Improvements in Decision Making Criteria for Thermal Warpage*

Neil Hubble
Akrometrix, LLC
Atlanta, GA. USA
nhubble@akrometrix.com

ABSTRACT

Surface mount components are commonly evaluated for out-of-plane warpage levels across reflow temperatures. Decision making for acceptable warpage levels is primarily made based on signed warpage levels of a single component surface, per industry standards. This paper discusses how a single signed warpage value is an oversimplified and incomplete way to describe a surface mount attachment between two mating surfaces that change in shape over temperature. Specific examples are shown where current industry standard gauges for thermal warpage are misleading. Issues include current industry standard equations for calculation of signed warpage.

Optimal understanding of effects of warpage on surface mount attachment includes analysis of both mating surfaces under the same thermal and test conditions. Examples are shown of dual surface analysis, where gap between mating surfaces becomes the critical value in place of signed warpage. Evaluating both sides of two attaching surfaces is the optimal way to understand surface mount defects related to thermal warpage. However, many companies dealing with SMT will not have reasonable access to the surfaces to which their products will be attached. The paper goes on to discuss different approaches to more effectively quantify a single surface over temperature. This includes, but is not limited to, adding equations for signal strength values to currently established signed warpage standards.

INTRODUCTION

How do you take a 3 dimensional surface rendering and fully quantify this surface by a single number? The short answer is that you cannot. However, this is exactly how pass/fail decisions are made for surface warpage in the microelectronics industry. Qualitative analysis of warpage looking at a 3D rendering itself has its place in understanding potential areas of concern, but cannot be expected to yield consistent conclusions between different companies and users.

Both JEDEC and JEITA have similar standards covering thermal warpage measurement of BGAs and LGAs. JESD22-B112A [1] from JEDEC and ED-7306 [2] from JEITA explain how to measure package warpage and, additionally, provide pass/fail criteria based on various sample dimensions. Similarly, a standard from IPC, IPC-9641 "High Temperature Printed Board Flatness Guideline" [3], covers appropriate methods for measuring thermal warpage of a PCB in the area where a surface mount component will be placed. The IPC standard stops at defining test approaches for thermal warpage and does not move on to define pass/fail criteria for local PCB areas.

This paper discusses weaknesses in the current "signed warpage" standard used for decision making for warpage on BGAs and LGAs. Common mistakes and areas of confusion in practical applications of available thermal warpage standards are shown. Analysis of both sides of attaching surfaces remains an optimal solution, though not always a practical solution for all companies. Therefore, additional approaches to better quantify and understand 3D surfaces shapes are presented.

SIGNED WARPAGE CALCULATION WEAKNESSES

JEITA ED-7306 defines signed warpage by the following equation:

$$AB_{MAX} + AB_{MIN} + CD_{MAX} + CD_{MIN}$$

where AB_{MAX} is the largest positive displacement and AB_{MIN} is the largest negative displacement of the package profile on the diagonal AB, and CD_{MAX} is the largest positive displacement and CD_{MIN} is the largest negative displacement of the package profile on the diagonal CD [2].

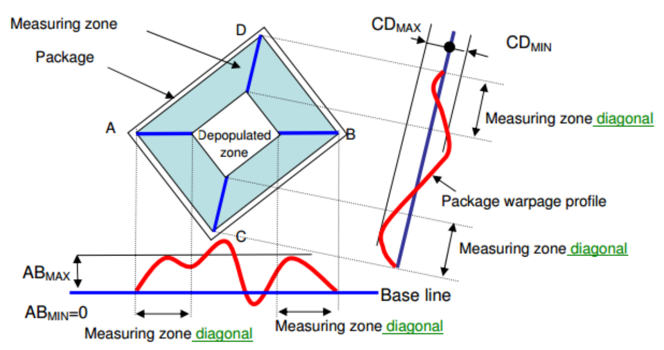

Figure 1. Calculation of signed warpage from JEITA ED-7306 [2]

For most samples and common shapes the signed warpage gauge defined by JEITA serves as an acceptable mathematical definition of warpage direction. However, the standard has three distinct weaknesses in defining warpage direction:

1. Areas of the sample surface outside of the diagonal lines are not considered when deciding the direction of warpage.
2. The gauge is highly sensitive to measurement noise or local height features since the equation is based on 4 single data points.
3. The gauge calculation fails if corner data is not included in the data set, since the diagonal lines cannot be normalized.

Consider the example surface in **Figure 2** below of a BGA with solder balls removed. In this example the entire surface area of the warpage map is covering the BGA interface.

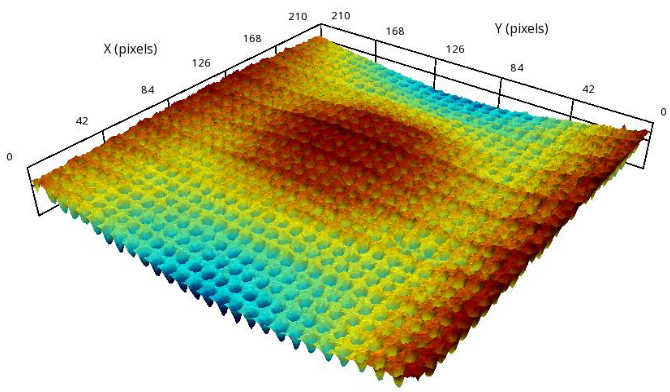

Figure 2. 3D Surface Warpage, BGA

This example can be used to illustrate the first two stated weaknesses of the signed warpage gauge. The third weakness considering no corner data is straight forward, and no example is provided here. First, to better highlight how the signed warpage gauge works, consider the surface diagonal line plot in **Figure 3**. Here the diagonal lines are simply an extraction of the data set from **Figure 2**. The signed warpage is specifically calculated by the "normalized" diagonals lines, meaning the ends of the diagonal line are rotate to the zero reference plane. **Figure 4** shows the normalized diagonals lines used in the signed warpage calculation.

As these figures are from a real, and rather detailed, surface map, the height values have been removed. However, even without the scale it is straightforward to determine that the signed warpage calculation will easily produce a negative number. In this real world example we would actually invert the sign of the signed warpage gauge to match the convention since the surface is shown in a "dead bug" position. For the purpose of this section let us consider the signed warpage to be negative, or bowl shaped, for this plot.

