Surface Mount Signed Warpage Case Study; New Methods for Characterizing 3D Shapes Through Reflow Temperatures

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Abstract

Surface mount components are commonly evaluated for out-of-plane warpage levels across reflow temperatures. Decision making from these measurements is primarily based on signed warpage of a single component surface, per industry standards. However, signed warpage as a gauge can mislead users when surface shapes are complex, or direction of warpage is uncertain. The presented case study analyzes a range of common surface mount components for signed warpage. This wide ranging case study is used to create newly proposed methods for further defining and characterizing surface warpage in a quantitative manner.

Analysis of the case study data focuses on two related surface parameters: signed warpage Signal Strength and surface shape naming. Signal Strength is used to classify samples that are in "transition" between positive and negative warpage directions. New methods are shown to represent these transition areas in signed warpage graphs. Surface shape naming is used to further classify surface types, wherein correlation between shape name and surface mount defects are discussed. Algorithms for calculation of Signal Strength and classifying shape names are offered. Real world examples are used to determine appropriate thresholds for sign transitions and shape names in said algorithms. The study proposes a new, industry wide, approach to how companies present component warpage data.

Introduction

Volume and demand for thermal warpage data continues to increase in the microelectronics industry. However, quantitative methods to effectively describe the warpage of a surface remain inadequate. Generically, two methods exist to quantify a 3-dimensional surface shape. One method is to make decisions based on a signed warpage value, which is essentially coplanarity with a positive or negative direction assigned. This gives users a numeric answer; industry standards exist from both JEDEC (JESD22-B112A) [1] and JEITA (ED-7306) [2] discussing how to quantify surface shape for BGAs and LGAs. Conversely, users can visually inspect surface data by looking at a detailed 3D rendering or a 2D diagonal line plot across the package surface. On the PCB side of the attachment interface, IPC-9641[3] establishes the how, though not the quantity, for warpage measurement over temperature. Whenever considering component warpage, the warpage of the attaching interface should not be ignored. In fact, the paper "PCB Dynamic Coplanarity at Elevated Temperatures" concludes that "…IPC and JEDEC form a joint evaluation WG to analyze the Dynamic Coplanarity specification and jointly set the requirements for board and package." [4]

Much of the basis for this case study was established in a previous paper "Improvements in Decision Making Criteria for Thermal Warpage" [5]. This paper goes into further detail on reasons why a new approach to quantifying surface warpage is being pursued. Issues discussed in this paper are not covered in detail, but key points and conclusions, which are critical to this discussion, are presented in the remainder of this section.

The current standards from JEDEC [1] and JEITA [2] have specific weaknesses for assigning warpage direction, generically referred to as signed warpage. The sign for this gauge is based on the normalized diagonal lines of the surface. An improved algorithm for signed warpage, JEDEC Full Field Signed Warpage (JFFSW), is used as part of the approach to this study. The JFFSW gauge is less sensitive to noise and considers the full field area of the sample. The mathematical concept behind the JFFSW approach, of using 2nd order polynomial fit data, is used extensively throughout this study.

The reason behind the need for the presented solutions comes from the confusion caused by samples changing sign direction. Regardless of the gauge used to determine signed warpage, simplifying a 3D shape to a positive or negative will lead to cases where the equation generates an answer near zero and the surface is neither very positive nor negative in shape. These data sets get reported in signed warpage over temperature graphs where signed warpage seems to flip from positive to negative, with little explanation as to the cause. This leads to an inaccurate impression of the surface shape, when considering the data without the full graphical rendering, as is commonly necessary when dealing with larger volumes.

The previous paper also established a new gauge, Signal Strength (SS). This gauge defines the "amount" that a surface is positive or negative. Two gauges are presented in the previous paper [5], one based on signed warpage and diagonals, and the other based on JFFSW and 2nd order polynomial fits. For the purpose of this study the Signal Strength gauge based JFFSW is only considered. Derivation of this gauge is not covered here. However, this gauge will be used in multiple sections in the study, so it has been provided below, shown as a percentage in Equation 1.

$$SS = ABS\left(\frac{em^2+fn^2}{4*coplanarity}\right) * 100\% \qquad \text{(Equation 1)}$$

…where e and f are coefficients of the x^2 and y^2, respectively, in a 2nd order polynomial fit. Terms m and n are x and y dimensions of the surface expressed in pixels or quantity of data points. These variables are used throughout the paper and maintain the same meaning.

The previous paper [5] also takes a first pass at assigning a name to a shape based on the same e, f, m, and n terms from Equation 1. Some of the shape name concepts originated in an iNEMI statement of work. [6] An early concept image is shown in Figure 1a. From these concepts specific rules and shape names were established. A graphical representation correlated the shape names to $em^2$and fn^2 terms is shown in Figure 1b.

