HIGH TEMPERATURE COMPONENT WARPAGE AS A FUNCTION OF MOISTURE SENSITIVITY (MSL) RATING

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ABSTRACT

Moisture exposure is a well-known variable that can affect surface mount package reliability. Moisture Sensitivity Level (MSL) guidelines are clearly established and frequently required for package storage and handling, under MSL levels 1-6, with the larger MSL numbers indicating higher moisture sensitivity and allowing for less moisture exposure. In more extreme cases moisture saturation can lead to internal separation of layers or delamination and "popcorning" effects on the sample surface.

The objective of this work is a case study showing the effects of moisture exposure on thermal warpage across reflow profile temperatures for a range of practical packaging applications. Multiple sample types and multiple samples of each type are studied to gather statistically significant data showing moisture's effect on thermal warpage. Currently known and accepted MSL levels of specific packages will be studied to see if the extremes range of these MSL levels could result in different surface mount reliability due to increased warpage levels. Thermal warpage results will be compared to current industry standards for acceptable package warpage. The study will also look for any overall trends of moisture's effect on warpage across the sample sets.

Key words: warpage, moisture sensitivity, MSL, surface mount defects, J-STD-020E

BACKGROUND

Moisture sensitivity requirements for nonhermetic surface mount devices are defined in the joint IPC/JEDEC standard J-STD-020E, "Joint IPC/JEDEC Standard for Moisture/Reflow Sensitivity Classification for Nonhermetic Surface-Mount Devices," last updated in December 2014.[1] This standard allows customers and suppliers to place electronics devices into specific categories, defined into 8 different moisture sensitivity levels (MSL). Test method criteria are defined within this standard to define MSL levels for different packages. A subsection of MSLs are shown in Figure 1 below, showing the MSL 3 and 4 used in this study.

LEVEL	FLOOR LIFE[4]		[SOAK REQUIREMENTS] STANDARD	
	TIME	CONDITION	TIME (hours)	CONDITION
1	Unlimited	[redacted]		
2	[redacted]			
2a	[redacted]			
3	168 hours	≤30 °C/60% RH	192[2] +5/-0	30 °C/60% RH
4	72 hours	≤30 °C/60% RH	96[2] +2/-0	30 °C/60% RH
5	[redacted]			
5a	[redacted]			
6	Time on Label (TOL)	[redacted]		

Figure 1. MSL table from J-STD-020E (partial redaction)

Multiple joint industry standards and test methods are further defined by JEDEC and other in standards such as J-STD-033D[2] and JESD22-A120[3].

The absorption of moisture inside a package can cause vapor pressure within the package. In some cases, this vapor pressure can cause internal delamination of the internal components of the package, and in more extreme cases a "popcorning" effect on the sample surface. The popcorn effect would be seen by warpage analysis, but it isn't clear whether lesser cases of internal delamination will play a role in warpage levels over reflow. Package warpage is generally accepted to be mainly driven by CTE mismatch between package materials, thus an additional force, such as vapor pressure, is expected to have some level of impact. However, the impact of vapor may not be statistically relevant and may be within the noise of measurement resolution and/or test variation.

One common method for identifying internal package delamination is scanning acoustic microscopy (SAM).[4] This method can look inside a package for delamination. SAM, or C-SAM, is performed in water and is not used for behavior of a package through reflow temperatures.

A previous iNEMI study "Recent Trends of Package Warpage Characteristic," also asked the question of relations between moisture exposure and warpage. [5] However, this study was unable to find any statistically relevant relation between moisture exposure and warpage. Further studies

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related to MSL levels have also found that the length of a reflow profile can play a role in the effects of moisture exposure on reliability. [6]

Component warpage is a well-established reliability and yield concern for electronics packaging. Multiple industry standards define allowable warpage levels and component testing best practices, including: JEDEC JESD22-B112B,[7] JEITA ED-7306, [8] and IPC-7095D.[9] These standards are used for testing approaches within this study, as well as data analysis.

Additionally, numerous published studies show the relationship between component thermal warpage and surface mount defects. These studies include such titles as: "Reflow Warpage Induced Interconnect Gaps between Package/PCB and PoP Top/Bottom Packages"[10] and "Effect of Package Warpage and Composite CTE on Failure Modes in Board-Level Thermal Cycling"[11], to name a few.

METHODOLOGY

Moisture Exposure

All samples were subjected to a 24hr 125°C prebake to establish a starting "dry" moisture condition. After this point samples were tested in 4 different tracks: Control, MSL3, MSL3 "reset track" (samples are baked 24hr at 125°C after moisture exposure), MSL4. Samples were always tested within 6 hours of each exposure condition end. The moisture exposure and preheat path of each track is summarized in Figure 2 below.

