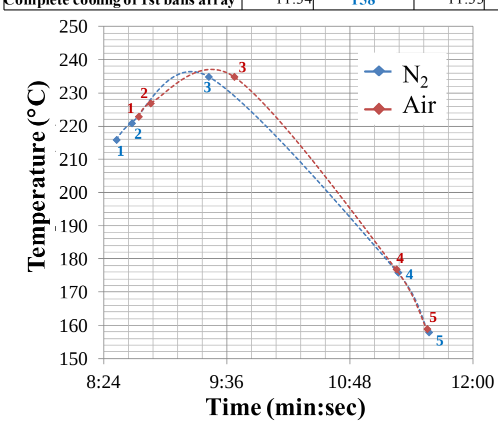

Figure 5. Comparative graph of Temperature vs. Time at specific stages along the reflow process in air vs. N_2 (~1400 ppm O_2 level) atmospheres for a 0.8 mm pitch BGA component. Under N_2 atmosphere, the reflow process can be achieved at lower temperatures (6 to 7 °C difference between air and N_2 reflow) in significantly shorter periods of time (15 sec). We note that the dashed lines are drawn to guide the eye.

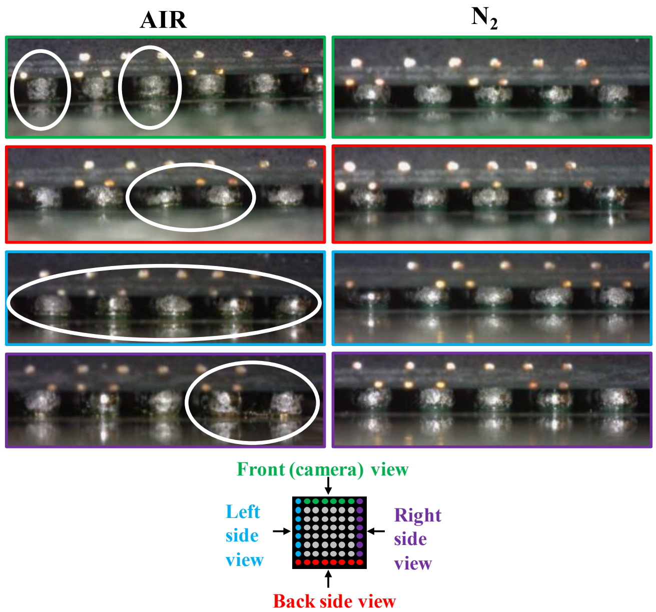

Figure 6. Pictures of the four side perimeter ball arrays of the BGA components reflowed in air (left column) and N_2 (right column) atmospheres. A schematic of the BGA component depicting the four color-coded perimeter ball arrays is provided on the right, for clarity. HIP defects formed during the air-reflow process (encircled areas) while the N2-reflowed component shows clean joints with good coalescence and seemingly no presence of HIP defects.

Air- vs. N_2-Reflow of 0.5 mm Pitch CSP Components

The aforementioned air and N_2 (~1400 ppm O_2 level) reflow experiments were also conducted using a smaller pitch size CSP component to investigate the effect of using a nitrogen blanket during the reflow of components with smaller solder ball sizes. We anticipated that the 0.5 mm pitch CSP solder balls of higher surface to volume ratio could potentially exhibit higher solder ball oxidation, and thus provide evidence of a more drastic air versus nitrogen differentiation during the solder joint formation. N_2-reflow is expected to show better wetting and coalescence between the solder paste and solder balls (i.e. fewer defects) as reduced polymerization of flux in a nitrogen environment provides a higher flux activity to remove oxide layers during the flux activation and liquidus stages.

