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WEIGHT LIMITS FOR DOUBLE SIDED REFLOW OF QFNS

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ABSTRACT
QFNs of two different sizes with different weights attached to them were used to determine the maximum potential weight of a QFN that could be held on a printed circuit board by SAC305 solder surface tension alone when the board was upside down in a reflow oven. Different pad geometries were used and the effect of voiding was also taken into consideration.

INTRODUCTION
Phil Zarrow of ITM has popularized an equation for determining the safe weight of a component that can be held upside down on a printed circuit board (PCB) by the surface tension of molten eutectic tin/lead solder during reflow[1].

$$\frac{\text{Weight of the component (grams)}}{\text{Sum of the area of all solder joints (square inches)}} < 30$$

However, to one of the authors this always seemed very conservative and the use of mixed units (English and metric) was not preferred. And although it is a workable empirical relationship, it is not grounded in the physics of the phenomena. The parts are held on by the surface tension of the molten solder. Solder wetting force (F) is equal to the solder's surface tension (γ) times the perimeter of the wetted surface (P) times the cosine of wetting angle (θ) minus a buoyancy correction consisting of the gravitational constant (g) times the volume of solder displaced (v) times the molten solder density (ρ). Since the situation being addressed is not dealing with immersion of a sample into solder, there is no buoyancy correction, so the equation:

$F = \gamma*P*\cos\theta - g*\rho*v$ simplifies to $F = \gamma*P*\cos\theta$.

The same solder is used throughout this study and assuming the wetting angle is constant, the only variable of concern is the wetting perimeter.

The problem with using wetted area instead of wetting perimeter can be seen in Figure 1. The two terms do not parallel track. As a function of the number of solder balls on a BGA, for instance, the difference becomes greater with the increasing number of solder balls. So even though the Zarrow equation has worked for many of the smaller BGAs, it might not for the even larger BGAs that are becoming more common, or at least the equation would produce a greater difference between what is required and what is actually required.

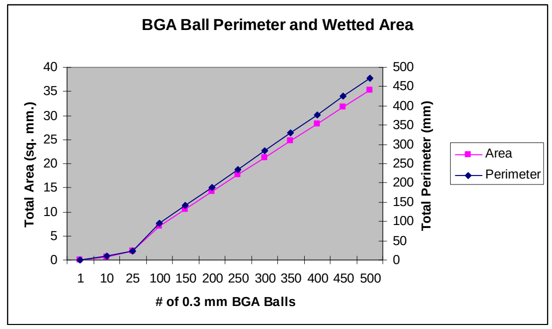

Figure 1 Difference between Wetted Area and Wetting Perimeter as a Function of the Number of BGA Balls

While working at Nortel one of the authors developed an alternative equation after examining the results of many hundreds of wetting balance tests for many different types of components – chip caps, resistors, PQFPs, J leaded devices, TSOPs, SOICs, SOTs and others. To test the equation twenty-four BGAs soldered to one side of a PCB had differing numbers of small aluminum plates glued to them. The board was then turned upside down and ran through the reflow oven using a typical reflow profile for the eutectic solder joints of the BGAs. The equation was used to correctly predict which BGAs would stay on the board while being reflowed upside. The validity of the equation was confirmed. This equation was then successfully used for all double sided reflow boards in that Nortel plant. Unfortunately that equation has been lost.

Dr. Ning-Cheng Lee of Indium has provided the surface tensions of four of the more common tin-based solder, as well as a worked example where he used the wetted perimeter and not surface area.[2] He considers a "buffer" of the total wetting force twice the size of the component weight to provide insurance for such engineering problems as:

1) vibration in the reflow oven conveyor belt
2) peel effect on the molten solder joints because of the conveyor belt, board or component not being level

The surface tension values provided by Dr. Lee are listed in Table 1.

Table 1 Surface tension of molten tin-based solders

Solder	Surface Tension
SAC305	567 dynes/cm (0.567 N/m)
SAC 387	560 dynes/cm (0.560 N/m)
Sn63	400 dynes/cm (0.400 N/m)
Sn62	376 dynes/cm (0.376 N/m)

Although the current QFNs and LGAs are reasonably small, at least in the mobile telecommunication portion of the electronics industry, it is expected, as more power is needed, parts are therefore going to be running hotter and hotter and soon there will be copper slugs in them as there have been in many BGAs used in computers. This study is partial preparation for that evolution.

