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# The Application of Digital Image Correlation for Measuring Residual Stress by Incremental Hole Drilling

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## Abstract

The measurement of residual stress using the incremental hole drilling is well established, but the main limitations with the conventional strain gauge approach are the requirements for surface preparation, the need for accurate alignment and drilling, the restricted range of hole geometries commensurate with the specific gauge designs, and the limited range of strain data averaged over the footprint of the strain gauge grid. Recent attempts to extend the method have seen the application of full field optical techniques such as electronic speckle pattern interferometry and holographic interferometry for measuring the strain fields around the hole, but these methods are sensitive to vibration and this limits their practical use to controlled laboratory environments.

There are significant potential benefits therefore of using a more robust technique based on Digital Image Correlation (DIC), and work is presented in this study on the development of the method for measuring surface displacements and strain fields generated during incremental hole drilling. Some of the practical issues associated with the technique development, including the optimization of applied patterns, the development of the optical system and integration with current hole drilling equipment are discussed, and although measurements are only presented for a single load case - the equi-biaxial stress state introduced during shot peening - the novel aspect of this work is the integration of DIC measurements with incremental drilling and an application of the Integral Method analysis to measure the variation of residual stress with depth. Validation data comparing results from conventional strain gauge data and FE models is also presented.

## Introduction

Incremental hole drilling is a well-established method for measuring residual stress. The conventional approach is relatively quick and straightforward [1-3] and the technique can be applied to a wide range of materials and components, but there are some limitations and restrictions with using strain gauges. In particular, the strain gauge approach requires thorough surface preparation, only permits a restricted range of hole sizes commensurate with the specific gauge design, must be carried out with accurate alignment and drilling, and only provides limited data averaged over the footprint of the strain gauge grid. There is significant interest therefore in using methods that replace the conventional strain gauge with full field non-contact strain measurements, where the residual stresses are determined from the strains (or surface displacements) that develop as a result of drilling the hole. Developments in recent years have already led to the application of grating interferometry (Moiré), electronic speckle pattern interferometry (ESPI) and laser holography in place of the strain gauge during the hole drilling process.

The techniques that use Moiré or grating interferometry offer increased resolution and sensitivity compared with the strain gauge, but still require some degree of surface preparation, as a diffraction grating must be bonded to the component; they are generally not as robust as an encapsulated strain gauge and must be handled carefully. Considerable development has been carried out by Wu et al [4-6] on a variety of components with different residual stress states. Other non-contact methods that have been developed for use with hole drilling include ESPI and digital holography. These methods have the advantage over grating interferometry because they generally do not require special surface preparation, other than the requirement for a diffusely reflective surface. Although the non-contact full field strain approach is attractive to a wide range of industries and applications, the current limitations with the methods are the high cost compared with using strain gauges, their sensitivity to vibration and limited portability.

Much of the early development work in combining holography with hole drilling was carried out in the mid-1980s [7,8]. Initial work focused on developing the analysis for residual stress fields that were uniform with depth, but this has been extended by various workers [9-14] to components with more complicated stress gradients, biaxial stress states and incremental drilling, including the novel approach of using variable diameter holes. Early studies relied on the use of holographic plates to capture the fringe patterns and manual fringe counting, but with the development of digital technology the speckles are sufficiently large to be resolved by conventional CCD cameras, and much of the data processing can now be carried out automatically. The *PRISM* system, developed by Steinzig et al [15-17] was probably the first commercially available system combining hole drilling with full field non-contact strain measurement.

The application of Digital Image Correlation (DIC) as a full non-contact strain measurement technique has increased significantly in recent years, and this is the method used in the present study. DIC works by comparing images of a component or test piece at different stages of deformation and tracking blocks of pixels to measure surface displacement [18]. The position of the centre of the pixel blocks is determined to sub-pixel accuracy over the whole image using sophisticated correlation functions, from which the vector and strain components can be calculated. The benefits of using DIC over other non-contact methods include the potential for rapid measurements with limited surface preparation, the ability to correct for rigid body motion and the limited specialised equipment required. The main reservations relate to the relatively poor resolution of the DIC technique compared with Moiré and ESPI (the claimed resolution of the DIC technique is 0.01 pixel on displacement), and practical issues associated with the scale of pattern applied and test setup.

