THERMAL SHADOW MOIRÉ TO CROSS-SECTION CORRELATION STUDY

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ABSTRACT
Assembly of large size BGA components poses great challenges on both SMT and rework processes. Therefore, a robust process window is extremely important to make sure reliable solder joints are formed. Warpage analysis (thermal shadow moiré) has been a common technique used in the semiconductor industry, and within the last years this technique has been implemented in the Assembly Manufacturing industry to predict component and PCB warpage, to prevent manufacturing issues such as HiP and solder shorts due to the warpage effect.

The objective of this work is to determine the correlation between interface analysis of shadow moiré data at temperature and standoff measurement of the BGA after cross-section on the assembled boards. Focus on the shadow moiré data is placed on shape matching between BGA and PCB around solder liquidus temperatures during reflow cooling. BGAs are cross-sectioned diagonally and compared to the diagonal data pulled from the shadow moiré surfaces. Multiple BGA and PCB attach locations are compared. The intention of this project is to determine the level of confidence of interface analysis of shadow moiré data at temperature when used as a predictive tool.

Key words: warpage, cross-section, metrology, surface mount defects, HiP, soldering

BACKGROUND
In the assembly of surface mount components, controlling component and PCB warpage is critical for reliable electrical contact. The primary source of warpage is generally accepted to be CTE (coefficient of thermal expansion) mismatch between the different layers and materials of component and PCB samples. Multiple studies have shown a correlation between component warpage and surface mount defects. [1][2][3] Less often the local PCB warpage is analyzed as a culprit for surface mount defects. [4] Even more rare seems to be analysis of both sides of the attaching surface to determine warpage related issues. [5] Such studies have generally concluded that to understand surface mount issues related to warpage, quantifying the warpage of both attaching interfaces is required.

In terms of industry standards, only BGAs and LGAs have industry standards for at temperature warpage related to surface mount components. Specifically, JESD22-B112A [6] was originally released in 2005 and updated in 2009 and 2018, and JEITA ED7306 [7] was released in 2007. Both state an acceptable level of package warpage based on ball pitch and diameter. Other attempts have also been made to improve how warpage can be quantified. [8] On the PCB side, there are standards for overall allowable twist of a PCB board with surface mount components, but no firm requirement for local surface mount warpage. IPC 9641 [9] shows methodology for testing of PCB local areas but doesn't conclude an allowable warpage specification for the PCB local area.

Perhaps the most similar comparison in the attempt to correlate interface analysis of shadow moiré (SM) data to cross-section data has been to observe solder ball behavior via camera while physically controlling the gap between solder ball and PCB under temperature. [10] Here the studies are similar in trying to bridge the gap between in-situ thermal measurement of the surface mount interface and final assembly defects or solder ball shape. Regardless of methodology, to best understand the gap between two mating surfaces, the warpage of both sides of the interface should be considered.

The cross-section is used for evaluating the quality of the solder process, components and PCBs. [11] Good solder structure, IMC, HoP, pad cratering, nonwet open, black pad, etc.are some of the regular issues found.

METHODOLOGY
Cross-sectioning (sometimes called micro-sectioning) is a metallographic technique used to characterize materials, perform a failure analysis and expose an internal structure of a printed circuit board (PCB) or an electronic component package. Cross-sectioning involves mounting a target segment of the PCB in a potting material to obtain support and protect the sample in the subsequent polishing process. The mounted sample is carefully polished using progressively finer media to reach the target examination plane of interest. The prepared specimen is then examined at various magnifications either under an optical microscope or a scanning electron microscopy (SEM). This process is defined by the IPC procedure [12].
To start the cross-section methodology, it is necessary to define the type of cut and the direction of the sample; cuts on solder validations for BGAs are in diagonal of the component or based on some special requirement of the requestor.
As a next step, general visual and X-ray inspections are made on the component and, after observing the evidence, a decision of the direction and the position of the diagonal cut is made.

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Figure 1. Cross-Section Example

The orientation of the component should be identified in order to know the direction and which spheres are being cut. The orange arrow indicates the orientation of the component. The yellow line indicates the diagonal cross-section cut level. The orange line indicates the lateral cross-section level.

Once the cross-section has been processed, the component standoff can then be measured. This can be done on a metallographic microscope or SEM equipment.