During the liquidus stage of the reflow process under a N_2 atmosphere, the solder balls on the component and printed paste on the solder lands coalesced more quickly (3 sec in N_2 versus 50 sec in air) and formed cleaner solder joints (with only one occurrence of HIP defect) while the air-reflowed component developed many HIP defects, as seen in Figures 7 and 8. This latter finding can be attributed to a higher flux activity under a N_2 blanket than under air. Consequently, the flux was able to successfully clean up the existing oxides and forming a protective layer on the molten solder balls and the surface of the paste to prevent further oxidation. We note that both air and N_2 reflow experiments were replicated twice and results showed that components could be reflowed at least three times faster in N_2 (~1400 ppm O_2 level) than in an air environment. The performance improvement in N_2 in this second trial was somewhat less, possibly due to variations in the amount of native oxide layers on the metal surfaces prior to the in-line process. In both reflow environments, the component started reflowing at the same temperature (235 °C) but the solder joints under air-reflow took longer to form and appeared to finish forming during the cooling stage, at ~228 °C. Additionally, the 0.5 mm pitch components necessitated a higher reflow temperature (235 °C) than the 0.8 mm pitch components (221-227 °C). This can be rationalized by the fact that the solder balls of the 0.5 mm pitch CSP component possess a higher surface area per volume ratio on which oxide layers can grow while being stored prior to the in-line process as well as during the heating and liquidus stages. Therefore, less flux per unit area is effectively available for oxide reduction, which likely delayed the start of the reflow in both air and N_2 reflow environment with respect to the reflow of 0.8 mm pitch BGA components. Furthermore, within the limit of our experimental setup, the printed solder paste did not properly melt upon heating in the air reflow experiments, preventing the formation of the solder joints (as seen in the high-resolution pictures – front and right side views of the solder ball perimeter arrays - in Figure 9). We note that the ball perimeter arrays for which the solder paste did not melt properly were located the farthest away from the hot air flow outlet within the chamber, likely creating a small thermal gradient across the board. This can be adjusted by increasing the reflow temperature but doing so can exhaust the flux and increase the formation of HIP defects. Although a thermal gradient would not likely happen in a conventional reflow oven, the components reflowed under N_2 showed improved solder joints quality with no sign of un-melted solder even when undergoing a small thermal gradient. This latter finding provides evidence that N_2 allows higher flux activity at the metal surfaces by preventing flux exhaustion prior to the liquidus stage, which allowed the removal of existing metal oxides as well as prevented the formation of new oxides at a reasonably low peak temperature. Additionally, the use of nitrogen in place of an air atmosphere will enhance the self-alignment of components to the printed circuit board pads due to reduced oxidation, to permit increased wetting of the solder alloy during reflow. In this study, the poorly-aligned component was able to self-align upon heating more readily in N_2 than in air (as seen in the online video for the reflow of the 0.5 mm pitch component), likely due to the higher surface tensions of the molten printed solder and solder balls, as a result of minimized oxidation.[6]