Nelson et al [19] were the first to describe the application of DIC with hole drilling, and reported results for blind hole measurements on an aluminium ring and plug and a shrink fit ring sample using a 3D DIC system with two 1 Megapixel cameras.

## System Development

The NPL DIC hole drilling measurements were carried out using a *Stresscraft RS 3-D* hole-drilling machine fitted with a compact air turbine assembly, as shown in Fig 1. The system uses a 3-axis stepper motor control, which enables precise drilling and repositioning of the drill head between increments. Various experimental set-ups were tried in the present work including the use of a stereomicroscope, high resolution cameras with macro lenses, but all the measurements reported were made with a single 1 Megapixel (1280 x 1024 pixel) CCD camera fitted with a telecentric zoom lens.

Using a single camera and 2D system only in-plane displacements can be measured. It is recognised however that the process of drilling and removing material will cause some out of plane displacement, which will affect the calculated in plane displacements and introduce errors into the calculations. FE models of the hole drilling process have shown that most of the out of plane displacement occurs close to the edge of the hole and at the radii examined for calculating the stress profiles in this work (1400μm to 2000μm), it is not believed to have a significant effect on the in-plane surface displacement measurements.

Specimens were prepared by applying a fine spray paint pattern with an airbrush to the surface to reduce reflections and generate the specular random pattern necessary for the image correlation, and cleaned using a fine brush and compressed air to remove the dust and debris generated from drilling that would otherwise affect the correlation process. Fig 2 shows an image of the specimen after drilling and the typical scale of pattern applied to the specimen (the diameter of the hole in this case is 2 mm). A modified, compact air turbine combined with an orbital drilling motion was used to produce the hole with a standard 1.6 mm drill and 0.3 mm offset to minimize the stresses that might be induced by the drilling process itself. The field of view is 7 x 5.6 mm, giving a scaling of ~5.5 μm/pixel and a hole diameter of 2 mm, drilled to a depth of 1mm. Fig 3 shows the basic vector field generated from introducing the hole. Nelson et al [19] reported in-plane surface displacements of the order of 4-5 μm from the introduction of a full depth 3.2 mm diameter hole, but because smaller hole diameters and incremental drilling was used in this work, the measured displacements are considerably smaller, and more challenging.

