Effect of Voiding on Solder Joint Shock and Thermal Cycle Reliability

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Abstract
Solder joint void has been considered a typical phenomenon in electronics assembly. Voids are caused by entrapped gases produced during flux volatilization during SMT, air entrapment in plated through holes and flux reaction with metal contaminates during the assembly reflow process. The factors affecting void formation are complex and subjective. It has been observed that BGAs with 2%Ag (62Sn36Pb2Ag) ball tend to create larger voids in reflow solder joints than eutectic (63Sn37Pb) ball. This study investigates the effect of different process conditions on void formation in the eutectic and 2%Ag solder joints and their effect on long term (2nd level) reliability.

A series of test vehicle PCBs were populated for 2nd level reliability testing using three different BGA packages (165PBGA, 144PBGA, and 1657 FCBGA). A DOE was designed using three factorials; 1) BGAs were acquired with eutectic balls and 2%Ag balls, 2) two reflow profiles were established, 245C peak volcano-type profile with 3C/sec ramp and long soak profile with 204C peak, 3) two package preconditioning, 60C/60%RH 10days and non-aged.

After SMT assembly test vehicles were x-ray inspected for void distribution and void size. X-ray results showed that large voids, greater than 35% of the solder joint diameter according to IPC-7095A for class 2, were observed in both eutectic and 2%Ag solder joints assembled using large solder paste volume and reflowed using fast ramp rate to 245C peak temperature. Approximately 60-250% higher distribution of voids was observed in 2%Ag ball packages than eutectic ball packages. It is believed that the lower melting of 2%Ag (179C) solder ball can reflow slightly before the eutectic (183C) solder paste, thus the solder ball collapses or encapsulates more solder paste/flux thus entrapping more gases within the bulk solder and consequently promoting void formation. The effect of voiding on solder joint shock and thermal reliability was investigated and discussed. It showed voids generated during board level assembly process do not degrade solder joint reliability.

Introduction

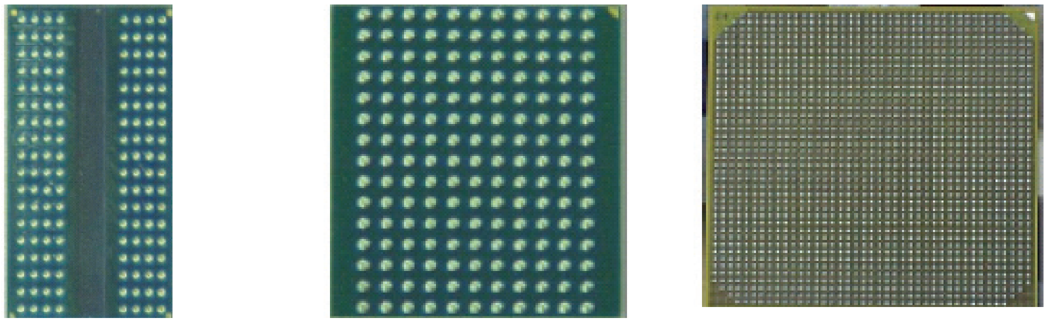
Voids within the BGA solder joints are inevitable. These voids are caused by entrapped gases produced from flux volatilization, air entrapment in plated through holes and flux reaction with the metal contaminants during the reflow process. Subsequent studies, internal to Cisco, showed that the 2%Ag ball has a tendency to increase voids occurrence in a BGA package assembled using Sn37Pb solder paste. These studies showed that the assembly process parameters can have significant impact in minimizing the voiding caused by volatiles but less control over voiding when using a 2%Ag BGA ball. In using 2% Ag solder balls the process engineer's ability to adjust or adapt the SMT process for all the packages became all the more challenging.

The reliability impact of these voids within the solder joints has been a topic of debate since the introduction of BGA components and X-ray inspection. D. R. Banks et al.[1] reported solder joint voiding caused no negative effect on PBGA board level reliability. Rather, solder joints voids improve reliability compared to joints without voids. However, M. Yunus et al.[2] reported voids that are greater than 50% of solder joint area cause potential reliability problems causing a 25-50% reduction in reliability. The effect of voids within the solder joint, more specifically at the pad interface, is likely to be a key consideration in determining the joint reliability. If there is an impact to reliability, then it becomes more important to understand if and to what extent the void within BGA solder joints impact 2nd level package reliability.

A study was initiated for better understanding of the influence of process parameters and alloy combinations that may cause significant voiding in the BGA packages and consequent failing of the IPC-7095A[3] void criteria. This study will evaluate the assembly process variables and alloy combinations that might trigger significant voiding, followed by a detailed solder joint reliability investigation. Any influence on thermal and electrical performance of a package due to voiding is not part of this study.

