EFFECT OF VACUUM REFLOW ON SOLDER JOINT VOIDING IN BUMPED COMPONENTS

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ABSTRACT

Voids affect the thermal characteristics and mechanical properties of a solder joint, thereby affecting the reliability of the solder interconnect. The automotive sector in particular is requiring the mitigation of solder voids in various electronic control modules to the minimum possible level. Earlier research efforts performed to decrease voids involved varying the reflow profile, paste deposit, paste alloy composition, stencil aperture, and thickness. Due to the various advantages they offer, the use of Ball Grid Array packages is common across all industry sectors. They are also prone to process voiding issues. This study was performed to determine if vacuum assisted reflow process can help alleviate the voids in area array solder joints. Test parameters in this study largely focused on vacuum pressure level and vacuum dwell time.

Experiments were also performed on a bench top oven to investigate the behavior of voids under vacuum. Tests were carried out at various pressure levels with samples solidified under vacuum to lock in the voids, which wouldn't be possible in an in-line convection vacuum reflow oven.

Test boards were also assembled on convection reflow oven using a linear ramp to peak reflow profile to provide comparative analysis.

Key words: Lead-free alloys, Solder Joints, Voids, Vacuum Reflow Processing

INTRODUCTION

One of the crucial stages in an electronic assembly process is reflow soldering. The reflow process for a solder joint starts with the transfer of heat to melt the solder paste and solder sphere, followed by the formation and coalescence of gas bubbles. These gas bubbles may be formed due to entrapment of flux outgassing, volatilization of solder paste solvent/solids, and moisture from the printed circuit board or component.

Voids deteriorate the ability of a solder joint to withstand stress/strain caused by CTE mismatch between PCB and the component, during thermal cycling, by vibration or by drop impact thereby compromising the mechanical robustness of the interconnect. Solder joints aid in dissipating the heat transferred to the PCB during operation to prevent the breakdown of the device circuitry. The amount of heat transferred is determined by the cross-sectional area of the solder joint. The presence of voids may increase the standoff height to maintain the initial volume of the solder joint, but the area might be smaller thereby affecting the thermal performance of the interconnect.

Nucleation of voids, gas and vapor bubbles cannot be avoided in a reflow process but it is necessary to manage the distribution of voids for the resulting solder joints to have structural integrity and thermal conducting performance by discharging them from the system. This could be possible by decreasing the external pressure of the system thereby increasing the differential pressure, facilitating the growth and movement of bubbles and finally evacuating them by a process known as vacuum soldering. Typically, small bubbles coalesce to form a large one and eventually escape from the molten metal at the free surfaces. The motion of bubbles in the molten metal is due to decreased flow resistance and increased buoyancy during vacuum process. Additionally, vacuum also promotes reduction atmosphere thereby lowering the partial oxygen pressure. The reduced oxygen partial pressure is expected to reduce the gaseous byproducts from the fluxing reactions, thereby reducing the quantity of voids generated. This leads to reduced entrapped gas volumes in the solder joints. The effect of vacuum reflow process and its effect on solder joint voids has been documented previously [1-7].

For a SnAgCu (SAC) solder joint, the solder paste at the periphery starts to melt when the local temperature reaches 217˚C to form a smooth surface, with gases formed inside the joint entrapped as gas bubbles. When a pressure differential is created between the gas bubbles and the surrounding environment, the gas bubble swells by the relationship PV = nRT, according to Ideal Gas Law. P is the surrounding environmental pressure, V is the volume of the void, n is the number of moles of void gas molecules, R is the ideal gas constant and T is the temperature.

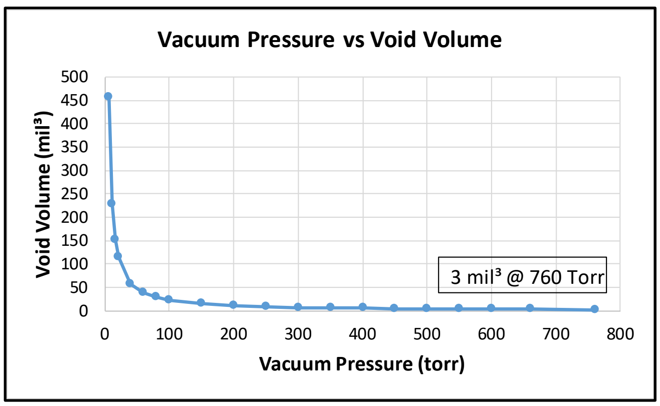

Figure 1. Plot of Vacuum Pressure vs. Void Volume for evolution of void size measuring 3mil^3 at atmospheric pressure based on Ideal Gas Law equation, assuming temperature is constant

The expansion of a bubble having a small initial size is evaluated under vacuum at constant temperature. The bubble is assumed to grow spherically symmetric in a motionless liquid. The relationship between void size and environmental pressure can be determined by using the Ideal Gas Law. For a constant temperature, PV is a constant and therefore void volume is inversely proportional to pressure.