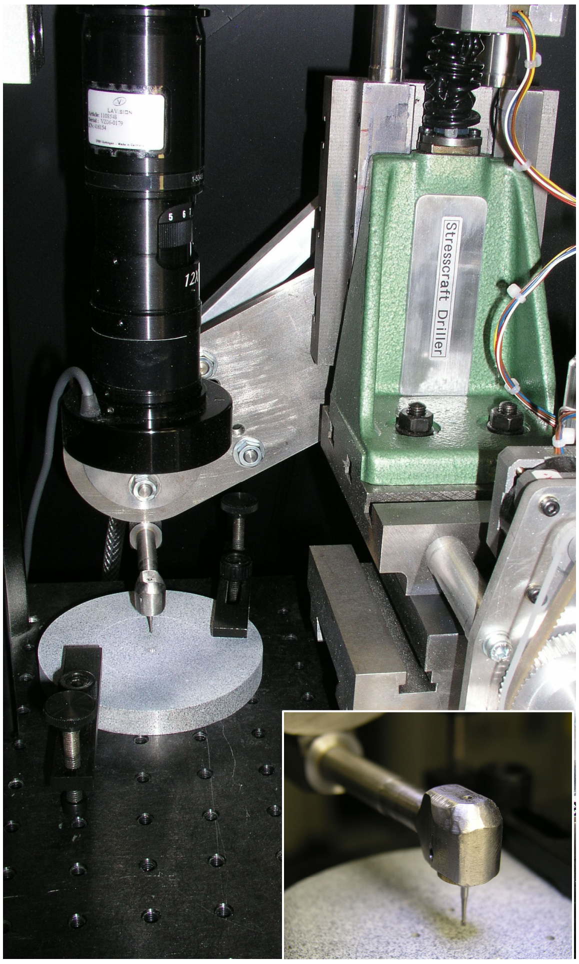


**Fig 1: NPL DIC hole drilling setup and (inset) close up of drill head**

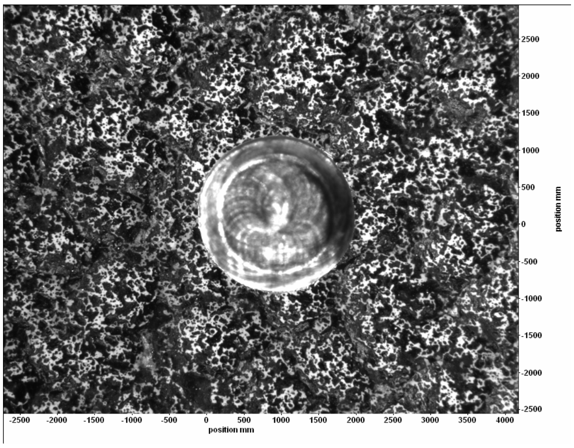


**Fig 2: Image after drilling**

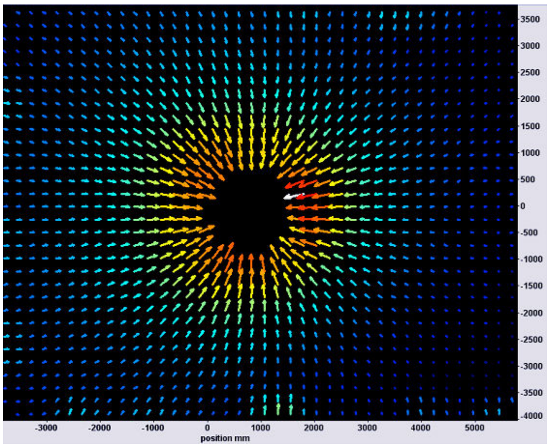


**Fig 3: Vector plot around the hole**

Initial measurements were made on a heavily shot peened 7055-T79 aluminium, with a single image captured after drilling to the full depth, but subsequently incremental drilling was carried out over a range of discrete depth increments (128μm, 256 μm, 512 μm and 1024 μm) to examine the variation of residual stresses with depth. Tests were carried out with the component clamped in position, and the camera positioned directly above the central drilling position, as shown in Fig 1. After each depth increment the drill head was retracted from the field of view prior to capturing the image around the hole. This arrangement alleviated the need for correcting for large rigid body motion, which might result if the sample is removed and repositioned between drilling. Although the DIC software can correct for this, the process can introduce smoothing and artefacts which may affect the images and calculated displacements.