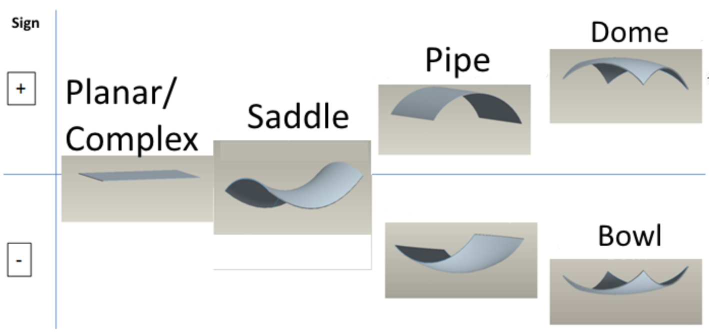


Figure 1a. Original Shape Concept

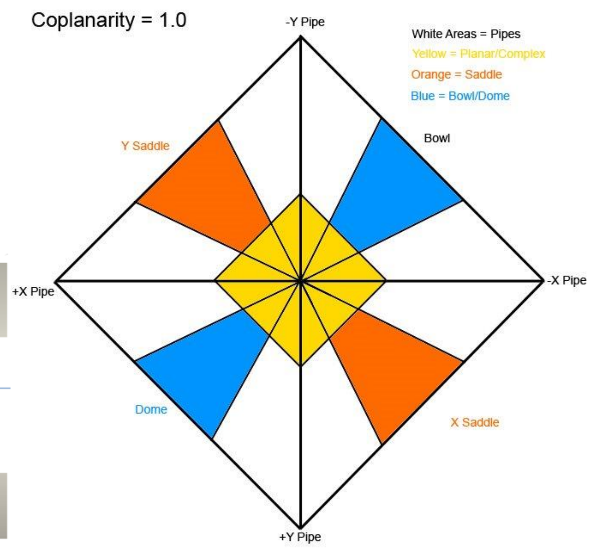


Figure 1b. Original Shape Rules

The original study goes on to consider the "dxy" term of the 2nd order polynomial as well, which affects the visual "twist" of the surface. These definitions were originally chosen on observation of a small subset of samples, to present a general concept. Whereas this study goes on to study a larger subset of real world samples and refines these concepts to an established proposal for industry use.

Case Study Samples and Test Methods

The samples chosen for the case study as well as testing methods are described here, fairly generically, for proprietary reasons.

- Type of samples which were included in this analysis:
  - BoC, 1DP 7.5 X 13.5mm
  - CoB, 2DP 13.5 X 13.5mm
  - Large FBGA, 1DP 11 x 18.5mm
  - MCP, 5DP 11.5 x 13.0mm
  - PoP, 1DP 14 x 14mm

These samples were chosen due to the varied nature of the devices. We also utilized a large enough sample size such that statistical validity could be gained and assured for the study. Numerous sample types were used to increase not only the span and applicability of the model(s), but also to increase the accuracy of our shape naming.

Since the focus of the effort included a broad range of package types, the validity of the study carries more merit regarding soundness.

The samples were measured using the outline below. This is a short description; however, it should be assumed that details of the actual processing are not included here for proprietary concerns.

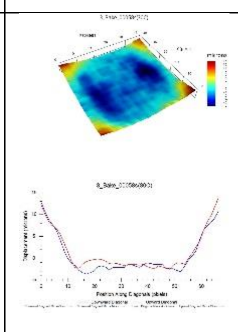
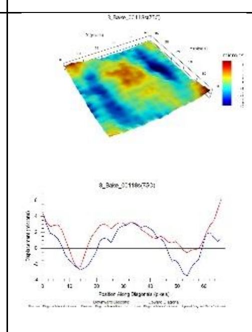
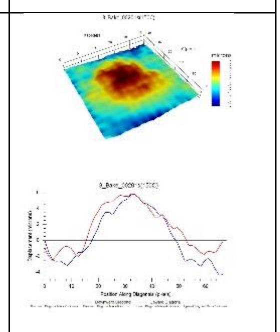
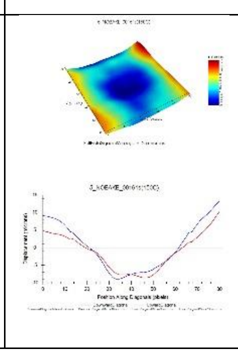
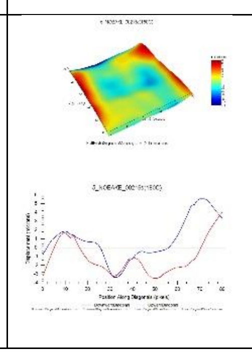
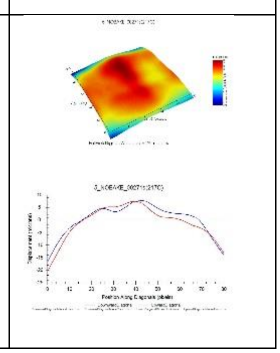
- Preconditioning was done following the manufacturing flow.
- Parts were measured ball side, with no solder balls
- Data was measured from 30C to 260C and back to 30C
- Numerous samples were used (samples sizes, not n=1)
- No more than 7 samples were measured at one time

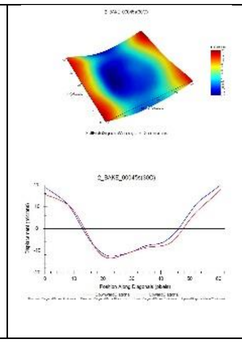
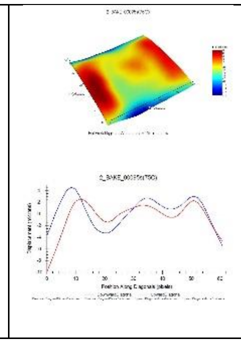
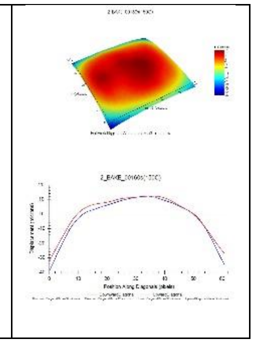
Classifying Warpage Sign Using New "3S Warpage" Gauge