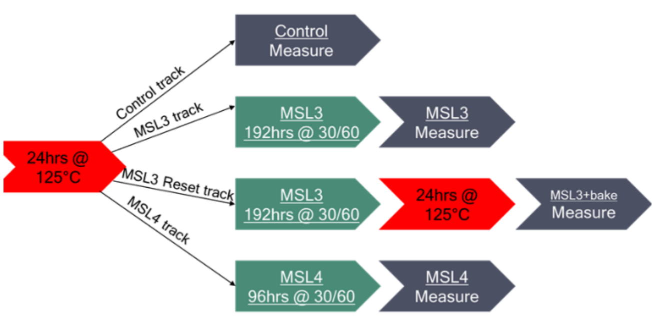

Figure 2. Moisture Exposure tracks

Test Samples

6 different sample types were tested in this study. 3-4 samples per test condition were tested depending on sample availability. Package type and size descriptions were kept generic in order to protect component manufacturer. For the same reason some of the sample sizes are approximate and not exact. A range of different sample types were chosen to represent a reasonable combination of different surface mount package types. Package type, size, and tested quantities are summarized in Table 1.

Table 1. Test Samples

Package		Sample Quantity per Test			
Type	**Size**	**Contr**	**MSL3**	**MSL3 Reset**	**MSL4**
Molded CSP	14 x 14 mm	4	4	4	4
Molded CSP	11 x 12 mm	4	4	4	4
Molded CSP	10 x 11mm	4	4	4	4
Bare Die FCBGA	20 x 15 mm	3	3	0	3
Molded BGA	27 x 27 mm	4	4	4	4
Molded PBGA	40 x 40 mm	4	4	4	4

Reflow Profile and Measurement Technique

A typical lead free reflow profile with peak at 250°C was used in this study. An example thermal output from a thermal warpage run is shown in Figure 3. For all tests an extra sample was used purely for capturing temperature within the system. The actual temperature is defined by the red line, Process 1. Other oven commands, including warpage acquisitions are shown on the graphical output in Figure 3. All samples were subjected to a comparable profile.

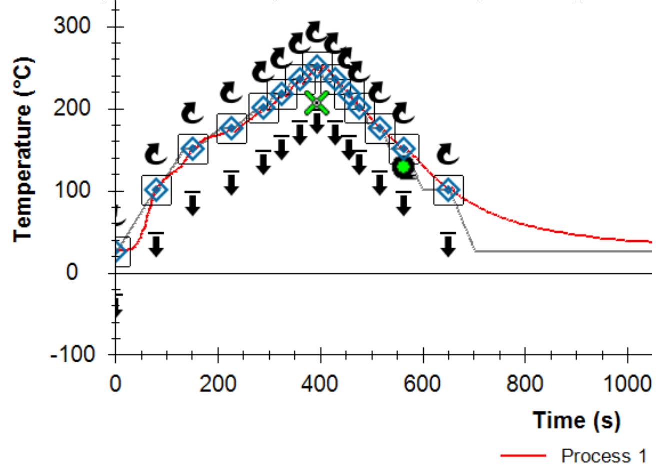

Figure 3. Example reflow profile output

Surface warpage measurements over temperature are taken using the shadow moiré (SM) technique with samples placed in an IR oven, in a metrology tool used for measuring surface shape over reflow temperatures. The SM technique measures surface height by shining a line light through a grating glass. An interference pattern between the lines and shadow cast by the same lines creates a contour map used for measurement. The SM technique utilizes a phase stepping method, applied for increased resolution. Camera images are captured with different distances between the grating and sample. Figure 4 shows a conceptual image of the behavior of light in SM, and Figure 5 shows a contour pattern created by SM on one of the samples under test.

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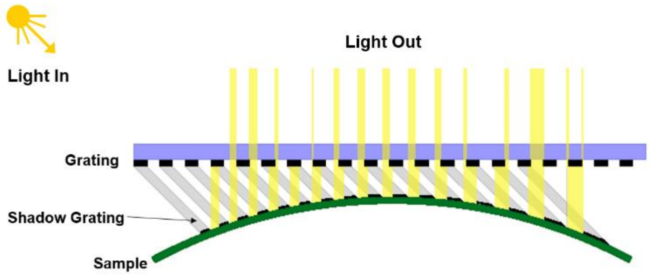

