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Digital Image Correlation over a Range of Temperatures Using High Magnification Optical Microscopy †

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Abstract: Full-field optical strain measurements as a function of temperature are difficult to perform at the micron scale. The thermal expansion mismatches result in stresses that can break interfaces and damage the parts. Digital image correlation is an ideal measurement technique for this type of application, but it requires surface features of a specific scale that can be tracked and a measurement surface that remains in focus throughout the range of temperatures. These requirements are not difficult at the centimeter scale, and have been demonstrated at the millimeter and nanometer scales, but have not been achieved at the micrometer scales that are ideal for electronic parts. The problems include the small depth of focus, movement of the specimen due to thermal expansion, damage to the microscope lens due to heating, optical distortions due to uneven air temperatures, and the application of surface features for tracking. A new test apparatus and test method has been developed to provide the conditions needed for high-quality digital image correlation measurements using a high-magnification optical microscope up to 1000x magnification over a range of several hundred degrees Celsius. In this paper, the apparatus and test methods are described, and test results are demonstrated.

Keywords: Digital Image Correlation 1; Optical Microscopy 2; Elevated Temperature 3

1. Introduction

Non-homogeneous materials are becoming more common in many different engineering disciplines. These aspects may include manufacturing-induced variations from 3D printing, non-isotropic material properties, composite materials, and composite structures. The differences in material properties and interfaces make it difficult to predict localized behaviors. Direct measurement of the displacement within these structures is ideal, but is difficult in small parts because of their scale.

Point and area measurements, such as extensometers and strain gages, have been used for many decades, but are limited in the sizes of the devices and in the amount of surface topology that they can tolerate, and cannot provide data across the entire face of the specimen. In addition, at small scales and on very thin specimens, the attachment of these devices to the specimen can change the results. Therefore, non-contact, full-field measurements are preferred.

Interferometry can be used to measure full-field displacement on the micron scale, but it has significant disadvantages to its use. Specimen preparation is labor intensive, requiring careful surface preparation and test setup [1]. The surface preparation involves carefully applying a grating to a smooth, flat specimen surface. The first grating then viewed through another real or projected grating, and the interference pattern can be used to calculate full-field displacement. Displacement can only be measured in one direction at a time with a linear grating, but can be measured in two

directions with a cross-line grating. The grating pattern may be projected onto the specimen surface to reduce surface preparation, but this comes at the cost of lower resolution, greater susceptibility to external vibration, and more restrictive test setup due to the fact that the specimen must be located close to the grating surface. Laser interferometry techniques offer higher resolution with reduced surface preparation, but come at the cost of high sensitivity to environmental vibrations and air fluctuations. All of these techniques also require very specialized equipment and training.

Digital image correlation (DIC) is a newer technique that offers several distinct advantages. DIC was developed at the University of South Carolina in the 1980s [2], and has become widely used due to advances in digital imaging and processing. Displacement and strain are computed by comparing taking a reference image at an initial state, taking a series of additional images as the test article is deformed, and calculating the change in the locations of surface features. The surface features that are tracked can be either intrinsic to the material or applied to the surface before testing. Surface preparation is typically less labor-intensive than for interferometry. The technique is scalable to any article that can be digitally imaged, and has been applied across the meter and nanometer scales.

Application of this technique to the micrometer scale, which is ideal for electronic parts, presents several technical challenges. While depth of focus is not a problem for most macro-scale camera lenses or for scanning electron microscopy [3], the depth of focus of optical microscope lenses is very small and decreases with magnification, so that even small out-of-plane motion caused by thermal expansion can cause the microscope to lose focus. Surface features of the proper size, which is typically less than 10 microns in diameter, are difficult to apply at this scale—paint speckles are too large, microspheres are too tall to be fully in focus, and fine powders combine into large clumps due to van der Waals forces. In addition to thermal expansion, two other thermal problems arise: uneven heating of the air diffracts light and results in displacement errors in the images, and the necessarily close proximity of the microscope lens to the specimen can cause the lens to be heated to damaging temperatures. Thermal window panes used to prevent this last thermal issue can create new problems by degrading image contrast and requiring more space than the working distance of the lens allows.