Most of the published work using the Zarrow equation was for eutectic tin/lead solder, rather than SAC305, the current "standard" lead-free solder formulation. Conceivably all that has to be done with the current equation is multiply by the ratio of the surface tension of the eutectic tin/lead solder and that of SAC305, but experimental data is always better.

In 2005 Liu et al[3] examined double sided reflow for lead free solder. Again using wetted area instead of perimeter, they found little difference between tin/lead and lead free solder results. Atmosphere (air or nitrogen) made little difference and neither did solder paste type (no-clean or water soluble). What did make a difference was stencil thickness and board pad finish. The latter two result in more solder spread and therefore more perimeter which of course affects the total surface tension forces.

MATERIALS

The PCBs used for testing were halogen-free QFN test boards with a high temperature organic solderability preservative (OSP) finish. SAC305 no-clean solder paste was applied to the PCBs using a 100 µm thick stencil. Figure 2 shows a PCB with only some of the sites populated with QFNs. Note that the board was designed to be used with either QFNs and/or PQFPs.

For the actual study only rows 3 and 5 were populated. Components used are shown schematically in Figures 3 and 4. These QFNs were used for this project because they were readily available and applicable to a current manufacturing process at RIM. QFN 1 has a center pad that is palladium and an outside square of 14 signal pins on each of the four sides of the bottom of the square component. QFN 2 is much smaller. QFN 2 has a center ground pad of matt tin and an outside square of 4 signal pins on each of the four sides of the bottom of the square component.

While the pad design on the bottom of the components remained constant throughout the project, there were four different SMT pad designs on the test board that were used for mounting the QFNs. These are shown in Figure 5.

The total possible surface perimeter for each mounting site depended on which pad design was present – 1 pad, 4 pads, 3x3 or 4x4. Note that the number of signal pads changes too. The total perimeter for each design was calculated using Image J software.[4]