Figure 4. Shadow Moiré Visual Concept

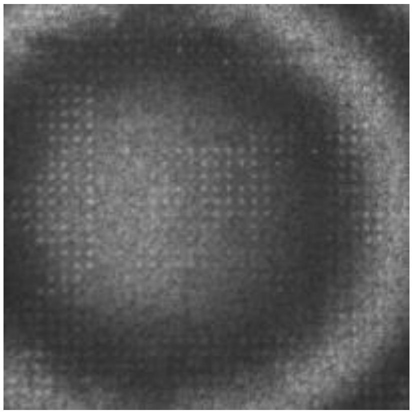
Figure 5. Shadow Moiré Pattern

Controls
The following parameters were kept as controls during all phases of each test:

- SM Grating Pitch: 200 lines per inch
- Sample Coating: White high temperature paint (for increased resolution)
- Temperature Profile: See Figure 3
- Sample Support: Dark red high temperature glass
- Sample Region of Interest: Sample edges tracked during heating via automatic edge recognition technology, with an inset to the center of the outer solder ball row
- Working distance from grating: 1.25 mm during acquisition, 3.75 mm during heating and cooling
- Temperature Uniformity: Top and bottom heating and multi-zone oven used to minimize temperature variation from sample to sample and within individual samples.

Variables:
Independent variables:

- Moisture Exposure
- Sample Type

Dependent Variables:

- Coplanarity gauge (highest point – lowest point)
- 3S Warpage gauge (Coplanarity + sign designation to indicate direction of curvature, including a "transition" category between positive and negative curvature)
- Shape Name gauge (Samples placed into 1 of 9 defined shape categories)

3S Warpage and Shape Names are further defined in the white paper, "Surface Mount Signed Warpage Case Study; New Methods for Characterizing 3D Shapes Through Reflow Temperatures."[12]

Additionally, sample shapes are considered from the perspective of both absolute shape at each given temperature as well as a relative shape change from a starting room temperature shape. As starting shape can often be a significant source of sample to sample variation, relative change of the surface over temperature can be an effective method to understand sample warpage. In these cases, the same gauges are used for analysis.

RESULTS
No "popcorning" was seen on any samples, so no extreme cases of delamination occurred. This suggests the moisture was well controlled and the samples do not easily show these extreme levels of delamination. Longer moisture exposure or faster and higher heating profiles could change this case. Some example 3D surface renderings of the samples are shown below in Figures 6-9. To give some understanding of surface shapes the most warped and least warped sample is shown from the smallest and the largest sample. The out-of-plane scale is consistent to the part type. Note that the most warped and least warped points occurred under different conditions between the two sample sizes.

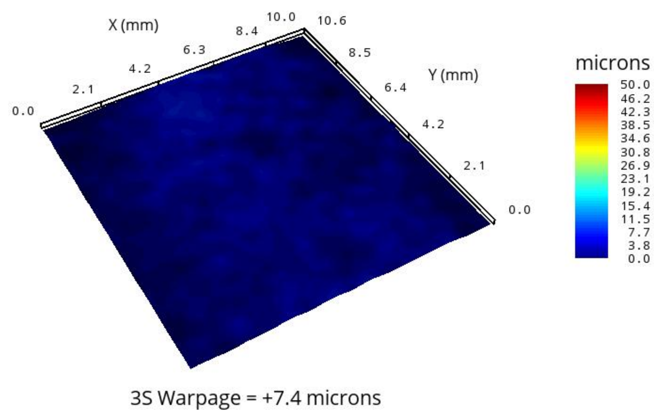

Figure 6. 10x11mm, MSL3, 200C cooldown, low warp

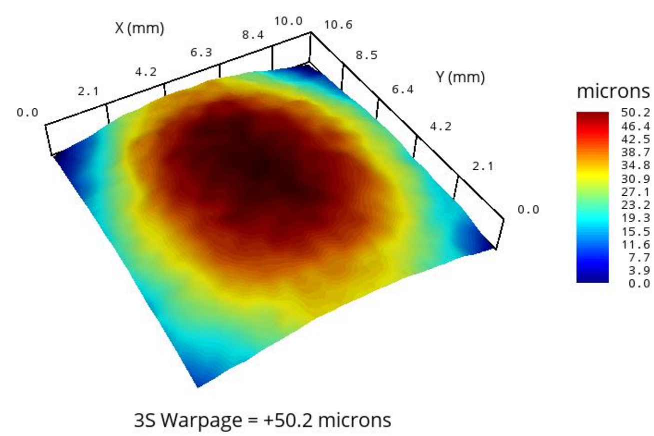

Figure 7. 10x11mm, MSL4, 217C heat-up, high warp

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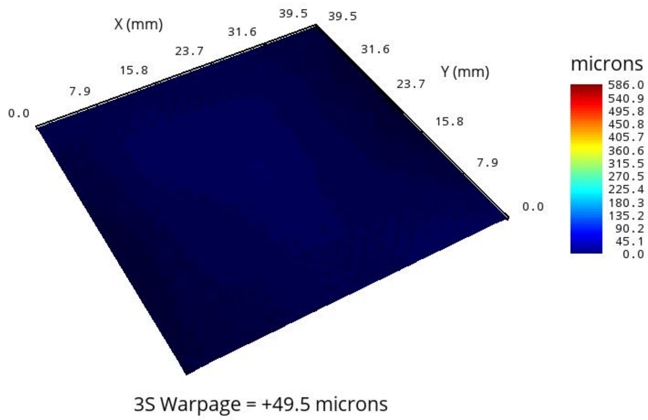