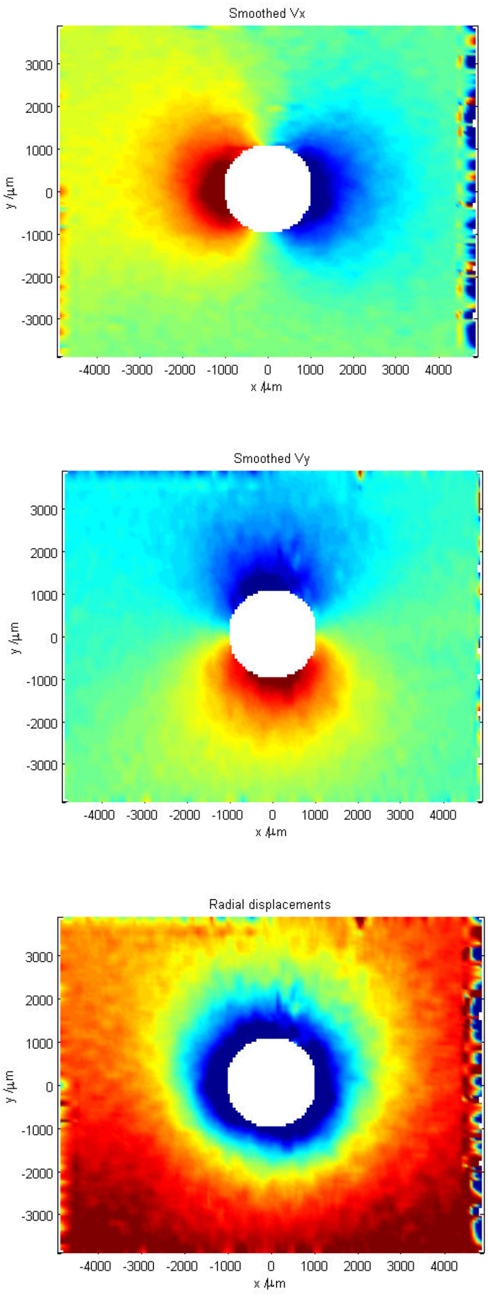
## Residual Stress Data Analysis

The DIC analysis was carried out using the *LaVision Strainmaster* software [20]. The area of the hole was masked out, as no correlation was possible here, and vector displacements calculated over the field of view, typically using a 128x128 pixel interrogation window, with 75% overlap, generating vectors on a 32 pixel grid spacing over the whole image. The original image of the specimen without the hole was used as the reference, and cumulative surface displacements calculated from images taken at subsequent hole depths. The accuracy of displacement measurement using DIC depends on the quality of the experimental set-up and the size of the interrogation window used to calculate displacement and strain. Generally for uniform displacement fields, larger windows give better strain accuracy, whilst smaller windows give better spatial resolution. For the parameters used in the DIC analysis in this work, the uncertainty in displacement is of the order 1-5% depending on the quality of the image and the contrast [20].

Fig 4 shows typical displacement fields and outputs generated from the DIC analysis after further processing in *Matlab*. Transformation of the displacement data was first carried out to ensure that the displacement axes and origin coincided with the hole centre for each image. The displacement data was then converted into polar coordinates, and the x, y and radial components calculated. During this step some smoothing of the data was carried out using a low order quadratic polynomial least-squares fit, typically over 11 or 13 points, to reduce the influence of noise and local anomalies on the calculated vector map. Fig 4a shows the calculated vector fields in the x, y and radial directions, Fig 4b a plot of the the radial displacements made around the hole at discrete radii (1200μm to 2000μm in 100μm increments), and Fig 4c the mean radial displacements around the hole. Generally it was not possible to get reliable data very close to the edge of the hole because of damage, small irregularities in the hole shape, and imprecise definition of the hole shape due to the DIC interrogation windows overlapping with the edge of the hole.

The surface displacement data from the DIC analysis were then processed to provide an array of radial displacements compatible with the Integral Method model, first proposed by Schajer [21,22] for analysing residual non-uniform stress profiles, for drilled hole depths of 128 μm, 256 μm, 512 μm and 1024 μm at 10° intervals around the hole (36 angular positions), and at radial intervals of 50μm over the range 1400μm to 2000μm (13 radial positions).

Four finite element models of a blind 2 mm diameter hole in a large, thick plate were created for the hole depths listed above. Each model was processed with a series of discrete load cases covering (‘a’) equal biaxial and (‘b’) pure shear stresses applied to the hole surface for each stress depth increment listed. The resulting 20 model displacement files were interrogated to provide arrays of radial displacements at the 36 angular and 13 radial positions listed above. The development of a suitable form of the Integral Method, was initially approached by comparing the shapes of the measured and model displacement data. However, there were significant differences in the corresponding measured and model displacements, particularly with the slope of the data close to the hole (Fig 5). It is interesting to note that the maximum radial displacement values at depths of 128μm and 256μm are less than 1μm, which is significantly smaller than those measured by Nelson et al [19] and a challenge for the DIC system.