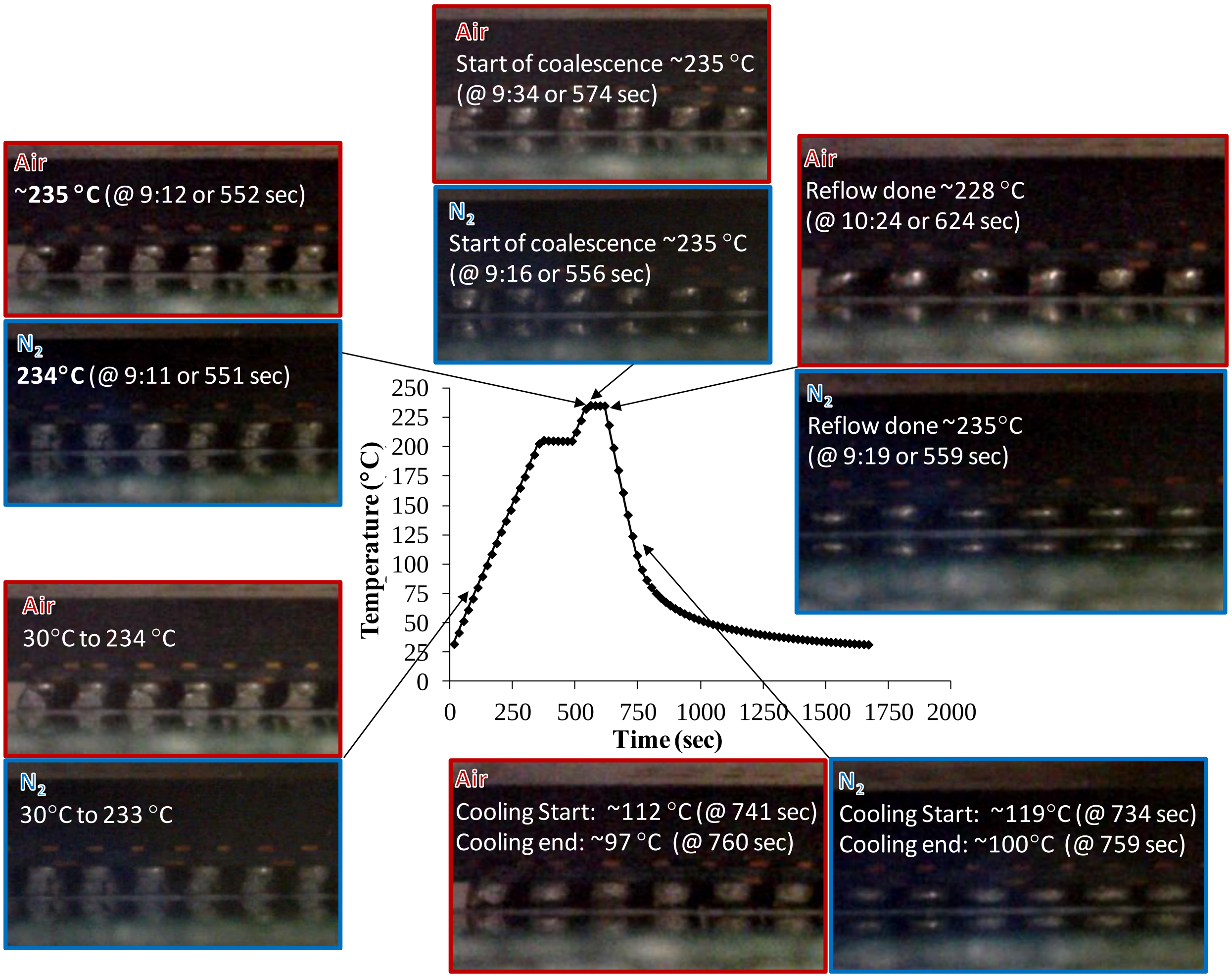

Figure 7. Air vs. N_2 (~1400 ppm O_2 level) reflow process of a 0.5 mm pitch CSP component onto an OSP finished-board. The graph of the reflow temperature profile depicts the different heating stages 1-5, as stated in Table 1. Snapshots of the experimental live footage are taken at different reflow process stages, illustrating the formation of HIP defects upon air reflow.

		N_2		Air	
		Time (min:sec)	Temperature (°C)	Time (min:sec)	Temperature (°C)
1	First sign of activity	9:11	234	9:12	235
2	Start of reflow of 1st balls array	9:16	235	9:34	235
3	End of reflow of 1st balls array	9:19	235	10:24	228
4	First sign of ball cooling	12:14	119	12:21	112
5	Complete cooling of 1st balls array	12:39	100	12:40	97

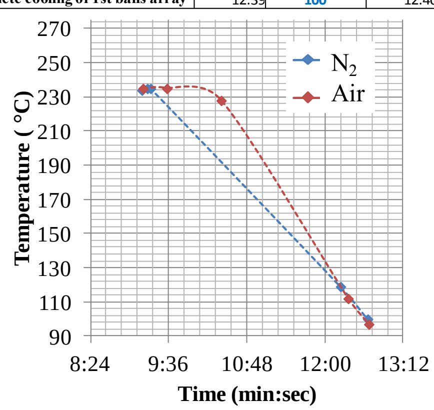

Figure 8. Comparative graph of Temperature vs. Time at specific stages along the reflow process in air and N_2 (~1400 ppm O_2 level) atmospheres for a 0.5 mm pitch CSP component. Under N_2 atmosphere, the reflow process can be achieved considerably faster (~3 sec in N_2 vs. ~50 min in air).