Figure 8. 40x40mm, MSL3, 175C heat-up, low warp

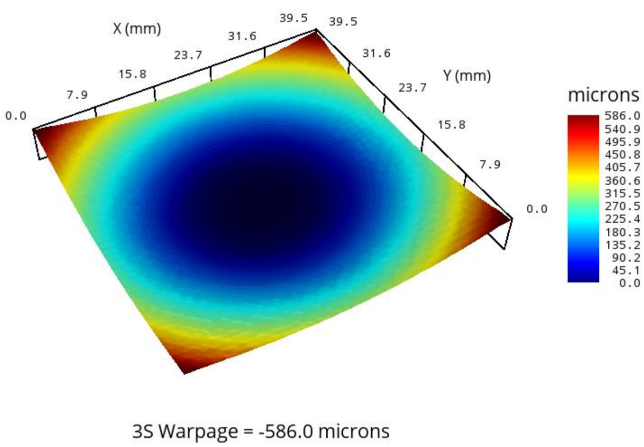

Figure 9. 40x40mm, MSL3, 250C peak, high warp

Quantitatively, the data is first summarized by the most basic gauge available here, coplanarity. In order to summarize the data, each sample type is averaged with the other 3-4 units in the test at each temperature. With easily over 1000 warpage measurements throughout the test, this makes the data quantity feasible to analyze. Figures 10-15 show average coplanarity over temperature for all 6 sample types respectively. The different moisture conditions are shown as four different series on the graphs.