The magnification depends on the size of the solder sphere of the component.

Standoff measurements are taken from PCB pad to BGA pad (Copper to Copper) as shown in figure 2. This measurement is performed on all spheres of the cross-section cut for measuring the ball collapse on the component as shown in the Figure 3.

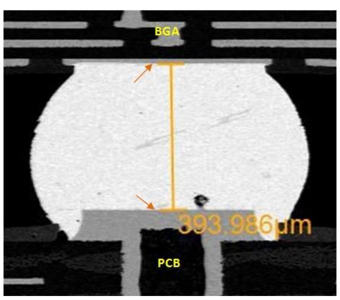

Figure 2. Standoff measurement

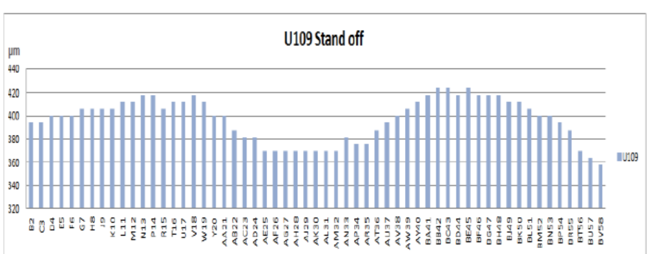

Figure 3. Standoff graph Example

Surface warpage measurements over temperature are taken using the SM technique and sample within 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. An interference pattern between the lines and shadow cast by the same lines creates a contour map used for measurement. A phase stepping technique is applied for increased resolution, where camera images are captures 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.

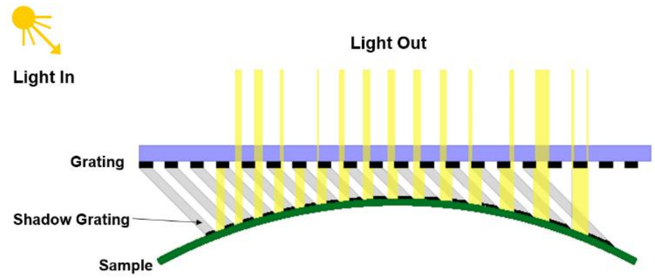

Figure 4. Shadow Moiré Visual Concept

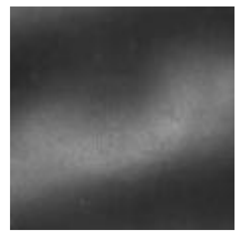

Figure 5. Shadow Moiré Pattern

Although component and PCB are tested separately, the orientation of each part is captured in the test, thus the two surfaces can be matched together in software to establish the gap between mating surfaces each at the same temperature. This approach is referred to as interface analysis (IA). An example is shown in Figure 6.

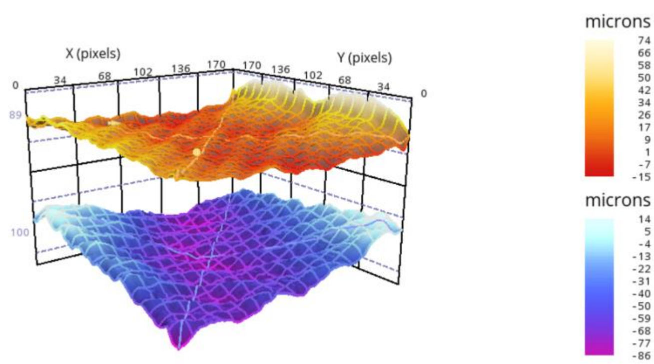

Figure 6. Interface Analysis Example, BGA to PCB

The full surface is available from this IA technique, but for comparison to the cross-section, the matching diagonal data is pulled from the data set. The final comparison to cross-section data is the difference between the orange (BGA) and blue (PCB) lines in Figure 7.