Test Components and Test Vehicles

Three different BGA packages were assembled on three different test vehicles, respectively. The test vehicles and the packages are daisy-chained for failure monitoring in reliability testing. The details and the ball array of the three different BGA packages used in this study are shown in Table 1 and Figure 1. The two smaller packages had both eutectic and 2% Ag balls, while the larger package had only 2%Ag balls. A test PCB of 0.093" thickness and coated with OSP as the surface finish was designed for each of the three component types. All the boards were 5.5" x 5.5" in size with eight copper layer stack up. Figure 2 shows the test vehicle for 165BGA package, and the 5 parts per board layout was used for the other two package types also. The outer 4 locations were assembled for ATC testing, while the center location was assembled for shock testing.



144 I/O BGA 165 I/O BGA 1657 I/O FCBGA

Figure 1 - Solder Ball Arrays in Three BGA Packages

Table 1 - Package Details

	144 I/O BGA	165 I/O BGA	1657 I/O FCBGA
Solder ball	Eutectic, 2%Ag	Eutectic, 2%Ag	2%Ag
Body size	10.5mm x 18.5mm	13mm x 15mm	42.5mm
Pitch	0.8mm x 1.0 mm	1.0 mm	1.0 mm
Substrate surface finish	Electrolytic Ni/Au	Electrolytic Ni/Au	ENIG (electroless Ni immersion gold)
Substrate pad size	NSMD 0.33mm	NSMD 0.4mm	SMD 0.55mm
Test board pad size	NSMD 0.38mm	NSMD 0.4mm	NSMD 0.5mm

Note: SMD: solder mask defined, NSMD: non-solder mask defined

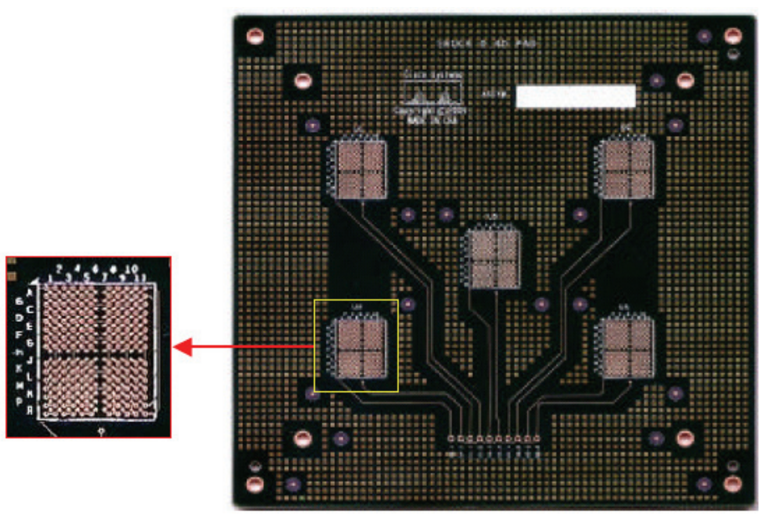


Figure 2 – Test Vehicle for 165 I/O BGA

Voiding and Assembly Process

To investigate the effect of different process parameters on bulk solder voids during assembly, an experiment was designed with two reflow profiles, two ball alloys, three packages and two preconditioning as shown in Table 2. Two reflow profiles, extreme and LSLP (Long soak and low peak) profile, were developed. The extreme profile uses a volcano type profile with 3C/sec ramp and 245C peak temperature while the LSLP (Long Soak and Low Peak) uses 90-120sec dwell at flux activation temperature and 204C peak temperature. The extreme profile was designed such that the fast ramp rates would entrap more volatiles and thus create significant voiding. The BGA packages were preconditioned at elevated temperature and humidity level of 60C/60%RH for 10days before assembly. This was added to ensure that sufficient voids are generated to meet our objectives. The solder paste stencils, laser cut and electro polished, used for the assembly were 6 mils thick. The assembled boards were inspected using 3D x-ray to observe the presence of voiding within the package and its size. This would enable us to inspect against the IPC-7095A void specifications and void effects on the joint reliability.

Table 2 - Experimental Design and Number of Test Packages Populated

Solder ball	Eutectic				2%Ag			
Reflow profile	LSLP		Extreme		LSLP		Extreme	
Preconditioning	Precon	No precon	Precon	No precon	Precon	No precon	Precon	No precon
144BGA	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs
165BGA	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs	23 pkgs
1657BGA	NA				24 pkgs	24 pkgs	24 pkgs	24 pkgs