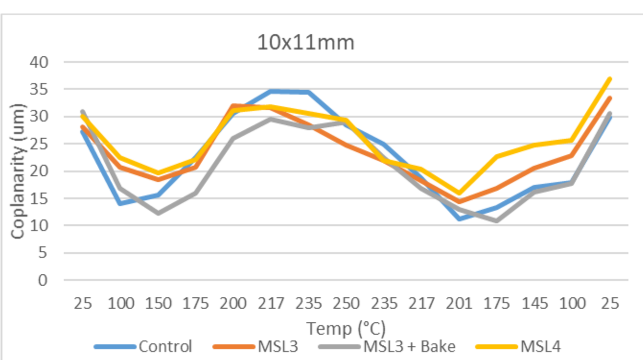

Figure 10. Avg Coplanarity Over Temp, 10x11mm

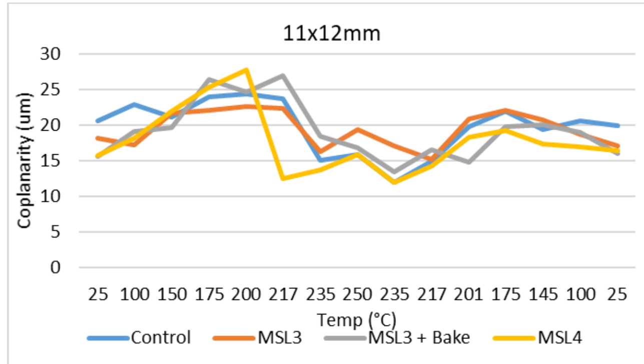

Figure 11. Avg Coplanarity Over Temp, 11x12mm

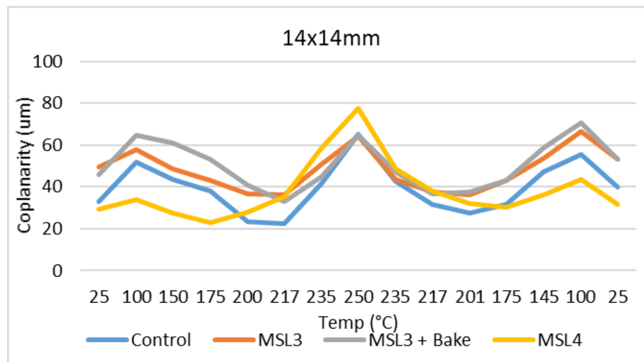

Figure 12. Avg Coplanarity Over Temp, 14x14mm

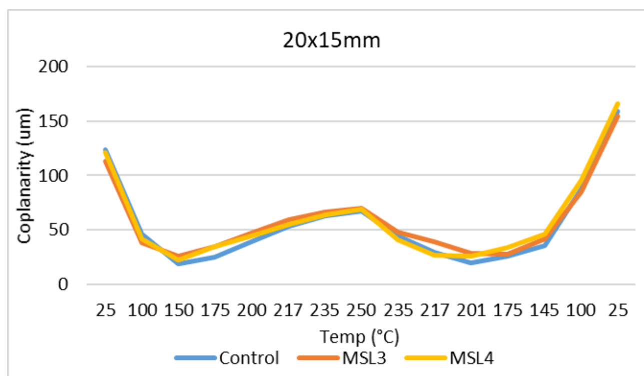

Figure 13. Avg Coplanarity Over Temp, 20x15mm

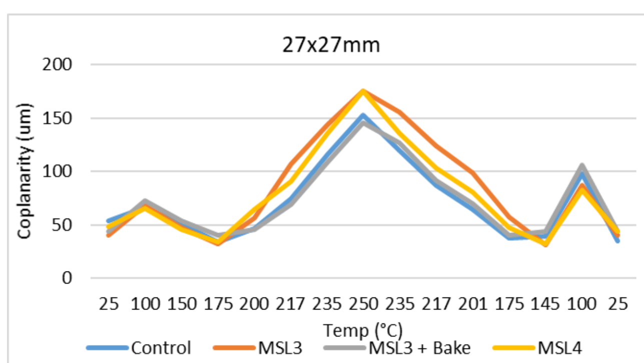

Figure 14. Avg Coplanarity Over Temp, 27x27mm

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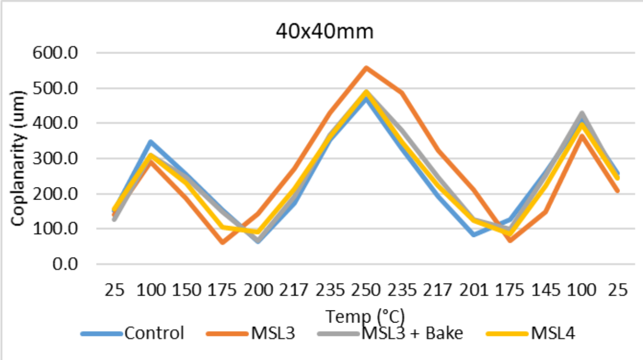

Figure 15. Avg Coplanarity Over Temp, 40x40mm

Some "W" shape patterns can be seen in the graphs. This is a result of looking at the data without any sign association. Each of the 89 different samples used in the study went through a transition between positive and negative at some point during the reflow profile. The transition point varies a bit between the different samples but is more often in the 150-200°C range on both heat and cool sides of the profile. For the smaller samples, this trend is harder to visualize due to the lower warpage levels of the sample. Looking closer at the individual sample plots on the 40mm samples at MSL4, all samples transitioned from negative to positive in heating between 175°C and 200°C and then back to negative in cooling from 200°C to 175°C. Maintaining good sample temperature uniformity is key to this transition happening consistently. See Figure 16 showing 3S Warpage.

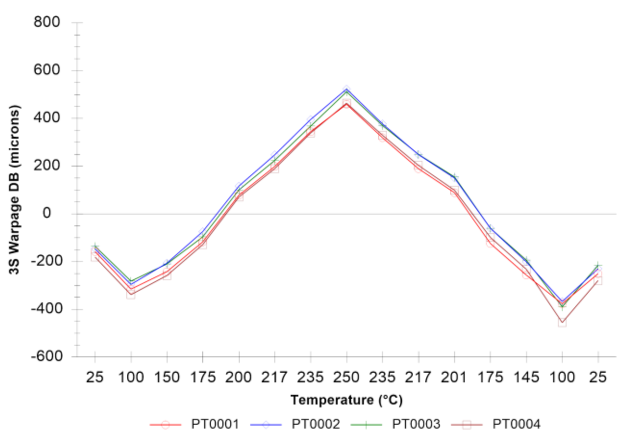

Figure 16. 3S Warpage, 40x40mm, MSL4

The same transition can also be seen in the shape name variable at each temperature. The 40x40mm sample at MSL4 exposure generally transitions from Dome (DM) shape to and Bowl (BW) shape, but in the transition some other shapes begin to arise, "X-Pipe" (XP) and Upward Twist (UT), as in Table 2.