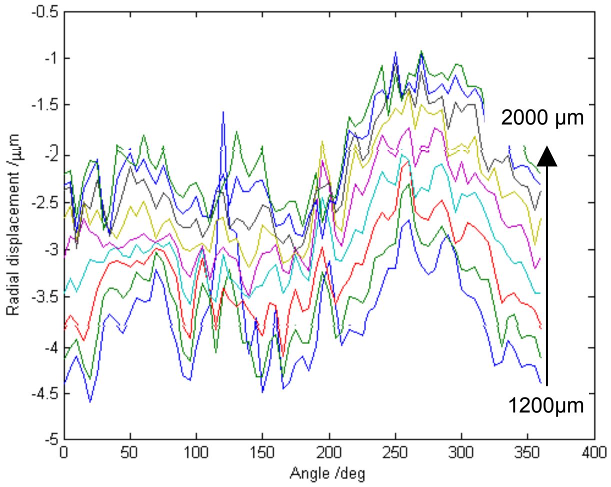


**Fig 4b: Variation of radial displacement with angle and distance from the hole centre**

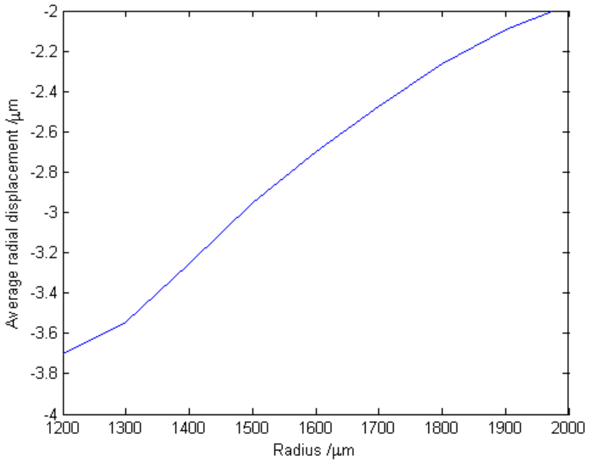


**Fig 4c: Mean radial displacement around the hole**

**Fig 4a: Distribution of Vx, Vy and radial components**

**Fig 4: Typical outputs and displacement fields from the DIC analysis**

For a revised approach, the Integral Method coefficients were calculated from simple average values of displacements within the radius range 1400µm to 2000µm. Average values of measured radial displacements at each angular position were plotted against corresponding model displacements, and a simple Fourier analysis of the data used to extract values at 0°, 45° and 90°, corresponding to the outputs from a typical three element strain gauge rosette. These values were then used in the shell of a conventional Integral Method spreadsheet to calculate the residual stress values at each depth increment. For the aluminium component being investigated in this work, the shot-peening process has produced generally equal biaxial stresses at all depths, thus, only the 'a' coefficients relating to this load case can be verified. Pure shear or uniaxial test-pieces would be required to verify the 'b' coefficients.

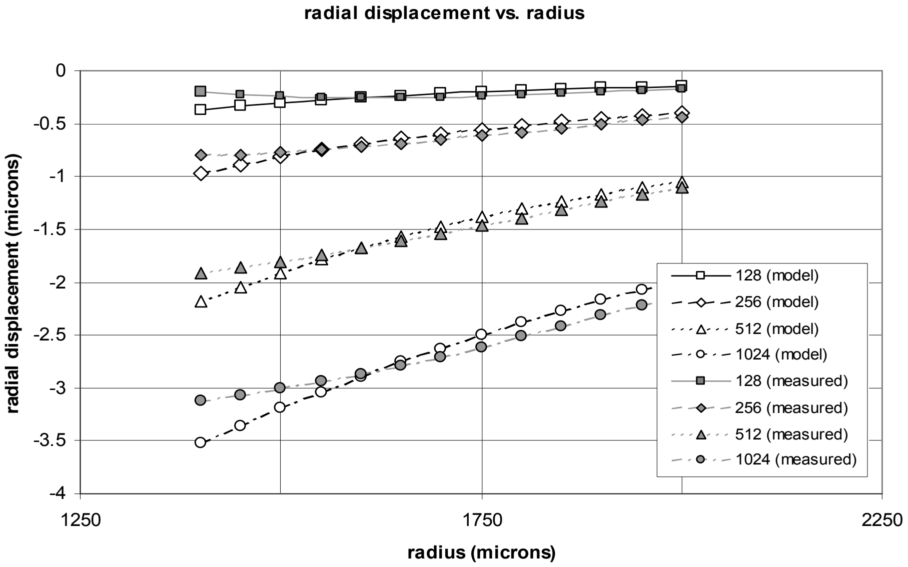


**Fig 5: Comparison of measured and predicted displacement fields for the Integral Method analysis (shot peened aluminium).**

Fig 6 shows the residual stress data from the initial DIC test compared with stress profiles generated from two tests using conventional target strain gauges. Because of the different drilling increments used in the strain gauge and DIC tests, the strain gauge profiles generated extend both closer to the specimen surface and deeper into the bulk of the material. There is reasonable agreement between the DIC and strain gauge data, but rather surprisingly the strain gauge data shows differences between the profiles measured in the two principal stress directions. This might be an anomaly in the strain gauge tests, as it was not expected.