"3S Warpage" is short for "Signal Strength Signed Warpage", which could more accurately be described as JEDEC Full Field Signed Warpage, also considering Signal Strength."3S" could also be taken to mean 3 "signs": positive, negative, and indeterminate. As is discussed in the introductory section of this paper a common cause of confusion is suddenly changing sign direction. Whereas signed warpage and JFFSW gauges put samples into two categories, positive and negative, 3S Warpage still uses the coplanarity value but has 3 categories for shape direction. The categories are defined as positive, negative, and "transition". The transition surface indicates a sample has low Signal Strength and is neither very positive in warpage direction nor very negative, thus the shape direction is indeterminate or in transition. During a thermal cycle, many samples will transition between a positive and negative shape during heating. However, due to sample to sample variation, the temperature during which this transition occurs can vary. Different samples will transition between positive and negative at different temperature points, often with very little difference between their shapes.

From the case study data, Table 1provides a good example of this concept. These examples, along with others from the case study, are used to experimentally establish a logical changeover point between positive/negative and transition surfaces. Note that sign convention depends on the orientation of the samples during measurement. In Table 1 the samples are correctly labeled to the sign convention as positive or negative, when measured in the "dead bug" position. The gauge footers in the remainder of the report ignore the measurement orientation and will be shown inverted when measured "dead bug".

Table 1: Example Positive, Negative, and Transition Surfaces from Case Study

	Positive	Transition	Negative
CoB, 2DP 13.5 X 13.5mm			
MCP, 5DP 11.5 x 13.0mm			

PoP, 1DP 14 x 14mm			

Historically all of the transition surfaces shown in Table 1 were forced to be defined as positive or negative. Another example from the case study is shown in Figure 12a and 2b. A transition from JFFSW of +21 to -23 microns could be perceived as a 44 micron change in shape. From the JFFSW data alone this is a valid hypothesis. However, visual inspection of these two samples, shown graphed in 3D space on the same scale, indicates minimal difference between the two sampleshapes. When dealing with a sample transitioning between positive and negative shape directions, the shape type more typically does not show a clear shape direction.

In the case of Figure 2a and 2b the visual appearance is very similar, the shape direction is unclear, and consequently the Signal Strength of each data set is low, 2% and 6% for Sample 1 and Sample 2, respectively. The Signal Strength gauge, defined in Equation 1, is used to better define the direction of warpage. Considering the full range of data taken in the case study, the new transition surface classification is defined as a surface with Signal Strength $\leq$ 25%. This transition threshold value was changed from 35%, using the same math, based on the feedback from the experimental data of this case study.

The next question that arises from having this new data is how to visually represent the information on a graph. Figure 3 shows the current approach with JFFSW. Figure 4 shows the proposed method to graph this information with 3S Warpage. For the transition surfaces a "candlestick" style area is used between the positive and negative range taken up by the transition surface. The line connecting the different data points to a transition surface will always rest at 0 microns on the Y axis, as the center point of the transition "candlestick" will always be 0.

