

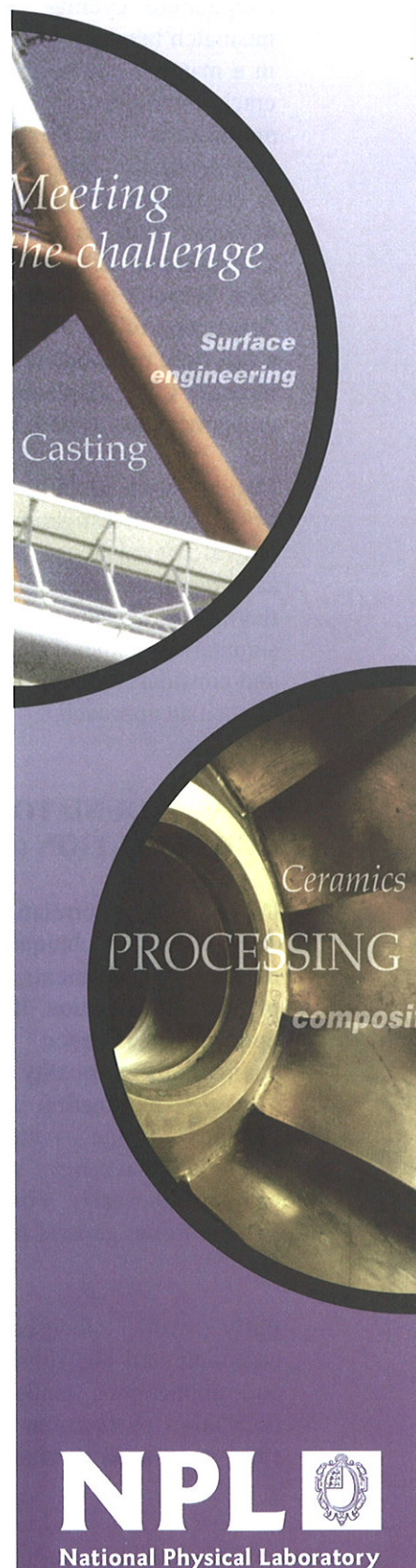
Measurement Note

The Potential Application of Digital Image Correlation for Measuring CTE – An Initial Study

Current work at NPL within Task 3 of Project MMS12 is investigating the potential of using an optical Digital Image Correlation (DIC) technique as a quick and accurate means of measuring the thermal expansion of printed circuit boards (PCB's).

This short note summarises some of the relevant work in this area and considers some of the merits and practicalities of such an approach.

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July 2002



INTRODUCTION

The coefficient of thermal expansion (CTE) is an important design parameter in many engineering systems, particularly where there is some form of temperature cycling, as the thermal expansion mismatch between different components or phases in a material can be the primary driving force for crack initiation and premature failure. One such application is in Printed Circuit Boards (PCBs) and electronics, where one of the key requirements is to design a system that can accommodate devices with a range of different CTEs. Conventional dilatometry is not suitable in this case because the small sample size requires the destruction of the PCB and the target is to develop a full field non-contact method that can be used to measure CTE, displacement and strain at both the component and system level.

Current work at NPL within Task 3 of Project MMS12 is investigating the potential of using an optical Digital Image Correlation (DIC) technique as a quick and accurate means of measuring the thermal expansion of PCBs. This short note summarises some of the relevant work in this area and considers some of the merits and practicalities of such an approach.

BACKGROUND TO DIGITAL IMAGE CORRELATION (DIC)

Digital Image Correlation (DIC) is a non-contact measurement technique that can be used to measure displacements, rotations, strains and out of plane deformation. It differs from conventional optical interference techniques by directly comparing high quality images of a component to measure deformation rather than by analysing complex fringe patterns. Image correlation techniques have been studied for some time and many of the early work was carried out in the 1980's. Some general papers are given in Refs 1-10.