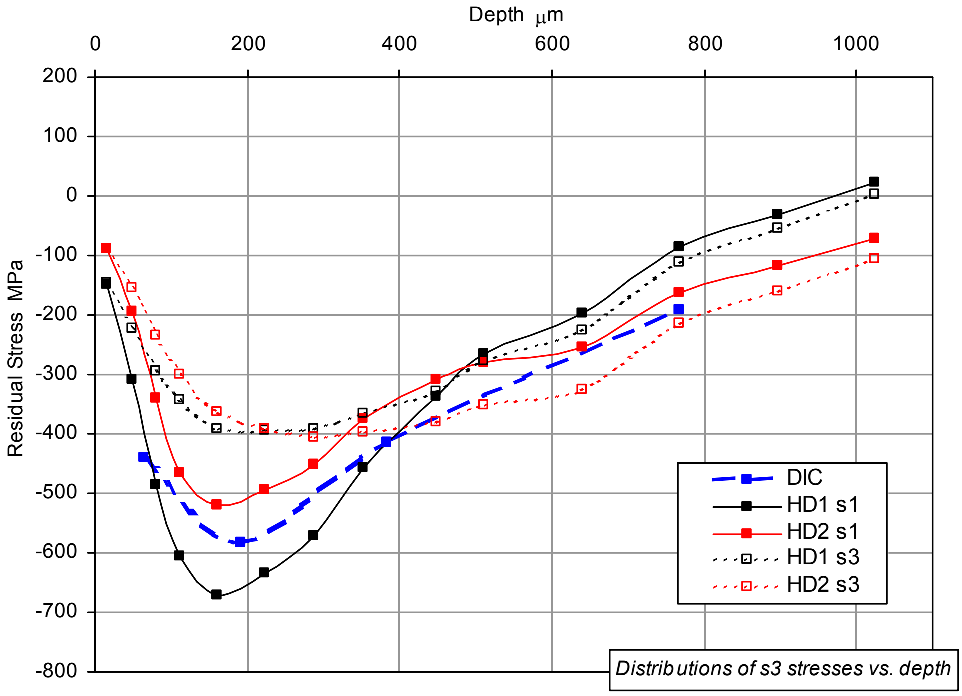


**Fig 6: Comparison of residual stress profiles generated from the initial DIC test and strain gauge measurements**

## Results

Table 1 and Fig 7 summarise the residual stress values measured from further repeat DIC tests on the shot peened aluminium to examine the accuracy and repeatability of the test capability.

| **Depth (mm)** | **Direct Stress s1 (MPa)** | | | | | **Mean** | **Std Dev** |
|---|---|---|---|---|---|---|---|
| | **Test 1** | **Test 2** | **Test 3** | **Test 4** | **Test 5** | | |
| **0.06** | -425 | -273 | -568 | -456 | -364 | **-417** | **110** |
| **0.19** | -574 | -648 | -700 | -699 | -580 | **-640** | **61** |
| **0.38** | -398 | -635 | -383 | -462 | -444 | **-464** | **100** |
| **0.77** | -195 | -188 | -83 | -197 | -127 | **-158** | **51** |
| | **Direct Stress s3 (MPa)** | | | | | | |
| **0.06** | -440 | -301 | -599 | -430 | -371 | **-428** | **110** |
| **0.19** | -584 | -671 | -756 | -745 | -575 | **-666** | **86** |
| **0.38** | -415 | -650 | -441 | -515 | -441 | **-492** | **96** |
| **0.77** | -191 | -187 | -20 | -195 | -199 | **-159** | **78** |

**Table 1: Details of repeat DIC measurements**

The direct stresses s1 and s3 correspond to the orientation of the gauge elements on the target strain gauge rosette. There are no significant differences in the calculated direct stress values which confirms the assumption of an equi-biaxial stress field for this component, and validates the use of a similar approach in the FE modelling and Integral Method implementation for this case. Although there is some scatter and variability in the data the results are encouraging and are in good agreement with the shape of the residual stress profiles measured from the strain gauge tests, particularly with respect to the magnitude and position of the sub surface peak. The thick black lines in Fig 7 are the profiles generated from the mean of all the measurements.