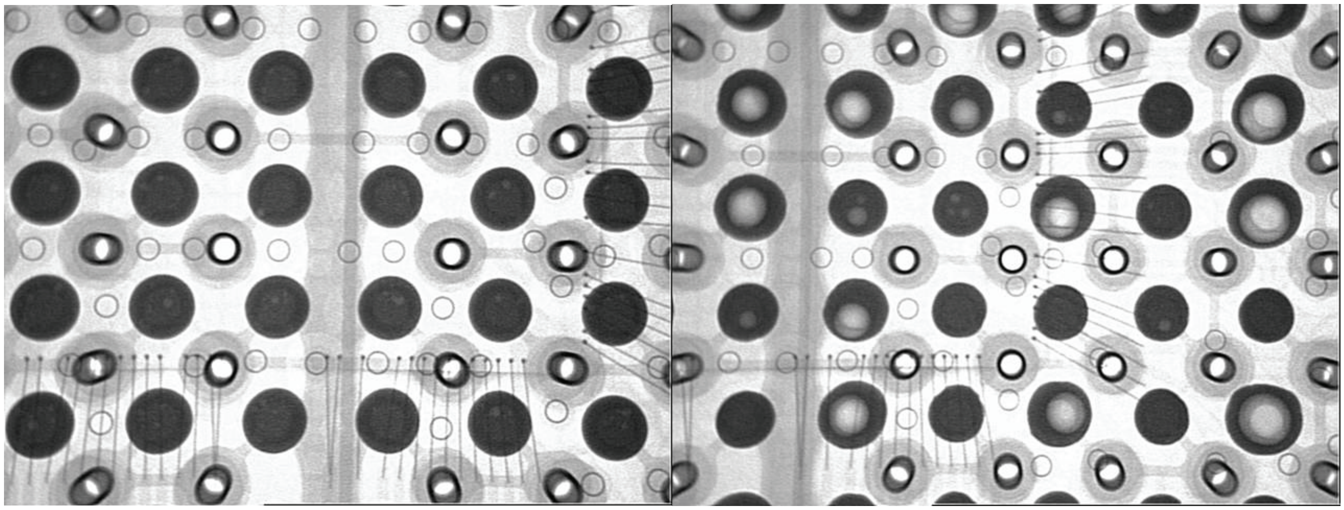
Post Assembly Void Results

The board assemblies were x-ray inspected to determine the void size and its occurrence within the solder joints. Every joint was measured for void diameter using x-ray. The number of joints with voids >35% of the joint diameter was counted and % joints per package calculated per IPC-7095A for class 2 in Table 3. Table 3 shows %joints with void diameter > 35% of joint diameter per IPC-7095A for class 2.

Table 3 - Joints Per Package with Void Diameter Greater than 35% of Point Diameter

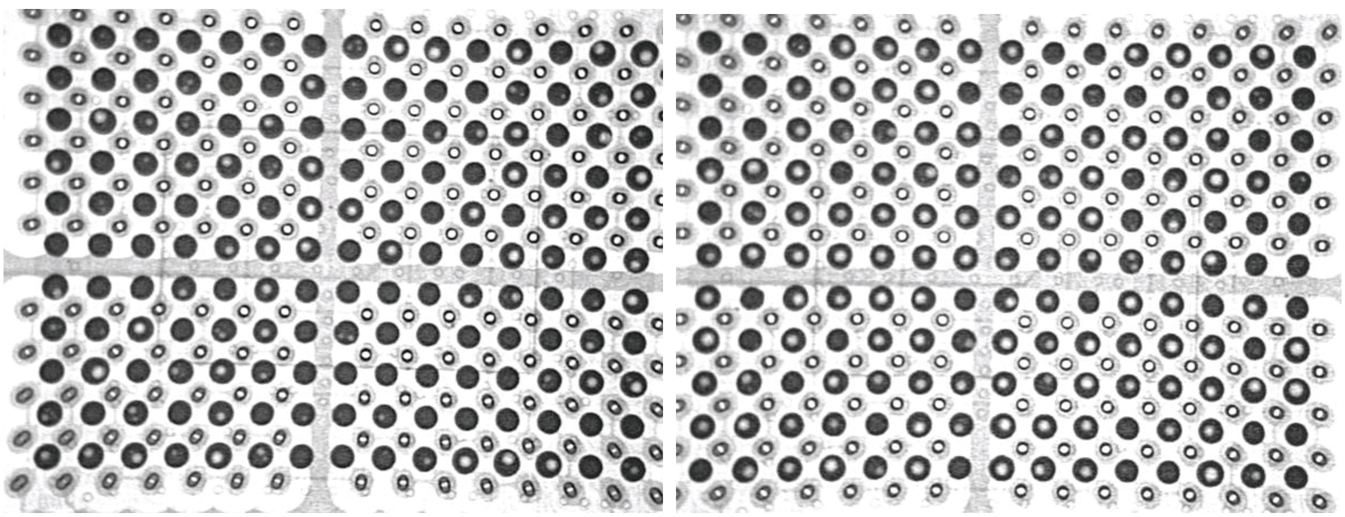
Solder ball	Eutectic				2%Ag			
Reflow profile	LSLP		Extreme		LSLP		Extreme	
Preconditioning	Precon	No precon	Precon	No precon	Precon	No precon	Precon	No precon
%Void joints 144BGA	0	0	8	30	0	0	31	48
%Void joints 165BGA	0	0	25	23	0	0	39	55
%Void joints 1657BGA	NA				0	0	7	2