The results presented in this paper have developed from work that was first published in 2013. The original publication presented test apparatus, test methods, and DIC results on full-sized electronic assemblies from -55 to 200 °C using traditional camera lenses. These tests produced thermal strains representative of manufacturing and reliability testing conditions in the electronics industry [4]. Those apparatus and methods were extended to continually smaller scales until the test apparatus and methods could no longer produce acceptable results at fields of view less than 4mm wide.

At higher magnification, the optics of the traditional camera lenses became insufficient, and an optical microscope was employed. The micrometer scale issues discussed above surfaced simultaneously, preventing usable images from being obtained and making simple trouble-shooting impossible. No published studies could be found that addressed these issues. These technical challenges have been systematically addressed by the authors in a number of ways, which are discussed in this paper. A new apparatus has been designed that addresses the issues of thermal expansion and heating of the microscope lens, and reduces errors caused by diffraction. Some surface preparation methods have been developed to create motion tracking features. Test data are presented to validate the results.

2. Materials and Methods

2.1. Apparatus

The original setup for testing electronics assemblies used a pair of cameras suspended over a small manufacturing oven. Many electronics assemblies, such as circuit boards, are manufactured in large reflow ovens that move the parts on a conveyor through temperature zones to ramp the assemblies up to near the melting temperature of the solder, push the temperature just above the

melting temperature, then ramp the temperature down to room temperature. Using DIC in this environment would require the cameras to move through the oven with the assemblies, which would destroy most cameras. A batch reflow oven can match the temperature profile, but keeps the assembly stationary and can have a double-pane window through which the assembly can be viewed. A commercial oven was modified for DIC by modifying the window to prevent refraction problems caused by convective air currents between the panes, and by re-designing the heating ducts to produce more even temperature across the entire viewing area. An external fan can be used to blow ambient air across the outer surface of the window and eliminate refraction between the window panes and the cameras. This setup has been proven capable of producing good results on images from 30 cm to 4 mm and from -55 °C to 300 °C.

When attempting to use this setup with an optical microscope, the specimen quickly went out of focus due to the thermal expansion of the metal oven structure and the specimen, causing the specimen surface to move towards the lens beyond the depth of focus of the lenses. In addition, the window—even with a single pane—greatly degraded the image quality of the microscope images. Also, the small focal length of the lenses was too small for a double-pane window, and a single-pane window caused the lens to heat unacceptably. Finally, airbrushed paint speckles were too large for this size of image, and small diameter particles grouped together into clumps that were too large. It should be noted that only single lenses can be used at this scale, due both to the size of the lens housings causing them to interfere with each other, and the small depth of focus of the lenses requires the lenses to be perpendicular to the viewing surface for the entire surface to be in focus.

It quickly became obvious that a new heated microscope stage needed to be developed to overcome these issues. Two key aspects of the design are an inverted specimen and a low thermal expansion stage, as illustrated in Figure 1. The inverted setup has several advantages. First, any thermal expansion of the part happens away from the stage. In order to do this in an upright orientation, the specimen would have to be clamped to the stage, which may introduce undesirable boundary conditions, while the inverted setup allows the specimen to be supported only by its own weight. The inverted setup also allows the heat to rise away from the microscope lens. This prevents heating of the lens, and reduces diffraction due to unevenly-heated air between the viewing surface and the lens. The stage is made of quartz, which has very low thermal expansion, and is supported on three ceramic spheres, which in turn rest on an x-y micrometer translation stage. The spheres allow the heated air to flow out from under the specimen stage, minimize heat conduction to the metal translation stage, and are made of low thermal expansion material to minimize out of plane motion. The stage has a viewing port in the center that is slightly larger than the maximum field of view of the microscope lens.