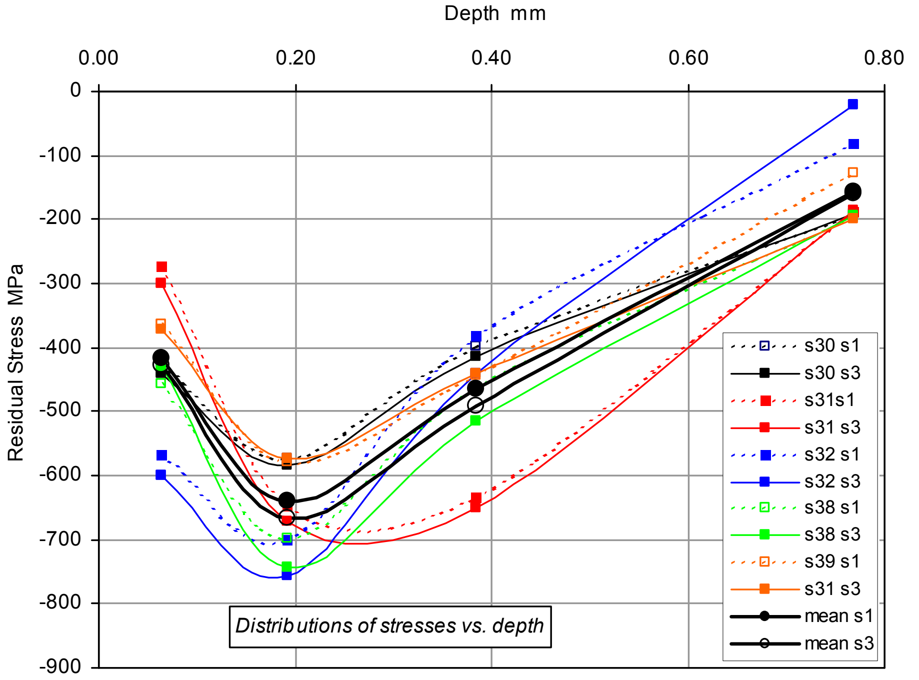


**Fig 7: Repeatability of DIC-generated residual stress profiles**

## Summary

The data presented is the first published attempt at using the DIC approach with incremental hole drilling and the Integral Method for generating residual stress data in components with non uniform stress profiles. The work has confirmed the application and capability of DIC for measuring surface displacements and residual stress profiles generated during hole drilling, for the equi-biaxial stress field generated during shot peening.

Results showed the expected stress profile resulting from the shot peening process, and although there was some variability between repeat measurements the data is in good agreement with that obtained from conventional strain gauge approach.

There are still practical issues that need to be considered and resolved with the DIC incremental hole drilling approach. Further validation of the technique and analysis method is required on components with different stress fields and materials, and for different combinations of hole size and depth increments. Only a limited set of depth increments have been used in this study, but there is a significant challenge in developing robust methodology to resolve the small displacements generated at finer depth increments. And, although the approach within this work has been to use a limited range of radial positions, there is scope for further study to get closer to the hole to extract additional data. This will have implications for 3D measurement as out of plane displacement may be significant and must be taken into account.

With the ongoing development of higher resolution DIC algorithms and the availability of low cost high-resolution cameras there is potential for significantly increased resolution within the physical limitations of the optical technique. Current DIC software developments are focused on providing higher accuracy data and real time measurements, and there is significant future potential for developing an integrated portable system that could be developed to carry out real-time measurements on components in the field.

## References

[1] ASTM E 837-08, Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain-Gauge Method, 2008

[2] Technical Note TN-503-5, Measurement of Residual Stresses by the Hole drilling Strain Gauge Method, Vishay Measurements Group, 1993

[3] Grant, P.V., Lord, J.D. and Whitehead, P., *NPL Good Practice Guide No. 53 – Issue 2.* The Measurement of Residual Stresses by the Incremental Hole Drilling Technique, Feb 2006

[4] Wu, Z., Lu, J. and Han, B., Study of Residual Stress Distribution by a Combined Method of Moiré Interferometry and Incremental Hole Drilling, Part I: Theory, *J. Appl. Mech., 65, pp.837-843, 1998*