Early work focused on developing the computational algorithms for processing the data and applications tended to be simple uniform translation or rotations [1-4]. The technique has since been used to crack growth and study strain

localisation during tensile testing [5], as well as the response of transversely loaded weld joints [6]. The majority of DIC work has been carried out on homogeneous materials, concentrating on uniform stress fields in tensile bars or stress field gradients found at crack tips. More recently work has also been carried out on a variety of heterogeneous materials including welded joints. DIC is now also being used in more diverse applications such as in biotechnology studies to determine the distribution of various proteins associated with particular viruses [7], and to monitor the deformation of concrete [8]. Little information is available however on the application of DIC at elevated temperatures which is the target of the current work.

Recent advances in computing power have seen renewed interest in the use of DIC for a variety of 2D and 3D applications. Commercial DIC software does exist, but many research groups are also developing their own systems and algorithms. The general NPL approach in the current project is described below.

The basic requirement for DIC is to have two images of the area of interest, one before and one after deformation. The images need to be of high quality and high resolution, if high sensitivity measurements are required. The basic digital image, which can be either a grey scale or colour image, is a collection of individual, non-overlapping elements or pixels that have distinct intensities. For grey scale images, the intensity of each pixel ranges from black (0) to white (255), which for many imaging systems (microscopes, etc), corresponds to 8 bits of intensity resolution. For colour digital images, each pixel contains 3 values, corresponding to the red, green and blue channels, giving 24 bits of colour resolution. The key advantage of digital images over analogue images is that digital images allow quantitative analysis - analogue images have to be digitised before analysis. Until quite recently, the only way of obtaining a digital image was to record an image using a conventional video or CCD camera but now, of course, digital cameras are commonplace. It is therefore a relatively straightforward process to obtain this digitised information, which gives a 2D array of intensity values for subsequent processing. It should be

noted however, that if the images are captured with a digital device then any compression used on the images should be lossless, i.e. the data should be stored in the gif, png or tif formats. Images that have been captured with a device that uses a lossy compression scheme like jpeg, will introduce artefacts.

The spatial resolution of the image depends on a number of factors including the experimental set-up, camera resolution, lens type and magnification, the relative size of the component and speckle pattern etc. Many commercial digital cameras now offer resolutions in excess of 2400 x 1600 pixels. Such high-resolution images offer a small pixel size with the potential for greatly increased sensitivity but, as there is a direct relationship between the number of pixels and the processing time required, a compromise must usually be made to achieve a practical and cost effective solution. For many applications an image of 200 x 200 pixels will be adequate.

The principle of DIC is reasonably straightforward. Comparison of the images can be carried out in a number of ways, but a simple method is to subtract an "original" pixel from a corresponding "deformed" pixel. In-plane displacements and strains are determined by correlating the position of pixel subsets or blocks in the original and deformed image, normally based upon contrast (grey levels). The size of the pixel block can be varied, thus allowing many random patterns to be correlated. In order to combine all the measurements in the block the difference is squared and summed for all individual pixels and divided by the number of pixels in that block. This number, which is defined as the *Correlation Coefficient*, has a lower bound of 0, and is assigned to the centre pixel in the block. If there is a perfect match then the sum will be zero, so the smaller the sum, the better the match. Using a larger block has the advantage of minimising the probability that a spurious match will occur due to chance, but at the expense of increasing the time required for the calculation.

In order to identify if there is any movement between the two blocks there must be sufficient detail for it to be considered unique. If there is some structure or detail in the image (such as grain

boundaries in a micrograph, or a pattern inherent to the component) DIC can be used on the original specimen without further preparation as this detail provides the pattern for analysis. More commonly however, the technique has been used with components that have been sprayed or painted with a random speckle pattern as shown in Fig. 1.