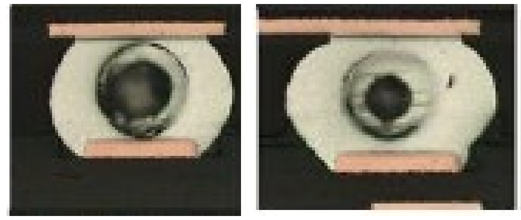

Figure 2. Examples of BGA large voids that have reduced the effective solder joint attachment area [1]

For example, a small void of 3 mil^3 at 1 atmosphere (760 Torr) might expand to 15 mil^3 at 150 Torr, 114 mil^3 at 20 Torr and 456 mil^3 at 5 Torr, as shown in Figure 1. This might not be representative of an actual void size but previous studies have shown Ball Grid Array solder joints having huge voids thereby decreasing the cross-sectional area (refer Figure 2).

Gaseous voids formed in BGA solder joints are observed near the PCB or component pads or suspended in the bulk solder with a spherical shape having a small surface area: volume ratio [8]. Sometimes, gas bubbles grow to fill the entire solder joint height. Since the liquid is incompressible, the solder joint increases in diameter to accommodate the bubble presumably growing in all directions making it unlikely for voids to come in contact with solder joint boundary and escape, as shown in Figure 3 [9, 10].

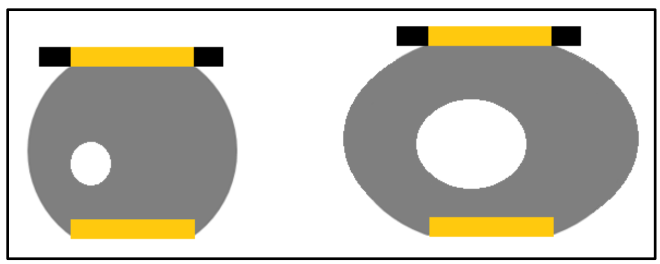

Figure 3. Graphics showing possible void formation in bumped solder joints. Large voids may significantly increase solder joint height and diameter. Voids may grow and shrink without escaping the solder [12].

During the vacuum reflow process, neighboring solder joints may come in contact with each other if they expand to accommodate a large enough internal gas bubble [11, 12]. This may lead to solder joint bridging with a likelihood determined by the pitch of the component. Using the Ideal Gas Law and simulating a spherical solder joint having internal void growth shows that applying vacuum significantly affects the size of the solder joint. As depicted in Figure 4, a void grows twice its original size (diameter) from atmospheric pressure to 100 Torr vacuum and 5 times its original size at 5 Torr vacuum. Considering most of the BGA applications use solder spheres of 30 mil diameter or less, it is evident that void volume would occupy a major portion of the solder volume under vacuum pressure.

It can be inferred from Figure 4 that if the initial void size is similar before the application of vacuum, small solder joints at fine pitches are more susceptible to bridging than larger joints at larger pitches. It is understood that due to the ballooning effect of voids under vacuum application, molten solder joints may physically contact the adjacent joint due to the expansion of solder joint. It is also possible that solder joints may retreat back to their original positions or stay bridged after atmospheric pressure is restored [13].

The only way to quantitatively verify and investigate the growth and behavior of bubbles is to perform a series of experiments with various parameters under vacuum and compare the data with results from standard reflow oven.

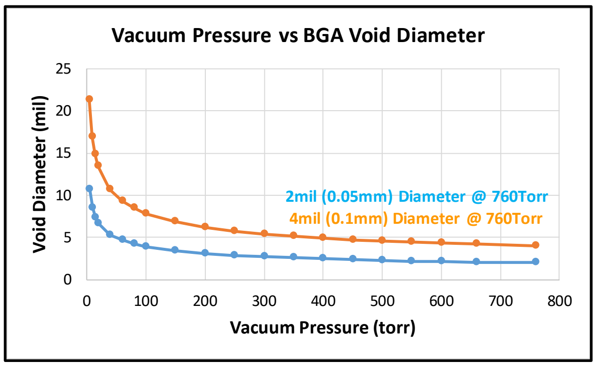

Figure 4. Vacuum Pressure vs. BGA Void Diameter based on Ideal Gas Law Equation [12]

EXPERIMENTAL DESIGN

Test Board Description

The vacuum reflow test board used was acquired with an ENIG surface finish. It measured 78 mm ×104 mm with 1 mm thickness and contained 2 signal layers. Apart from the Wafer Level Chip Scale Package (WLCSP) footprint – the focus of this paper – the primary side of the board also included footprints for Quad Flat No-Lead (QFN), Land Grid Array (LGA), Surface Mount Resistor (SMR), and D2PAK MOSFET device types. The component and board properties are shown in Table 1.