Table 2. Shape Names, 40x40mm, MSL4

Temperature, °C	25	100	150	175	200	217	235	250	235	217	201	175	145	100	25
PT0001	DM	DM	DM	DM	BO	BO	BO	BO	BO	BO	BO	DM	DM	DM	DM
PT0002	DM	DM	DM	DM	BO	BO	BO	BO	BO	BO	BO	XP	DM	DM	DM
PT0003	DM	DM	DM	DM	BO	BO	BO	BO	BO	BO	BO	UT	DM	DM	DM
PT0004	DM	DM	DM	DM	BO	BO	BO	BO	BO	BO	BO	DM	DM	DM	DM

In some cases, the transition between positive and negative has higher sample to sample variation and is more difficult to find a trend. Here the ability to look at the relative change of the sample is helpful. Figure 17 shows 3S Warpage data for the 14x14mm sample at MSL3. The vertical lines on the graph represent "transitional" shapes in the sample data. This graph is difficult to interpret due to the high sample to sample shape variation at room temperature.

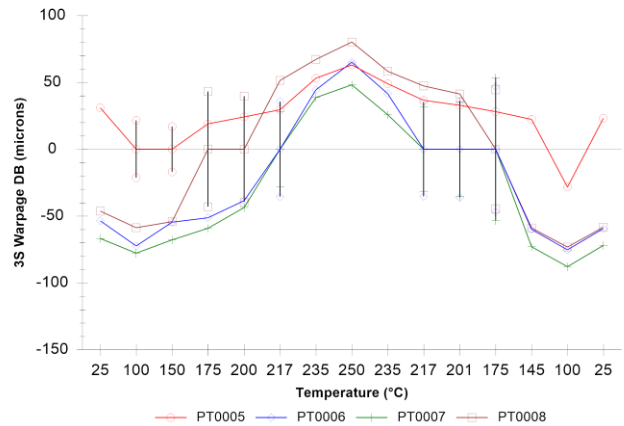

Figure 17. 3S Warpage, 14x14mm, MSL3

However, if we subtract the matrix of the original room temperature shape of each sample, the warpage becomes clearer. The "PT0005" comes out as a clear outlier in this data set. The relative warpage data is plotted against the 3S Warpage gauge in Figure 18.

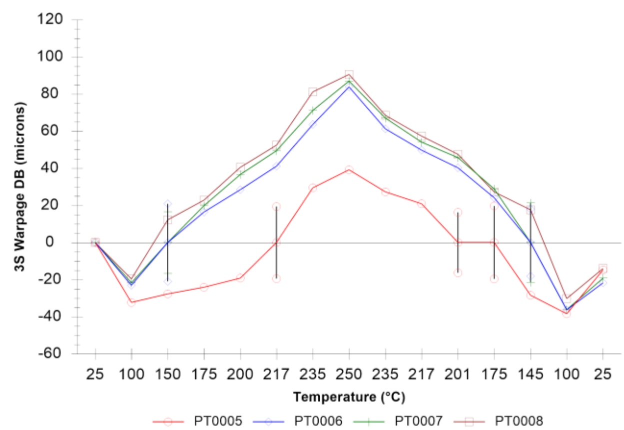

Figure 18. Relative 3S Warpage, 14x14mm, MSL3

Figure 18 shows that analysis of the data via relative change can be helpful to interpret the data.

ANALYSIS AND DISCUSSION

Further analysis requires a closer look sample by sample, considering the construction of the part, die to mold ratios, substrate thickness and relative shape change of the samples.

20x15mm Sample

Starting with the simplest case, the 20x15mm sample showed no discernable change from the different moisture exposure levels tested in this study (Figure 13). This is an unsurprising outcome, given that it is also the only bare die sample and contains no mold compound. The die is also quite large relative to the package size. While the package does show shape change as the substrate expands at a faster rate than the die, the shape change is perceivably unaffected by moisture, with no mold to soak up moisture and the relatively thin substrate not holding enough water to affect the warpage.

27x27mm and 40x40mm Samples

The two larger samples in the study exhibit the most obvious cases of moisture effecting warpage. Both samples have prominently thicker molded areas and small die to mold ratios. The higher warpage is clear for MSL3 and MSL4 for the 27mm package and clear for MSL3, the worst-case moisture exposure, on the 40mm package. It is unclear specifically why the MSL4 exposure matched better with the control and MSL3 + Bake warpage than the MSL3.

Additionally, both samples exhibit the ability to reset the moisture condition through prebake. For these samples the number of prebakes and the moisture exposure between them plays no significant role. However, the study does not show the affect of extended exposure to prebake temperatures or numerous cycles in an oven on sample warpage. With only two prebake cycles it is difficult to exclude the possibility that prebake conditions can affect sample warpage.