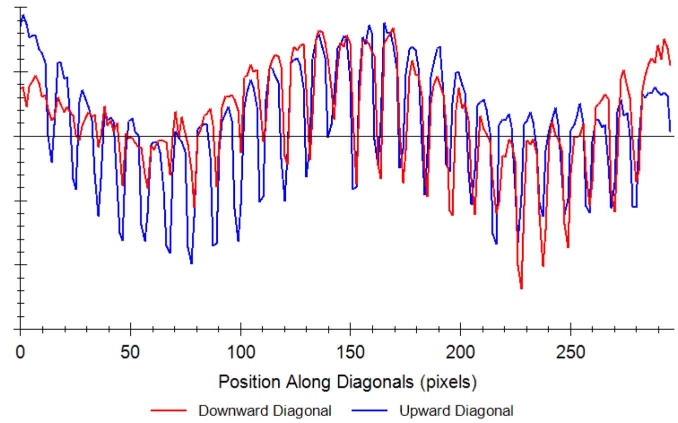

Figure 3. 2D Diagonal Plot, BGA

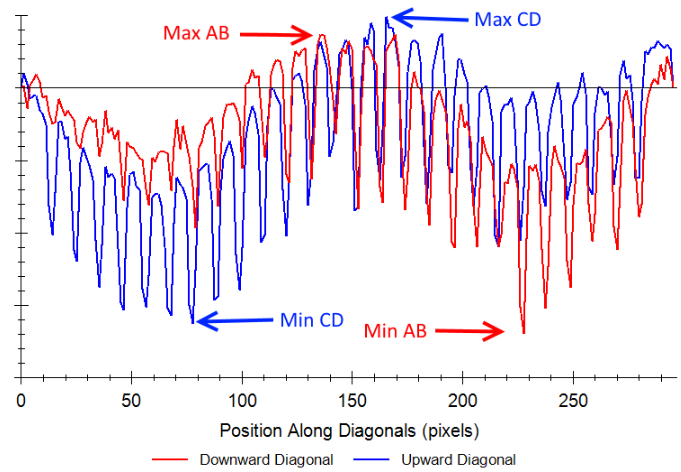

Figure 4. 2D Diagonal Plot (Normalized), BGA

With this example in place we can consider the original statements about the weakness of the signed warpage gauge. Restated:

1. Areas of the sample surface outside of the diagonal lines are not considered when deciding the direction of warpage.

Qualitatively, a strong argument can be made for the BGA sample shown in **Figure 2** to be considered positive, or dome shaped. This appearance of a dome shape comes primarily from the data in the near and far edges of the surface, which are not shown in the 2D Diagonal plots. A quantitative argument is made further in this paper for this shape to be correctly named a positive warpage sign or dome. However, the signed warpage calculation calculates a negative number by a sizeable margin.

2. The gauge is highly sensitive to measurement noise or local height features since the equation is based on 4 single data points.

This BGA has some shaped overall contours, but the data set provided by a shadow moiré measurement tool also shows the details of the BGA solder pads. The height of these local features plays a large role in the signed warpage calculation. While the local features for this data set are rather patterned, consider the effect on the signed warpage calculation if only one of these solder pad low points is part of the data set. If taking a lower subset of warpage data, as with a point to point technique, this issue can be exacerbated if some points fall on the solder mask area and others fall into solder pad areas.

IMPROVED SIGNED WARPAGE BASED ON FULL FIELD

To address the weaknesses of the signed warpage gauge a different mathematical approach to the data set can be used. The gauge referred to as "JEDEC Full Field Signed Warpage (JFFSW)" is already an established best practice for Akrometrix, a thermal warpage measurement OEM, and is recommended over the current signed warpage industry standard in best practice documentation.

To calculate JFFSW the data set is fit to a second order polynomial surface fit. The equation for this two variable 2nd order polynomial is:

$$z = a + bx + cy + dxy + ex^2 + fy^2$$

where z is the out-of-plane shape and x and y represent the in-plane coordinate system for the sample. Applying this surface fit to the example from **Figure 2** generates **Figure 5** below.

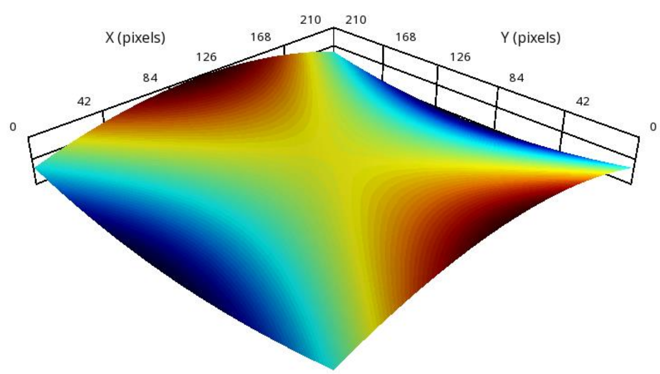

Figure 5. 3D Surface after 2nd Order Polynomial Fit

The curvature of this surface can now be defined by the "e" and "f" coefficients on the x^2 and y^2 terms of the 2nd order polynomial equation. In order to appropriately relate the "e" and "f" terms the ratio of the x and y dimensions of the surface must be considered. Note that this does not require physical dimensions of the surface to be known; only the relationship between the x and y dimensions needs to be known. Here the "distance" of the surface in x is defined by the variable "m" and the "distance" of the surface in y is defined by the variable "n". When a 2nd order polynomial fit is done on a data set the JEITA provided signed warpage equation on the normalized diagonals can also be considered.

Having only a single inflection point in the case of the 2nd order polynomial fit surface the normalized diagonals by definition will always have maximum and minimum occur at either both end points or the center point of the diagonal. With this information we can use the terms defined in the 2nd order polynomial equation to solve for signed warpage.

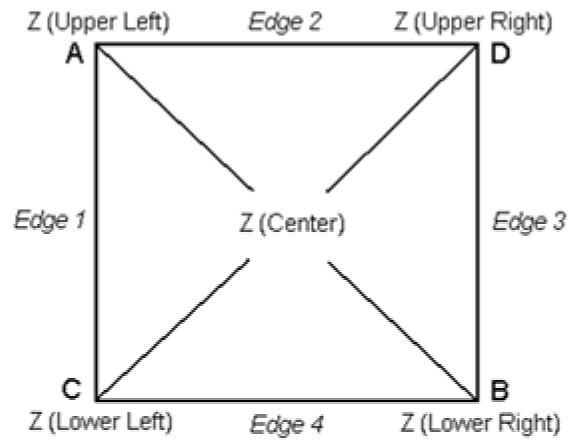

Figure 6. Data Set Top View

We will define Z at the four corners and center point of our part as shown in **Figure 6** above. Here the upper left corner is at (X, Y) = (0,0):

For a 2nd order polynomial:

$$Z(UL) = a$$

$$Z(UR) = a + bm + em^2$$

$$Z(BL) = a + cn + fn^2$$

$$Z(BR) = a + bm + cn + dmn + em^2 + fn^2$$

$$Z(Center) = a + b\frac{m}{2} + c\frac{n}{2} + d\frac{mn}{4} + e\frac{m^2}{4} + f\frac{n^2}{4}$$

Without knowing the shape of the part one cannot say whether the maximum or minimum will occur at the ends of these diagonals or the center. Still we know that both must occur at these locations and that, with the normalized diagonal, the end points will be equal to zero. Therefore we can re-write the signed warpage equation in the following manner, by averaging the end points and using the Z height at the data center point to replace the max and min terms of the diagonals:

$$\max(AB) + \min(AB) = \frac{Z(UL) + Z(BR)}{2} + Z(Center)$$

$$\max(CD) + \min(CD) = \frac{Z(UR) + Z(BL)}{2} + Z(Center)$$

Notice that in this equation which term represents the diagonal max and which represents the diagonal min does not matter since the order of the terms does not matter, as they are added to one another.