Reflow profile is a primary factor affecting void size. Figure 3 shows the effect of reflow profile on void formation. The extreme profile generates large voids, up to 60% of joint diameter, in eutectic solder joints of 165 I/O BGA, while LSLP profile does not create such large voids with the same paste volume and precondition. There were no voids greater than 35% of the joint diameter in 144 I/O BGAs and 165 I/O BGAs assembled using LSLP reflow profile. Also, x-ray showed that the 2%Ag balls have more (60~250%) voids than the eutectic ones. Figure 4 shows the void distribution difference in the 165 I/O BGA between eutectic and 2% Ag solder joints. It is believed that 2%Ag solder ball starts reflowing earlier than eutectic solder ball due to lower melting temp (179C vs. 183C), entrapping more outgassing flux and consequently causing more voids than the eutectic ball. Also, a larger number of voids was observed in 144 I/O BGA and 165 I/O BGA than 1657 I/O FCBGA. It was found that the preconditioning increases the void occurrence as shown in Figure 5, but the effect is not as significant as reflow profile and ball metallurgy. Since the %joints in 144 I/O BGA and 165 I/O BGA reflowed using extreme profile is greater than 8%, these components will require corrective action to reduce the number of voids per IPC-7095A for class 2.



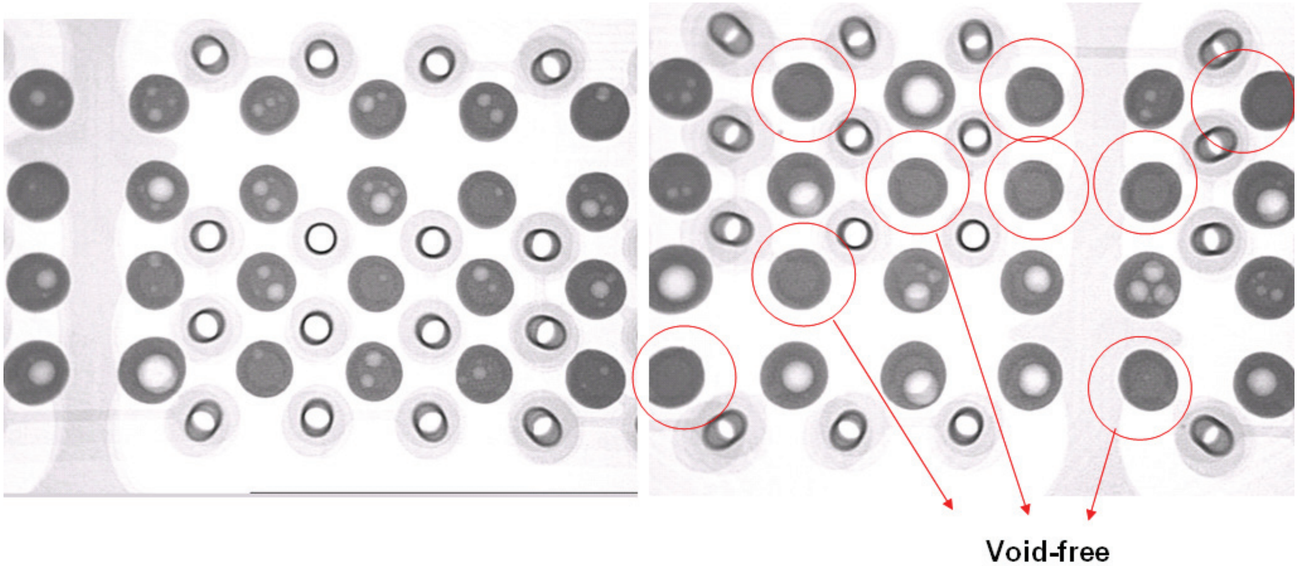
(a) (b)

Figure 3 - X-Ray Pictures of Voids in Eutectic Solder Joints of Non-Preconditioned 165 I/O BGA (a) Reflowed Using Long Soak and Low Peak Profile (b) Reflowed Using Extreme Profile



(a) (b)

Figure 4 - X-ray Pictures of Voids Distributed in non-Preconditioned 165 I/O BGA Reflowed Using Extreme Profile (a) Eutectic Solder Joints (b) 2%Ag Solder Joints



(a) (b)

Figure 5 - X-ray Pictures of Voids Distributed in Eutectic Solder Joints in 144 I/O BGA Reflowed Using Extreme Profile
(a) Preconditioned (b) Not preconditioned