10x11mm, 11x12mm, and 14x14mm Samples

Overall warpage levels of the smaller dimensioned samples, particularly the 11x12mm samples are much smaller than the larger dimensioned samples. This makes the warpage offset caused by moisture an even larger factor than visually shown in the graphs. Certainly, larger samples will tend to have larger solder balls and solder ball pitch, thus larger allowable warpage.[7] However, the offset here is significant as seen in Figure 19.

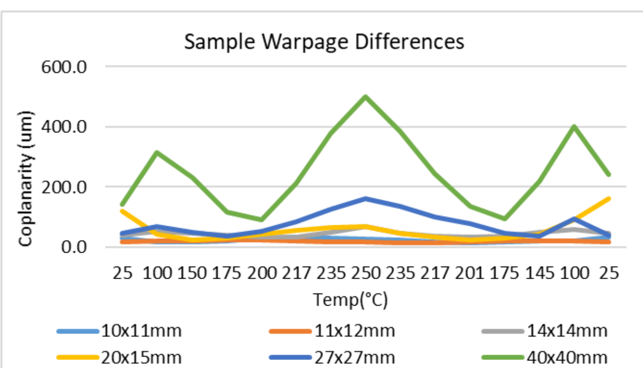

Figure 19. Overall Coplanarity by Sample Size

Figures 10-12 showing warpage over temperature for the different moisture conditions, are difficult to interpret. The sample to sample variation at starting room temperature plays a large role in the coplanarity variation. In order to better understand the differences in thermal warpage caused by moisture, the coplanarity can be analyzed with all surfaces shown as relative changes from the room temperature shape.

Figures 20-22 replicate the data from Figures 10-12 but are shown as relative warpage plots instead of absolute shape.

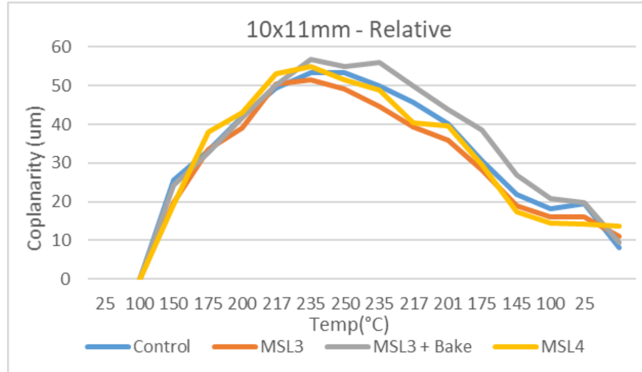

Figure 20. Avg Relative Coplanarity, 10x11mm

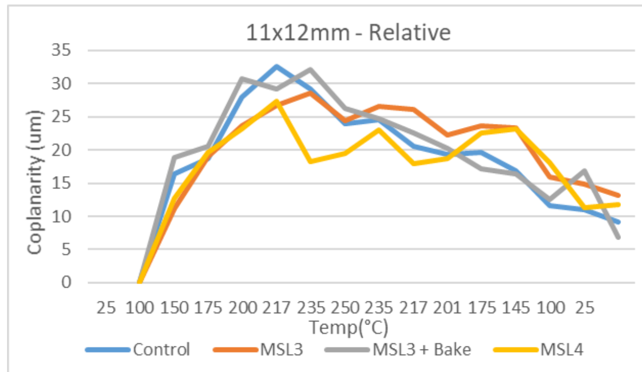

Figure 21. Avg Relative Coplanarity, 11x12mm

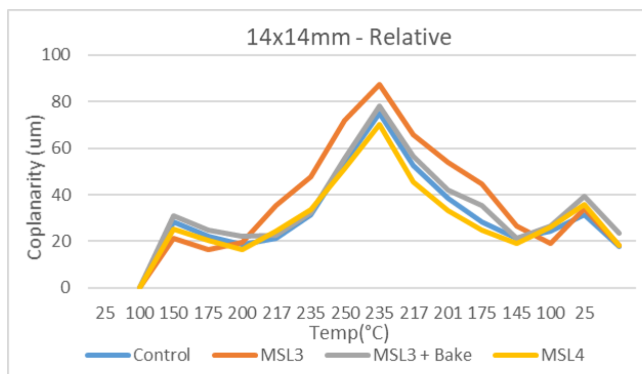

Figure 22. Avg Relative Coplanarity, 14x14mm (with outlier from Figure 18 removed from average)

Taken from the relative warpage perspective the MSL3 data on the 14x14mm sample, Figure 22, begins to stand out. This isn't true for the 10x11mm or 11x12mm, which seem to show no clear trend in terms of higher warpage with increased moisture exposure. So, there are 3 package types showing signs of higher warpage at MSL3 (14, 27, and 40mm) and 3 that do not show higher warpage.