Replacing the Z values with the terms from the 2nd order polynomial gives:

$$\frac{Z(UL)+Z(BR)}{2}+Z(Center) = \frac{(a)+(a+bm+cn+dmn+em^2+fn^2)}{2}+(a+b\frac{m}{2} + c\frac{n}{2}+d\frac{mn}{4}+e\frac{m^2}{4}+f\frac{n^2}{4})$$

and…

$$\frac{Z(UR)+Z(BL)}{2}+Z(Center) = \frac{(a+bm+em^2)+(a+cn+fn^2)}{2}+(a + b\frac{m}{2}+c\frac{n}{2}+d\frac{mn}{4}+e\frac{m^2}{4}+f\frac{n^2}{4})$$

We also know that all the diagonal corner terms equal 0 and can simplify this to:

$$\frac{Z(UL)+Z(BR)}{2}=a+\frac{bm}{2}+\frac{cn}{2}+\frac{dmn}{2}+\frac{em^2}{2}+\frac{fn^2}{2}=0$$

and…

$$\frac{Z(UR)+Z(BL)}{2}=a+\frac{bm}{2}+\frac{cn}{2}+\frac{em^2}{2}+\frac{fn^2}{2}=0$$

We can pull these terms from the Z(Center) term as well since it is known they equal 0.

$$Z(Center)=(a+\frac{bm}{2}+\frac{cn}{2}+\frac{dmn}{2}+\frac{em^2}{2}+\frac{fn^2}{2}) + (-\frac{dmn}{4}-\frac{em^2}{4}-\frac{fn^2}{4})$$

and…

$$Z(Center)=(a+\frac{bm}{2}+\frac{cn}{2}+\frac{em^2}{2}+\frac{fn^2}{2})+(\frac{dmn}{4}-\frac{em^2}{4} -\frac{fn^2}{4})$$

Now adding the AB and CD diagonal terms together and canceling terms:

$$\max(AB)+\max(CD)+\min(AB)+\min(CD) = \frac{-dmn-em^2-fn^2+dmn-em^2-fn^2}{4} = -\frac{em^2+fn^2}{2}$$

Since magnitude is not considered for JFFSW we can further simplify the algorithm for JFFWS to:

$$-(em^2+fn^2)$$

Again considering **Figure 2**, the result of applying the JFFSW gauge to this data set now generates a positive result, which is opposite of the result from the signed warpage calculation. We can readdress the initial issues with the signed warpage gauge as follows:

1. JFFSW considers all areas in the data set and not just the diagonals of the surface.
2. JFFSW final results are calculated based on a surface fit of the entire data set and are not highly influenced by spikes in the data.
3. Abnormal shapes or areas of missing data pose no problem for JFFSW to define positive or negative warpage direction.

CONFUSION WITH CHANGING WARPAGE SIGN

Now that our gauge to calculate warpage direction has been improved, the issue remains that many 3D surfaces do not effectively fit into the positive dome and negative bowl shape definitions. Different ways to define these complex shapes are discussed further in this paper, but first we should look at real world examples that can confuse engineers analyzing warpage data. This discussion is valid regardless of the gauge choice for the signed warpage convention.

Two 3D and 2D diagonal data sets are shown in **Figure 7**-**Figure 10** below. These data sets are from two different packages of the same model taken at the conclusion of a reflow profile at room temperature.