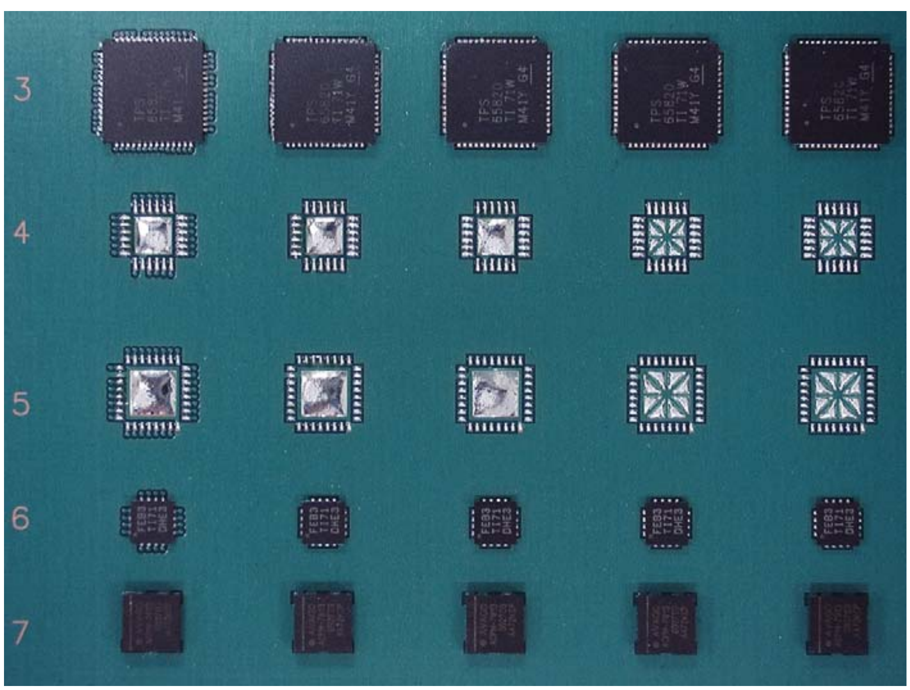

Figure 2 Portion of the QFN Test Board

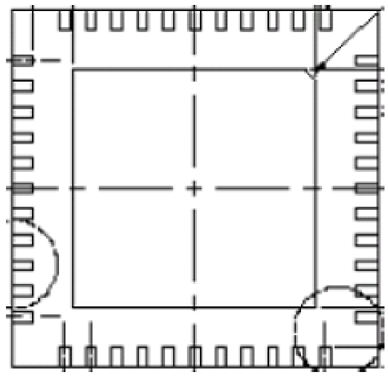

Figure 3 QFN 1

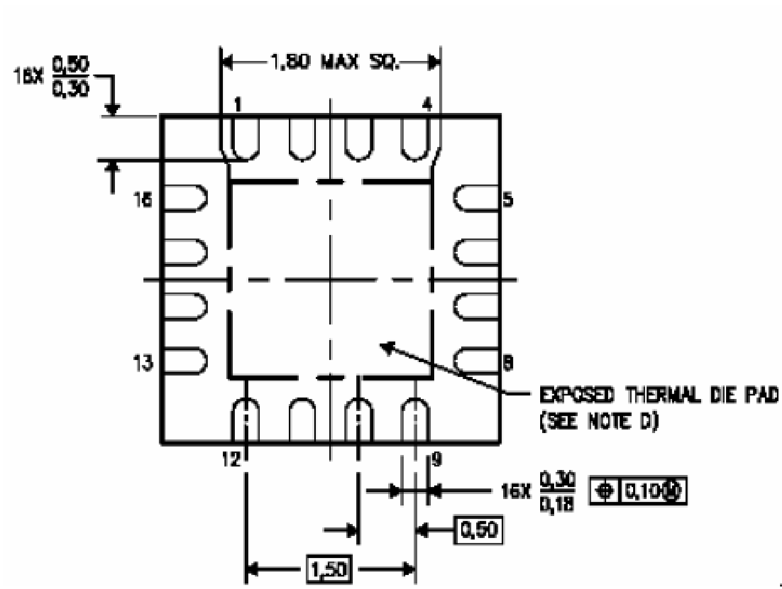

Figure 4 QFN 2

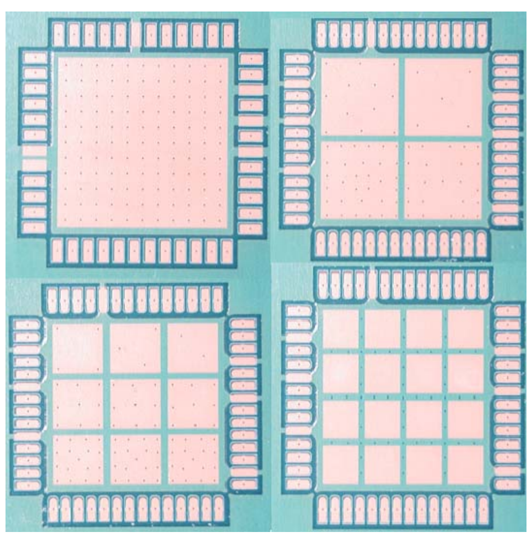

Figure 5 The Four Different PCB SMT Pad Designs

METHOD

The question then becomes: what to use as the total wetting perimeter – the sum of the perimeter of the pads on the component or that of the board pads? Initially, whichever was the smallest perimeter was used. However, after x-ray analysis, it was observed that there was significant voiding in most of the test board solder joints, as shown in Figure 6.

In order to account for the effect of voids on total wetting perimeter, void analysis was performed on all QFN test boards after the QFNs were soldered to the boards and prior to the actual testing of surface tension effects. A Fein Focus Fox-160.25 x-ray system in conjunction with the Image J software was used to collect x-ray images and then determine the perimeter of the internal voids in the solder joints.

In order to vary the component weight versus total wetted surface perimeter, the addition of weights was applied to the top surface of the QFNs. The majority of the weights were composed of tungsten carbide, due to the high density of this material and the weights were attached to the components using Loctite chip bonder adhesive. The glue was cured at 170°C for approximately ten minutes to ensure adequate adhesion.

All boards were equipped with type k thermocouples for temperature profiling by drilling into the secondary side of the PCB and inserting the thermocouple in a solder joint. Thermal tape held each thermocouple in place on the PCB. These thermocouples were connected to a Super M.O.L.E. Gold data manager system to record the reflow profiles. An additional thermocouple was added to each board to profile the ambient temperature in the reflow oven.