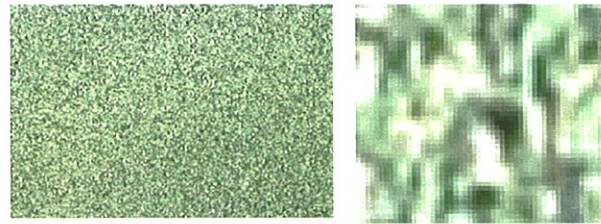


Fig 1: Random speckle paint effect (high magnification on right)

If the two images have been moved by an integral number of pixels relative to each other then for a block in each image to match, some initial knowledge of the typical offsets of the block in the x and y directions is required. An iterative algorithm is used to search for these offsets. Initially a guess is made of the new position of the offsets and a search is made either side of these offsets to try and find the position that give the minimum correlation coefficient for the block.

If the system were just restricted to integral values for displacements then the resolution would not be very great. Techniques and algorithms have been developed to provide sub-pixel resolution. Normally, pixels are thought of as touching rectangular blocks of a height corresponding to the pixels value, but the discrete data obtained is in reality only a sampled version of the actual intensity distribution present on the surface of the specimen. If pixels are now considered as vertical lines with no horizontal size, then it is possible to fill the gaps between two adjacent pixels by a linear interpolation. Bilinear interpolation then interpolates that line in an orthogonal horizontal direction. Figure 2 compares the original intensities for a series of 10 x 10 pixel blocks with the typical intensity pattern reconstructed using bilinear interpolation.

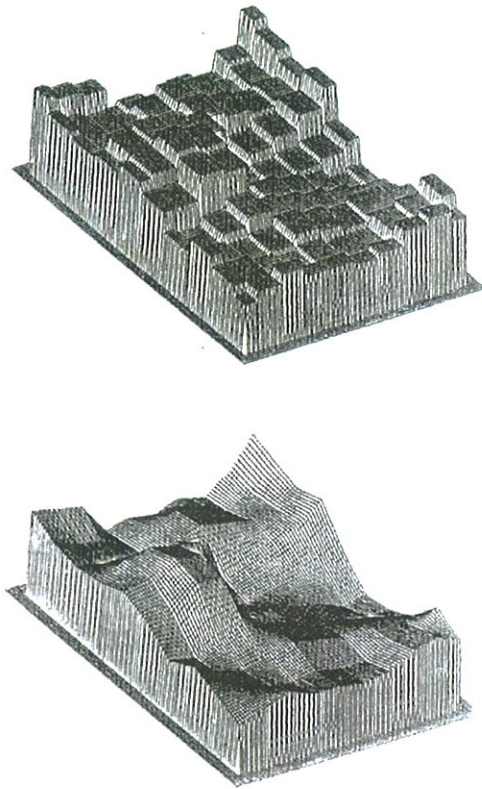


Fig 2: Representative surface intensity values before and after interpolation [1]

Many of the interpolation algorithms used are based on the *Newton-Raphson* method of partial differential correction, and by representing the data in continuous form and increasing the measurement resolution, it is possible to develop the sub-pixel resolution necessary for most displacement and strain measurements. Depending on the quality of the data therefore, bilinear interpolation allows sub-pixel measurement, possibly to 0.1 to 0.01 pixels. The main disadvantage is a corresponding increase in processing time. Other interpolation methods, including bicubic spline interpolation [4], are being developed to offer the potential for higher accuracy and increased resolution.

DIC is not just limited to measuring displacements, strain can also be measured within each block now that bilinear interpolation is used, by moving each pixel in a block by the corresponding displacement caused by the strain in the x and y directions. In a similar manner rotation can be measured by considering displacements

caused by shear. Out of plane deformation can also be measured by considering the effects that the magnification or reduction in the size of the block will have on the local displacements. However this is generally not a very accurate measurement and is seldom used.

To give the reader some examples of the requirement for sub-pixel resolution consider 2 cases – a simple tensile test and the displacement caused by thermal expansion. In the tensile test, a 0.1% strain value corresponds to a displacement of 1 in 1000 pixels. If the image of the gauge length is only 200 pixels, the strain corresponds to a shift of 0.2 pixels. Consider also the expansion of a material with a CTE of $20 \times 10^{-6} / ^\circ\text{C}$ over a temperature range of 100 $^\circ\text{C}$. In this case the linear expansion over the temperature range gives a displacement of 2 pixels in 1000; which over the same 200 pixel grid corresponds to a shift of 0.4 pixels (a 500 pixel image will give a shift of 1 pixel in this case). In both cases it is clear that an accurate experimental set-up be used, with good quality images to fully realise the potential of the method. Increasing the number of pixels will have a significant effect on the accuracy and resolution of the measurements but at the expense of processing time. A further consideration is to match the pixel size to the speckle pattern or surface features, such that individual pixels or blocks of pixels have individual and discrete values.

