Optics and Lasers in Engineering 93 (2017) 9–18

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

A general strategy of in-situ warpage characterization for solder attached packages with digital image correlation method

Yuling Niu*, Huayan Wang, S.B. Park

Opto-mechanics and Physical Reliability Laboratory, State University of New York at Binghamton, Vestal, NY 13850, USA

ARTICLE INFO

Keywords:
3-D digital image correlation
In-situ measurement
Warpage characterization
Solder ball attached packages
Facet size and step
Image correlation quality

ABSTRACT

Recently, 3-D Digital Image Correlation (DIC) is widely applied to the reliability analysis of electronic packages, which particularly characterizes the in-situ deformation of ball grid array (BGA) packages. During the image correlation procedure, many parameters influence the accuracy and data integrity of measurement result. Facet (subset) size is the principal parameter and has been studied with much effort. However, the solder balls, which are built on the substrate surface, make the scenario different with the conventional 3-D DIC experiment for the planar samples. The undulant surface generates more obstacles for the successful image correlation. In order to summarize an effective solution of 3-D DIC measurement method for solder balls attached packages, camera angle, facet size and facet step are studied with different BGA packages and different stereoscopic camera systems to achieve the best correlation quality. Also, a novel surface treatment method is introduced to guarantee the surface speckles are generated uniformly on the fluctuant surface.

1. Introduction

Achieving higher integration level of electronic packages demands an effective in-situ warpage characterization method to guarantee the interconnectors' reliability during the reflow process [1–3]. From the aspects of economy and efficiency, conventional reflow method is always selected during the packaging assembly process [4–6]. About 200 °C temperature gap of reflow method generates severe warpage [7–9] and puts the interconnectors at risk of failure [10]. The non-contact and totally in-situ advantages made the 3-D digital image correlation (DIC) a perfect choice to understand the electronic package behavior, especially warpage, during reflow process. It helps to learn the package behavior at each temperature load to analyze the effects of different components and materials of the packages. Compared to the accustomed in-situ warpage measurement technique, like Shadow Moiré [11–13], 3-D DIC is equipped with higher out-of-plane measurement sensitivity (± 1/64,000 of field of view), multi-plateau measurement capability, simpler surface treatment requirement and more uniform heat sources without any gratings on the sample surface in a convection chamber [14–16]. In light of the benefits, 3-D digital image correlation is widely applied in packaging reliability analysis area and becomes the JEDEC standard for package warpage measurement method [17–19].

Upon the birth of digital image correlation technique, many efforts have been made to understand the potential errors during both experiment steps and data post process. Starting from sample preparation step, the speckle size, density and the contrast ratio are the main concerns on the specimen surface [20–23]. During the experiment, the rigid body motion and the out-of-plane deformation may affect the focal quality and generate errors for the displacement calculation [24]. At the post data process, the selection of facet (subset) size, which is the fundamental correlation unit, attracts researchers' attentions and has great effect on the result deviations [25–28]. These works provide good guidance in each DIC measurement step and improve the accuracy of the image correlation result.

However, the objectives of these DIC parameter studies concentrate on the planar tensile test samples. Another important application realm for the 3-D DIC is the warpage measurement of electronic packages. There is no general solution to assist parameter adjustment for the electronic packaging samples. To carry out the in-situ warpage measurement of solder ball attached packages with 3-D DIC, the conventional strategy is to remove the solder balls mechanically or melt the solder balls on the substrate surface to generate a flat surface before the experiment [29,30]. It is destructive and poses the risks of damaging the copper pad. In Fig. 1(a), the blue part is the surface scratch on the copper pad, which is generated by removing the solder balls mechanically. Otherwise, the measurement result suffers from the remaining roots of the melted solder balls on the sample surface (Fig. 1(b)).

To avoid these issues, the warpage measurement of 3-D DIC is attempted to be executed directly with the solder balls on the substrate surface. Through adjusting the camera angle, facet (subset) size and facet (subset) step, a general selection strategy of these parameters is collected and summarized. The minimum facet (subset) size is con-

* Corresponding author.

http://dx.doi.org/10.1016/j.optlaseng.2017.01.008
Received 14 July 2016; Received in revised form 1 December 2016; Accepted 13 January 2017

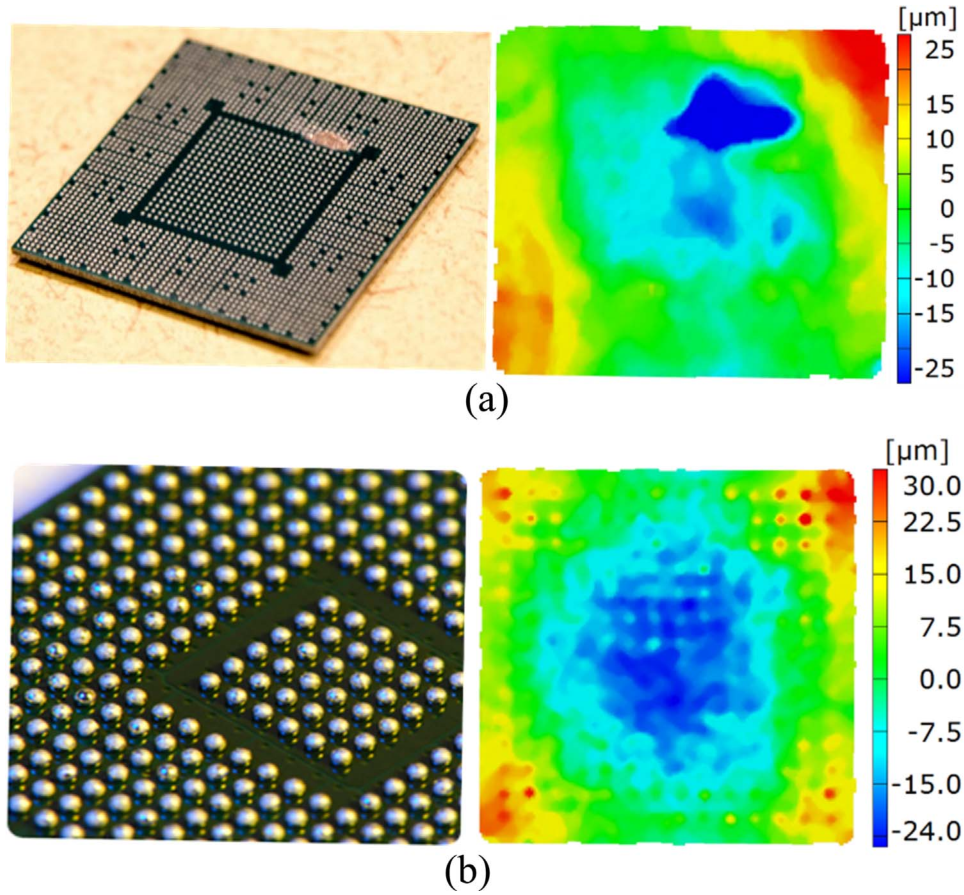


Fig. 1. (a) Surface scratch due to the solder ball elimination on copper pad; (b) The warpage contour of BGA package with the remaining roots of solder balls.

firmed with the literatures to guarantee the systematic error in a low level [25,27,28]. Then the optimal facet size is studied with the standard of data integrity. By measuring three BGA packages with different dimensions and solder ball diameters, the feasibility and effectiveness of this method is demonstrated.