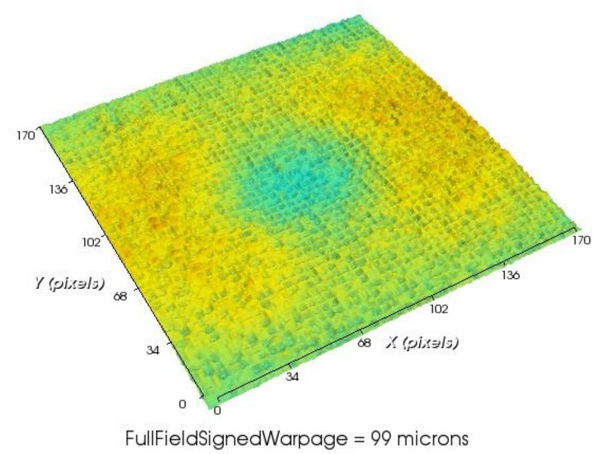

Figure 7. Saddle shape, BGA1

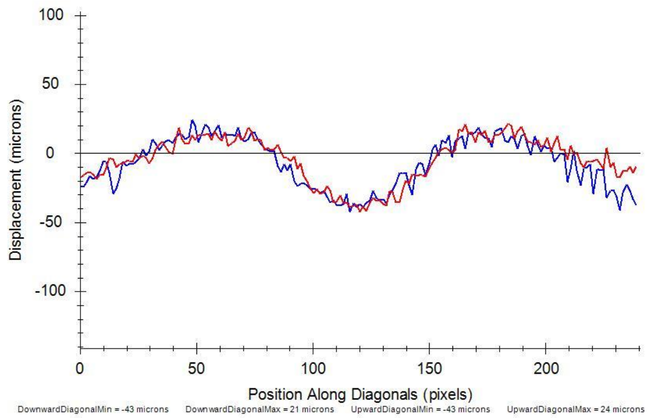

Figure 8. Saddle Shape, BGA1, Diagonals

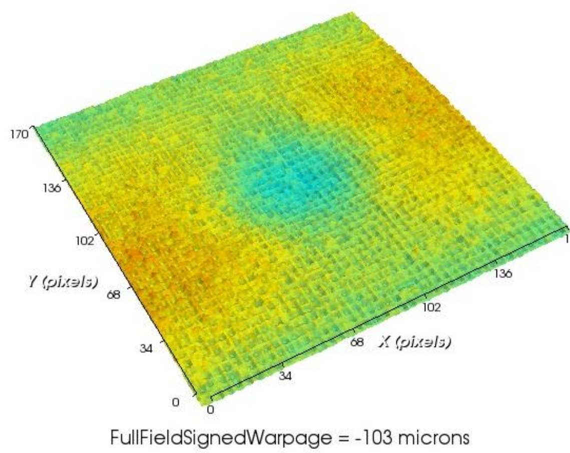

Figure 9. Saddle Shape, BGA2

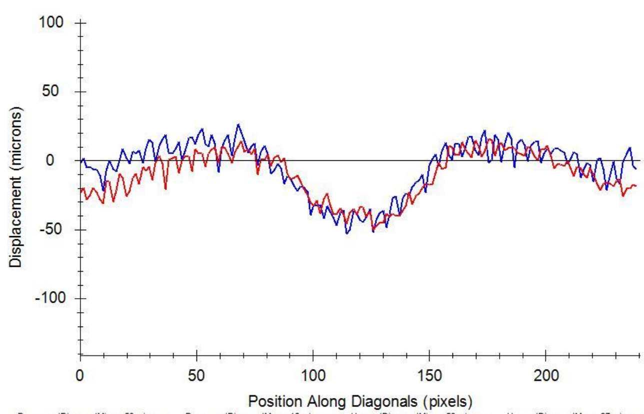

Figure 10. Saddle Shape, BGA2, Diagonals

Visually the two parts in the diagrams above look very similar. However, the gauge information shows JFFSW for BGA1 at -99 microns, and for BGA2 at +103 microns. The conclusion of this fact is that without examining the part surface images, graphing the JFFSW gauge does not give enough information. Based solely on the JFFWS gauge the customer can be led to believe that there could be as much as a 200 micron relative difference in shape between BGA1 and BGA2. Numerous real examples of warpage direction inverting for very similar data sets can be found, as this is a common misconception concerning signed warpage data.

Further sections in this paper discuss how to resolve the misconception that can be caused by analysis of surface topography by only a single signed warpage value.

DUAL SURFACE ANALYSIS

The optimal approach to resolve confusion in representation of sample shapes as gauge values is to analyze both surfaces of a surface mount attachment. By analyzing both surfaces and making decisions based on the gap between two 3D surfaces, complexity in numerical representation of shape goes away. With dual surface analysis complex shapes are already taken into account when being matched with a mating surface.

Conclusions suggesting the component warpage standards by JEITA and JEDEC are not enough to fully define issues with surface mount attachment due to warpage have been made previously and at some length. 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] Similarly, "Advanced Second Level Assembly Analysis Techniques - Troubleshooting Head-In-Pillow, Opens, and Shorts with Dual Full-Field 3D Surface Warpage Data Sets" concludes that "To best avoid and compensate for designs that have a tendency to develop shorts, opens, or head-in-pillow defects, companies responsible for development of components on either side of the assembly also need to plan for how the shape of that component will match with its mating part, to ensure that expected gaps at each critical temperature point are appropriate." [5]

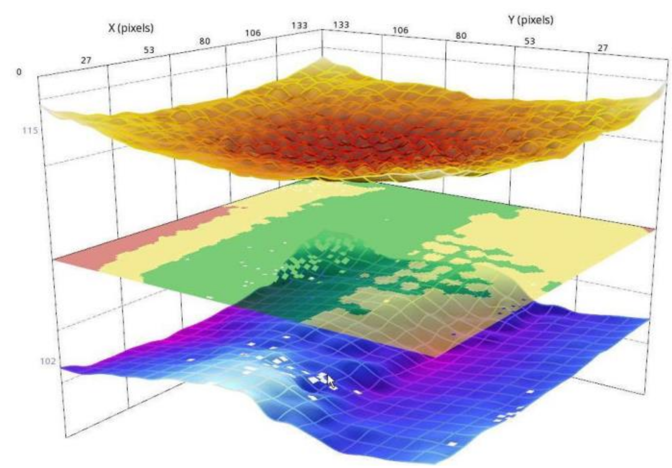

Figure 11. BGA to PCB mating with Pass/Warning/Fail Map [5]

Advanced interface analysis technologies can be used to quantify maximum gaps between two mating surfaces at each point in time and temperature to best understand areas of highest risk for surface mount defects. As this topic has been discussed at length in previous publications, this paper will not focus on this point.

While the dual surface analysis approach is optimal, it is not always practical. Component manufacturers are looking to perform quality assurance on their products going out the door. Finding all surfaces that said components will be attaching to, may be impractical and requires much coordination between different companies. Realistically, quality decisions on package warpage are still frequently being made based on signed warpage and not dual surface gap analysis. With JFFSW defined to improve upon signed warpage, how else can we further communicate package shape numerically?

SIGNED WARPAGE SIGNAL STRENGTH

In order to better represent a shape as a "positive" or "negative" warpage direction, a method of quantifying to what degree that shape is positive or negative is needed. Signed warpage or JFFSW use the coplanarity value (highest point – lowest point) as the magnitude of the gauge, so the saddle shapes seen in **Figure 7**-**Figure 10** are not conveyed unless an engineer visually reviews the plots.

In order to quantify the amount of positive or negative shape in a 3D surface, a new parameter, "Signal Strength" (SS), is defined here. Consider the case of a perfect bowl or dome shape and the signed warpage gauge. The signed warpage equation will result in the largest and smallest possible values for this equation if the surface is a bowl or dome shape. Returning to the signed warpage equation:

$$AB_{MAX} + AB_{MIN} + CD_{MAX} + CD_{MIN}$$

For a perfect dome shape:

$$AB_{MAX} = Coplanarity, AB_{MIN} = 0$$

$$CD_{MAX} = Coplanarity, CD_{MIN} = 0$$

thus

$$AB_{MAX} + AB_{MIN} + CD_{MAX} + CD_{MIN} = 2 * Coplanarity$$

For a perfect bowl shape:

$$AB_{MAX} = -Coplanarity, AB_{MIN} = 0$$

$$CD_{MAX} = -Coplanarity, CD_{MIN} = 0$$

thus

$$AB_{MAX} + AB_{MIN} + CD_{MAX} + CD_{MIN} = -2 * Coplanarity$$

Therefore, if we define Signal Strength as a percentage:

$$Dome: SS = \frac{Coplanarity + 0 + Coplanarity + 0}{2 * Coplanarity} = 100\%$$

$$Bowl: SS = \frac{0 + -Coplanarity + 0 + -Coplanarity}{2 * Coplanarity} = -100\%$$

Since sign is already indicated by the signed warpage gauges, we can take the absolute value of the equation result.

$$SS = ABS(\frac{MaxAB + MinAB + MaxCD + MinCD}{2 * Coplanarity})$$

To take advantage of this new gauge definition we can apply this math to the shapes in **Figure 7**-**Figure 10**. As expected the Signal Strength numbers for the two saddle shape surfaces are rather low. **Figure 7** has a Signal Strength value of 23% and **Figure 9** has a Signal Strength value of only 5%. Looking at a graph of JFFSW in **Figure 12**, the final room temperature measurement jumps out to the user as an outlier, even though visual inspection of the surfaces shows that they are quite similar. The following table shows the JFFSW numbers alongside corresponding Signal Strength values with highlights on lower Signal Strength results.