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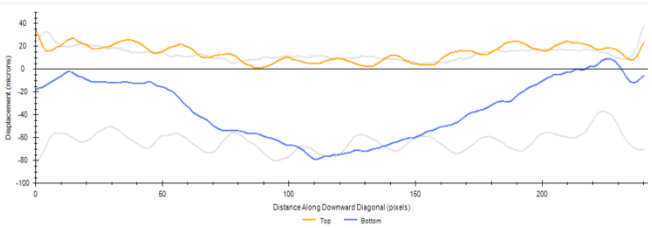

Figure 7. Interface Analysis Diagonal, BGA to PCB

Interface Analysis vs Cross-Section Graphical Comparison

The first method used to compare the similarities between data from interface analysis and cross-section was a graphical method. Even when data have different sources and different length measurement units (the position along the diagonal line of the BGA is expressed in pixels on interface analysis and the same distance is expressed in microns in the cross-section); however, both represent gap variation magnitudes between BGA and PCB along the same diagonal length dimension. As shown in Figure 8, in order to compare data from these sources within the same graph, the X axis on the graph is using two different scales for the same length dimension (top scale represent the sphere location value for cross-section, and bottom scale represent the pixel location for interface analysis data). The Y axis represents the gap magnitude between PCB and BGA expressed in microns (for interface analysis this gap variation is the difference between the BGA and PCB lines, and for cross-section, this gap variation is obtained by subtracting the standoff measurement at the specific point to the minimum standoff found along all the diagonal cross-section).

As solder joint is solidified during the cooling phase around the alloy melting point temperature (217°C to 221°C for SAC305), the expectancy is that the best similarity between the two graphs will occur around this temperature.

In order to determine the temperature at which interface analysis and cross-section graphs present the best similarity, interface analysis graphs at different temperatures were generated to be compared against each case of the cross-section. An example of this comparison is shown in Figure 8.

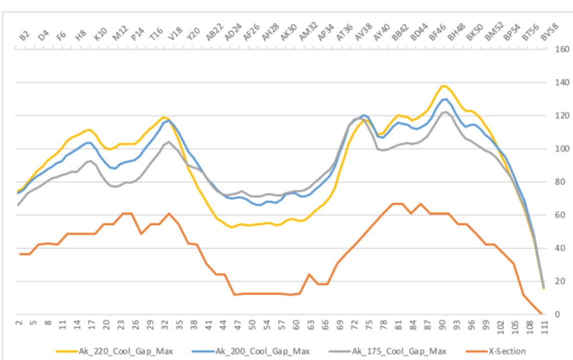

Figure 8. Interface Analysis vs Cross-Section Graphical Comparison

Interface Analysis vs Cross-Section Correlation Factor

Although the graphical comparison provides us with a visual reference to determine the similarities between cross- section and interface analysis data, it does not provide us with a numerical value to determine the strength of the association. ANOVA and comparison of means are the most common methodologies used to determine if statistical differences are found between the values from different populations or sets of data. However, in this case, use of these methodologies is not applicable, as even when the graphs from cross-section and interface analysis may be similar in shape, there are significant differences in warpage magnitude values. These differences may be attributed to the fact that cross-sections include the additional variable of solder in between the component and PCB, whose effect is not included in the interface analysis, where the samples are analyzed without being soldered. This effect, and its impact on the standoff vs warpage magnitude value is not part of this analysis, and a separate study will need to be performed to determine the causes of the differences in magnitude.

Correlation is a statistical method used to assess a possible linear association between pairs of continuous variables. There are several types of correlation coefficients, but in general terms, correlation coefficient formulas are used to determine the strength of the relationships between data.

Pearson's correlation is a correlation coefficient commonly used in linear regression and, when applied to a sample, is represented by the letter *r* and expressed as in the following equation:

$$r = \frac{\sum_{i=1}^{n}(xi-\bar{x})(yi-\bar{y})}{\sqrt{\left[\sum_{i=1}^{n}(xi-\bar{x})^2\right]\left[\sum_{i=1}^{n}(yi-\bar{y})^2\right]}}$$

Where

n= the sample size

xi and yi = the values of x and y for the ith individual data point

$\bar{x}, \bar{y}$ = the sample mean

Formulas return a value between 1 and -1, where 1 indicates a strong positive relationship, -1 indicates a strong negative relationship and zero indicates no relationship at all.

