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Abstract: Electronic packages are composed of various components that have different coefficients of thermal expansion (CTE) values. Thermal strain occurs due to CTE mismatch of the components. However, when the thermal strain distributions are measured by digital image correlation (DIC), a periodical measurement error is observed. In this study, a displacement measurement method with periodical error elimination is applied to the measurement of thermal strain in an electronic package structure. In this method, rotated and multiple translated images in the horizontal and vertical directions are used to determine actual translation amounts. The periodical errors are eliminated using the relation between measured and actual translation amounts. As a result, the periodical errors in the measured thermal strain distributions on a test specimen can be eliminated, and measurement spatial resolution and accuracy are improved. In addition, precise thermal strain distributions can be observed. This method is effective for in-plane thermal strain measurement of electronic packages.

Keywords: Electronic package, Thermal displacement, Thermal strain, Digital image correlation, Periodical error

1. Introduction
An electronic package consists of heterogeneous materials such as solder and silicon that have various coefficients of thermal expansion (CTE) values. Cyclic thermal stress tends to occur when using these packages, resulting in breakage of the packaging structure (the solder joint, wire joint, substrate, ceramic chip, etc.). If the structure can be designed on the basis of accurately measured thermal stress and strain, the electronic packaging will have an appropriate lifetime.

In the past, thermal strain has been evaluated by direct measurement using tools such as strain gauges and calculated by analytical methods such as finite element analysis (FEM). However, the structures are constantly being downsized, which makes thermal strain measurement by direct measurement methods quite difficult. Also, thermal stress estimation by analytical methods is not always accurate because the mechanical properties of the structures may be different from the test results due to the use of bulk materials when making the test specimen. The mechanical properties are affected by grain texture when the structure is miniaturized [1], and currently we have insufficient knowledge of the mechanical properties of minute structures. Therefore, a new method to measure and evaluate thermal strain on electronic packaging is needed.

In this research, we propose a method for measurement and evaluation using digital image correlation (DIC), a full-field noncontact method for the measurement of strains [2]. The experimental environment and procedures of DIC are simpler than any other optical method, but one of the issues facing this method is a characteristic periodical error in the displacement distribution obtained by DIC. This occurs because of the interpolation of pixel values, the speckle pattern of specimens, and a lack of pixel value caused by a gap between sensors in CCD cameras. Although these systematic errors are typically very small (just a few hundredths of a pixel), they affect the calculation of strain. Specifically, the correct strain cannot be obtained because the strain is calculated by displacement gradient. Various researchers have investigated ways of reducing the measurement error in displacement obtained by DIC. Bornet et al. investigated the effect of speckle pattern size and order of the interpolation function for measurement error and found that a smaller pattern size and higher order of interpolation function could reduce the error [3]. Schreier et al. investigated the effect of pixel value distribution shapes in images for the measurement results and found that, as the error increases in images that contain high-frequency content, it can be reduced by reducing high-frequency content using a low pass filter [4].

Although the measurement accuracy is improved by these methods, the periodical error is not eliminated. To obtain correct strain distribution by DIC, systematic error must be eliminated completely. Arikawa et al. proposed a method of periodical measurement error elimination that uses rotated and multiple translated images to find out the relationship between the actual translation amounts and the measured value. They applied this method to the biaxial displacement measurement [5–6]. We applied this method to the uniaxial thermal strain measurement of electronic packaging structure and found that it did not have any effect on the periodical error [7]. In this study, we use the displacement measurement method with the periodical error elimination to measure the horizontal and vertical thermal strain of electronic packaging structure. The effect of periodical error elimination on the spatial resolution and the accuracy in the thermal strain measurement is investigated.

2. Periodical Error Elimination
The periodical error elimination method we developed is based on the method proposed by Arikawa et al. [5-6]. Figure 1 show the relationship between the measured...
values obtained by parallel movement. The parallel movement is performed by moving the camera or the measurement objects. If we can grasp the correct amount of translation, the position of the plot is determined and the inclination of the straight line passing through \( P_0 \) to \( P_4 \) becomes clear. A correct displacement value can be obtained from the relationship between this inclination and the inclination of the ideal value that is 1. This error correction method it is necessary to know the amount of translation. In order to obtain the translation amount sufficient precision to eliminate the error, Arikawa have proposed a high-precision calculation method of the amount of translation using the in-plane rotation. This method is based that average of in-plane rotational displacement distribution including the translation is equal to the true amount of translation.

In this study, we use translated images in the horizontal and vertical directions to eliminate two directional periodical errors. Figures 2 and 3 show the outline of the proposed method. Micro parallel translations are implemented. Multiple images are used to determine the two directional actual displacement. Images of after the rotation and after the thermal load are used to calculate an in-plane thermal displacement and eliminate the periodical error.

3. Experiments
We performed thermal strain measurement of the electronic packaging structure to determine the effectiveness of the proposed method. A schematic drawing of the test equipment is shown in Fig. 4. This test equipment is composed of a thermostatic chamber for heating, a test specimen, and a CCD camera. The number of effective pixels of (JAI; CV-M4+CL) is 1280 × 1024. The tone is a monochrome 8-bit. The CCD camera can be moved in the horizontal and vertical directions, so the equipment can shoot multiple translation images. The test specimen, shown in Fig. 5, is a silicon chip soldered by a Pb-free solder on a copper base to simulate the electronic packaging structure. Thermal strain on the surface of a chip was measured by the proposed measurement method. Dimensions of the chip were 15 × 15 mm and the measurement area was 11 × 11 mm. We painted a speckle pattern on the specimen by a boron nitride spray and a lacquer spray. The temperature condition is incalescence from room...
temperature (298 K) to 453 K. The rigid rotation for error elimination is 0.2 degrees. The translation is performed in increments of 3.8 μm and is given to the specimen ten times. The interpolate function for DIC is bi-linear. The subset size for analysis is 51×51 pixels and the analysis range is 780×780 pixels, which is the range of specimen. The thermal displacement gradient was determined by the plane approximation by the least squares method of the displacement distribution. The thermal strain was obtained by differentiating the displacement gradient. A $L_g$ of the approximation condition is the gauge length. The $L_g$ is 51–351 pixels every 30 pixels.