The reflow profile type used for this project was a straight ramp profile. The reflow profile was prepared based upon a current manufacturing process using a Vitronics Soltec XPM3 forced convection reflow oven with eight heating zones heat and two cooling zones. Figure 7 is the reflow profile developed for the QFN test boards. Peak temperature was 244°C, definitely above the melting point of SAC305 solder.

The work was started with a reflow profile completed using the Vitronics Soltec XPM3 forced convection reflow oven, all further reflow work was done using an Advanced Technologies US Inc. PRO 1600 forced convection reflow oven. This oven was not equipped with a conveyor belt to move the PCB into the various heating and cooling zones, but is a batch reflow oven. Parameters such as ramp rate were adjusted accordingly to mimic the typical reflow profile of the multi-zone conveyorized oven. Figure 8 shows a time temperature profile for a PCB using the Pro 1600 forced convection reflow oven.

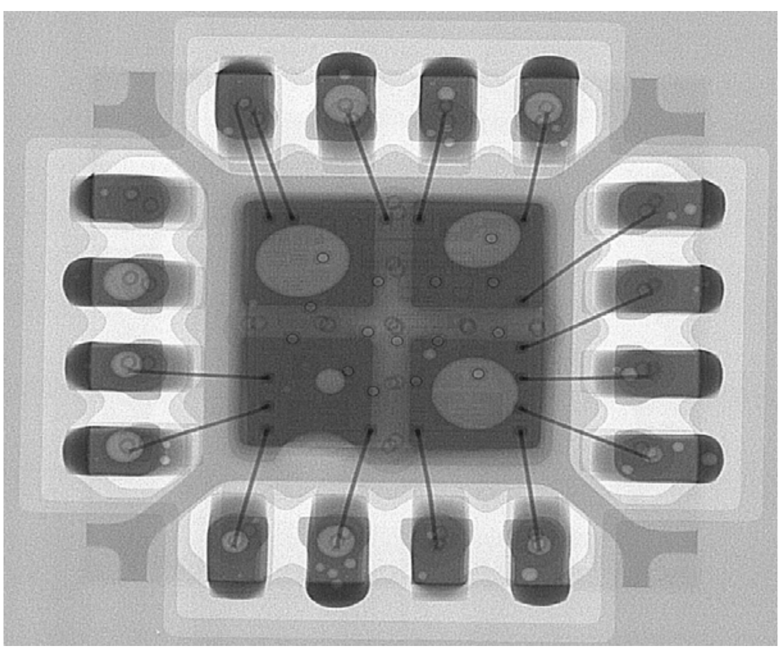

Figure 6 X-Ray Image of PCB Test Board with QFN2 Attached

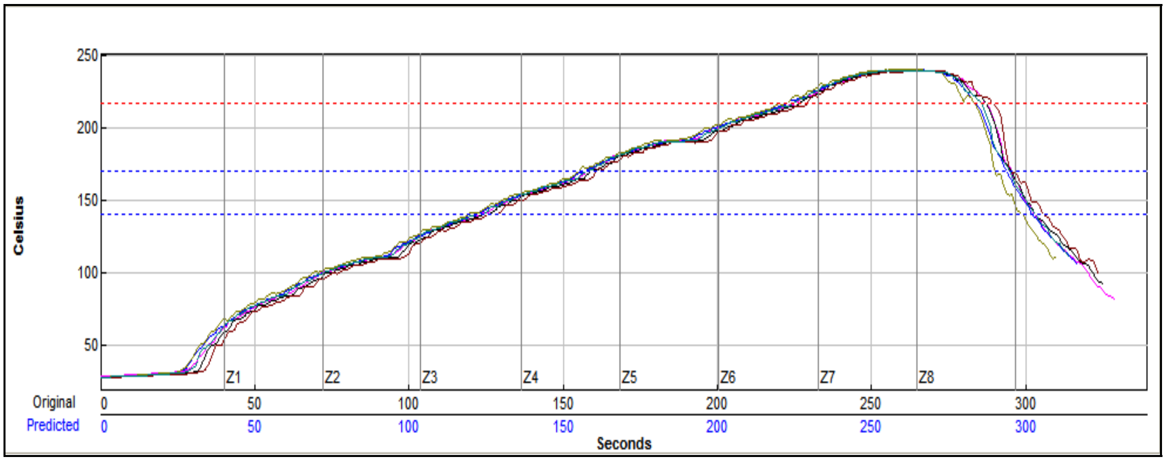

Figure 7 Time Temperature Profile for the QFN Test Board Soldered with SAC305 developed using a Vitronics Soltec XPM3 Forced Convection Reflow Oven