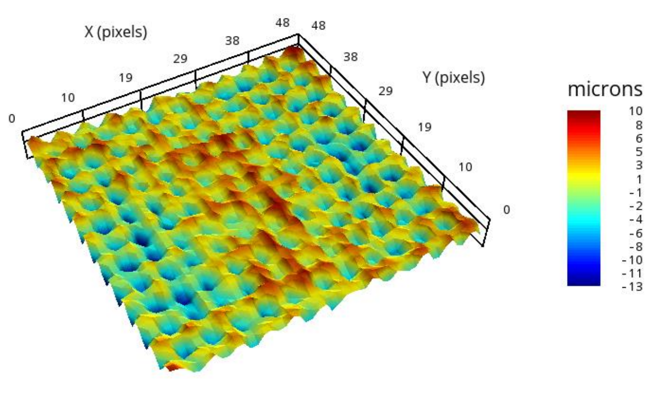


Figure 2a. CoB Sample 1, 150°C Cooling

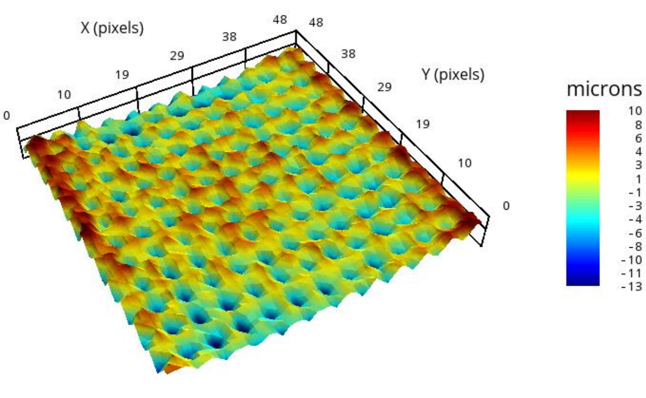


Figure 2b. CoB Sample 2, 150°C Cooling

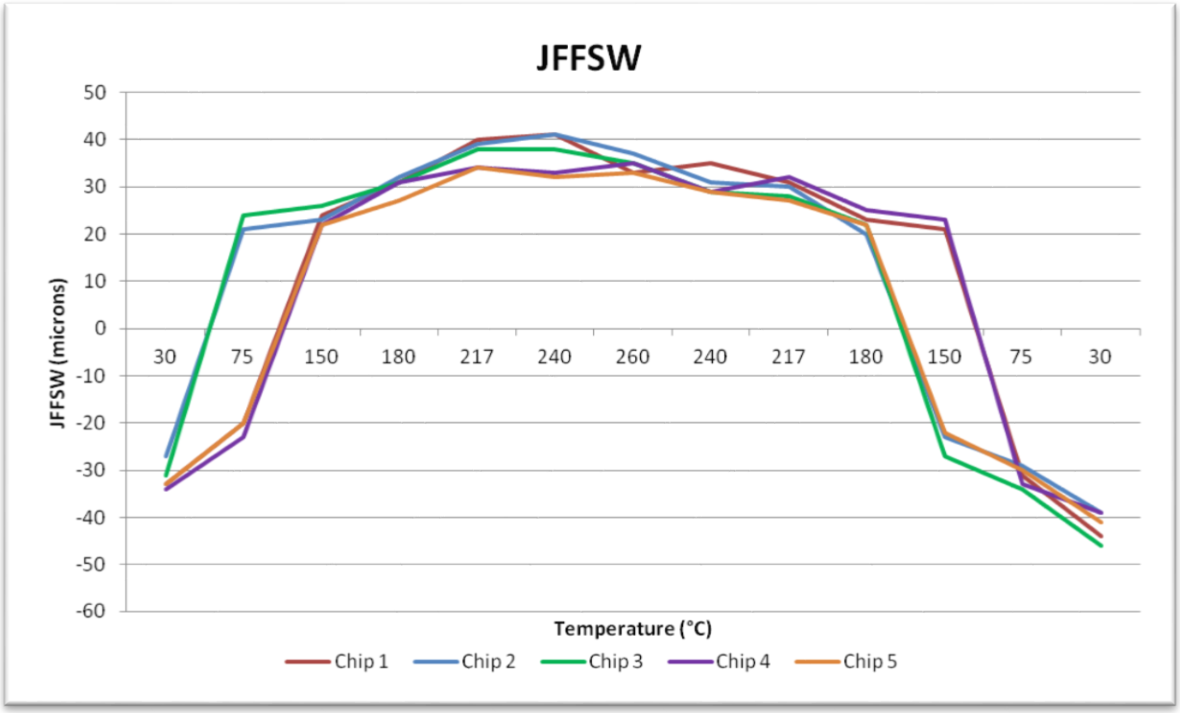


Figure 3. JFFSW, 5 Chip on Board Samples

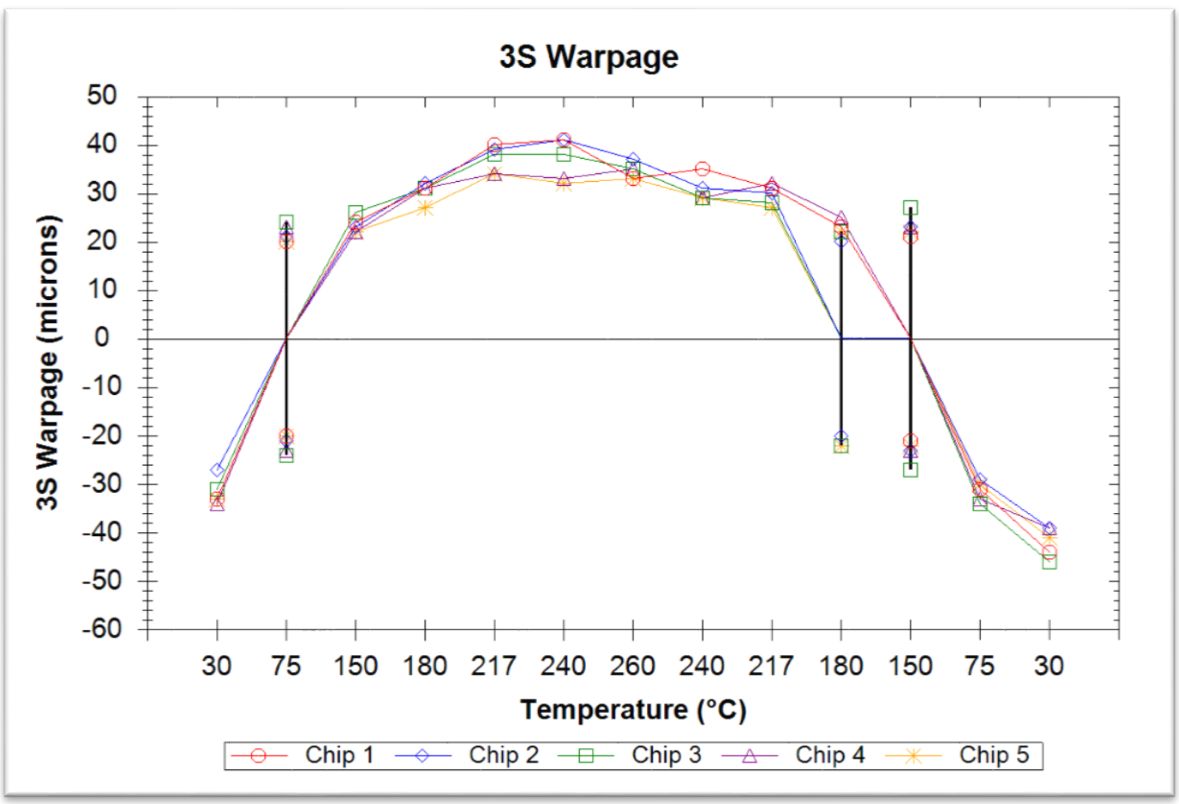


Figure 4. 3S Warpage, 5 Chip on Board Samples

In more extreme cases the swap from positive to negative can further misrepresent the difference in two sample shapes, as in the example from the previous paper [5], seen in Figures 5, 6a and 6b.