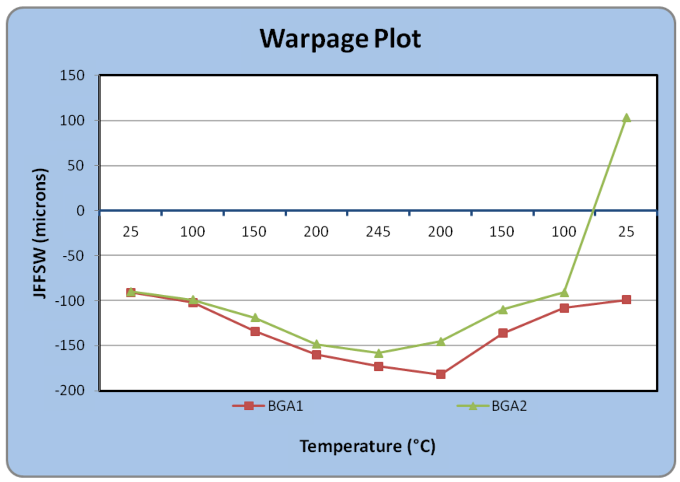

Figure 12. JFFSW for BGA1 and BGA2

Table 1. JFFSW with Signal Strength included

		JFFSW (microns)								
		Temperature (°C):								
Sample:	**Side:**	25	100	150	200	245	200	150	100	25
BGA1	Attach	-91	-102	-134	-160	-173	-182	-136	-108	-99
BGA1 Signal Strength		46%	57%	69%	73%	81%	71%	72%	57%	23%
BGA2	Attach	-90	-99	-119	-148	-158	-145	-110	-91	103
BGA2 Signal Strength		44%	60%	65%	67%	72%	77%	52%	42%	5%

To show a contrast in the appearance of a surface based on the Signal Strength calculation, **Figure 12** shows BGA1 at 245°C with a Signal Strength result of 81%.

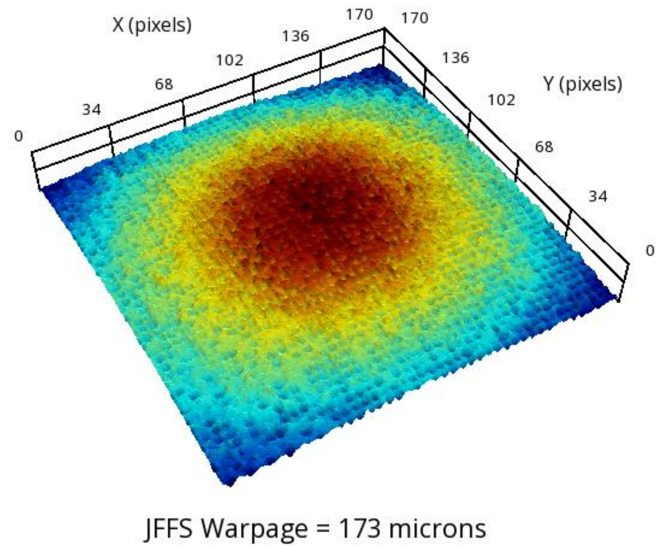

Figure 13. BGA1 at 245°C with an 81% Signal Strength

APPLYING SIGNAL STRENGTH GAUGE TO JEDEC FULL FIELD SIGNED WARPAGE

A similar approach to define a Signal Strength gauge based on the JFFSW gauge can be taken. Again, considering a perfect dome or bowl shape, the corners and center point would define the maximum and minimum of your data set.

$$ABS(Average\ Z\ height\ of\ the\ 4\ data\ set\ corners - Z\ height\ of\ the\ center\ point) = coplanarity$$

or

$$ABS(\frac{Z(UL) + Z(UR) + Z(BL) + Z(BR)}{4} - Z(Center)) = coplanarity$$

Again, for a 2nd order polynomial:

$$Z(UL) = a$$

$$Z(UR) = a + bm + em^2$$

$$Z(BL) = a + cn + fn^2$$

$$Z(BR) = a + bm + cn + dmn + em^2 + fn^2$$

$$Z(Center) = a + b\frac{m}{2} + c\frac{n}{2} + d\frac{mn}{4} + e\frac{m^2}{4} + f\frac{n^2}{4}$$

Therefore:

$$ABS(\frac{4a + 2bm + 2cn + dmn + 2em^2 + 2fn^2}{4} - \frac{4a + 2bm + 2cn + dmn + em^2 + fn^2}{4}) = coplanarity$$

Canceling terms:

$$ABS(\frac{em^2 + fn^2}{4}) = coplanarity$$

This equation would define a perfect bowl or dome shape and can therefore also be used as a signal strength gauge.

$$SS = ABS\left(\frac{em^2 + fn^2}{4 * coplanarity}\right)$$

The result also matches the previous theory found in using the JFFSW algorithm. Again the denominator in the equation is not of concern when determining positive or negative sign.

$$-(em^2 + fn^2)$$

The results of considering Signal Strength in dealing with the JFFSW data will certainly produce different results than our equation for Signal Strength based on the diagonal lines. Going back to BGA1 and BGA2 at the final room temperature measurement gives Signal Strength values of 2% and 10%, respectively, whereas these values were 23% for BGA1 and 5% for BGA2 when considering only the diagonal lines.

A final point should be made in relation to mathematical validity of the JFFSW Signal Strength algorithm. The assumption that the perfect bowl/dome shape will create a 100% Signal Strength is valid, but the assumption that the perfect bowl or dome is the largest possible result of the Signal Strength calculation is invalid. In practical testing, values as high as 102% have been observed. Despite the weakness in this assumption the gauge stills serve the purpose of quantifying the degree to which a surface fits the concave or convex convention.

NAMING OF 3D SURFACE SHAPES

A further step that can be used to classify surface topography is to essentially create specific surface shape categories. This concept has been raised in previous discussions in understanding warpage including a statement of work from iNEMI "Warpage Characteristics of Organic Packages", [6] but the concept has not been pursued at any known length for practical use in understanding surface warpage data.

The purpose of naming the shapes would be a compliment to Signal Strength to help predict how well two surfaces will interface. Mating surfaces could quite possibly have very similar JFFSW and Signal Strength, but poor shape matching. Again, analysis of both mating surfaces is optimal and removes the need for such naming, but this paper focuses on the case where warpage data from both mating surfaces is not attainable.

The d, e, and f coefficients of the 2nd order polynomial provide the information necessary to define the shape of a least square fit surface. Deciding how many different shapes to classify and the transition where one shape becomes another is more difficult.

$$z = a + bx + cy + dxy + ex^2 + fy^2$$

For the purpose of this paper we will classify shapes into the following categories as defined in **Figure 14**.