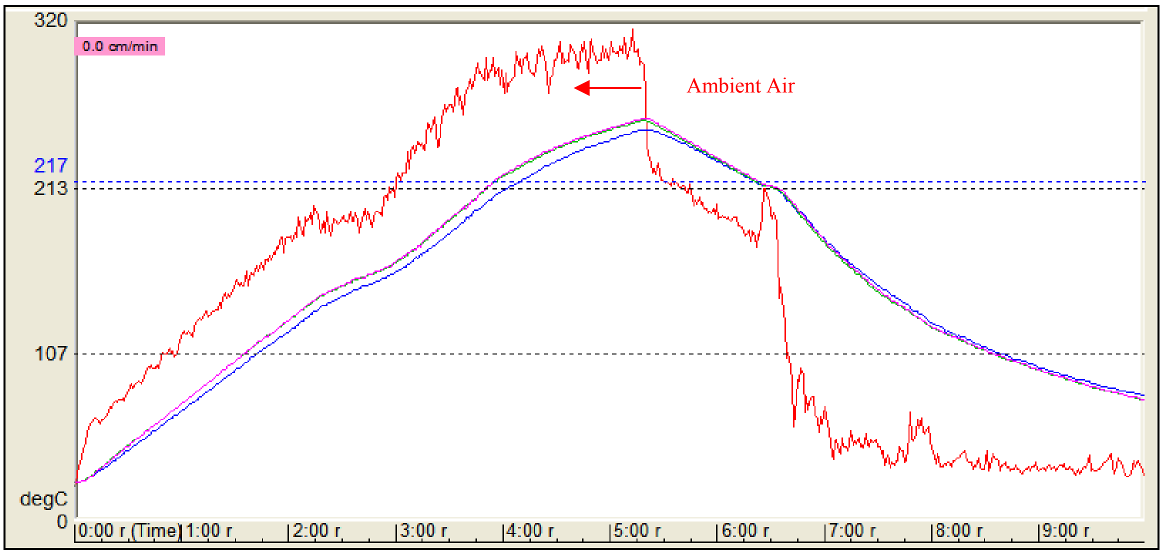

Figure 8 Reflow Profile for the Test Board in the Pro 1600 Forced Convection Reflow Oven

It is apparent from the x-axis in Figure 8 that the time required to reach the peak temperature was much greater when the Pro 1600 forced convection reflow oven was used. This oven required a slower ramp rate in order to maintain a linear profile, thus the time required to reach the peak temperature was longer. The ambient air time temperature inside the oven is very "noisy" and this is attributed to the high level of turbulence caused by the fans used for forced convection. Each test ran for approximately ten minutes, including the cooling zone.

All QFN test boards were mounted to an elevated stand to make sure the oven rack did not interfere with any components that might fall off a board during the reflow tests. Figure 9 shows the elevated stand used during testing. Each QFN test board was only used a maximum of three times. This was done to avoid board blistering or warping that may have altered the co-planarity of the board pads or introducing other unknown problems.

RESULTS AND DISCUSSION

Prior to accounting for voiding in the total perimeter of wetted surface, inconsistent results were generated from the application of the ratio of component mass versus total perimeter of wetted surface. After accounting for solder joint voiding using Image J software, a constant of approximately 0.0269 represented the ratio at which the molten solder "joint" failure occurred, as a function of component mass versus total perimeter of wetted surface. A standard deviation of 0.00132 from the average failure ratio demonstrated minimal variance between the two component types tested.