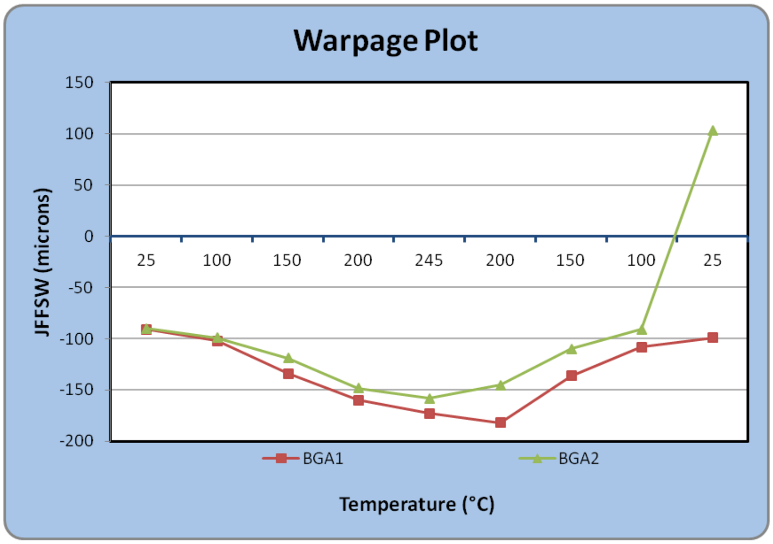
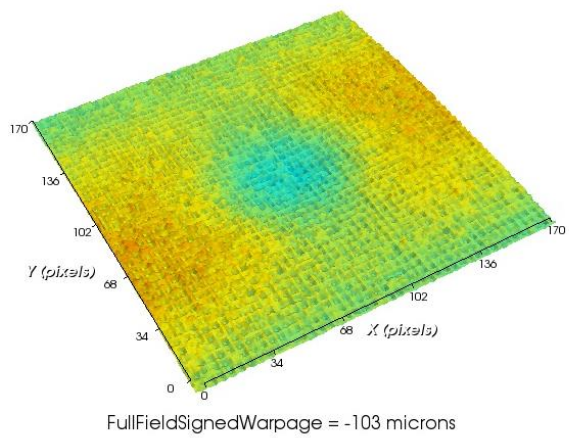


Figure 5. JFFSW, Sign Confusion Case [5]



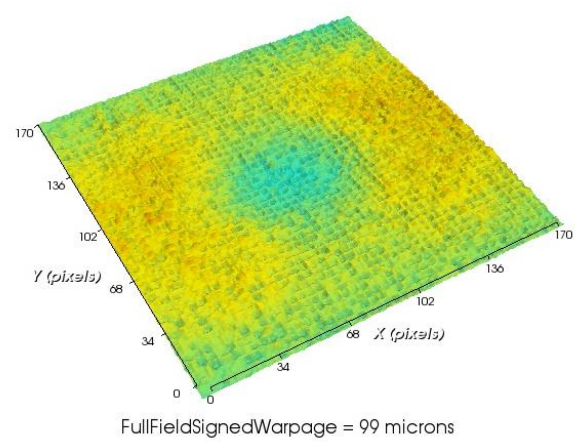


Figure 6a. Negative Saddle [5]

Figure 6b. Positive Saddle [5]

Certainly the sample surfaces from Figure 6a and 6b should not be interpreted as having a difference of 202 microns, which is the difference in their signed warpage. This new approach including transition surfaces will reduce confusion between companies and users attempting to communicate sample thermal warpage. 3S Warpage stands alone in the industry at this time as a proposal to improve thermal warpage interpretation and decision making. However, some of the same concepts can be taken a step further and lead to classifying shape types by name.

Refining Shape Naming Based on Case Study Examples

Initial concepts for shape naming put samples into four general categories: planar/complex, saddle, pipe, and dome/bowl. Realistically, samples will have any number of surface contours, but these general categories define a realistic starting point. In further efforts it became straight forward to give the saddle and pipe categories an X and Y direction. The final goal is to understand how surfaces fit together in SMT. Thus two "pipe" samples with equal JFFSW values would conceptually fit well together, this assumption would only hold true if the pipe ran along the same axis in X and Y. Take two pipes that fit together and rotate one 90°; this leaves two surfaces that have noticeable gaps in attachment while at the same JJFSW value. Similar to Signal Strength, shape naming was done by using the "ex^2" and "fy^2" terms of a 2nd order polynomial fit of the surface. Additionally, examples were found in a 2nd order polynomial fit where the "dxy" coefficient was much larger than the "ex^2" and "fy^2" terms. Considering only e and f coefficients a sample appearing to be "twisted" would fall into the complex/planar category. A clear shape could be seen, similar to a saddle shape, but running diagonally across the sample. In the initial iteration of this concept the twist factor was used as an additional descriptor of the sample shape.

For these original classifications a few examples were used to mathematically classify surface shapes. Primary goals for shape naming and this case study include:

- Deciding on a realistic group of shape names, balancing complexity and specificity.
- Experimentally finalizing mathematical thresholds for shape names.