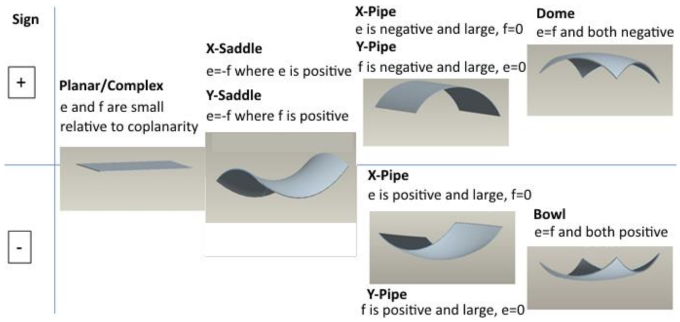

Figure 14. Shape names

These conditions are of course ideal shapes and not realistic to most part surfaces. While these general rules are fine, the critical decision becomes where we transition between each surface. The critical point is to have the software mathematically define a surface shape instead of different users using different shape names for the same surface. Adjustments of the mathematical shape criteria can easily be done later. We can analyze real world examples to help define the transition between surface shape types experimentally. For now let's consider the e and f coefficients dealing with the x^2 and y^2 terms and discuss the d coefficient later. "m" and "n" are also considered as the length in x and length in y of the data set, respectively.

Practical Example 1:

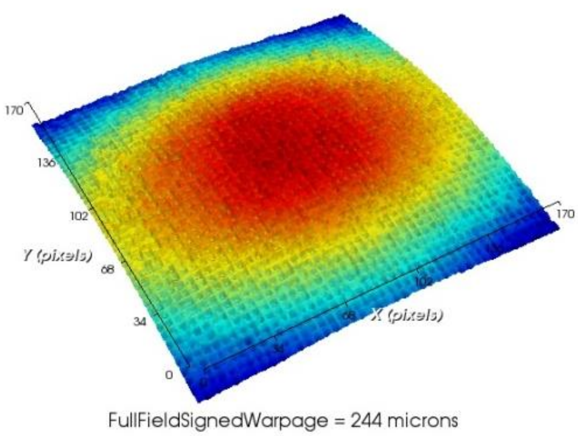

Figure 15. Practical Surface 1, Dome or Y-Pipe

JFFSW: +244 microns
e: -0.000414 (Note that coefficients units are mils)
f: -0.000938
m: 170
n: 170
Signal Strength: 101.69% (This is possible because the real surface is being approximated by a 2nd order surface fit.)

The direction of warpage is very clear. With large Signal Strength and both e and f coefficients negative, the shape can either only be a dome or positive Y-Pipe. The critical decisions will be made based on the ratio between the em^2 and fn^2 terms.

We know that if the two terms are approximately equal then we have a dome. We also know that if the fn^2 term is much larger than the em^2 this describes a Y-Pipe. In this case:

$$\frac{fn^2}{em^2} = 2.26$$

For now let's consider this a Y-Pipe based on qualitative decisions and create a rule for shape definition. With "high" Signal Strength and e and f coefficients with the same sign the Pipe shape will be defined by:

$$\frac{fn^2}{em^2} > 2 \; or \; \frac{em^2}{fn^2} > 2$$

where the larger of the two terms is placed on top. A ratio greater than 2 can be used to define a Pipe.

Practical Example 2:

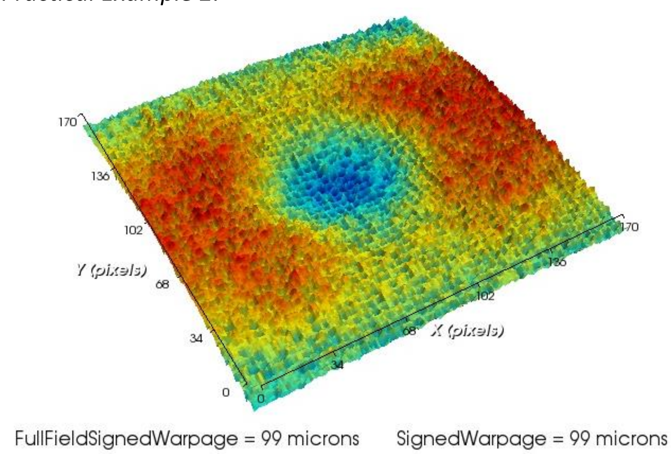

Figure 16. Practical Surface 2, X-Saddle or Planar/Complex

JFFSW: +99 microns
e: +0.000098
f: -0.000107
m: 170
n: 170
Signal Strength: 1.67%

The shape indicates an X-Saddle if it can be defined into anything but a Planar/Complex shape. There is certainly some complexity to the shape. The very low Signal Strength indicates a shape where it is difficult to assign positive or negative, which is also characteristic of a saddle shape. The e and f coefficients are nearly equal and opposite where e is positive, as the X-saddle definition suggests. The only other consideration is the ratio of the e and f terms versus coplanarity. For example if e and f were lower values but opposite and equal, the shape definition would more accurately be Planar/Complex.

Because the opposite sign of the e and f terms yields a low Signal Strength, let's consider:

$$\frac{ABS(em^2) + ABS(fn^2)}{4 * coplanarity} = 38.6\%$$

By not allowing the em^2 and fn^2 terms to be subtracted from one another, only the ratio of curvature to coplanarity is considered. Let's use this example to set a rule for now that:

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

represents a planar/complex surface. The 35% value is very much a rather arbitrary number that can be adjusted with further study and use in the naming concept.

These two rules on the transition between shapes, along with the rules stated in **Figure 14** are actually enough to define all real surfaces into these categories.

However, let's look at one real world example of a Planar/Complex shape before moving on.

Practical Example 3:

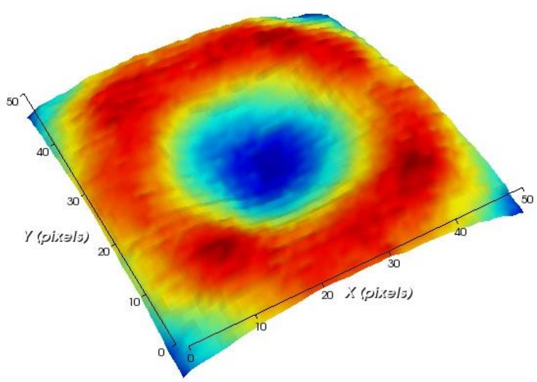

Figure 17. Practical Surface 3, Planar/Complex Shape

JFFSW: -110 microns
e: +.000054
f: +0.000872
m: 50
n: 50
Signal Strength: 13.36%

Here, the Signal Strength is very low considering that the e and f coefficients have the same sign. Also, the f coefficient is noticeably larger than the e coefficient even though this is not very apparent in the image. This is the type of image that should be defined as a Planar/Complex negative shape.