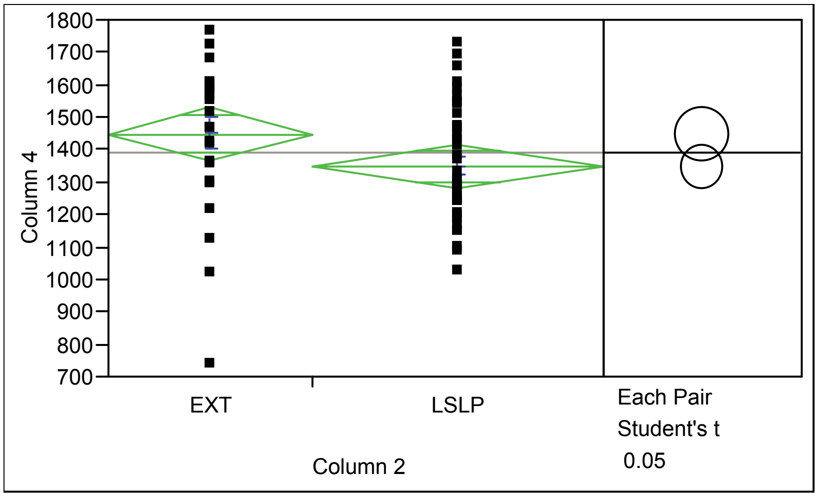
Reliability Summary
The reliability study involves ATC and Mechanical shock testing to ascertain the extent of acceptable void size and occurrence in the BGA joints. 32 test vehicles each were built for the 144 I/O BGA with eutectic and 2%Ag ball. Similarly, 32 test vehicles were built for 165 I/O BGA. However, the 1657 I/O FCBGAs were assembled using 2%Ag ball on 40 test vehicles, and the eutectic balls were not part of the study for this package.

ATC Test Results
Accelerated thermal cycling test was run with 0-100C, 30min cycle (5min dwell, 10min ramp) per IPC-9701 and the results are shown in Table 4. 100% failures were observed in 144 I/O BGA during 3500 cycles, but only a few failures were observed in the 165 I/O BGAs and the 1657 I/O FCBGAs.

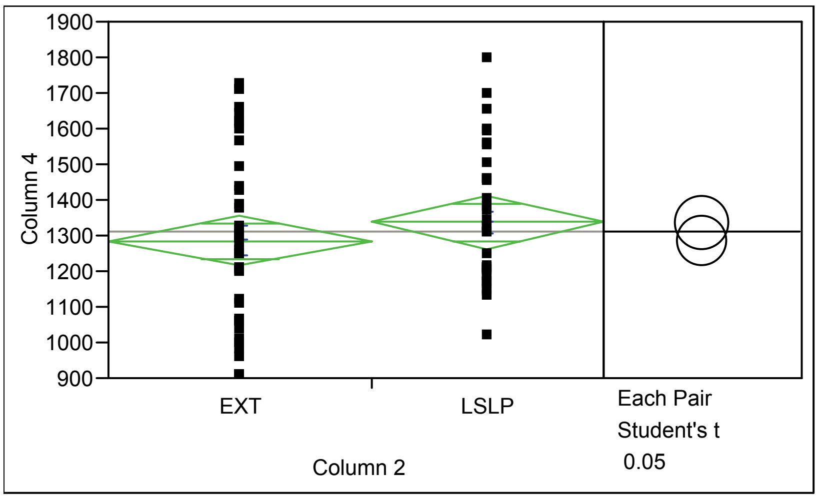
Table 4 - Characteristic Failure Cycles at 0-100C 30min Profile

Solder ball	Eutectic				2%Ag			
Reflow profile	LSLP		Extreme		LSLP		Extreme	
Preconditioning	Precon	No precon	Precon	No precon	Precon	No precon	Precon	No precon
144 I/O BGA	1443 β=8.8	1406 β=7.3	1520 β=6.9	1233 β=6.7	1374 β=7.7	1475 β=9.6	1452 β=5	1637 β=11.5
165 I/O BGA	Only few failures occurred, and thermal cycling stopped at 3500cycles							
1657 I/O FCBGA	NA				Only few failures occurred, and thermal cycling stopped at 3500cycles			

The Student t test[4, 5] was run to compare the failure cycles of void-containing solder joints in 144 I/O BGA with the void-free solder joints, as shown in Figure 6. The results showed their failure cycles in eutectic and 2%Ag solder joints are not significantly different each other. Therefore, the voids neither worsened nor improved the 2nd level reliability of 144 I/O BGA.