Table 1. WLCSP49 and printed circuit board attributes

WLCSP49 Package Attributes	
Designation	WLCSP49
Die Size	3 X 3 mm
Ball Array	7 X 7
Ball Pitch	0.4 mm
Ball Diameter	0.254 mm
PCB Attributes	
Dimensions	78 X 104 X 1mm
Surface Finish	ENIG
No. Cu Layers	2
Glass Transition Temperature, Tg	170˚ C

Assembly Process

The test boards were assembled using an in-line convection vacuum reflow oven consisting of 10 convection heating zones followed by two heated zones located inside a sealable vacuum chamber followed by two cooling zones. The reflow profile configured was a direct ramp-to-peak profile with a peak temperature at 242˚C, as shown in Figure 5. The basic temperature profile was maintained throughout the experiment, however, vacuum dwell time was varied in the Design of Experiment from 5 to 40 seconds. This added to the time above liquidus with the shortest at~80 seconds and the longest at~120 seconds. Longer dwell times inside the vacuum chamber resulted in slightly higher peak temperatures.

For comparative purpose, test boards were assembled in a standard (ambient pressure) forced air convection reflow oven – 10 heating zones and two cooling zones at the end. The samples were heated to peak temperature~240˚ C and TAL of 57 seconds, as shown in Figure 6.

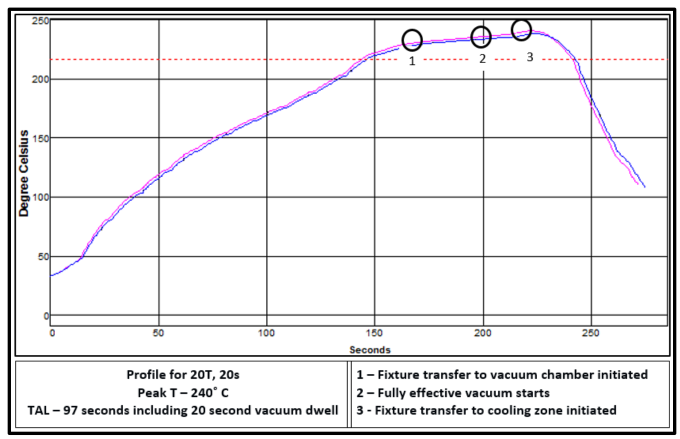

Figure 5. Example of in-line vacuum reflow profile:
Stage 1 – Fixture transfer to vacuum chamber begins
Stage 2 – Vacuum reaches set point
Stage 3 – Fixture transfer to cooling zone begins
All the tests were performed in N_2 atmosphere using a lead-free solder paste.

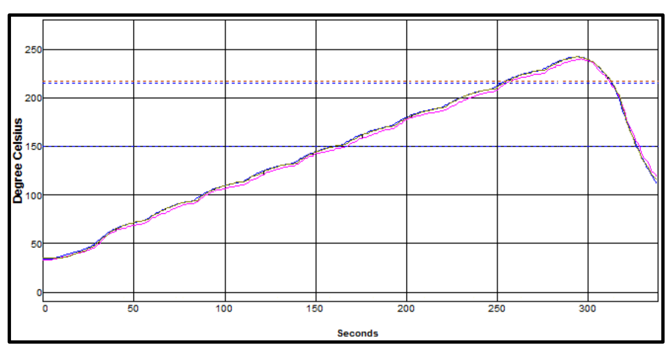

Figure 6. Standard Convection reflow profile used in the process

Void Analysis Methodology

WLCSP49 was selected to investigate the effect of vacuum reflow process on fine pitch ball grid array solder joints. Once the samples were assembled, they were examined using a Dage XD7600 x-ray imaging system. The x-ray inspection process used a semi-automated method. The x-ray imaging system was not used to determine the actual void size but instead quantified voids as a percent area fraction of the defined Region of Interest (ROI). For WLCSP solder joints, the automated method to define the ROI based on 2D x-ray area of solder joint boundary had 'floating' reference points, where two voids of different sizes will have the same area percentages because large solder joint with a large void will have a larger joint area than a similar joint with a smaller void. The effect due to the floating reference point is believed to be negligible.

A function was configured by defining the ROI, contrast, layout for one entire WLCSP package and utilized as an automated method to determine the void area. But the drawback of this technique is, if the size of a solder joint size is different from the normal dimension, then ROI has to be customized. Hence, the function cannot be totally relied on and the contrast needed to be modified occasionally for different defined ROIs. Additionally, due to the varying contrasts on the boundary of the solder joint and towards the center it was challenging for all voids to be recognized by the software. Hence, it was determined that analyzing WLCSP solder joints in groups of six produced better results as it was convenient to discern the smallest voids. Missing or false voids were added or deleted during the process, as shown in Figure 7.