The thermal strain is measured by strain gauges to validate the measurement accuracy of the proposed method. The measuring points are shown in Fig. 6 and the coordinate points of the strain measuring are listed in Table 1. The measurement results by the strain gauges have the appearance strain due to the temperature effect. The correct thermal strain that does not have the appearance strain was obtained by compensation of temperature change. The apparent strain was obtained from the thermal strain measurement result of the copper plate that knows the coefficient of the thermal expansion. The measurement results by the proposed method are compared with the results by the strain gauges.

### 4. Results and Discussion

The measurement results of the thermal strain distributions on the chip surface are given in Fig. 7. These results are x directional normal strain distributions ($\varepsilon_x$), y directional normal strain distributions ($\varepsilon_y$), and z directional normal strain distributions ($\varepsilon_z$). Strain distributions before and after applying the proposed method are shown. In both cases, the results by the proposed method have a relatively smooth strain distribution. In order to evaluate the effectiveness of the proposed method quantitatively, we compare the measurement results by the proposed method with the values by the strain gauges. The results by the strain gauges are treated as reference values.

Figure 8 shows the thermal strain values on the surface of the chip. These results were obtained by the conventional method, the proposed method, and the strain gauges. The measurement results are shown by the conventional method, the proposed method, and the strain gauges. The apparent strain was obtained from the thermal strain measurement result of the test specimen. However, this apparent strain was obtained from the thermal strain measurement result of the
strain value is constant with each measurement method, so a comparison of these thermal strain values is effective in terms of evaluating the effect of the displacement error elimination and the accuracy of the measurement. The strain values measured by each method are relatively consistent with the reference values except for the strain on a point B measured by the conventional method. In particular, the strain values measured by the proposed method are more similar to the reference values than the strain values measured by the conventional method. This demonstrates that the proposed method can eliminate the effect of the periodical displacement error in the thermal strain measurement and accurate strain values can be obtained.

If the length of $L_g$ for computing strains is the same as the integral multiple of a period of the periodical error, strain values without the influence of the periodical error are obtained by the conventional method because the average strain value within one period of the error is zero. If the $L_g$ is smaller than the period, strain values contain the influence of the periodical error. In addition, this error is repeated with a period of one pixel and the deformation amount is inversely proportional to the length of the period of the error in the strain measurement area, so the $L_g$ is increased to obtain the strain values without the influence of the periodical error when measuring a small displacement. The large $L_g$ condition means the strain measurement spatial resolution is low. However, the strain measurement of a minute electronic packaging structure requires improved measurement spatial resolution. In this case, the periodical error elimination method has the advantage, as it is possible to reduce the $L_g$.

The standard deviations of the strains obtained by various $L_g$ conditions are compared to evaluate the improvement of the spatial resolution by the proposed method.

Figure 9 shows the relationship between the $L_g$ and a standard deviation $\sigma$ of the strain values on a 2×2 mm area of the center of the chip. As described above, these results exhibit measurement variation due mainly to the periodical...
displacement error being reduced when the $L_g$ increases. The standard deviation of the strain values with the error elimination is lower than that without the error elimination. Furthermore, the difference in the variation increases as $L_g$ increases. Thereby, using the proposed method is effective to reduce variation and $L_g$ length, and we consider it effective for the quantitative improvement of strain measurement spatial resolution. Improvement factor $R_i$ is defined as

$$R_i = \frac{L_C}{L_P}$$

In this equation $L_C$ is $L_g$ when using conventional method, $L_P$ is $L_g$ when using proposed method. Each plot in Fig. 9 is a curve approximation to evaluate the $R_i$. As a result, $R_i$ is over about 1.4 in the range of $L_C=51–351$ pixels. This indicates it is possible to improve the strain measurement spatial resolution by at least about 1.4 times under this evaluation condition.

5. Conclusion

In this study, we proposed a thermal displacement and strain measurement method using DIC to eliminate the periodical measurement error. The effectiveness and improvement of the strain measurement spatial resolution are evaluated by measurements of the electronic packaging structure, which was a silicon chip soldered by Pb-free solder on a copper base. Results showed that the periodical error in the measured thermal strain distributions on the surface of the chip can be eliminated, thereby improving the measurement spatial resolution and accuracy and enabling the observation of precise thermal strain distributions. We also found it is possible to improve the strain measurement spatial resolution by at least about 1.4 times. These results demonstrate the proposed method is effective for the in-plane thermal strain measurement of electronic packaging structure.

Nomenclature

- $\theta$ angle of rotation [degree]
- $d_x$ translation amount for x direction [pixel]
- $d_y$ translation amount for y direction [pixel]
- $L_g$ gauge length [pixel]
- $\varepsilon_x$ x directional normal strain
- $\varepsilon_y$ y directional normal strain
- $\sigma$ standard deviation of thermal strain
- $L_C$ $L_g$ value when using conventional method [pixel]
- $L_P$ $L_g$ value when using proposed method [pixel]
- $R_i$ improvement factor of strain measurement spatial resolution

References