Rule of thumb for interpreting the size of a correlation coefficient [14] is provided as follows:

Table 1. Rule of thumb for interpreting the size of a correlation coefficient

Size of correlation	Interpretation
0.9 to 1.0 (-0.9 to -1.0)	Very high positive (negative) correlation
0.7 to 0.9 (−0.7 to −0.9)	High positive (negative) correlation
0.5 to 0.7 (−0.5 to −0.7)	Moderate positive (negative) correlation
0.3 to 0.5 (−0.3 to −0.5)	Low positive (negative) correlation
00 to 0.3 (.00 to −.30)	Negligible correlation

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RESULTS

A total of five sample types were used for this study, four samples were selected for their size greater than 47.5x47.5 mm as large BGAs are more likely to present significant warpage levels, and they present more challenges to process on the SMT production line. One additional sample that is smaller in size was chosen due its history of warpage issues in the past. The final sample is a plastic sample, there are two ceramic sample and the rest are FCBGA. All samples were soldered using SAC305 solder alloy. The sample details are summarized in Table 2.

Qualitatively, graphical analysis shows a good similarity on behavior between the interface analysis and cross-section results, an example is shown in figure 9.

Table 2. Sample summary

Summary of samples				
Case #	BGAs			
	Dimensions (mm)	Ball Diameter (mm)	Pitch (mm)	Type
1	60x60	0.635	1	FCBGA3477 Metal Lid
2	55x55	0.6	1	FC-PBGA Metal Lid
3	27x27	0.4	0.8	640-LBGA Package (Landed BGA)
4	55x55	0.635	1	Ceramic FC-BGA Metal Lid
5	52.5x52.5	0.6	1	FPB42GS

Cross-Section to Interface Analysis Correlation Initial Results

The results obtained show a high correlation against the cross-section standoff in all the cases on at least one temperature. Case #1, #4 and #5 show a high correlation at all temperatures. Case #2 and #3 shows a high correlation at 195°C.

Pearson’s Correlation results are shown in Table 3.

Table 3. Initial results summary

Summary of samples						
Case #	Pearson's Correlation at temperature					
	220°C	215°C	210°C	205°C	200°C	195°C
1	0.887	0.865	0.930	0.932	0.896	0.890
	0.859	0.771	0.883	0.873	0.864	0.883
2	0.574	0.586	0.634	0.717	0.651	0.756
3	-0.872	-0.872	-0.629	-0.037	0.675	0.879
4	0.760	0.725	0.730	0.752	0.762	0.756
5	0.732	0.782	0.788	0.757	0.722	0.735

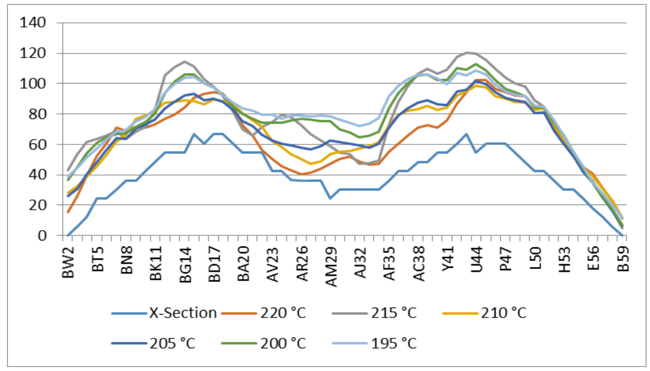

Figure 9. Correlation from case #1, it was observed a correlation on behavior between cross-section standoff and Shadow Moiré IA analysis.

Sample Variation and Correlation Improvements Through Multiple Tests

Due to the correlations obtained from initial results and in order to have a better statistical sample it was decided to perform multiple runs on the samples to obtain a greater sampling, with this process an average of each run was calculated and correlated against the cross-section standoff. In most of the cases a marginal improvement on the correlation was observed. Case #4 maintained the same correlation; case#3 shows a marginal improvement with higher correlation at 195°C, case #1 and #2 had some marginal improvement except the case #5 that the correlation went down.

Updated Pearson’s Correlation results are shown in Table 4 and case #1 graphical analysis is shown in Figure 10 after averaging multiple thermal shadow moiré runs.