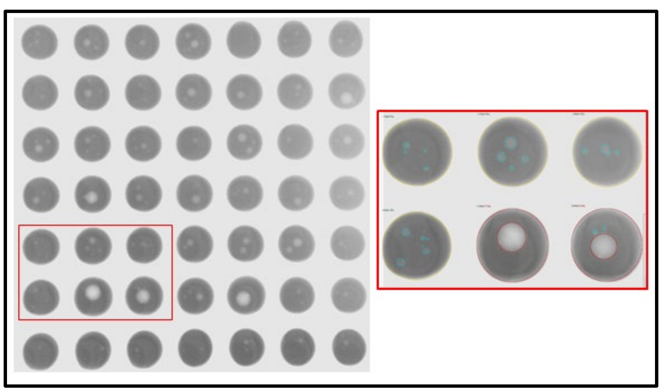

Figure 7. Example of WLCSP void analysis. Small voids were identified and manually outlined.

RESULTS

Void level analysis, including cumulative voiding, were performed on the x-ray area of single solder joint and in this way, solder joints having no voids, which existed in all process conditions – albeit very few – were eliminated from the study. All the WLCSP49 samples processed in the standard convection reflow oven in nitrogen environment using lead-free solder paste on ENIG test boards produced normal levels of solder voiding as shown in Figure 8.

The samples reflowed in this method consisted of a combination of joints with negligible voiding, multiple small voids, and joints with one or two large voids sometimes with small voids. The largest individual gaseous void was observed to be 18% of the solder joint area and the largest cumulative void size of a single solder joint was 18.1%.

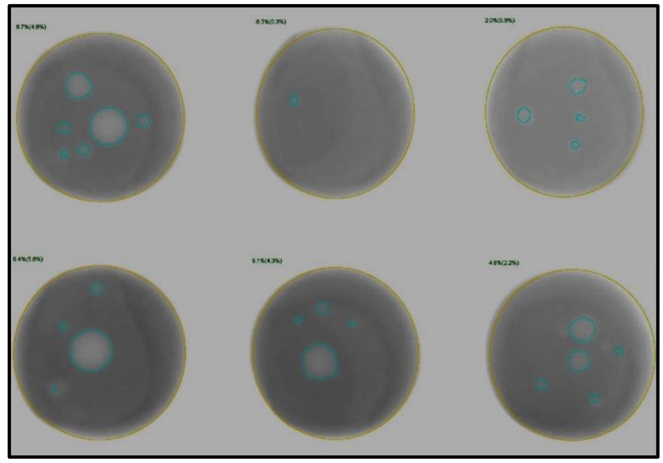

Figure 8. x-ray image of WLCSP49 solder joints assembled with convection oven at ambient atmosphere

The vacuum reflowed samples produced interesting results, with solder joint void size seeming to remain consistent irrespective of vacuum pressure between 1 to 120 Torr, as depicted in Figures 9 and 10. The x-ray images also show instances of solder joint bridges among samples assembled on vacuum reflow oven. Solder joint bridges lead to shorting defects and it is evident that vacuum process gives rise to these electrical defects. The largest cumulative void observed in a single solder joint was 25% and the largest individual void was measured at 21% of an x-ray area of solder joint among the vacuum reflowed samples, conforming to IPC-A-610G [14] which limits the voiding in a BGA joint to 30%.

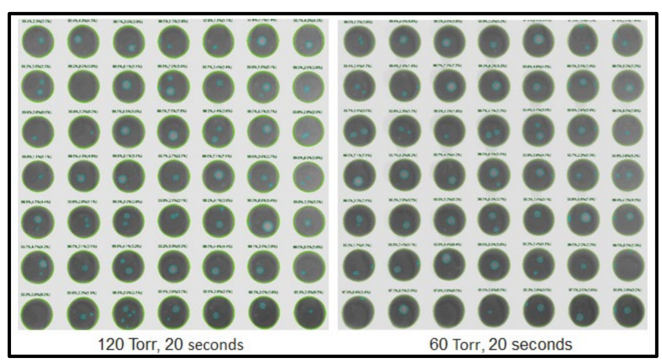

Figure 9. X-ray images of WLCSP49 assembled using in-line vacuum reflow oven with 120 Torr (left) and 60 Torr (right) for 20 seconds.