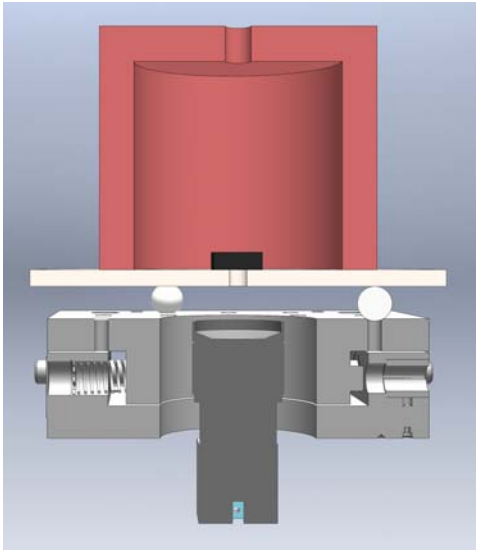


Figure 1. Schematic of Prototype Microscopy Apparatus

The original microscope was not adequate for DIC measurements due to low resolution (2 megapixel) CMOS sensor. A new microscope has been purpose-built for this application. The camera includes a 5 megapixel CCD sensor with a high-magnification telecentric lens to improve depth of focus. Specimen lighting in both microscopes was through the lens, which provided the best results while bypassing space constraints in the area around the lens. The light in the new camera is fully manual, which allows for more repeatable contrast between tests. The microscope is attached to the support stand for the stage to reduce rigid-body motion between the optics and the specimen. Heat is provided by a resistance heater that is placed on top of the specimen stage. Temperature is measured using a thermocouple attached to the surface of the specimen.

2.2. Specimen Preparation

DIC requires contrast features on the measurement surface in order to track the displacement in the images. These features need to be a certain number of pixels in size and remain consistently identifiable throughout the test. For some test articles, the surface has sufficient intrinsic surface features, such as material microstructure or surface texture.

It is more often the case that the specimen must be prepared in some manner to add or reveal high contrast features. So far, two techniques have been used successfully to create contrast in microscopy specimens. The first is to finely polish the specimen surface to reveal microstructural features, which may include the grains or dendritic structures of metals, small inclusions or voids, filaments in composites, or any other feature that produces sufficient contrast. An example of this is shown in Figure 2(a), where the interconnection between a microprocessor die and substrate has been polished to reveal the solder dendrites, voids in the copper traces and silicon, and features in the polymeric underfill and substrate resin. All of these features produced sufficient contrast for DIC. The second technique is to create surface features by polishing. This can either be done by polishing the surface to just less than a mirror finish, or by finely polishing the surface and then "de-polishing" the surface with a coarser grit. An example of this is shown in Figure 2(b), where small scratches produce contrast in an aluminum specimen.

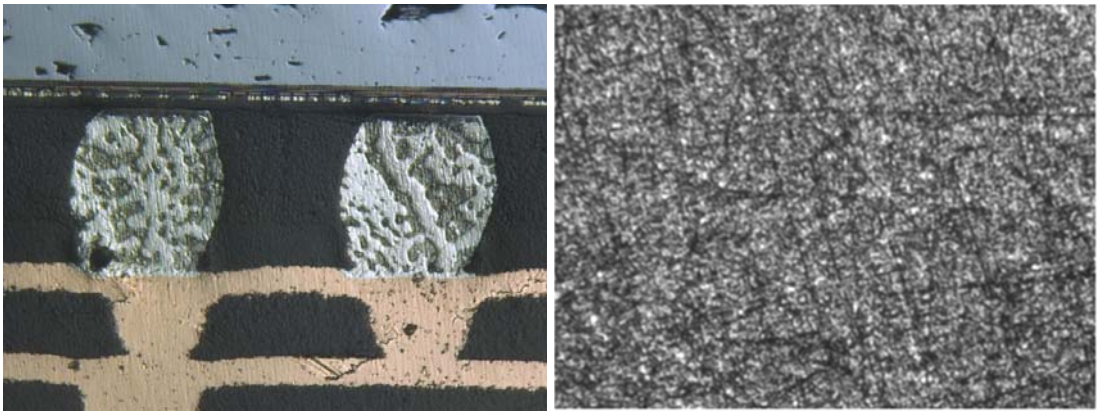
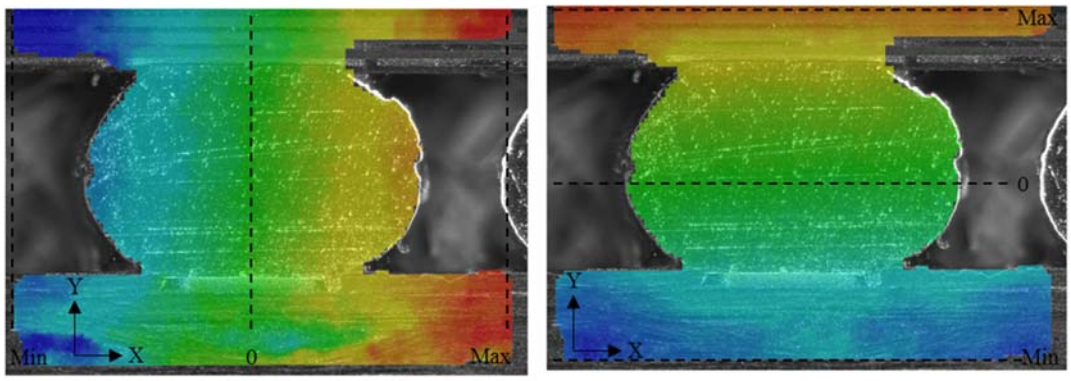