Table 4. Averaged results summary shows improvements on correlation

Summary of samples with four run average						
Case #	Pearson's Correlation at temperature					
	220°C	215°C	210°C	205°C	200°C	195°C
1	**0.90**	**0.9**	0.92	0.92	**0.91**	**0.91**
	0.89	**0.88**	**0.91**	**0.91**	**0.90**	**0.90**
2	0.54	0.55	0.62	0.68	**0.71**	**0.76**
3	-0.82	-0.61	0.07	**0.75**	**0.91**	**0.94**
4	**0.76**	**0.72**	**0.73**	**0.75**	**0.76**	**0.76**
5	0.71	0.72	0.72	0.69	0.64	0.68

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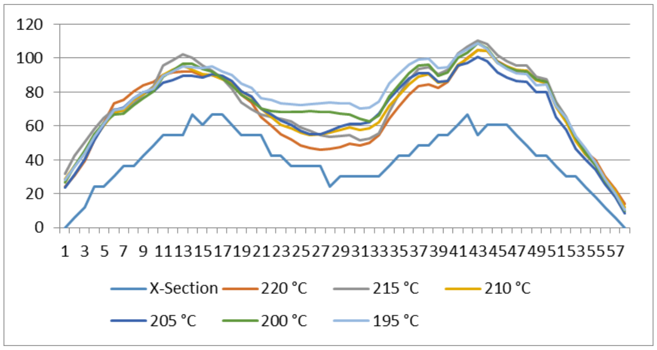

Figure 10. Correlation from case #1, it was observed a marginal improvement on correlation respect the initial results.

Optimal Correlation Temperatures for Different Package Types

The results from initial and averaged results indicates that the temperature in which all cases concur with higher average correlation is 195°C, disregarding the type of the component and size. Average correlation at each temperature is added in Table 5.

Table 5. Averaged results summary

Summary of samples with four run average						
Case #	Pearson's Correlation at temperature					
	220°C	215°C	210°C	205°C	200°C	195°C
1	**0.90**	**0.9**	0.92	0.92	**0.91**	**0.91**
	0.89	**0.88**	**0.91**	**0.91**	**0.90**	**0.90**
2	0.54	0.55	0.62	0.68	**0.71**	**0.76**
3	-0.82	-0.61	0.07	**0.75**	**0.91**	**0.94**
4	**0.76**	**0.72**	**0.73**	**0.75**	**0.76**	**0.76**
5	0.71	0.72	0.72	0.69	0.64	0.68
Avg correlation @ Temperature	0.50	0.53	0.66	0.78	0.81	0.83

DISCUSSION AND CONCLUSION

Based on final results the following conclusions were found:

- Interface Analysis provided a good prediction of the real behavior of the components after solder process (cross-section), showing high positive Pearson correlation factor. Even though graphical method provides a good guidance regarding the behavior of the component it is recommended to perform the numerical analysis in order to identify the strength of the IA prediction with respect to the real behavior of the component.
- Average values after several measurement of the samples on Interface Analysis do not exhibit a significant improvement respect to the initial Interface Analysis values (measuring only one time).
- Temperature in which all cases concur with higher average correlation is 195°C, disregarding the type of the component and size

SUMMARY

The method of graphical comparison between IA and cross-section provide a visual reference to determine the similarities between cross-section and interface analysis data, however it does not provide a numerical value to determine the strength of the association.

It was determined to use the Pearson's correlation factor in order to establish a numerical value to determine the strength of the similarity between IA and cross-section results. Using this method, a good correlation factor was found between the IA and cross-section under analysis.

Two methods were used to obtain the correlation data from IA. For this study, averaging multiple measurement runs did not show a significant improvement on the results in comparison to the initial one-time measurement.

Analysis on correlation factors obtained from both measurement methods revealed that the best approximation from IA to the real behavior of the component after the soldering process was found at 195ºC.

NEXT STEPS

Standoff vs warpage magnitude differences between Interface Analysis and cross-section values were found, however are not part of this analysis, and a separate study will need to be performed to determine the causes of the differences.

Temperature uniformity between the thermal shadow moiré tests and the actual reflow oven is believed to have played some role in the correlation between interface analysis and cross-section. The reference temperatures shown in results tables is not an absolute constant across the BGA or PCB in either shadow moiré testing or the production reflow oven itself. Some effort was placed in tracking this differential, but no final conclusions were made. By using some of the latest technology available in reflow emulation on the testing side, further understanding could be gained related to differences in optimal IA to cross-section correlation and solder solidification temperature.

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