2. Experiment methodology

3-D DIC does not require white painting on the entire sample surface, while the sample surface is required to display patterns or features to be distinguished and traced. For the object surface that has no feature, artificial speckles should be generated on the sample surface. The conventional speckle generation method is dusting. For a flat surface, such as the printed circuit board or metal plate, dusting guarantees formation of a uniform layer on the surface. However, the existence of solder balls on the substrate surface make it impossible to uniformly apply the paint material to cover the substrate surface (Fig. 2). It will produce initial errors due to the surface treatment process.

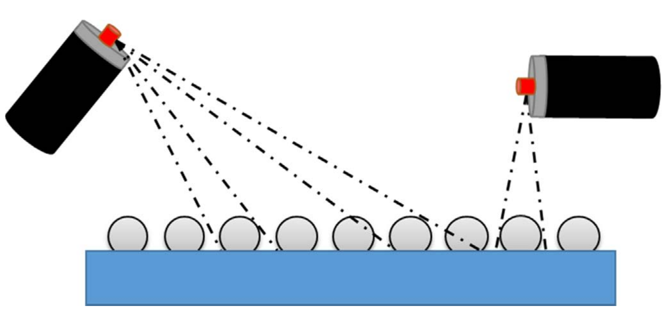


Fig. 2. Schematic of painting process on the BGA package with the solder balls blocking the substrate surface.

To uniformly cover the substrate surface with features, carbon coating is introduced to generate fine black patterns on the fluctuant surface. Originally, this technique helps improve the samples' conductivity of scanning electron microscopy (SEM) test. Carbon powders are equally distributed on the sample surface in the electric field. It guarantees the production of uniform black layer to prevent optical dulling of solder balls (Fig. 3(a)). To generate contrast patterns to be recognized, white spraying patterns are applied on the substrate surface later (Fig. 3(b)).

After settling the pattern generation method, the next issue is to adjust different parameters to achieve optimal image correlation quality. For the successful image correlation, many parameters influence the correlation result, such as the speckle size and density, camera angle, facet size and step, calibration deviation, image contrast ratio and camera shutter time. These factors raised many concerns from previous works to understand their effects on the correlation deviation. During the actual experiment operation, the speckle size and density are hard to resize. The pattern quality and the contrast ratio mostly rely on the investigator's judgement. To some extent, the references of these factors can only improve the accuracy theoretically, not practically. So, this study concentrates on the adjustment of camera angle, facet size and facet step, which can be readily controlled and resized. Considering that the stereoscopic systems have different pixels, the optimal facet size is summarized in a proportion format, instead of a certain pixel amount, to guide all the current 3-D DIC systems to utilize the result based on their system capacity.

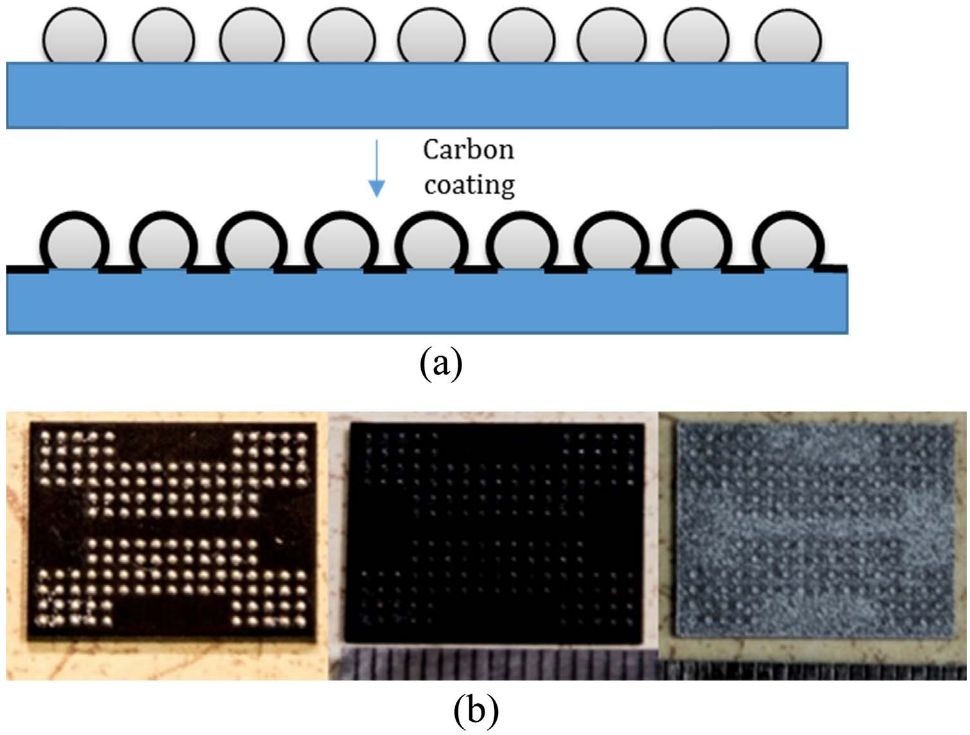


Fig. 3. (a) Schematic of carbon coating on the BGA package; (b) BGA package patterns after carbon coating and white dusting.

3. Experimental parameters study

3.1. Camera angle

Compared to the 2-D DIC with one camera, 3-D DIC is designed to eliminate the effects of rigid body motion. By adding an additional camera, the system is capable of recognizing the out-of-plane deformation. Two sensors focus on the sample surface with a certain angle. Most manuals and papers introduce this camera angle between 25 and 35 degrees. A large angle can exaggerate the image deformation to recognize the displacement accurately. In addition, it helps to reduce the potential error sources in the triangulation calculation. A 30- or even 50-degree camera angle works well for the planar sample test. However, for the solder balls attached packages, the large camera angle makes the image correlation difficult. The schematic (Fig. 4) shows, that with a large angle, the view of the two cameras concentrates on the different locations of the solder ball. Only the green area on the top of the solder ball is the common area. Meanwhile, the solder joints produce blind areas on the substrate surface. Then, left and right images are totally different due to these variances and cannot correlate with each other. In view of this concern, the camera angle attempts to be reduced to increase the common area to assist the image correlation calculation. Several BGA samples and different camera angles are tested to improve the correlation quality.

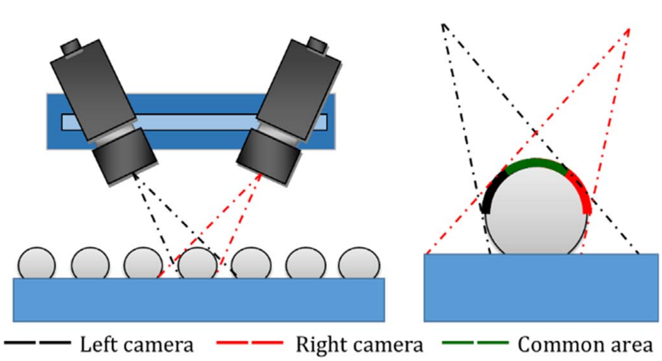


Fig. 4. Schematic of optical paths on the solder ball.