Prior to this paper the working mathematical concepts and shape name logic were as follows: [5]

If

$$\frac{ABS(em^2) + ABS(fn^2)}{4 * coplanarity} < 35\%$$

then shape is Planar/Complex, if not then classify as follows:

$$\frac{fn^2}{em^2} < 2 \; and \; \frac{em^2}{fn^2} < 2, where\ e\ and\ f\ are\ positive = Bowl$$

$$\frac{fn^2}{em^2} < 2 \; and \; \frac{em^2}{fn^2} < 2, where\ e\ and\ f\ are\ negative = Dome$$

$$\frac{fn^2}{em^2} < 2 \; and \; \frac{em^2}{fn^2} < 2, where\ e\ is\ positive\ and\ f\ is\ negative = X\ Saddle$$

$$\frac{fn^2}{em^2} < 2 \; and \; \frac{em^2}{fn^2} < 2, where\ e\ is\ negative\ and\ f\ is\ positive = Y\ Saddle$$

$$abs(\frac{fn^2}{em^2}) > 2 = Y\ Pipe$$

$$abs(\frac{em^2}{fn^2}) > 2 = X\ Pipe$$

Additionally, twist was used as an additive term, as in “twisted” bowl shape, defined when:

$$\frac{abs(dmn)}{abs(em^2) + abs(fn^2)} > 0.35$$

This was a good starting point for shape names, but with a more extensive case study, numerous improvements and refinement of these thresholds could be made. In order to establish a “correct” shape, an experienced user went through the majority of the case study data and qualitatively assigned shape namesbased on the samples 3D surface rendering and, at times, 2D diagonal plots. With this qualitative data the math was refined, reorganized, and renamed in an iterative process to maximize the match with the qualitative findings.

The following steps were taken during the iterative, experimental method to adjust shape naming:

- Using twist as an additional modifier was determined to be too confusing and complex, thus twist was made its own shape category, coming at the beginning of the beginning of the logic statements, since it was the only equation considering the “dxy” term. Direction of twist is also differentiated, “Upward Twist” and “Downward Twist”.
- Changed the pipe threshold to include absolute value in the logic statements and change the threshold from 2.0 to 2.5, causing more bowl, dome, and saddle shape names, and fewer pipe results.
- Adjusted weighting of pixel dimensions in shape definitions. Lateral dimensions squared makes sense for the Signal Strength calculations, but with shape naming, squaring lateral dimensions put too much emphasis on the longer dimension in rectangular samples. A linear relationship was attempted, but this did not place enough weight on lateral dimensions. The best match with qualitative shape assignments became a 3/2 power used in pipe, bowl/dome, and saddle definitions.
- Changed the “transition” threshold to 25%, as referenced in earlier sections. Similarly, the threshold for the Planar/Complex was adjusted from 0.35 to 0.25. The category was renamed to Complex/Flat.

With these changes in place the final shape name logic is proposed as follows. Note that the order is critical to the logic:

If ,

$$\frac{ABS(dmn)}{ABS(em^2)+ABS(fn^2)} > 0.35, AND\ d > 0;\ then\ shape = Upward\ Twist$$

$$\frac{ABS(dmn)}{ABS(em^2)+ABS(fn^2)} > 0.35, AND\ d < 0; then\ shape = Downward\ Twist$$

$$\frac{ABS(em^2)+ABS(fn^2)}{4 * coplanarity} \leq 25\%; then\ shape = Complex/Flat$$

$$ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) \geq 2.5; then\ shape = Y\ Pipe$$

$$ABS\left(\frac{em^{1.5}}{fn^{1.5}}\right) \geq 2.5; then\ shape = X\ Pipe$$

$$ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) < 2.5, AND\ ABS\left(\frac{em^{1.5}}{fn^{1.5}}\right) < 2.5, AND\ e > 0, AND\ f > 0; then\ shape = Bowl$$

$$ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) < 2.5, AND\ ABS\left(\frac{em^{1.5}}{fn^{1.5}}\right) < 2.5, AND\ e < 0, AND\ f < 0; then\ shape = Dome$$

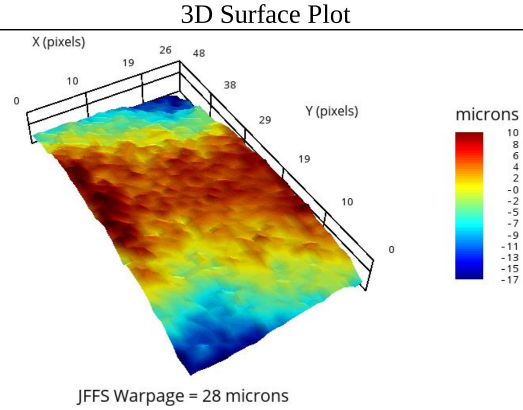
$$ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) < 2.5, AND\ ABS\left(\frac{em^{1.5}}{fn^{1.5}}\right) < 2.5, AND\ e > 0, AND\ f < 0; then\ shape = X\ Saddle$$