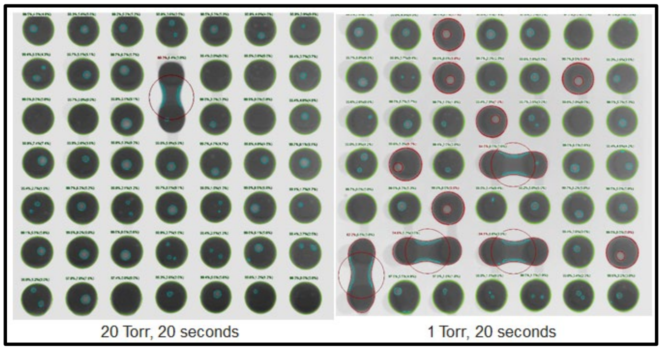

Figure 10. X-ray images of WLCSP49 assembled using in-line vacuum reflow oven with 20 Torr (left) and 1 Torr (right) for 20 seconds.

The distribution of individual void sizes, not the cumulative area%, is compared among different process conditions for WLCSP49 solder joints in Figure 11. The samples processed on a standard reflow oven have been indicated as 760 Torr, 0 seconds. The data show that the non-vacuumed assemblies have the highest number of voids, most of them measuring less than 5% of the total solder joint area. Furthermore, there is a modest decrease in total void quantity as the pressure is decreased from atmospheric pressure (760 Torr) to 1 Torr.

The declining number of small voids (1-5%) in Figure 11 with decrease in pressure is due to the fact that many of these voids coalesce into medium voids (6-10%), as is evident from the moderate growth in the number of 6-10% voids with decreasing pressure. Furthermore, the number of large voids (>10%), is relatively constant with decrease in pressure. It may be indicative of the fact that large voids still remain in the solder joints, possibly with existing large voids escaping the joints during the vacuum process and replaced by coalescence of smaller voids into larger ones.

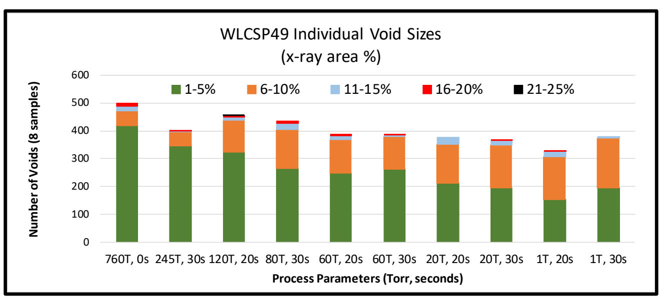

Figure 11. WLCSP49 Distribution of Individual Void Sizes. Solder joints that were bridged do not contain voids, thus the decrease in total voids as pressure decreases.

The cumulative voiding of WLCSP49 solder joints are analyzed at different process conditions and it is discernable from Figure 12 that vacuum processing had little effect on overall solder joint voiding.

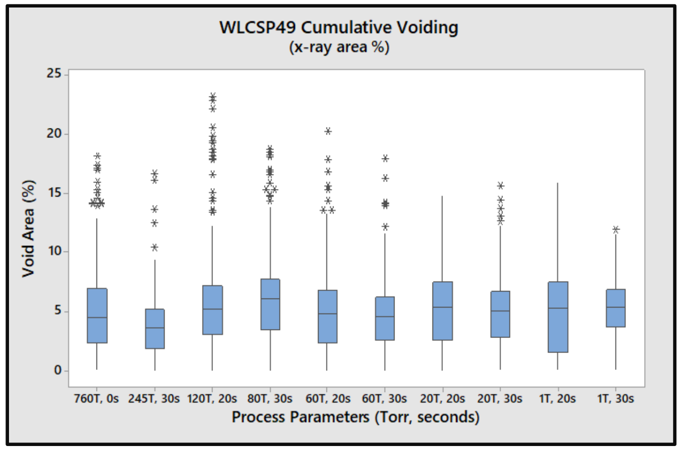

Figure 12. WLCSP49 Cumulative Voiding

The number of bridging across various process conditions is compiled in Figure 13. Although it appears that the data doesn't have a particular trend, it appears that occurrences of solder bridges generally increase with a decrease in pressure. These bridges are a result of inflation of solder joints to the point where adjacent solder joints come into physical contact with each other during vacuum reflow process. This can also be understood from Figure 10 in that solder joints that have shorted do not contain voids as they escape as a result of bridging. The effect of increased bridging defect occurrences also contributes to the decreasing number of voids with decreasing pressure as vacuum reflow process often generated solder joint bridges.

Although the vacuum reflow process appeared to be the cause for solder joint bridging in fine pitch WLCSP device-type, solder paste used in the assembly process was also found to be a contributing factor for this defect. When the samples were assembled at 20 Torr pressure with 20 seconds dwell time using a flux dipping, or flux printing process (no paste), the processed sample did not have a bridging defect apart from having relatively low voids, in terms of numbers and size, when compared to paste assembled samples.