Given that it is difficult to correlate the undulant surface, data integrity is set as the standard of correlation quality for the experimental parameters study. The correlation result of a 45 × 45 mm BGA packages with different camera angles are shown in Fig. 5. Various systems are utilized for the study. The systems A, B and C vary on their pixel amount. 1.4 M means 1.4-million-pixel sensor, so it is the same as 5-million-pixel and 2-million-pixel sensors. When the camera angle increases to 30 degrees, it totally fails to correlate any area on the substrate surface because the shared area on the sample is not big enough to define any common facet on it. As the camera angle is reduced to be less than 20 degrees, the algorithm realizes most of the image correlation.

Similarly, two more tests, one 18 × 14 mm and one 30 × 30 mm packages, are performed to confirm the camera angle effect (Fig. 6(a) and (b)). It demonstrates the same trend of the camera angle effects on the correlation result. A large camera angle affects the correlation quality on the undulant surface. Because the solder balls do not cover the full surface of the substrate, when the camera angle reaches the 30-

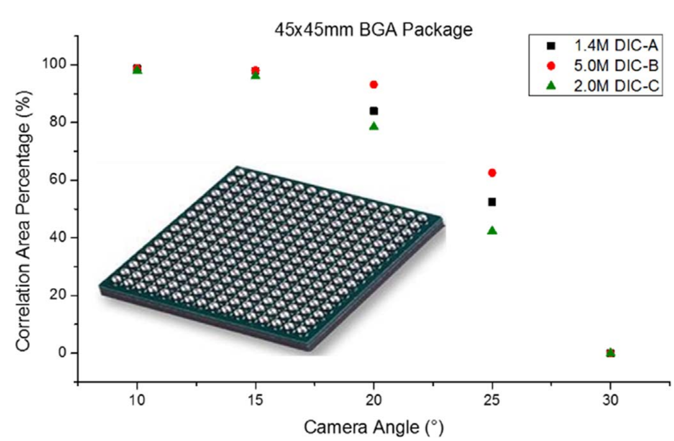
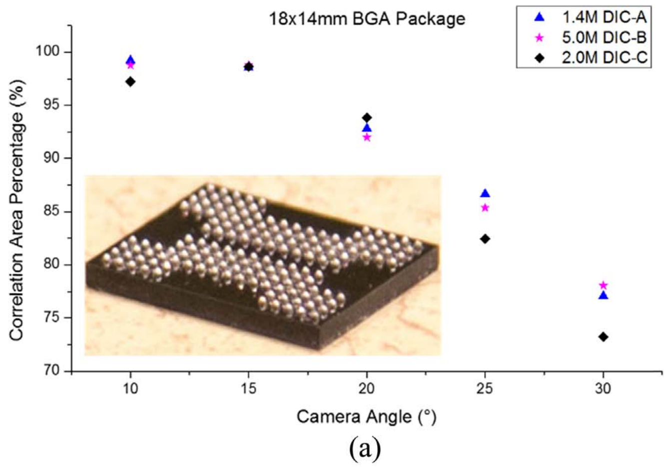


Fig. 5. Correlation area percentage with different camera angles and stereoscopic systems of a 45 × 45 mm BGA package with solder balls attached.



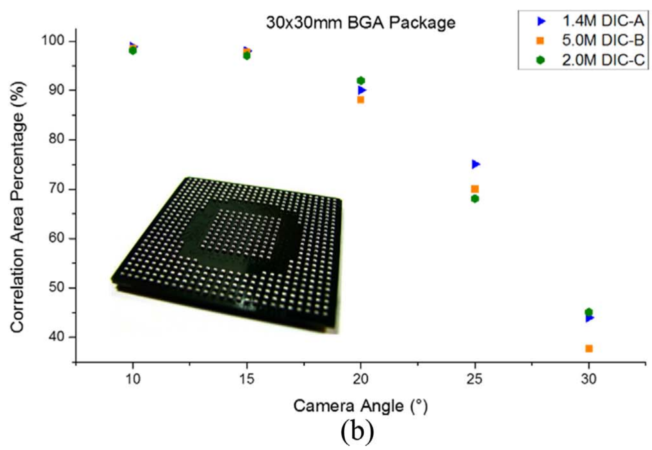


Fig. 6. Correlation area percentage with different camera angles and stereoscopic systems of (a) 18 × 14 mm BGA package with solder balls attached; (b) 30 × 30 mm BGA package with solder balls attached.

Table 1
The average correlation percentage with different camera angles and solder ball diameters.

Average correlation	10 degrees	15 degrees	20 degrees
650 µm	98.58%	97.40%	85.24%
550 µm	98.51%	97.64%	90.09%
450 µm	98.42%	98.68%	92.89%

degree camera angle, it still correlates the few areas of flat surface. To plot the consummate warpage contour, a camera angle that is around 10–20 degrees is the best choice. In these diagrams, three 3-D DIC systems manifest different correlation qualities at 20 degrees. So, the more reliable camera angle will be 10 or 15 degrees. Meanwhile, different diameters of the solder ball will change the sheltered areas on the substrate surface. Table 1 displays the relationship between the average correlation percentage of three 3-D DIC systems with different camera angles and the solder ball diameters. Ten or 15 degrees can guarantee the correlation quality to be maintained more than 97%. Given that the larger angle can exaggerate the facet deformation and reduce the potential errors during post data process, 15 degrees is recommended. At a 15-degree camera angle, from the aspect of the solder ball diameter, the smaller it is, the more correlation percentage it has. This phenomenon is more evident when the camera angle reaches 20 degrees. Based on previous analysis, 15 degrees can be used as a reference value. For the large solder ball diameter, the camera angle can be as small as 10 degrees, and for smaller solder ball, more than 15 degrees is still safe for the successful image correlation.

3.2. Facet (subset) size

With a fine surface treatment method and camera angle orientation, the study moves on to the facet (subset) size adjustment. During the image correlation process, the image is divided into several small facets. A facet consists of several pixels and becomes the basic calculation unit during the correlation process. By learning the distance information through calibration and comparing the orientation of the facets, the correlation algorithm defines the location of each facet on the sample surface. Fig. 7 is the identical facet of 15 × 15 pixels from the left and right camera. It works like our eye perception. For a square shape from our left eye, it is shown as the parallelogram shape in our right eye if it is a flat surface. After correlating all the facets, 3-D DIC combines them together smoothly and generates the complete out-of-plane deformation contours.