Figure 2. (a) Polished Microprocessor Interconnection and (b) De-Polished Aluminum Viewed at 1000x Magnification

3. Results & Discussion

Tests using the inverted microscope apparatus have been performed over a range of temperatures up to 300 °C, over a range of magnifications, and on a variety of microelectronics parts and homogeneous metal plates. The higher magnification tests are more difficult due to the fact that the depth of focus decreases as magnification increases. When focus is lost, re-focusing cannot correct the problem because this changes the contrast of many of the features. For purposes of illustration of the capability, two tests are presented below. The first test is of a microprocessor feature up to 170 °C. The second test is a calibration using an aluminum specimen at similar magnification to validate the results.

The microprocessor test was performed on a solder connection between a microprocessor substrate and printed circuit board at 200x magnification. The solder ball pitch is approximately 1 mm wide, and the entire image is approximately 1.4 mm wide. The part was cross-sectioned and polished down to a mirror finish with 1 micron diamond paste. The solder ball that was imaged was the second to last from the outside edge—approximately 17 mm from the center of the microprocessor—in order to increase the magnitude of strain. The specimen was photographed every 20 °C from 30 to 170 °C. The relative displacement response of the specimen in the x and y directions is shown in Figure 3. The DIC data covered nearly the entire surface of the specimen and show responses such as the different thermal expansion between the two fiber directions in the circuit board and the effect of the solder ball's expansion on the circuit board and microprocessor substrate.



(a) (b)

Figure 3. Relative Displacement at 170 °C in the (a) X-Direction and (b) Y-Direction at 200x Magnification

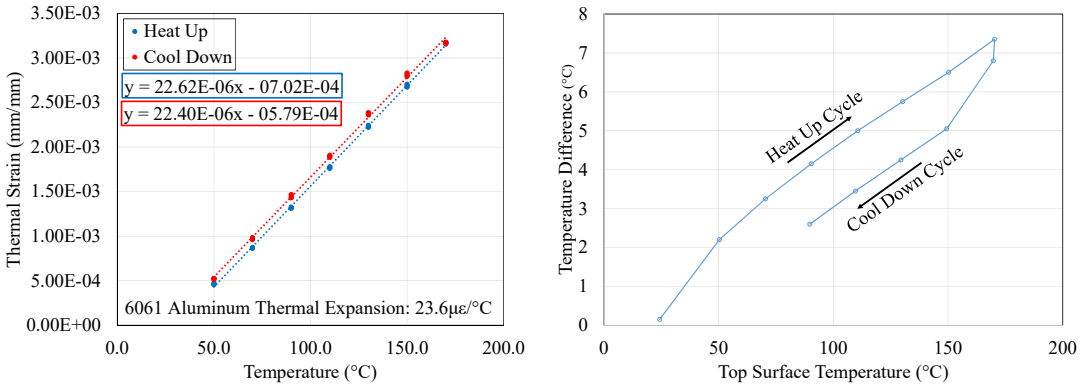


Figure 4. (a) Thermal Strain of the Aluminum as a Function of Top Surface Temperature and (b) the Temperature Difference Between the Top and Bottom Surfaces