There is another previous undiscussed variable related to the moisture exposure of the samples, which is die to mold ratio summarized in Table 3. Exact numbers on die to mold ratio are either unknown or kept vague to protect company information.

Table 3. Die to Mold Ratio of Test Samples

Package Type	Package Size	Die/Mold Ratio	Higher Warpage at MSL3
Molded CSP	14 x 14 mm	<10%	Yes
Molded CSP	11 x 12 mm	>15%	No
Molded CSP	10 x 11mm	>15%	No
Bare Die FCBGA	20 x 15 mm	N/A (No mold)	No
Molded BGA	27 x 27 mm	<10%	Yes
Molded PBGA	40 x 40 mm	<10%	Yes

Adding this variable to our data set, a clear trend is shown that samples with more molded area, relative to die size, will absorb moisture and cause larger effects on thermal warpage at higher temperature.

A final attempt is made to better interpret the 10x11, and 11x12mm data to see if any trend related to moisture can be found. Using the relative warpage data 2nd order polynomial trendlines are fit to the average coplanarity data. The general curve of the relative warpage fits the general 2nd order curve shape. Figures 23 and 24 show the trendlines for the different moisture conditions using the same color scheme as before with orange and yellow as MSL3 and MSL4 respectively.

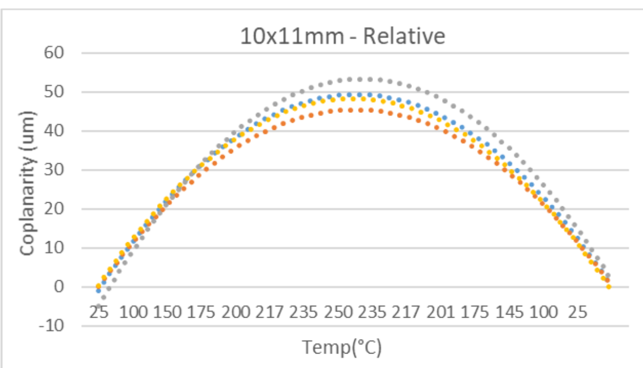

Figure 23. Avg Relative Coplanarity, 2nd Order Polynomial Fit, 10x11mm

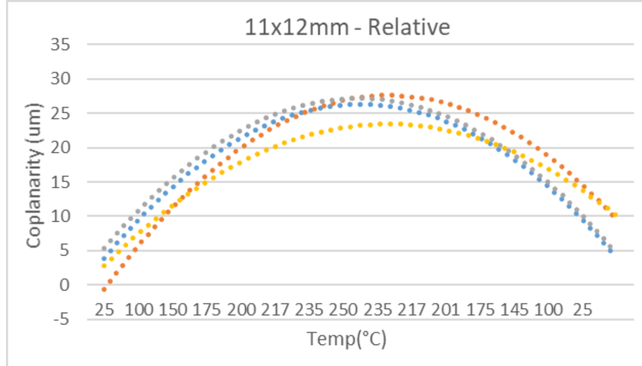

Figure 24. Avg Relative Coplanarity, 2nd Order Polynomial Fit, 11x12mm

While little can be concluded from Figures 23 and 24 in terms of sample behavior over warpage. The trendlines do show a minor pairing with MSL3 and MSL4 slightly separated from the trend of the Control and MSL3 + Bake data. More than anything this helps to justify the validity of the data set and the conclusion that moisture is not having a significant effect on the overall warpage of these samples with higher die to mold ratios.

CONCLUSION AND SUMMARY

Unlike previous studies in the space of package moisture vs. thermal warpage,[5] a tangible correlation between warpage and moisture was found for certain package types. This is possibly due to better variable control with increased understanding over time as it relates to different conditions that can affect thermal warpage.

For the samples in this study, those with larger mold volumes relative to die size exhibited specifically higher warpage levels near and above reflow temperatures. As expected, the longer MSL3 moisture soak showed higher warpage levels than the MSL4 exposure. Samples with less mold and more substrate and die exhibit no relevant variation in thermal warpage due to moisture exposure. Certainly, the larger samples also showed higher warpage overall, as is to be expected.

Samples that were prebaked, subject to MSL3 and then prebaked again, or “reset”, correlated with the control data set which went through a single prebake. This shows the ability for a sample to be exposed to moisture then prebaked again, without playing a tangible role in thermal warpage.

NEXT STEPS

More samples can of course be tested using a similar setup. Further sample types would help to enforce the correlation between die to mold ratio and higher warpage at elevated temperatures. In particular, a larger sample with higher die to mold ratio and a smaller sample with a lower die to mold ratio would be valuable, though possibly difficult to find.

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