Previous literatures [27,28] provided a consistent conclusion that the larger the facet size is, the smaller the systematic error it will be. There is no doubt that larger facet size can obtain better correlation quality because more features are included in one facet. Then the comparison of left and right image is more accurate. However, these works are limited to define the best facet size with a certain amount, such as 30 × 30 pixels or 45 × 45 pixels. The 3-D DIC systems have different image pixel capacities. For a 1920 × 1628 pixels system, a 30 × 30 pixels facet size is large enough to limit the systematic error smaller than 0.01 pixel, but this facet size cannot be utilized in a 1280 × 1024-pixel image system because a 20 × 20 pixels facet size is the same view dimension in the new system. For a certain sample

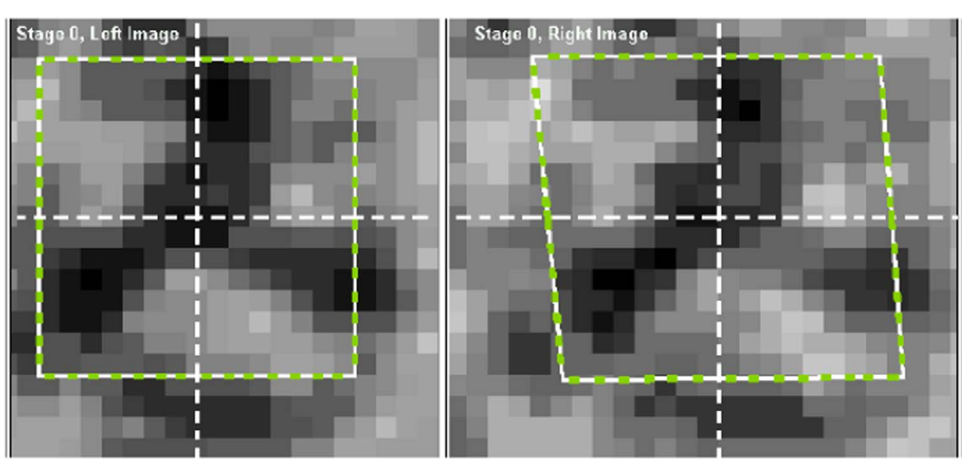


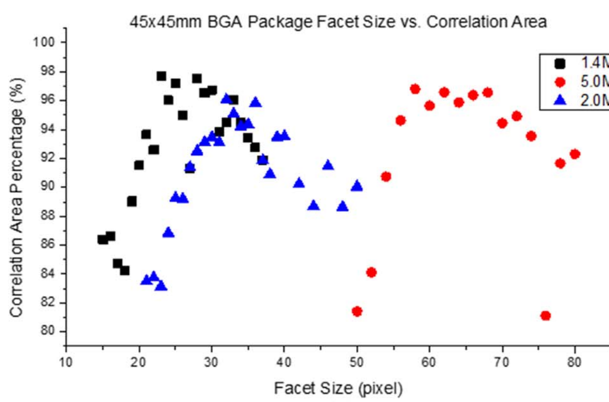
Fig. 7. The identical 15 × 15-pixel facet from left and right image for a flat sample surface.

Table 2
Parameters of BGA packages and the stereoscopic systems for facet size analysis.

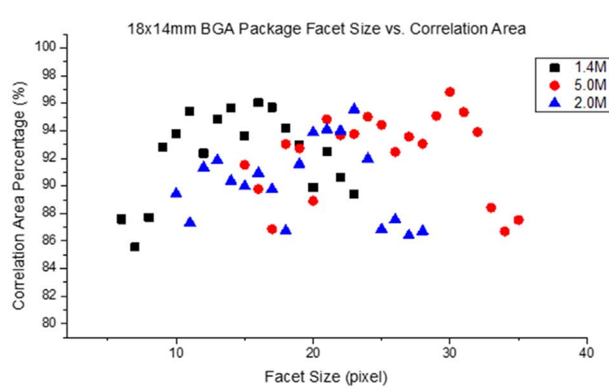
BGA package	Solder ball diameter	Field of view	Test system
45 × 45 mm	650 µm	70 × 60 mm	1.4 M, 5.0 M, 2.0 M
30 × 30 mm	550 µm	45 × 40 mm	1.4 M, 5.0 M, 2.0 M
18 × 14 mm	450 µm	30 × 25 mm	1.4 M, 5.0 M, 2.0 M

Table 3
The information of the stereoscopic systems and their minimum facet size settings.

Stereoscopic system	Image pixel amount	Minimum facet size (pixel)
1.4 M – A	1280 × 1024	15 × 15
5.0 M – B	2560 × 2048	30 × 30
2.0 M – C	1628 × 1236	20 × 20



(a)



(b)

Fig. 8. (a) The 45 × 45 mm BGA package data integrity result with different facet sizes; (b) The 18 × 14 mm BGA package data integrity result with different facet sizes.

dimension, the larger facet size means fewer data points and details. To find a general solution for facet size selection, three stereoscopic systems are tested to seek for a ratio of facet size over the system pixel capacity instead of a constant facet size amount. Referring to the literature, the selection of different facet sizes is guaranteed to keep the systematic deviation in a low level. Then the data integrity is set as the standard for image correlation quality due to the particularity of the BGA package's undulant surfaces.

Three BGA packages with different dimensions and solder ball diameters are analyzed with three stereoscopic systems (Table 2). According to the previous works, the minimum facet size for each stereoscopic system is set to minimize the systematic error (Table 3).

The correlation result of three solder ball attached packages is collected with different facet sizes (Fig. 8(a) and (b)). It is evident that the percentage of correlation area changes together with facet size, and

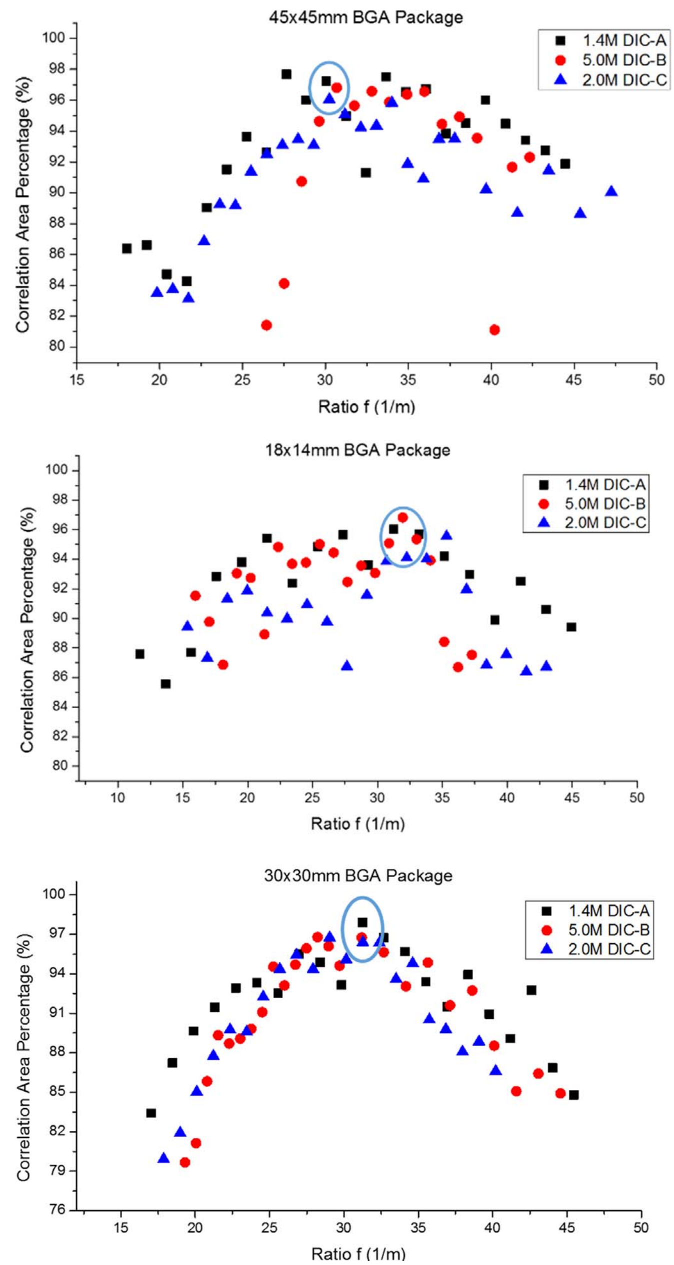


Fig. 9. The data integrity result vs. unified ratio f with three systems and three BGA packages.

has a peak value to produce the best correlation quality. A 90% correlation area means there is one data point missing among every 10 data points, while a 98% correlation quality increases this ratio to 1 over 50. So, the tiny percentage difference has great influence on the contour quality. However, the problem turns out that three systems shift the result due to different image sensors. For a new camera or package, the optimal facet size selection will be different. This result cannot be applied to all the 3-D DIC systems and packages.