(a)



(b)

Figure 6 - Student t-Test Results of Failure Cycles of 144BGA
(a) Eutectic Solder Joints (b) 2%Ag Solder Joints

Shock test Results

Along with thermal fatigue study, mechanical shock test was run to study the effect of void on solder joint. As mentioned earlier, the same test vehicles with only one component site populated in the middle of test vehicle, were dropped 6 times at 340G using 1.7ms half sine wave impulse. A summary of the shock test results is shown in Table 5, and the maximum principal strains observed are shown in Figure 7.

Table 5 - Shock Test Results

Solder ball	Eutectic				2%Ag			
Reflow profile	LSLP		Extreme		LSLP		Extreme	
Preconditioning	Precon	No precon	Precon	No precon	Precon	No precon	Precon	No precon
144 I/O BGA	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail
165 I/O BGA	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail	340g x6 No fail
1657 I/O FCBGA	NA				NA	Failed at 385g	Failed at 341g	NA

There were no failures for the 144 and 165 I/O BGAs but some failures were observed for the 1657 I/O FCBGAs, which was caused by brittle failure due to Electroless Nickel Immersion Gold (ENIG) finish[6] rather than the voiding. The test results show no degradation of shock reliability of solder joints due to bulk solder voids. As one would expect, it was observed that higher strain was measured for packages with larger body size under same acceleration g level as shown in Figure 7.

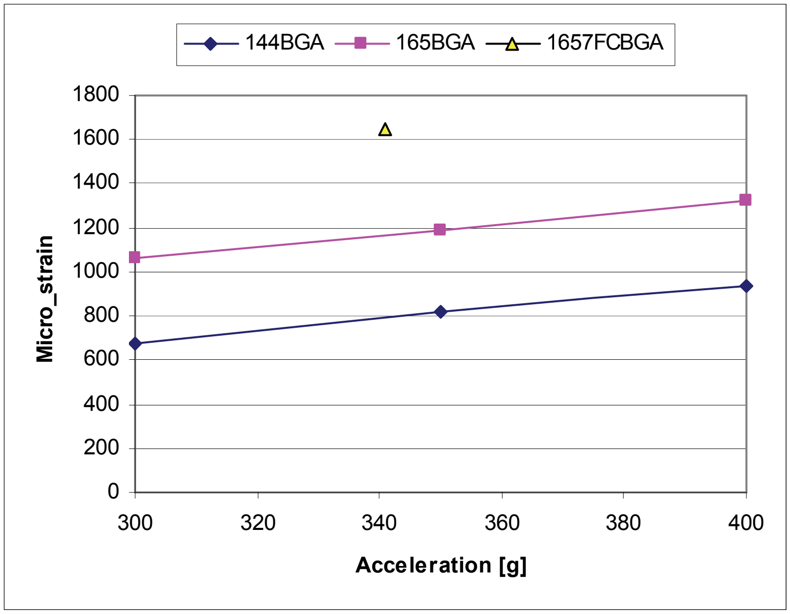


Figure 7 - Max. Principle Strain Measured During Shock Test

Discussion

Effect of paste volume on voiding

As found in this study, reflow and soaking stages during SMT assembly in Figure 8 affect voiding in solder joints significantly. Short soaking entraps gas from flux activation, and the high reflow temperature makes the entrapped voids larger. However, the contribution of reflow profile to solder joint voiding should be understood along with solder paste volume, since solder paste provides a potential void source when it becomes gaseous. In this study, the smaller void size was observed when smaller paste volume was used as shown in Figure 9.