In order to validate the results, a specimen with known strain needed to be measured. Validation specimens were made from aluminum, copper, and silicon, which were first tested in a calibrated thermal expansion dilatometer to ensure that the thermal expansions were precisely known. Of these materials the aluminum produced the best combination of expansion and contrast when polished, as shown in Figure 2(b). The copper specimen changed contrast during testing due to oxidation during heating, which may have not been an issue during subsequent tests. The initial tests with aluminum produced large errors of up to 100%, which were traced to two causes: 1) the low resolution and scanning rate of the CMOS sensor, and 2) a thermal gradient through the specimen. The camera problem was solved with the higher resolution CCD camera, which reduced the majority of the error, as well as eliminating error fluctuation with time. The tests with the new

microscope gave a uniform thermal expansion of approximately 22.5με/°C, compared to 23.9 με/°C measured in the dilatometer (compare to published values of 23.6 με/°C for 6061 aluminum)—a difference of less than 5% between measured values. The strain versus temperature response is shown in Figure 4(a). The response continues to differ between the heat-up and cool-down portion of the test. Repeating the test with thermocouples on the top and bottom of the specimen showed a thermal gradient between the viewing surface (bottom) and the surface to which the thermocouple was applied (top). The gradient appears to be due to a lag in temperature between the heated chamber and the viewing stage, as shown in Figure 4(b), which creates a heat conduction path between the air, specimen, and stage. Using the measured temperature difference to adjust the thermal expansion curves produced 23.6 με/°C thermal expansion for the aluminum sample.

4. Conclusions

A new test apparatus has been developed to enable DIC using high-magnification optical microscopy by inverting the specimen on a low-expansion stage and heated with a resistance heater. A high-resolution CCD camera attached to a telecentric lens with through-lens lighting works well for imaging. The current apparatus and specimen preparation method has been has been validated by measurement of the thermal expansion of a uniform material that compares well to known values. Additional tests have shown capability to 1000x magnification and 300 °C. A temperature measurement method that more accurately measures the viewing surface without displacing the specimen or obstructing the view would improve the results.

Specimen preparation is performed by polishing the specimen surface either to reveal intrinsic material features or to produce small surface features. Additional techniques to create artificial surface features would increase the types of materials that can be measured to include those with no high-contrast surface features.

This capability provides the ability to measure thermally-induced deformation in small structures using the full-field, non-contact digital image correlation technique. This technology allows these measurements to be taken at millimeter to micrometer scales with equipment that is available to most microscopy laboratories. Additional testing opportunities will exercise this capability and continue to mature the apparatus and methods.

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Conflicts of Interest: "The authors declare no conflict of interest."

References

1. Davidson, R.J., A Comparison of Moiré Interferometry and Digital Image Correlation, Air Force Institute of Technology, Wright Patterson Air Force Base, Ohio, March 2008.
2. Kammers, Daly, Digital Image Correlation under Scanning Electron Microscopy: Methodology and Validation, Experimental Mechanics, Volume 53, Issue 9, pages 1743-1761, November 2013.
3. Ralph, W.C.; Moss, C.B.; Connolly, K.B. Digital Image Correlation Using High Magnification Optical Microscopy, Proceedings of SMTA International, Rosemont, Illinois, September 27 – October 1, 2015.
4. Ralph, W.C.; Raiser, G.; Assembly Level Digital Image Correlation Under Reflow and Thermal Cycling Conditions, Proceedings of the 63rd Electronic Components & Technology Conference, pages 2223-2227, Las Vegas, NV, May 28-31, 2013.