To unify all the different samples for different systems and provide the guidance for all the 3-D DIC systems, a ratio f is defined to unify the variances of samples and systems.

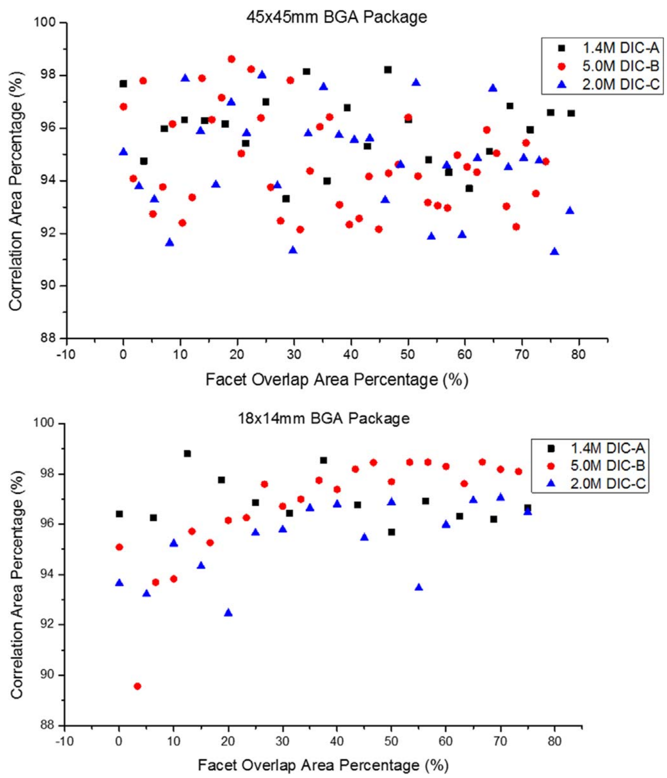


Fig. 10. The 45 × 45 mm and 18 × 14 mm BGA package data integrity result with different facet steps with the optimal facet size selection.

$$f = \frac{\textit{Actual facet size length}}{\textit{Solder ball diameter}\cdot\textit{length of field of view}} = \frac{\textit{Facet size}}{\textit{Long side pixel}\cdot\textit{Solder diameter}} = \frac{\textit{Facet size}}{\textit{Image length pixel}\cdot\textit{Solder diameter}\,(\mathrm{m})}$$

The ratio f is equal to the actual length of facet size divided by the product length of the image and the solder ball diameter. After simplifying the equation, the ratio f equals the facet size over the product of systematic pixels in length and the solder ball diameter. Here, the ratio of the facet size to the image pixels is the principal concern. Due to the variance of solder ball diameters, the ratio is shifted. Some calculation examples prove that the optimal facet size selections of different systems have a similar ratio f.

$$f = \frac{54\quad(\textit{pixel})}{2560\quad(\textit{pixel})\quad\times 650\quad\times\quad 10^{-6}\mathrm{m}} \approx 32\quad(1/\mathrm{m})$$
$$f = \frac{17\quad(\textit{pixel})}{1280\quad(\textit{pixel})\quad\times 450\quad\times\quad 10^{-6}\mathrm{m}} \approx 30\quad(1/\mathrm{m})$$
$$f = \frac{28\quad(\textit{pixel})}{1628\quad(\textit{pixel})\quad\times 550\quad\times\quad 10^{-6}\mathrm{m}} \approx 31\quad(1/\mathrm{m})$$

Adjusting the x axis with the help of ratio f, all the results are unified in the same scale (Fig. 9). For different samples measured by different 3-D DIC systems, the optimal correlation result can be achieved when this ratio f is between 30 and 32.

With the consideration of systematic deviation and image correlation percentage, this ratio is a comprehensive strategy for performing measurement with BGA packages. The facet size selection can be easily chosen through calculating the systematic pixels and the solder diameter. A relatively large facet size guarantees a reduction of systematic error, while correlation percentage of the undulant surface

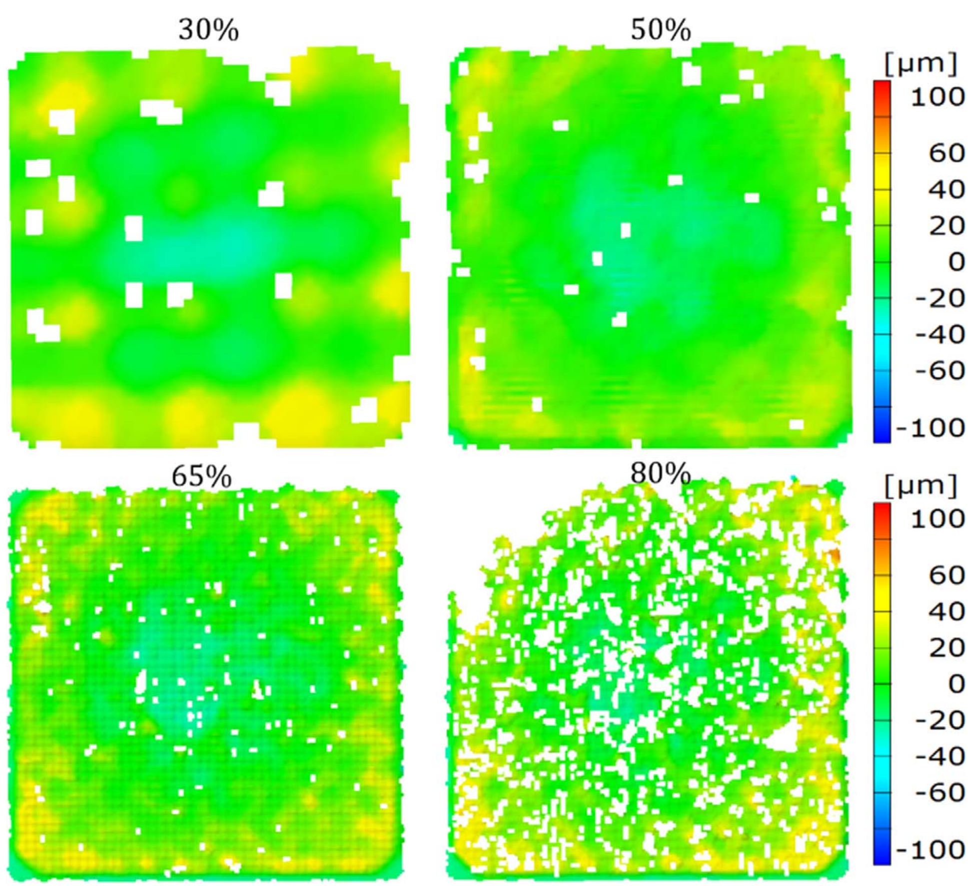


Fig. 11. The warpage contours of the 45 × 45 mm BGA packages with the 30, 50, 65% and 80% facet overlap at 180 °C.