To highlight the low magnitude of the e and f coefficient terms in relation to part dimensions and coplanarity we can reuse the equation

$$\frac{ABS(em^2) + ABS(fn^2)}{4 * coplanarity} = 13.36\%$$

Here this part easily falls into the planar/complex category. For this case we can observe that the order the established rules are applied would dictate the naming as well. The logic flow is as follows:

If

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

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

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

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

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

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

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

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

These shape definitions can be represented visually as below in **Figure 18** considering em^2 and fn^2 terms and coplanarity set here to 1 for simplicity.

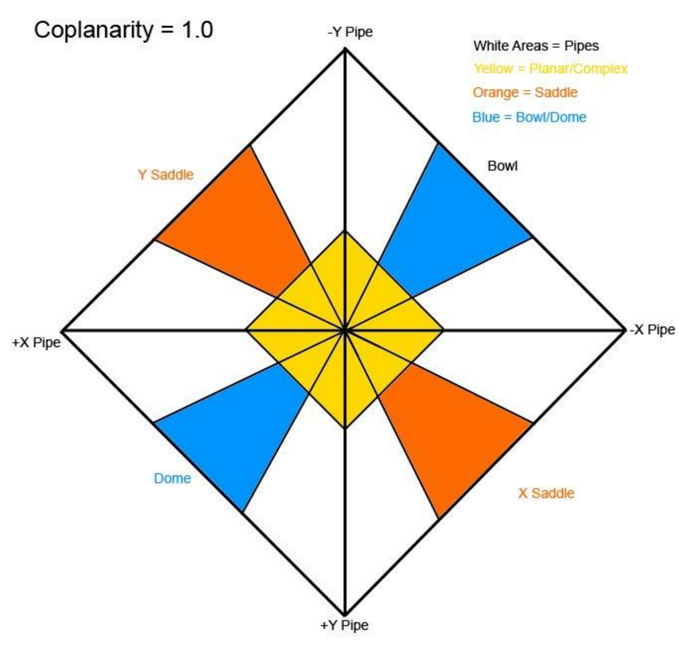

Figure 18. Shape Rules on Coordinate System

To further visualize the transition between shapes, artificially created shapes based on the established rules are shown in **Figure 19** through **Figure 26** below.