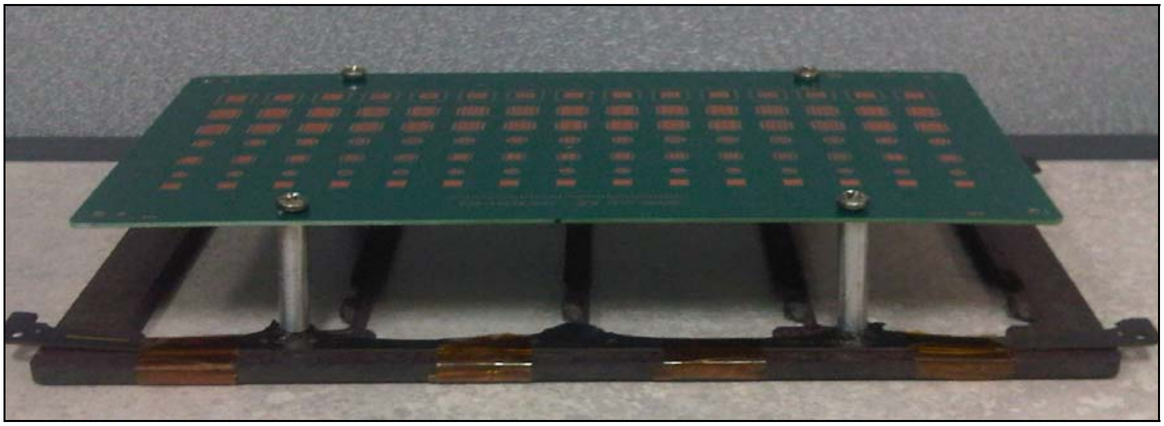

Figure 9 Elevated Stand Setup and Mounted Test Board

During testing, the same number of tests for each ratio could not be done due to testing circumstances and board restrictions. Thus, results were based on percentage failure for each ratio value tested to provide quantifiable data. Figure 10 shows the rate of percentage failure as a function of component weight versus total perimeter of wetted surface ratio for QFN 1 with and without taking into consideration void perimeter.

The smallest percentage failure for QFN 1 occurred in the 0.0275-0.03 ratio range with fluctuating increases at higher ratio values, shown in Figure 9. The highest percentage failure (100%) occurred in the 0.035-0.0375 range, with lower percentage failures observed at higher ratios. Higher levels of percentage failure were expected at higher ratios based on an increase in the weight of the component and the extra weights added. These contradictions could have been the result of several factors. Some possibilities, in no particular order, are given here.