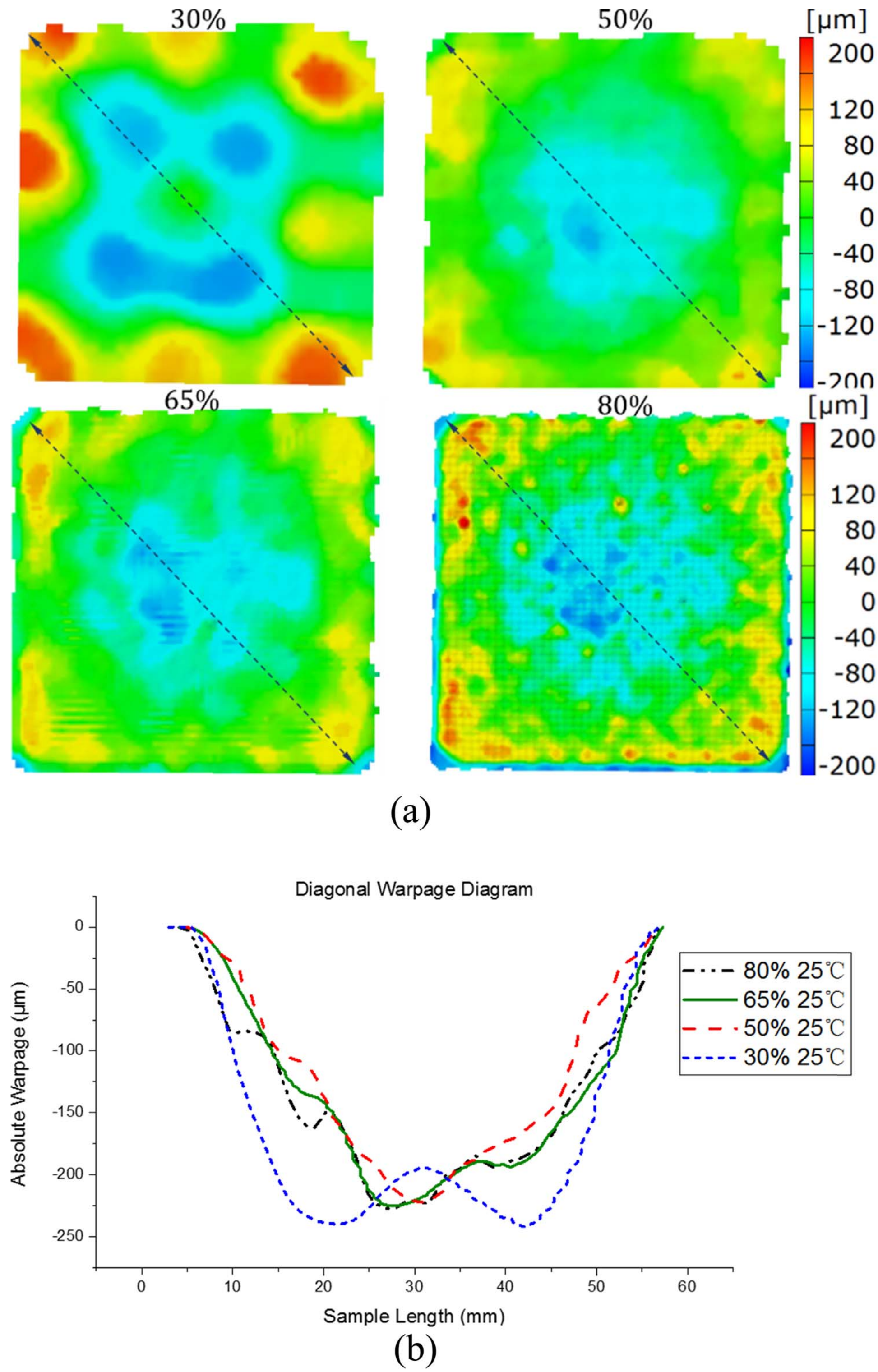


Fig. 12. (a) The warpage contours of the 45 × 45 mm BGA packages with the 30, 50, 65% and 80% facet overlap at room temperature; (b) The warpage plot of BGA package along the diagonal.

remains at a high level. It provides a general solution to measure the warpage of BGA packages.

3.3. Facet (subset) step

Instead of defining the specimen surface into several independent facets, some more facets are overlapped to generate more data points in a limited area. The overlapped facet pixels are called the facet (subset) step. The facet step assists to describe the surface topography accurately and make the approximated surface smoother. Meanwhile, the excessive overlapped facets will make the algorithm cannot recognize the actual surface topography and fails to achieve convergent solution.

In the facet step study, through setting the facet size with ratio f between 30 and 32, data integrity with respect to the facet overlapping percentage is plotted in Fig. 10.

Through the measurement results of two BGA packages from three

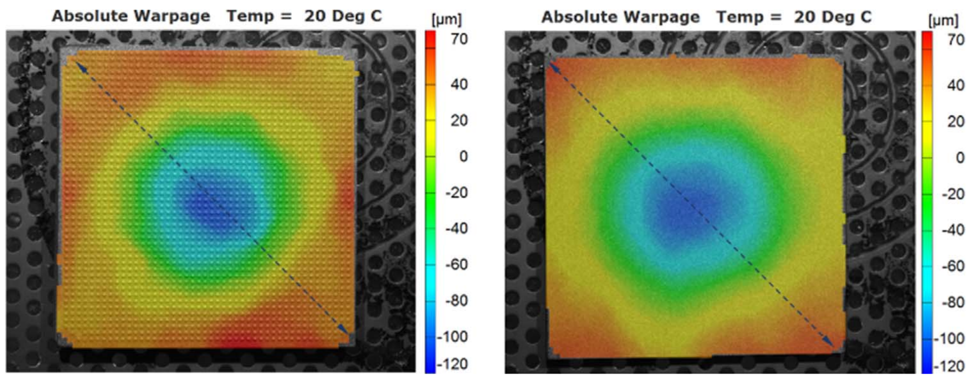


Fig. 13. Warpage contours of BGA package at 20 °C with and without solder balls attached.

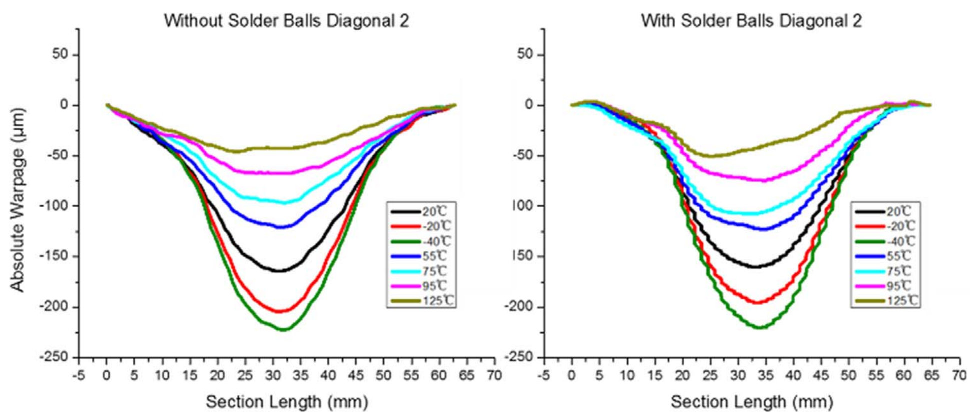


Fig. 14. The warpage plot of BGA package with and without solder balls attached during the thermal cycle.