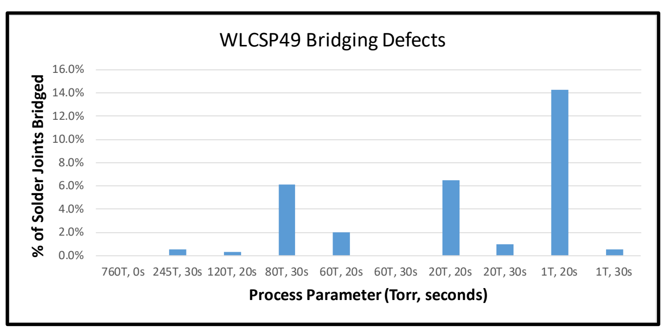

Figure 13. WLCSP49 Solder Bridge Occurrences

BENCH TOP OVEN EXPERIMENTAL DESIGN

While solder voiding in fine pitch bumped components does not show a strong dependency on vacuum parameters (see Figure 12), it appears that occurrences of solder bridges do increase with decreasing pressure (see Figure 13). In order to take a closer look at the void formation process, a bench top reflow oven with viewing port was used. This experimental apparatus was capable of achieving high vacuum with solder in the liquid state. Enlarged voids in the evacuated state could be "frozen-in" while still under vacuum. This was is not possible in a production in-line vacuum reflow oven where atmospheric pressure is always restored before solidification. The bench top solder samples could similarly be solidified with vacuum released, if needed.

Test Setup

The bench top viewing experiments explored the formation, growth dynamics, and evolution of voids in a vacuum or non-vacuum process. The major components of the test setup are shown in Figure 14. The bench top oven is constructed from an aluminum block with a glass viewport on top. The PID controller has the capability to ramp to the set temperature by auto-tuning. Alternately, the ramp rate could be manually defined. The oven chamber is connected to a flowmeter with an in-line regulator to regulate the air/ N_2 inflow and a vacuum pump connected to a pressure gauge. The vacuum pressure is modified using an in-line valve. The solder void viewing experiments were conducted in air or N_2 environments.

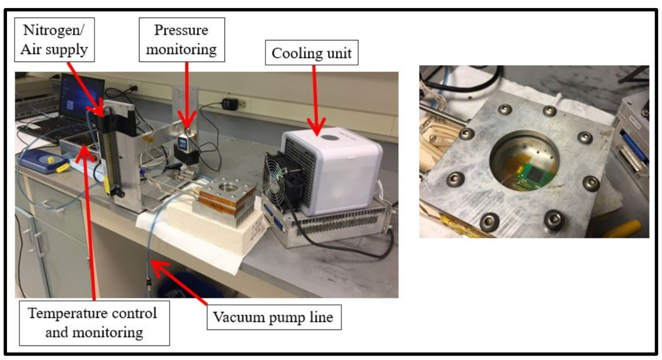

Figure 14. Experimental setup (left) and bench top oven with test sample visible in window (right). Thermocouples may be mounted to sample.

RESULTS

The process begins with printing solder paste on the component footprint of a PCB using a standard printing machine, then manually placing the component on the printed deposits before transferring to the sealed oven chamber. The sample can then be reflowed with the vacuum / temperature profile of interest. Samples run with the bench top vacuum process are reflowed and cooled under vacuum to solidify the solder with voids still in the enlarged state. In the non-vacuum process, samples are reflowed and solidified without vacuum, emulating a conventional ambient pressure reflow process.

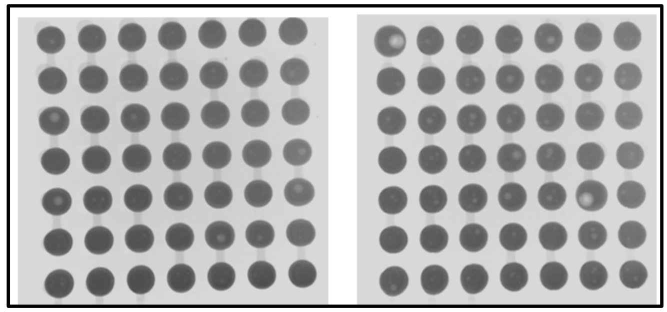

Figure 15. X-ray images of WLCSP49 assembled in the bench top oven without vacuum (left) and 300 to 350 Torr (right)

When the WLCSP test part is reflowed and solidified in 200 to 250 Torr range, the resultant voids are larger. Void sizes captured at this vacuum level are shown in Figure 16. At 50 Torr, captured voids are larger yet (compare Figures 15 vs. 16) with instances of balloon-like solder joints observed. Some of these voids might have escaped if vacuum was released before solidification. Similarly, it is possible that solder bridge formed at 50 Torr might have remained or solder joints might have retreated back to their original positions with the void released if atmospheric pressure was restored before solidification.