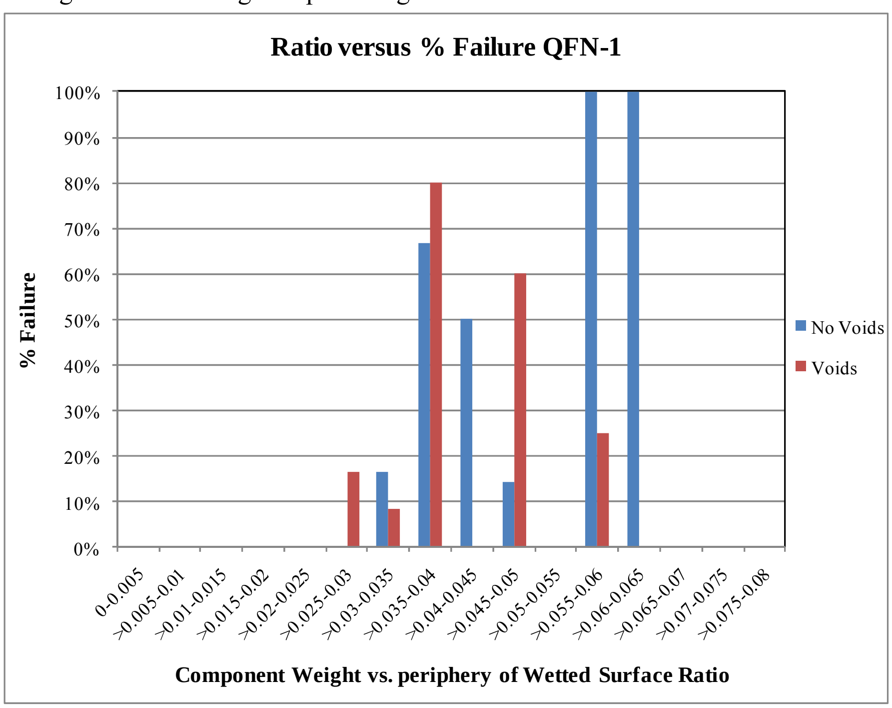

Figure 10 % Failure QFN 1

1) In order to attach various weights to the components on the PCB tests boards, chip bonder was applied manually. While an effort was made to apply a uniform amount of chip bonder to all components, variations in application could have occurred. These variations would have meant slightly different forces were being applied to the molten solder during reflow because of the different weights of glue.
2) During the reflow soldering process, the fans of the batch oven created a significance amount of turbulence. High levels of turbulence may have acted on the "sail" of the added weights and resulted in inconsistent results.
3) In order to minimize the cost of the test materials, each QFN test board was used up to a maximum of three times for the double reflow experiment. This does not count the initial reflow to solder the components to the test board. While no signs of PCB stress were visibly apparent up to three runs, the QFN test boards exhibited blistering and warping after the fourth run. Figure 11 shows blistering on a QFN test board after the fourth run through the reflow oven. While the blistering shown in Figure 11 did not occur until the fourth run of the QFN test boards in the reflow oven, internal board stress may have started to occur prior to the fourth run. This may have temporarily altered the co-planarity of the SMT pads on the board, which was not seen during subsequent visual inspections after runs 1 to 3.
4) If the added weights were not placed exactly on the center of the component, then they could exert a torquing force on the component's molten solder joints during the reflow and this would mean that the force applied to the molten joints would not have been equal for all joints.

Figure 11 shows the percentage failure as a function of component weight versus total perimeter of wettable surface ratio for QFN 2. With the exception of the component weight versus total perimeter of wetted surface ratio range of 0.0375 to 0.0475, the percentage failure was very consistent at 100% for the ratios from 0.025 and higher. The top surface area of the main body of the QFN 2 component was much smaller in comparison to that of QFN 1, which may have resulted in less variance in added weight placement. This may have contributed to a higher level of consistency in percentage failure for QFN 2, as shown in Figure 12 with and without taking into consideration void perimeter. For QFN 2 taking into account void perimeter resulted in a tighter grouping of the failures.

Application of a 20% engineering "safety buffer" is recommended to be applied to the experimental component weight versus total perimeter of wetted surface failure ratio. It is interesting to note what happens to the Zarrow equation in an attempt to express it in terms of metric units. Replacing square inches by square millimeters (1 inch^2 = 637.54 mm^2) results in an equation that looks like:

$$\frac{\text{Weight of the component (grams)}}{\text{Sum of the area of all solder joints (square millimeter)}} < 0.0471$$

Assuming a 10% correction factor to change it to perimeter from area changes 0.0471 to 0.0434, which is very close to the actual surface tension of tin/lead solder (0.04 gm/mm). There appears to be little room for error.

In the present work a component weight versus total perimeter of wetted surface ratio of 0.0215 with a standard deviation of 0.00106 represents the average failure ratio with a 20% failure buffer. The standard deviation for this ratio when comparing the runs of the two different components was minimal, indicating its possible applicability to various other components.