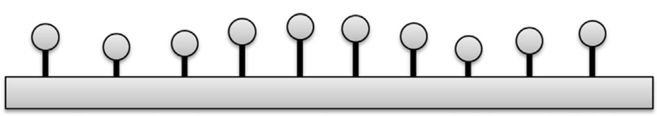


Fig. 15. The schematic of BGA connector with suspended solder balls above the substrate surface.

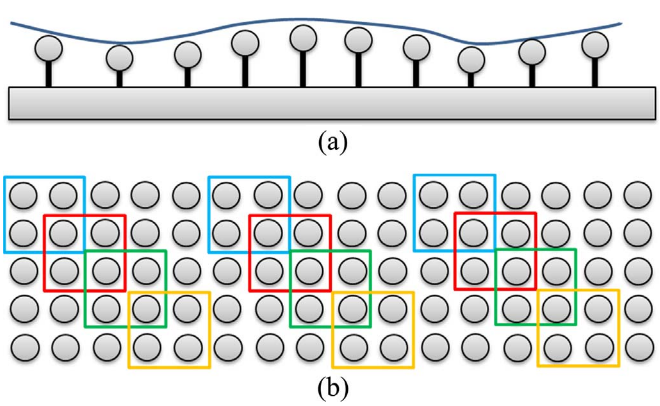


Fig. 16. The schematic of general solution to measure the solder balls height variance for BGA connector.

stereoscopic systems, the data integrity keeps more than 90% with a proper facet size selection and camera angle orientation. It indicates that the facet size and camera angle are the dominant parameters for correlation quality. The adjustment of the facet step does not have a consistent tendency or principle.

Given that the facet step helps to depict more details, the raw warpage results are plotted with different facet overlapping ratios (Fig. 11). The 45 × 45 mm BGA package is heated up to 180 °C. Fewer than 95% of data points at 180 °C can be correlated to the room temperature image. The contours imply that 30% overlap is lack of accuracy because fewer data points are generated. However, the 80% overlap produces many divergent points. The thermal deformation makes the correlation process more difficult than it is at room temperature. The 50% and 65% facet step plots complete warpage contours, which includes both data integrity and result accuracy. Through the experience of this study, facet step is suggested to generate about 40–65% overlapping areas for the optimal correlation integrity and accuracy.

4. Discussion

4.1. Facet step effects on the warpage result

The effectiveness of 3-D DIC measurement has been validated. The validated works are based on the very fine adjustment of the facet size and step. In Fig. 11, the contours imply similar warpage distribution but different details. It is necessary to look into the details of the surface topography variance with different facet steps. The contours of the solder ball attached packages, at 25 °C, are plotted (Fig. 12(a)). They show the concave shape that center is low and corners are high. However, the color distribution becomes less accurate as the facet step decreases. The warpage diagram along a diagonal is extracted and plotted in Fig. 12(b).

In the diagram, four warpage values are around 232 µm with the maximum warpage of 240 µm and minimum warpage value of 224 µm, which shows the warpage variation is about 4% for different facet overlapping percentages. Except for the 30% facet step curve, the other three curves indicate the identical warpage value and distribution. It is Considered that 80% overlap poses the risks of generating divergent data points at high temperature. The 40–65% facet step is recommended to guarantee the accuracy of the warpage measurement result.

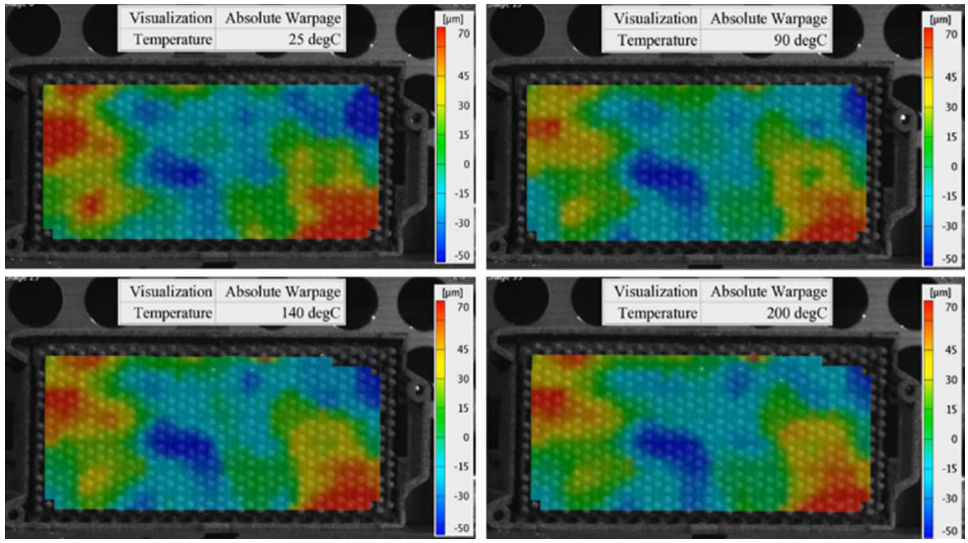


Fig. 17. The virtual surface profile on the top surface of solder balls at different thermal loadings.

4.2. Warpage comparison without solder balls

Before this work's method, all the 3-D DIC experiments of BGA packages were performed by initially shaving or melting the solder balls. Customers were always suspicious about the solder ball elimination effects on the final warpage results. In Fig. 13, the warpage distribution of the identical BGA package validates the warpage result when the substrate is attached with and without solder balls. Furthermore, the diagonal warpage diagram (Fig. 14) solidifies that fine solder ball elimination will not affect the warpage distribution of the packages because there is no other method available to compare the in-situ warpage result with solder balls attached. With the novel 3-D DIC method in this work, the potential risks of damaging the sample surface vanish, which validates the accuracy.

4.3. BGA connector warpage measurement

For the 3-D DIC tests, both the tensile test samples and the BGA packages have continuous planes to define the facet. For some special samples, the BGA connector has the solder balls built on the top of a pin (Fig. 15) and the height variance of its solder balls is the main concern. 3-D DIC has the capability to measure multi-planes, but the solder balls are too small to define individual facets on them. The problem is that the surface is incoherent and the solder balls is removed from the substrate. The suspended solder balls cannot share the same facet with the substrate surface. There is no in-situ measurement tool available for this special sample in current electronic packaging area.

In order to measure the BGA connector with 3-D DIC, the particular solution is to assume a virtual plane on the top of all the solder balls (Fig. 16(a)). Then the substrate surface is covered with black to function as a black background in the image. Each facet attempts to depict the virtual plane (facet), which consists of four solder balls on the top surface (Fig. 16(b)). With this strategy, the measurement was performed (Fig. 17) and the result was validated by the optical profilometer at room temperature. The special case shows the applicability and flexibility of the 3-D digital image correlation technique.