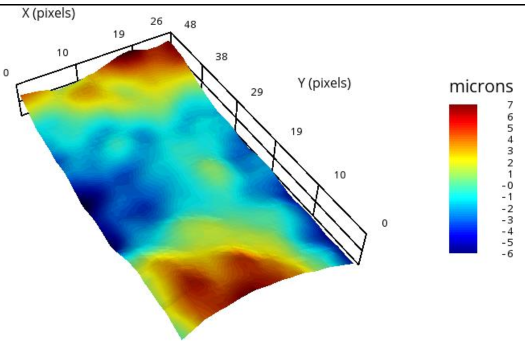
$$ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) < 2.5, AND\ ABS\left(\frac{em^{1.5}}{fn^{1.5}}\right) < 2.5, AND\ e < 0, AND\ f > 0; then\ shape = Y\ Saddle$$

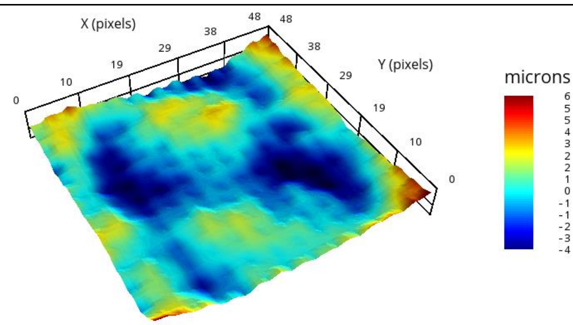
Following the order of this logic the $ABS\left(\frac{fn^{1.5}}{em^{1.5}}\right) < 2.5, AND\ ABS\left(\frac{em^2}{fn^2}\right) < 2.5$ term can be removed from the Bowl, Dome, X Saddle, and Y Saddle definitions, but they are shown here to explain the concept, and define each shape individually.

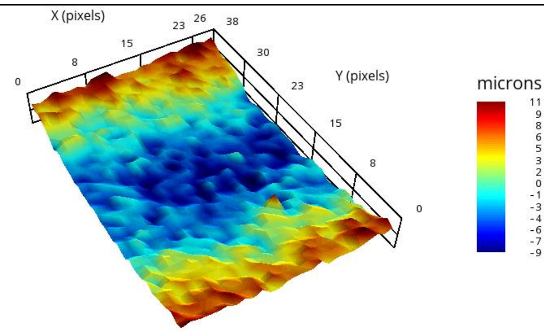
Case Study Results Summary with 3S Warpage and Shape Naming
A single 3D surface plot for each shape name is shown, from the case study samples, in Table 2 below.

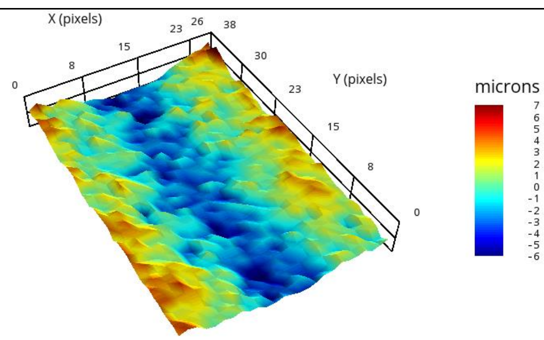
Table 2. Shape Examples from Case Study

Shape Name	3D Surface Plot
Upward Twist	

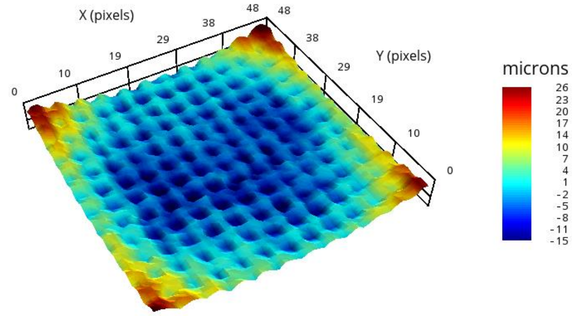
<table>
<tr><td>Downward Twist</td><td>

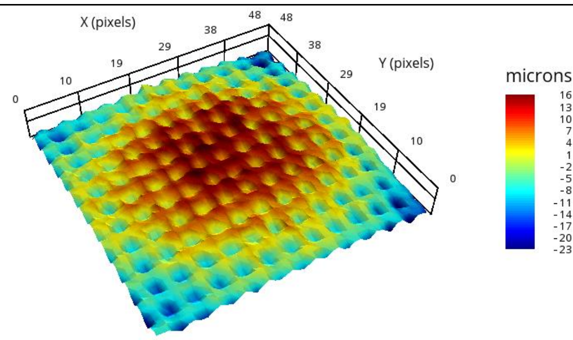
JFFS Warpage = -13 microns</td></tr>
<tr><td>Complex/Flat</td><td>

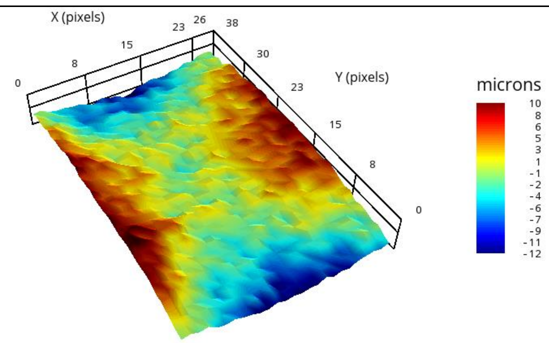
JFFS Warpage = -10 microns</td></tr>
<tr><td>Y Pipe</td><td>