[5] Wu Z., Lu, J. and Han, B., Study of Residual Stress Distribution by a Combined Method of Moiré Interferometry and Incremental Hole Drilling, Part II: Implementation, *J. Appl. Mech., 65, pp. 844-850, 1998*

[6] Wu Z., Lu, J. and Han, B., On the Accuracy of Moiré Interferometry and Incremental Hole-drilling Method, *SEM Annual Conference on Theoretical, Experimental and Computational Mechanics*; Cincinnati, OH; USA; 7-9 June 1999. pp. 743-745. 1999

[7] Antonov, A.A., Inspecting the Level of Residual Stresses in Welded joints by Laser Interferometry. *Weld Prod. 30, pp29-31,* 1983

[8] Nelson, D.V., and McCrickerd, J.T., Residual Stress Determination Through Combined Use of Holographic Interferometry and Blind Hole Drilling. *Exptal Mechs*, 26*, pp.371-378, 1986*

[9] Nelson, D.V., Fuchs, E.A., Williams, D.R. and Makino, A., Experimental Verification of the Single Axis Holographic Hole Drilling Technique, *1991 SEM Spring Conference on Experimental Mechanics, Milwaukee, 10-13 June 1991, pp.293-300*

[10] Lin, S.-T., Hsieh, C.-T. and Hu, C.-P., Two Holographic Blind-hole Methods for Measuring Residual Stresses, *Experimental Mechanics*, *pp.141-147, 1994*

[11] Makino, A., Nelson, D.V., Residual-stress Determination by Single-axis Holographic Interferometry and Hole Drilling – Part I: Theory, *Experimental Mechanics*, *pp. 66-78, 1994*

[12] Nelson, D., Fuchs, E., Makino, A. and Williams, D., Residual-stress Determination by Single-axis Holographic Interferometry and Hole Drilling – Part II: Experiments, *Experimental Mechanics*, *pp.79-88, 1994*

[13] Diaz, F.V., Kaufmann G.H. and Galizzi, G.E., Determination of Residual Stresses using Hole-drilling and Digital Speckle Pattern Interferometry with Automated Data Analysis, *Optics and Lasers in Engineering, 33, Part 1, pp. 39-48, 2000*

[14] Focht, G. and Schiffner, K. Determination of Residual Stresses by an Optical Correlative Hole-Drilling Method. *Experimental Mechanics*, *43, Part 1, pp. 97-104, 2003.*

[15] Steinzig, M., Hayman, G. and Rangaswamy, P., Data Reduction Methods for Digital Holographic Residual Stress Measurement, *Proc. 2001 SEM Conf. Exp. Appl. Mech, June 4-6, Portland, OR, 2001*

[16] Steinzig, M., Hayman, G.J. and Prime, M.B., Verification of a Technique for Holographic Residual Stress Measurement, *Residual Stress Measurement and General Nondestructive Evaluation, PVP 429,* The ASME Pressure Vessels & Piping Conference; Atlanta, *July 2001*

[17] Steinzig, M. and Ponchione, A., Effect of Hole Drilling Parameters on the Accuracy of Residual Stress Measurements for ESPI Hole Drilling, *2002 BSSM Int. Conf. Advances Exp. Mech.*, 27-29 August, 2002

[18] Sutton, M.A., McNeil, S. R., Helm J.D, Chao, Y.J "Advances in 2D and 3D computer vision for shape and deformation measurements" Photomechanics, Ed Rastogi, P.K.(Springer-Verlag, Germany 2000)

[19] Nelson, D.V, Makino, A. and Schmidt, T. Residual Stress Determination Using Hole Drilling and 3D Image Correlation, *Experimental Mechanics* (2006) 46, p31-38

[20] LaVision Strainmaster Davis 7.0 User Manual, November 2004

[21] Schajer, G.S., Application of Finite Element Calculations to Residual Stress Measurements, *J. Eng. Mat. And Tech.*, 103, pp. 157-163, 1981

[22] Schajer, G.S., Measurement of Non-Uniform Residual Stresses Using the Hole Drilling Method, *J. Eng. Mat. And Tech.*, 110 (4), Part I: pp.338-343, Part II: pp.3445-349, 1988

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