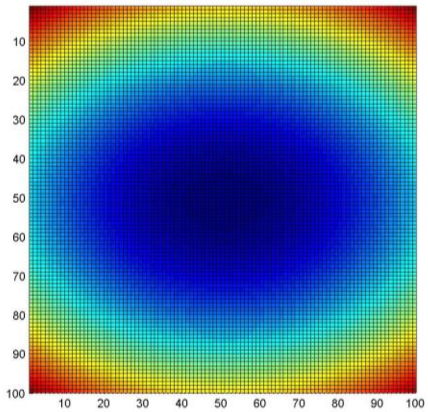

Figure 19. -Y Pipe to Bowl Transition

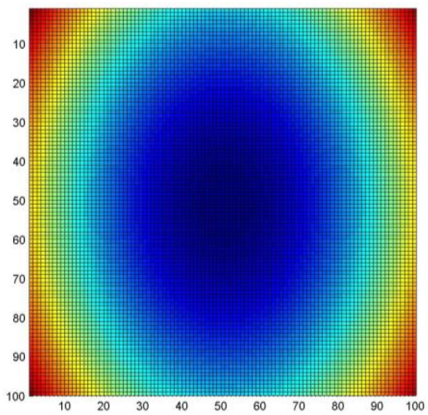

Figure 20. Bowl to -X Pipe Transition

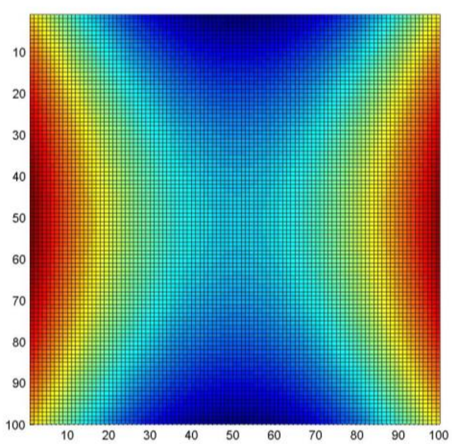

Figure 21. -X Pipe to X Saddle Transition

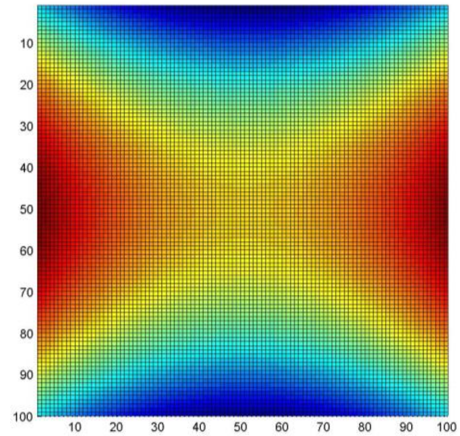

Figure 22. X Saddle to +Y Pipe Transition

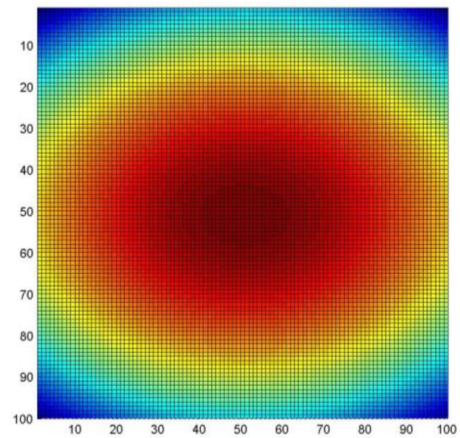

Figure 23. +Y Pipe to Dome Transition

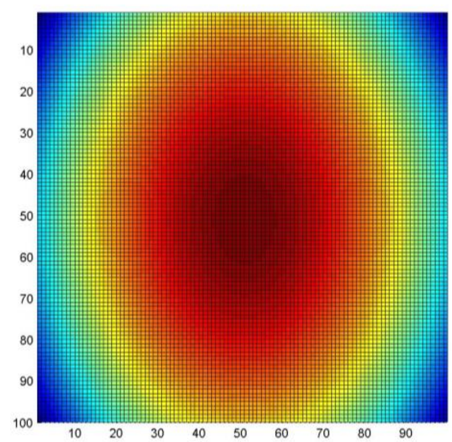

Figure 24. Dome to +X Pipe Transition

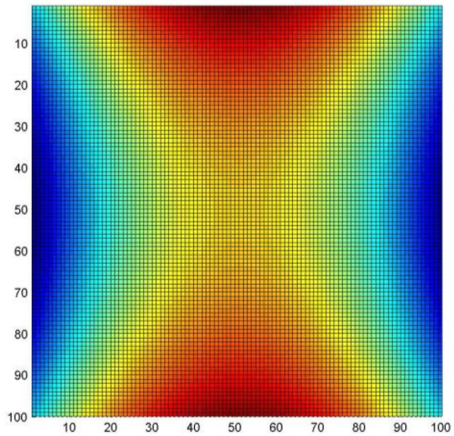

Figure 25. +X Pipe to Y Saddle Transition

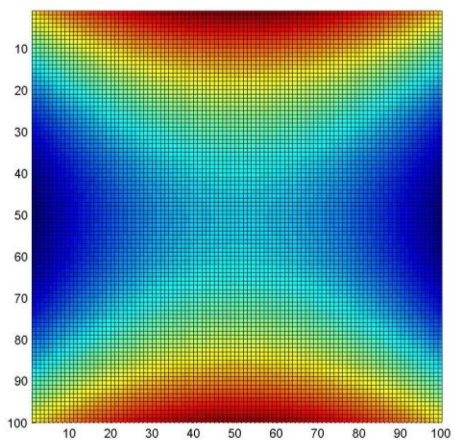

Figure 26. Y Saddle to -Y Pipe Transition

FACTORING TWIST INTO SHAPE NAMES

The issue of shape names can be further complicated and/or strengthened by factoring in the "d" coefficient of the 2nd order polynomials. Serious consideration should be given to the benefit of this added information versus complexity in shape naming. Similarly, the Planar/Complex category we have defined, undoubtedly, could be further broken into more category names (i.e. M and W shapes). Additional breakdown of the Planar/Complex category is not pursued here, but the effect of the d coefficient is discussed below for completeness.

The d coefficient, of the xy 2nd order term, will essentially contribute to the visual "twist" of a surface. This can be quantified in relating d to e and f.

$$Twist\ factor: \frac{ABS(dmn)}{((ABS(em^2) + ABS(fn^2))}$$

A larger ratio of the dmn term versus the em^2 and fn^2 terms would suggest large twisting of the surface. Again a real world example is used to establish viable ratios for this term.

Practical Example 4:

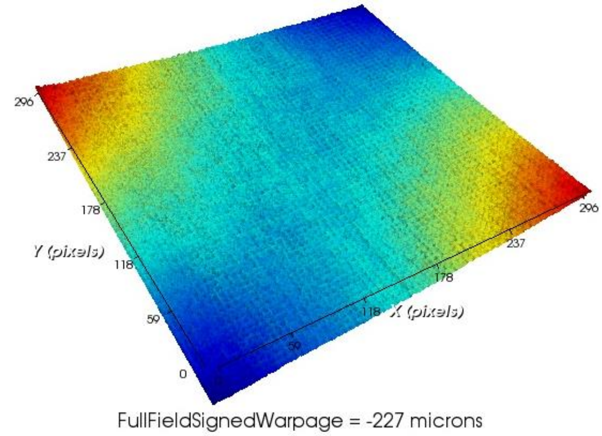

Figure 27. Practical Surface 4, Twisted Planar/Complex Surface

JFFSW: -227 microns
e: +0.000043
f: +0.000027
d: +0.000191
m: 296
n: 296
Signal Strength: 25.79%

Using the rules previously defined with two positive e and f terms and signal strength below 35% this surface is defined as a negative Planar/Complex shape.

Arguably, it would be difficult to classify this shape into any of the Saddle, Pipe, or Bowl/Dome shapes. However, the surface does have a very clear shape that has not been considered with the rules set forth to this point. In previous examples the d coefficient term has always been smaller than the absolute value of either the e or f coefficient. However, in this example the d coefficient is easily larger than the e and f terms. This term defines the "twist" shape for this surface.

Here we could keep all the established shape rules but add an additional check that considers the twist produced from the d coefficient. The shapes already established could then be defined as "twisted" Planar/Complex, Saddle, Pipe, and Bowl/Dome. The twist could be further defined to be given a direction. The positive and large d coefficient characterizes high A and B corners using the established corner naming convention from **Figure 6**. Therefore, we could call this shape an AB Twisted Planar/Complex shape.

To relate d, e, and f, and the sample dimensions the following equation is used:

$$\frac{abs(dmn)}{abs(em^2) + abs(fn^2)} = 2.73$$

To establish a reasonable threshold for this twist characteristic a more subtle example should be used.

Practical Example 5:

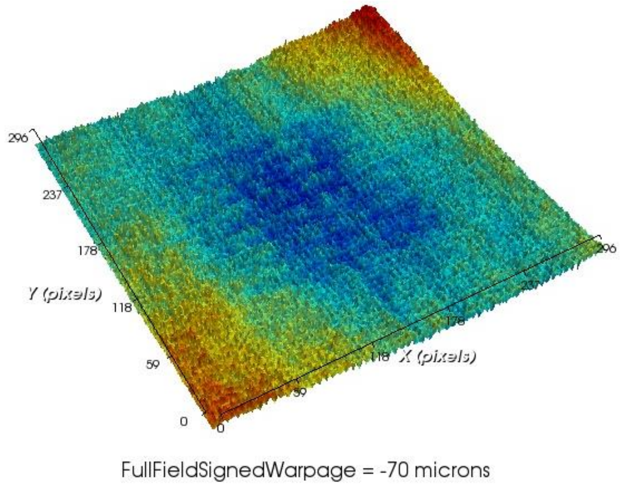

Figure 28. Practical Surface 5, CD Twisted Bowl

JFFSW: -70 microns
e: +0.000038
f: +0.000024
d: -0.000030
m: 296
n: 296
Signal Strength: 35.56%

This surface is considered a Bowl by current rules in this document, though the surface is not far from being considered either an X Pipe or a Planar/Complex surface. The d coefficient in this case is around the average of the e and f coefficient terms. A CD twist can be seen in the image but it is not as dominant as in **Figure 27**. In this case:

$$\frac{abs(dmn)}{abs(em^2) + abs(fn^2)} = 0.48$$

Here we will choose 0.35 as the ratio for a surface to be considered "twisted". Therefore,

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

defines a twisted surface. Also, a positive d coefficient defines an AB twist (high AB corners) and a negative d coefficient defines a CD twist (high CD corners).

CONCLUSIONS

Current standards for decision making on thermal warpage data of electronics component can misrepresent actual surface shape. At a minimum, an improvement in the gauge used to calculate signed warpage is straight forward to implement and has already been adopted by many companies. Analysis of both surfaces in a surface mount mating area for warpage is optimal for diagnosis of warpage related causes of surface mount defects. However, when only one surface is available for measurement, the addition of a Signal Strength gauge adds more information to quantify 3D surface shapes and avoid confusions in changing warpage sign. Taking this thought process further,, surfaces can be classified into different shape names. Further work can be pursued to improve mathematical conventions for shape naming. Decisions to implement these concepts into thermal warpage criteria come down to the amount of useful information versus the added complexity in communicating surface topography.

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