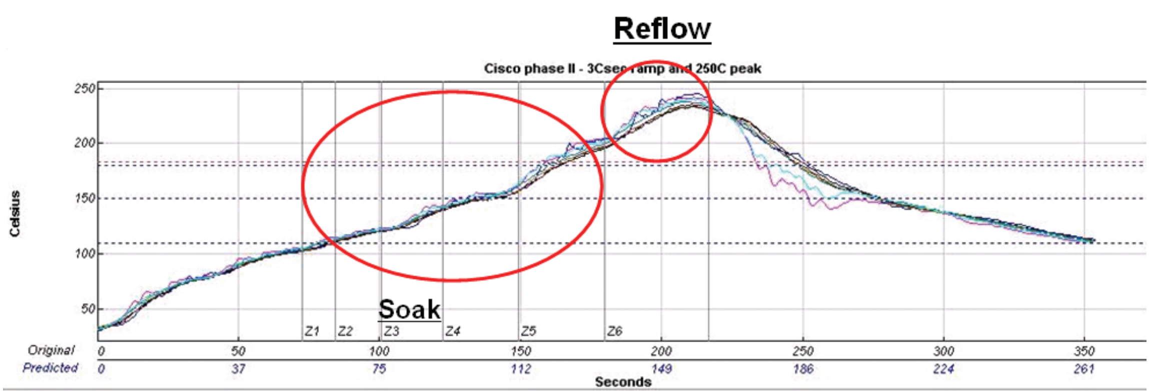
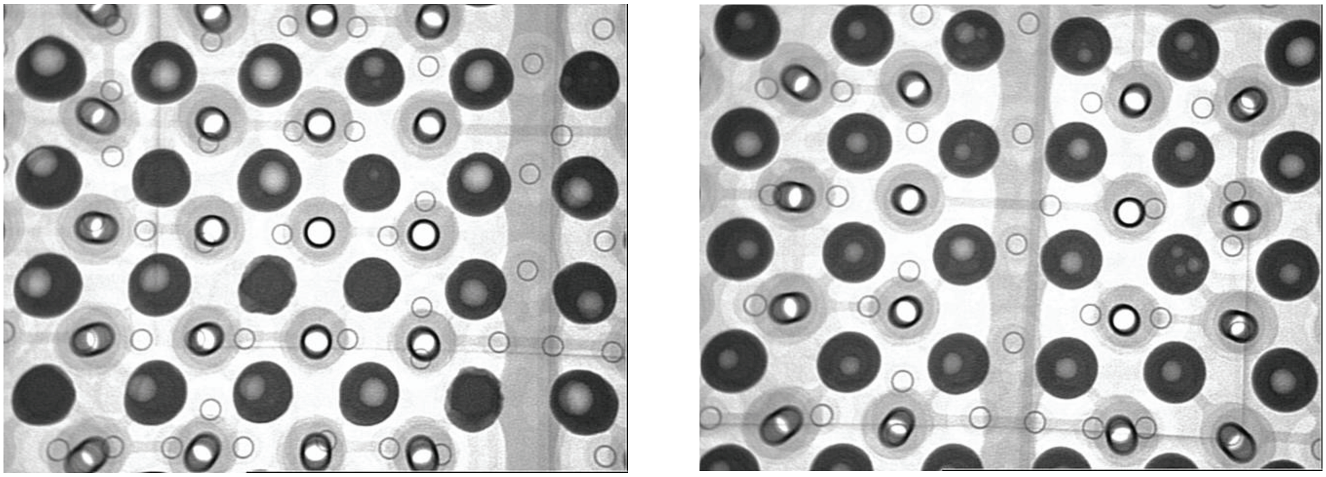


Figure 8 - Extreme Reflow Profile with 3C/sec ramp and 250C Peak



(a) (b)

Figure 9 - Voids Distributed in 2%Ag Solder Joints in Non-Preconditioned 144 I/O BGA Assembled at Extreme Profile
(a) 6mils thick stencil used (b) 4mils thick stencil used

Effect of void on solder joint reliability and package reliability

It is commonly accepted that crack propagates along the package interface due to shear strain imposed at the joint interface. Similar crack propagation was observed in the void-free solder joints of 144 I/O BGA as in Figure 10. However, the direction of cracks and the path within the solder joint was observed to change when a solder joint has a large bulk solder void as in Figure 11. It was observed the void did not increase the solder joint standoff height, rather it created a wider joint.

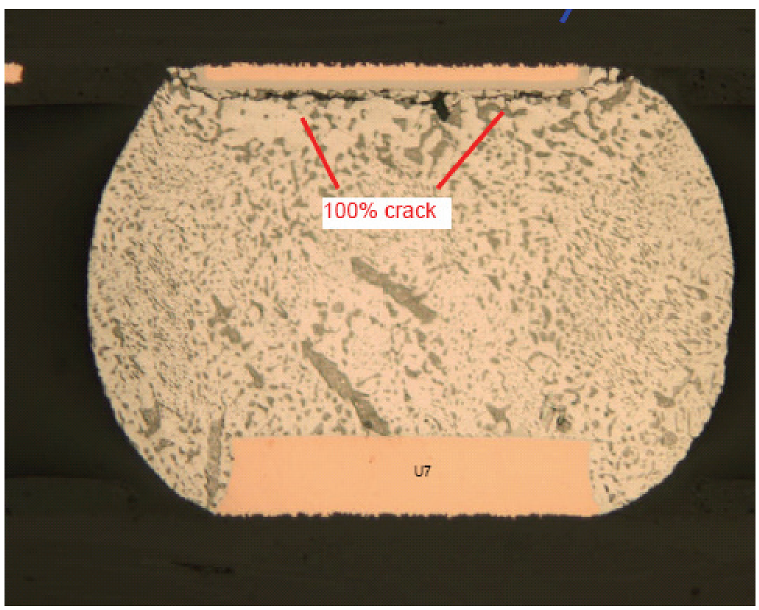


Figure 10 - Crack Propagation in a Void-free 2%Ag Solder Joint in 144BGA Assembled at LSLP Profile