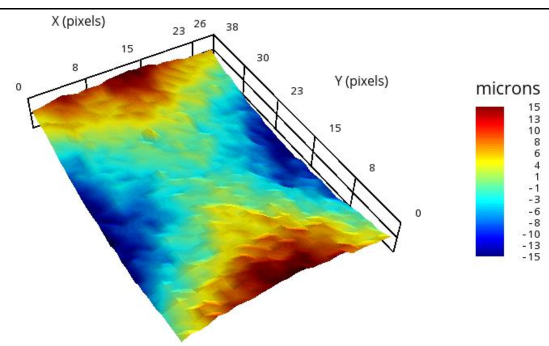
JFFS Warpage = -19 microns</td></tr>
<tr><td>X Pipe</td><td>

JFFS Warpage = -13 microns</td></tr>
</table>

<table>
<tr><td>Bowl</td><td>

JFFS Warpage = -41 microns</td></tr>
<tr><td>Dome</td><td>

JFFS Warpage = 40 microns</td></tr>
<tr><td>X Saddle</td><td>

JFFS Warpage = 22 microns</td></tr>
<tr><td>Y Saddle</td><td>

JFFS Warpage = -30 microns</td></tr>
</table>

The case study, covering 5 different sample types, included over 1500 warpage measurements, and thus a full list of all shape names is not included in this report for practicality. Instead a count for each sample descriptor category is shown in Table 3, summarizing quantities of positive, negative, and transition surfaces, as well as a count for each sample shape.

Table 3. Summary of 3S Warpage and Surface Shapes for Case Study (sign convention corrected for orientation)

Sample Type	Pos.	Neg.	Tran.	Flat	Y Pipe	X Pipe	Y Saddle	X Saddle	Bowl	Dome	Down Twist	Up Twist
BoC, 1DP	104	75	120	3	84	53	35	61	15	26	9	13
CoB, 2DP	24	31	62	8	8	2	0	2	29	56	7	5
Large FBGA, 1DP	40	83	150	23	84	10	7	0	0	141	4	4
MCP, 5DP	56	110	146	8	93	28	4	23	50	89	7	10
PoP, 1DP	35	82	481	7	42	32	0	9	40	425	34	9
Totals:	259	381	959	49	311	125	46	95	134	737	61	41

New Warpage Data Deliverable Proposal

So, why does this matter?

As BGA and other package types become thinner, the propensity for the ill effects of warpage to impact the electronics industry increases dramatically, and can affect all package types with some detrimental impact. Thinner and larger package types, translate to a shape-naming movement away from the normal "concave" and "convex" shapes. This movement will demand that engineers involved with warpage analyses incorporate novel methods to not only predict these shapes, but to also assure a consistent approach to (1) identifying the shapes, and (2) describing with uniformity the shape profiles.

Algorithms associated with the predictive nature of this method will also be required when developing the data crunching processes within the tools which are used in warpage analysis. These algorithms will therefore be required to have consistency, such that the output can be readily used to effect changes to the manufacturing and engineering that may be associated with warpage improvement.

There will also be a requirement for GR&R (gauge repeatability and reproducibility) methodologies for the tools used in these processes. The GR&R topic will be approached in another paper, which will attempt to present a novel methodology when solving GR&R limitations within the warpage analysis field.

Overall, the intent of the case study and analysis is to present to the user several improvements for warpage prediction, leading to:

- Better predictions for warpage compatibilities between two contacting surfaces.
- A clearer understanding of warpage shapes, and what can be accomplished with the improved methods for categorizing complex warpage shapes.
- Better refinement with respect to the accuracy surrounding the "zero point" for complex shapes.

Summary/Conclusions

A large quantity of surface mount packages were measured by shadow moiré metrology to capturewarpage levels, as the samples were heated through a reflow profile. Found warpage data was used to improve upon new methods of communicating surface shape, when dealing with large quantities of data.

JEDEC Full Field Signed Warpage (JFFSW) is already an often preferred gauge over the industry standard signed warpage, used by many industry leading companies, as the critical gauge for package warpage. This paper goes a step further in refining understanding of package shape, by introducing a new gauge, 3S Warpage. 3S Warpage not only classifies shapes as positive and negative, but also mathematically defines a third indeterminate category,labeled as a transition surface. This added category is designed to limit confusion in summarizing package 3D surface shape with a single gauge.

Packages from the case study were also assigned a shape name, established by newly established algorithms. Shape naming algorithms were improved through an iterative process, when compared with qualitative shape assignments. The shape name adds a new variable that can be tracked and correlated over time with surface mount attachment reliability and surface to surface mating. These shape names can be used in establishing package trends and for further, future understanding of assembly yield based upon package warpage.

Next Steps/ Future Work

One of the more applicable approaches to this analysis would be to run the modeling and data from the paper through a Monte Carlo simulation. Several benefits can be garnered from this approach: innumerable model runs which can be associated with any one particular mathematical model, a multiplicity of model definitions can be reviewed quickly for application to the various complex shapes, no defined limit on the order of the algorithms, etc. This will be a main next step, to define the Monte Carlo simulation parameters and run several iterations. The process now is manually-iterative in nature, thus the Monte Carlo approach will afford the opportunity to perform simulations at a greater speed with a greater span of coverage.

Further analysis using newer PoP devices, can be used to compare the results to the complex shapes garnered thus far. This addition to the model family will not only yield a larger span of influence for strength in our predictive power, but it will also allow the development of "subsystem trending" and apply those trends to future package development activities.

We also plan to invoke these improved algorithms within the shadow moiré metrology equipment lines, so that the industry at-large can benefit from this increased accuracy concerning the analysis and comparison of complex shapes to warpage performance.

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