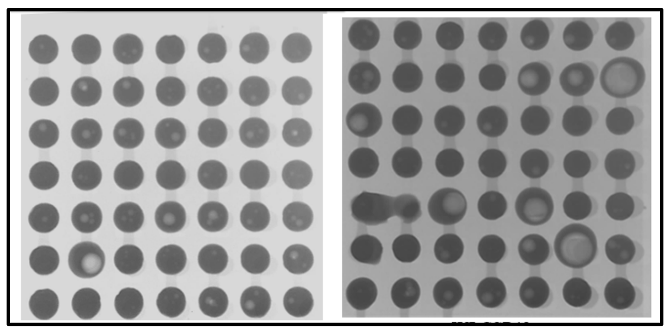

Figure 16. X-ray images of WLCSP49 assembled in the bench top oven at 200 to 250 Torr (left) and 50 Torr (right)

The fact that fine-pitch components may have larger voids and bridging defects in a vacuum reflow process has been established, now the question becomes how big can a void grow and how big a pitch is large enough to avoid bridging. The largest pitch available, 1.27 mm pitch part, was picked to investigate the voiding and bridging behavior and these samples were processed as repair/rework. No flux was involved in the rework process and the samples were reflowed in air environment. The samples were assembled in convection oven and then reflowed a second time in the bench top oven. In order to gain understanding of an already existing void (from first reflow), the samples were processed this way. The sample assembled in a convection reflow oven contains few voids but they are small enough not to be seen on the x-ray image shown on left side in Figure 17. When the same sample is processed again in the bench top oven between 60 and 70 Torr and frozen in place, the voids are clearly visible. They are large but not large enough to form a bridging defect and if vacuum were to be released before solidification, these voids might basically shrink down to nothing or simply get smaller due to gases that might escape.

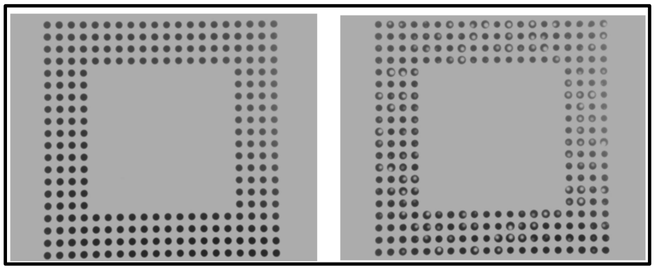

Figure 17. X-ray images of WLCSP49 assembled in ambient pressure convection oven (left) and bench top oven (right) at 60 to 70 Torr (Air).

Along the same lines, one more sample was reworked at 50 Torr and the voids were observed to be larger than the previous experiment (see Figure 18). The published diameter of the solder spheres used here in the assembly was 30 mil (0.76 mm). Therefore, a free floating solder ball would have a diameter of 0.76 mm. If there is no void, the value should be closer to that value, which is evident from a solder joint having a diameter of 0.72 mm without the presence of a void. There are also instances of few joints with diameters above 1 mm, having voids almost spanning the entire x-ray area of solder joint and the cross section confirms the huge void area. However, there was no solder bridging for this pitch at 50 Torr pressure.

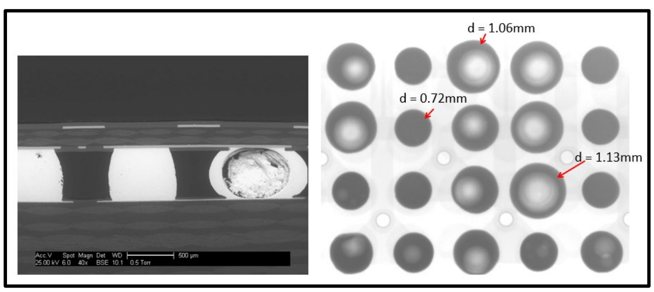

Figure 18. X-section and x-ray image of 1.27mm pitch PBGA256 Reworked and frozen @ 50 Torr

When the pressure was further decreased to 20 Torr, two adjacent joints bridged. The before and after reflow images are shown in Figure 19. Despite forming a solder bridge during the evacuated reflow process, it is possible that the bridge might separate if atmospheric pressure was restored before solidification, as would be the case in the production in-line vacuum reflow oven. Also, in the right image of Figure 19 (after vacuum rework), two adjacent solder joints almost bridge due to the huge size of voids, even at this pitch. It might be one of the instances where small voids coalesce into large voids and essentially do not leave the system. They have to grow large enough to reach the boundary of the solder joint to escape. If a void is located at the center, or even at the edge of a solder joint, there is a possibility that these voids don't grow big enough and don't move around. These voids don't go anywhere – they just grow under vacuum and shrink when restored to atmospheric pressure.