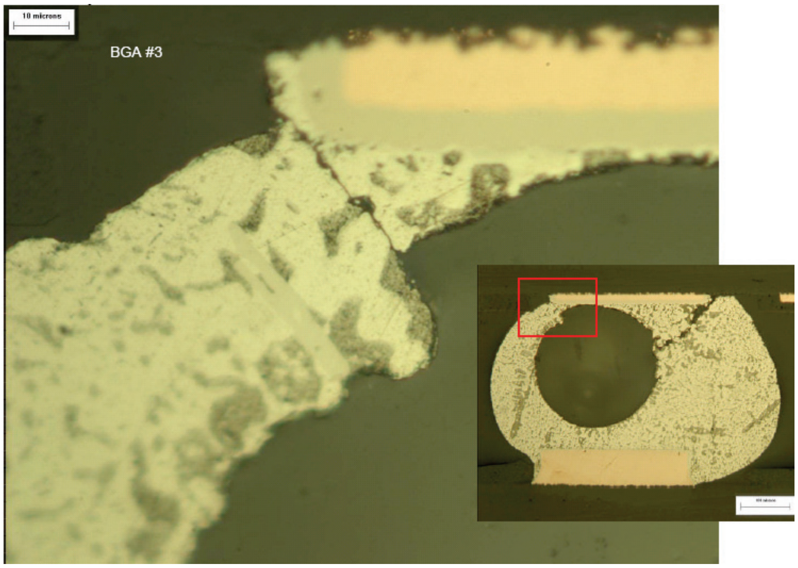


Figure 11 - Crack Propagation in a Large Void-Containing 2%Ag Solder Joint in a 144 I/O BGA Assembled with the Extreme Profile

Fracture mechanics[7] defines the reliability of a solder joint as a function of energy release rate and crack path. In other words, the reliability of a solder joint with voids is expected to be different from a solder joint without voids. However, on the contrary, this study showed that the voids did not affect the package reliability. It is believed that themo-mechanical loads in these BGA packages are shared by both void-containing solder joints and the neighboring void-free joints, hence voids did not impact the overall package reliability. As shown in Figure 12, not every solder joint within package has a void. Half of joints in a row have voids, while the other half does not have voids.

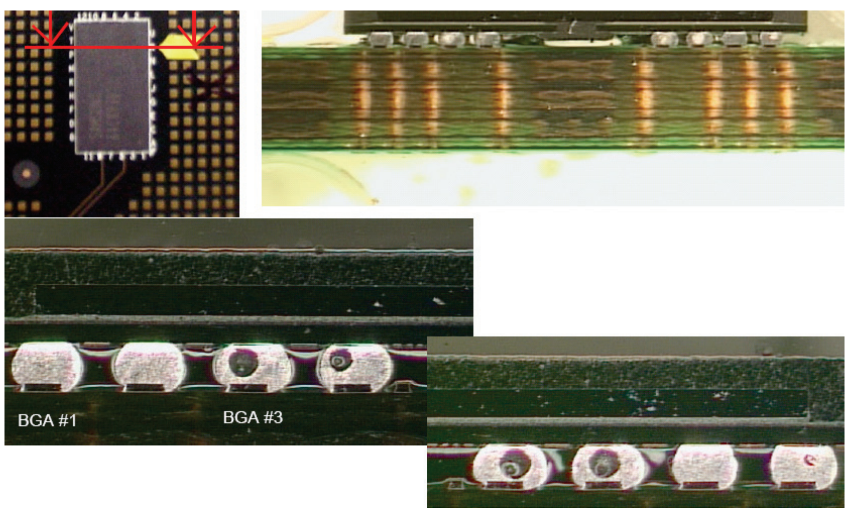


Figure 12 - Void Distribution in 2%Ag Solder Joints in Preconditioned 144 I/O BGA Assembled with the Extreme Profile

Conclusions

This study identified the key factors that affect void formation and observed different voiding behavior between 2%Ag and eutectic ball. Also, the solder joint reliability was evaluated through thermal cycling test and mechanical shock test. The summary of major findings in this study is as follows.

Reflow profile is a primary factor affecting void size. However, it becomes a even more important factor when a larger paste volume is used. The 2%Ag ball packages have up to 250% more voids than eutectic ball packages under the same assembly profiles. Voids are located at the substrate package interface. 144 I/O BGA and 165 I/O BGAs are more susceptible to void formation than the 1657 I/O FCBGA. This is believed to be due to the smaller package bodies. ATC test showed failure cycles of void-containing joints are not significantly different from void-free joints. Shock testing showed no solder joint failures caused by voids. Only failures were observed in 1657 I/O FCBGAs, but they are brittle-fracture failures due to the ENIG finish. For BGAs that have ~50% of their solder joints with void diameters of 35-60% of the joint diameter, voids do not degrade/improve board-level shock and thermo-mechanical package reliability.

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