5. Conclusion

A general strategy for in-situ warpage characterization of solder ball attached packages is introduced. The effectiveness and accuracy are validated. Compared to the conventional DIC method, it does not require shaving the solder balls before the experiment.

This method helps adjust the camera angle, facet (subset) size and facet (subset) step in current 3-D DIC systems. Various measurement results are concluded as a ratio f to guide all the stereoscopic systems to conduct the similar experiment with the optimal image correlation quality. The ratio format result can be widely utilized with different system capabilities.

The comparison study of warpage result with or without solder balls shows the effectiveness of this new method. At the same time, the nondestructive test is more convenient and safe. The special BGA connector experiment shows the universality and robustness of 3-D DIC technique. More application areas and complicated samples can be tested with this method in the future.

3-D DIC requires more than 10 parameters be adjusted during or after the measurement. The complicated settings make it difficult to be applied widely to all industrial warpage measurement. This study provides the guidance to settle the three important factors for the 3-D DIC experiment process. All the warpage measurements for electronic packages can follow the equation and the method in this work to achieve the optimal correlation quality for any operator who lacks experience. By knowing the system pixels and the sample's dimension, the corresponding facet size and step can be calculated directly through the empirical equation in this paper. In addition, the relatively small camera angle can also help to generate less calibration deviation because the left and right images are more similar to each other with less image variance from left and right sensor. This study helps to find the issues during reflow process to improve the reliability of BGA packages without removing the solder balls. The nondestructive and in-situ warpage measurement also make the experiment more convenient and closer to the actual packaging assembly process and the warpage result more convincing to customers because the package structure is not damaged.

References

[1] Kwak JB, Park S. Integrated hygro-swelling and thermo-mechanical behavior of mold compound for MEMS package during reflow after moisture preconditioning. Microelectron Int 2015;32:8–17.
[2] Chung S, Tang Z, Park S. Effects of phase change of Pb-free flip-chip solders during board-level interconnect reflow. IEEE Trans Adv Package 2007;30:38–43.
[3] Yin CY, Alam MO, Chan YC, Bailey C, Lu H. The effect of reflow process on the contact resistance and reliability of anisotropic conductive film interconnection for flip chip on flex applications. Microelectron Reliab 2003;43:625–33.
[4] Fan SH, Chan YC. Effect of misalignment on electrical characteristics of ACF joints for flip chip on flex applications. Microelectron Reliab 2002;42:1081–90.
[5] Chiang K, Lin Y, Cheng H. On enhancing eutectic solder joint reliability using a second-reflow-process approach; 23:9–14; 2000.
[6] Chung S, Park SB. Numerical investigation of underfill failure due to phase change of Pb-free flip chip solders during board-level reflow. IEEE Trans Compon Package

Technol 2008;31:661–9.
[7] Petriccione GJ, Charles Ume I. Warpage studies of HDI test vehicles during various thermal profiling. IEEE Trans Adv Package 1999;22:624–37.
[8] Srikanth N. Warpage analysis of epoxy molded packages using viscoelastic based model. J Mater Sci 2006;41:3773–80.
[9] Wang Y, Hassell P. Measurement of thermally induced Warpage of BGA packages/ substrates using phase- stepping shadow MoirC. Package Technol 1997:2–8.
[10] Vogel D, Grosser V, Schubert A, Michel B. MicroDAC strain measurement for electronics packaging structures. Opt Lasers Eng 2001;36:195–211.
[11] Verma K, Columbus D, Han B. Development of real time/variable sensitivity warpage measurement technique and its application to plastic ball grid array package. IEEE Trans Electron Packag Manuf 1999;22:63–70.
[12] Amagai M, Suzuki Y. A study of package warpage for package on package (PoP). Proc – Electron Compon Technol Conf 2010:226–33.
[13] Han B, Guo Y, Choi H-C. Out-of-plane displacement measurement of printed circuit board by shadow moire with variable sensitivity. Adv. Electron. Package, 4. ASME; 1993. p. 179–85.
[14] Park S, Dhakal R, Joshi R. Comparative analysis of BGA deformations and strains using digital image correlation and moiré interferometry [Portland]. Proc Soc Exp Mech 2005.
[15] Schmidt T, Tyson J, Galanulis K. Full-field dynamic displacement and strain measurement using advanced 3D image correlation photogrammetry: Part 1. Exp Tech 2003;27:47–50.
[16] Niu Y, Lee H, Park S. A new in-situ warpage measurement of a wafer with speckle -free digital image correlation (DIC) method. Proc – Electron Compon Technol Conf 2015:425–31.
[17] Sutton MA, McNeill SR HJ, CY. Advances in two-dimensional and three-dimensional computer vision. Top Appl Phys; 2000. 1. p. 323–72.
[18] Standard JEDEC. Package Warpage Measurement of Surface-Mount Integrated Circuits. JESD22-B112; 2009.
[19] Niu Y, Wang H, Shao S, Park SB. In-situ Warpage characterization of BGA packages with solder Balls attached During Reflow with 3D digital image correlation (DIC). IEEE 66th Electron Compon Technol Conf 2016:782–8.
[20] Lecompte D, Smits A, Bossuyt S, Sol H, Vantomme J, Van Hemelrijck D, et al. Quality assessment of speckle patterns for digital image correlation. Opt Lasers Eng 2006;44:1132–45.
[21] Fazzini M, Mistou S, Dalverny O, Robert L. Study of image characteristics on digital image correlation error assessment. Opt Lasers Eng 2010;48:335–9.
[22] Crammond G, Boyd SW, Dulieu-Barton JM. Speckle pattern quality assessment for digital image correlation. Opt Lasers Eng 2013;51:1368–78.
[23] Pan B, Lu Z, Xie H. Mean intensity gradient: an effective global parameter for quality assessment of the speckle patterns used in digital image correlation. Opt Lasers Eng 2010;48:469–77.
[24] Sutton MA, Yan JH, Tiwari V, Schreier HW, Orteu JJ. The effect of out-of-plane motion on 2D and 3D digital image correlation measurements. Opt Lasers Eng 2008;46:746–57.
[25] Schreier H, Sutton M a. Systematic errors in digital image correlation due to undermatched subset shape functions. Exp Mech 2002;42:303–10.
[26] Hassan GM, MacNish C, Dyskin A, Shufrin I. Digital image correlation with dynamic subset selection. Opt Lasers Eng 2016;84:1–9.
[27] Lane C, Burguete RL, Shterenlikht A. An objective criterion for the selection of an optimum DIC pattern and subset size. Proc XIth Int Congr Expo 2008:1–9.
[28] Sun YF, Pang JHL. Study of optimal subset size in digital image correlation of speckle pattern images. Opt Lasers Eng 2007;45:967–74.
[29] Kim Y, Lee H, Zhang X, Park S. Optimal material properties of molding compounds for MEMS package. IEEE Trans Compon Package Manuf Technol 2014;4:1589–97.
[30] Singh C. Comparative study of analytical models to predict warpage in microelectronics packages. Int. Mech. Eng. Congr. Expo., Montreal: ASME; 2014, p. 1–6.