NPL EXPERIMENTAL SYSTEM

Work is underway within the current MMS12 project (Task 3/M10) to develop and investigate the application of DIC for measuring the thermal expansion behaviour of PCBs and the deformation and strain in high volume fraction metal matrix composites. Figure 3 shows the typical experimental set-up used at NPL in the current project. Initial studies to develop and calibrate the experimental system have used a Nikon D1 digital camera with a 90mm f2.8 lens to capture high-resolution images (up to 2400 x 1600 pixels) of materials under controlled deformation. Initial calibration studies using uniform translation are almost complete. Processing of the images is being carried out using in-house software.

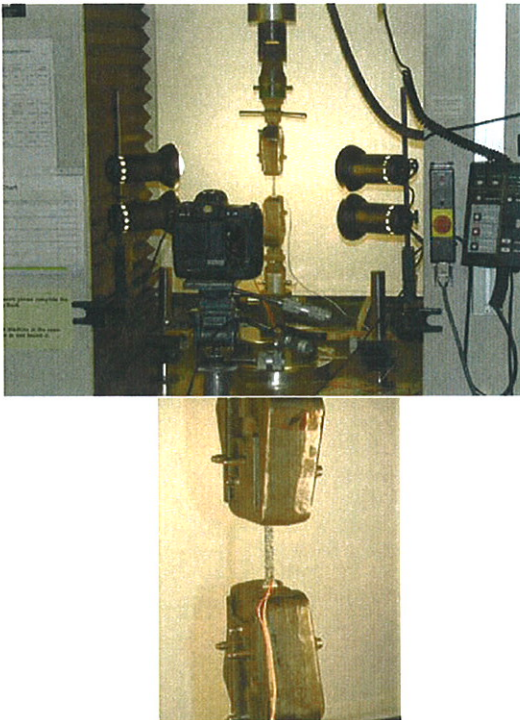


Figure 3: Typical DIC set-up

One of the key findings in the development of the experimental system was the importance of controlled, uniform lighting to ensure that there are no shadows or bright highlights present. A number of solutions are currently being examined for applying the speckle pattern and further development and optimisation of the system is ongoing.

PRACTICAL CONSIDERATIONS

The specific use of DIC for CTE measurement is a novel technique, and as such has not been considered before. Most of the applications of DIC reported in the literature are for room temperature situations and there are a number of complications that must be addressed when considering its use at elevated temperatures. For the CTE work in the current project these include....

- Maintaining the integrity of the applied speckle pattern at elevated temperatures
- Practical access to the component in a furnace or temperature cabinet

- Potential effect of thermal currents on image quality
- Thermal gradients across the specimen
- Translation of mount /reference point

These will be addressed and reported in the final report for the project.

COMMERCIAL DIC SOFTWARE AND SYSTEMS

The field has attracted a lot of interest in the last few years with the increased use of digital media in many aspects of research. Many image analysis software packages are commercially available, including the following:

- LaVision
- Correlated Solutions VIC-2D
- Archive4Images
- Clemex Technologies
- Imaging Associate
- Pixlock
- Universal Imaging
- VayTek

Not all of these are specifically suitable for DIC because many deal with general image analysis. The inclusion on the list above does not imply any recommendation by NPL, and the reader is recommended to contact or visit the relevant web sites themselves for further information.

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Acknowledgements

This research was carried out as part of project MMS12, which is part of the MMS programme on *Measurements for Materials Systems*, funded by the Engineering Industries Directorate of the UK Department of Trade and Industry.

Additional Information

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