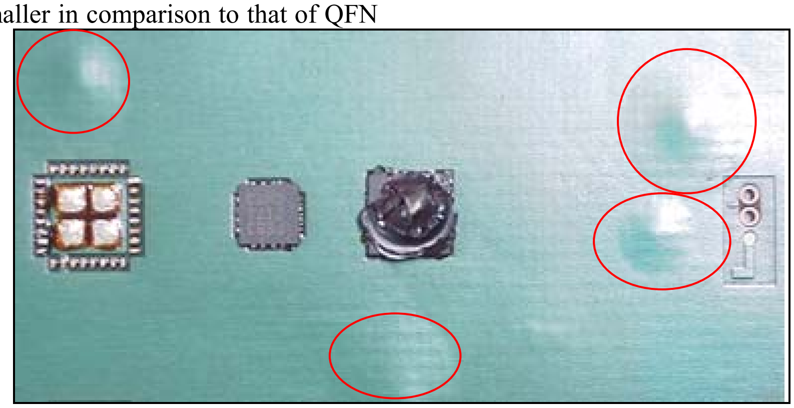

Figure 11 Board Blistering after a total of five reflows

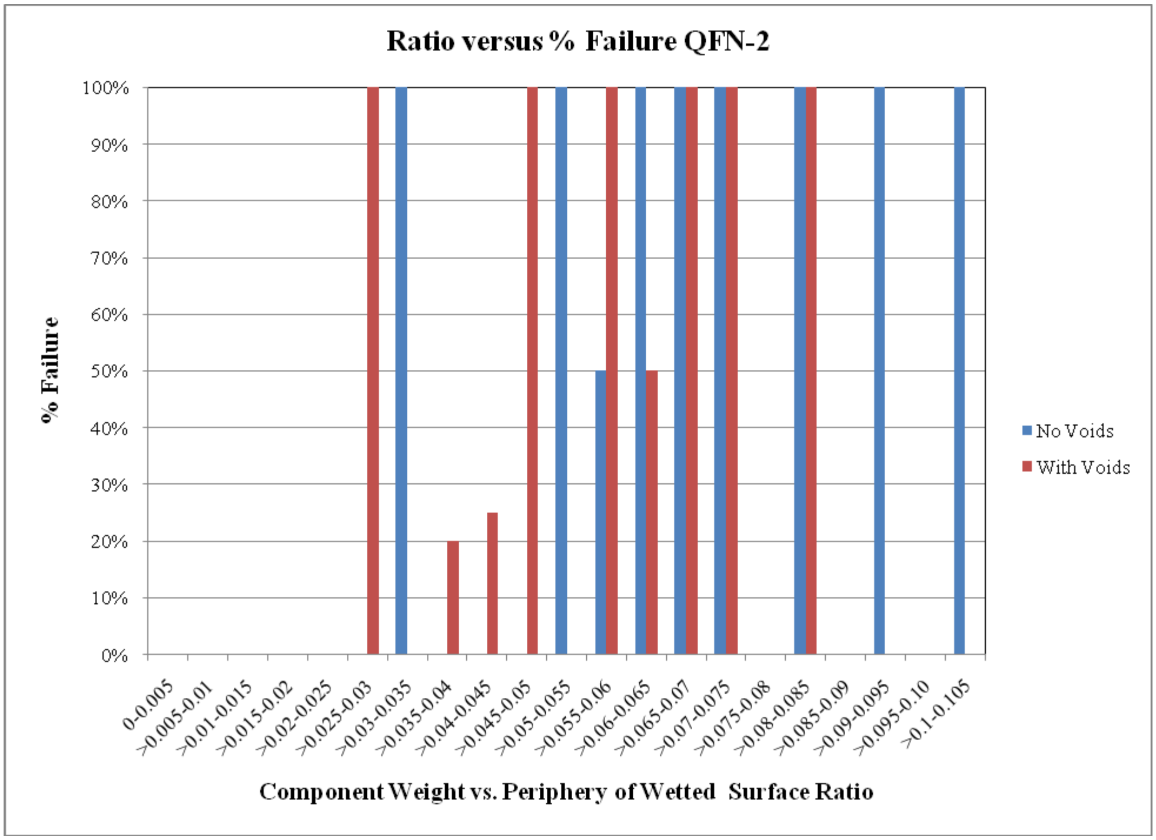

Figure 12 % Failure QFN 2

CONCLUSIONS AND RECOMMENDATIONS

A constant of approximately 0.0269 g/mm represented the ratio at which a molten SAC305 solder joints failed to hold a QFN on the bottom side of a PCB during reflow, as a function of component mass versus total perimeter of wetted surface. Applying a 20% failure buffer to this value produced an average failure ratio of 0.0215. The standard deviation associated with this value was very small indicating minimal variance and most likely well suited to applications that involve many different component types. Certainly for QFN 2 taking into account void perimeter resulted in a tighter grouping of the failures.

QFN components with a greater surface area demonstrated a higher level of variance for the percentage failure as a function of the component weight versus total wetted perimeter ratio. A recommendation would be to custom make added weights so they cover the entire surface of the part to be tested. This would result in less chance of not having the weight centered and it would provide less surface area to be affected by oven air turbulence. Monolithic weight would also mostly eliminate different amounts of glue sued to hold multiple weights to the parts being tested.

The range of components tested should be expanded. A wider range of components should be tested to verify whether or not it would be appropriate to the apply the ratio determined from this experiment to various other components involved in the manufacturing process.

All work should be duplicated in batch and conveyorized ovens to see if there is a major difference due to oven type.

Reduce the number of runs for each test board. Board stress such as blistering and warping was observed on boards that had been tested more than three times. While boards were only tested a maximum of three times with no visible stress, internal stress may have occurred after the first run. Fewer runs for each board should be done to determine if this will have an effect on the consistency of results.

REFERENCES

1) Phil Zarrow, "Soldering", Surface Mount Technology (SMT), August 2000.
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