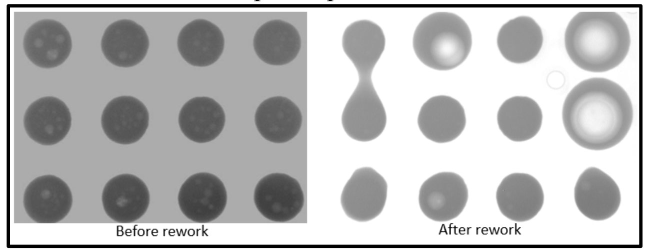

Figure 19. Cross-section and x-ray image of 1.27mm pitch PBGA256 Reworked and frozen @ 20 Torr

CONCLUSION

Gas voids may form in a molten metal without being initially present and, as the pressure is decreased, more and more nucleation sites become available and capable of generating and releasing gas bubbles. Solder joint voiding cannot be eliminated with vacuum reflow. Vacuum reflow process can also introduce defects in area array solder joints in the form of solder joint bridges. Small voids will be prevalent throughout the process. Few voids may coalesce into a large void and leave the system while others may remain entrapped in the joints. The voids grow in a vacuum reflow process but will shrink back when atmospheric pressure is restored. Vacuum reflow process had little effect on the cumulative voiding (2-dimensional projection) of WLCSP49 solder joints. The use of solder paste for BGA attachment increased the occurrence of solder joint bridges in a vacuum reflow process. Samples assembled using a flux-dipping process did not bridge, presumably because the flux-only assembly process did not generate voids.

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REFERENCES

[1] Richard Coyle, Dave Hillman, Michael Barnes, David Heller, Charmaine Johnson, Richard Popowich, Richard Parker, Keith Howell, Joerg Trodler and Adam Murling, "The Effect of Vacuum Reflow Processing on Solder Joint Voiding and Thermal Fatigue Reliability," Proceedings of SMTA International Conference, Rosemount, IL, 2016.

[2] Keith Sweatman, Takashi Nozu, and Tetsuro Nishimura "Optimizing Solder Paste for Void Minimization with Vacuum Reflow," *Proceedings of SMTAI 2012*, 903-910, Orlando, FL, October 2012.

[3] M. Barnes, D.W. Lee, D. Heller, M.Holtzer, T. Cucu, J. Fudala, J. Renda, Void Reduction in Bottom Terminated

Components Using Vacuum Assisted Reflow," *SMTnet*, July 2019.
[4] Weicheng Lin, "The Void-free Reflow Soldering of BGA with Vacuum," *8th International Conference on Electronic Packaging Technology*, pp. 1-5, Shanghai, 2007.
[5] P. Wild, D. Lorenz, T. Grözinger and A. Zimmermannd, "Effect of Voids on Thermo-Mechanical Reliability of Chip Resistor Solder Joints: Experiment, Modelling and Simulation," *Microelectronics Reliability*, pp. 163-175, Volume 85, June 2018.
[6] Siang Miang Yeo, Azman Mahmood and Shahrul Haizal Ishak, "Vacuum Reflow Process Characterization for Void-Less Soldering Process in Semiconductor Package," *IEEE 38th International Electronics Manufacturing Technology Conference*, pp. 1-7, Melaka, 2018.
[7] Mitsuharu Yamabe, "Effect of silver content and vacuum reflow soldering on thermal fatigue life of Sn-Ag-Cu solder," *International Conference on Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC)*, pp. 590-595, Kyoto, 2015.
[8] Ronald L. Panton, Jong W. Lee, Lakhi Goenka and Achyuta Achari, "Simulation of Void Growth in Molten Solder Bumps," *ASME. J. Electron. Packag 125(3)*, pp. 329-334, 2003.
[9] John Kizito, R. Balasubramaniam, Henry Nahra, Juan Agui, and Duc Truong, "Vapor-Gas Bubble Evolution and Growth in Extremely Viscous Fluids under Vacuum," *47th Aerospace Sciences Meeting and Exhibit*, Orlando, January 2009.
[10] Y. C. Chan, D. J. Xie and J. K. L. Lai, "Characteristics of porosity in solder pastes during infrared reflow soldering," *Journal of Materials Science*, pp. 5543-5550, 1995.
[11] Fred Dimock, "Operation of a Vacuum Reflow Oven with Preliminary Void Reduction Data," *Proceedings of SMTA International Conference*, Rosemount, IL, 2018.
[12] Michael Meilunas and Arvind Karthikeyan, "APD8A: Void Analysis of In-Line Vacuum Reflow," *Proceedings of AREA Consortium Meeting*, Binghamton, NY, October 2018.
[13] Michael Meilunas, "APD8A: Solder Voiding Behavior in Vacuum Reflow Soldering," *Proceedings of AREA Consortium Meeting*, Binghamton, NY, March 2019.
[14] IPC-A-610G, "*Acceptability of Electronics Assemblies*," IPC, October 2017.