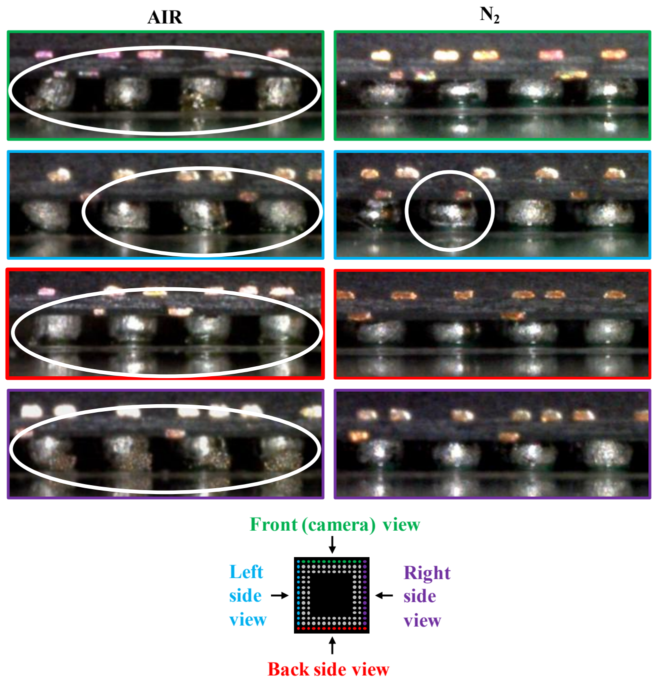

Figure 9. Pictures of the four side perimeter ball arrays of the CSP components reflowed in air (left column) and N_2 (right column) atmospheres. A schematic of the CSP component depicting the four color-coded perimeter ball arrays is provided on the right, for clarity. Many HIP defects are formed during the air-reflow process and poor solder melting occurred, particularly for the perimeter side arrays furthest to the hot convective air flow within the chamber. The N_2-reflowed component shows clean joints with good wetting and coalescence and presence of few HIP defects.

SUMMARY

Solder pastes with low activity rosin-based flux chemistry (mainly used in devices that do not require high reliability devices) are usually considered low-performing materials because they are not necessarily designed to provide enhanced oxidation barrier or better wetting performance. Nowadays, high performance lead-free solder pastes used in high reliability devices are being developed with enhanced oxidation barrier capability and high fluxing capacity with increased thermal stability to reduce process issues such as HIP defects. However, these highly performant materials contain high molecular weight flux vehicles, making boards more difficult and costly to clean, particularly when highly reliable devices are needed. In this study, the use of nitrogen (~1400 ppm O_2) during the reflow process of BGA and CSP components with a low activity rosin-based paste demonstrated better wetting performance than under an air reflow environment: N_2 reflow prevented the formation of new oxides while avoiding the use of solder pastes with high fluxing capacity, which provided improved wetting performance, reduced amount of HIP defects, and improved quality and cleanliness of the solder joints for use in high reliability devices. Additionally, components reflowed under N_2 coalesced more quickly and readily than air-reflowed components. The 0.8 mm pitch BGA components, reflowed under an N_2 blanket, necessitated lower reflow temperatures and reflow time. Similarly, smaller size and pitch components such as the 0.5 mm pitch CSPs employed in this study, could be reflowed in at least three times less time in N_2 than in an air atmosphere, which could allow for improved in-line productivity and overhead costs.

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