

Uncertainties in complex weld induced residual stresses

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Abstract Residual stress measurement techniques using mechanical strain relaxation (MSR) depend on a number of physical quantities and are therefore sensitive to errors associated with the measured data. Deep-hole drilling (DHD) technique is a popular MSR method due to its ability to measure stresses deep into components with a very high spatial resolution in the measured data. An error analysis procedure for the DHD measured stresses using propagation error technique considering measurement errors in various stages has been developed and successfully applied in different measured data. However, one essential factor namely the influence of the initial reference hole drilled in the DHD technique has not been considered in the error analysis procedure.

The error due to the creation of the initial reference hole can only be obtained from the numerical simulation using finite element analysis (FEA). The FEA predicted stress error due to the creation of the reference hole is combined with other sources of measured error in order to formulate a combined total error. The total error analysis procedures for the modified incremental deep-hole drilling (iDHD) technique were developed and applied to measure the near yield complex triaxial residual stress distributions generated within a welded circular disc. The experimental results are used to illustrate the errors.

Error in residual stress measurement by deep-hole drilling method

Deep-hole drilling method The standard deep hole drilling technique [1-2] determines the through thickness residual stresses in a component using four main steps. (1) A reference hole is drilled using gun drill through the component. (2) Precise measurement of the reference hole is made using an air-probe system at a number of angles θ at several depth increments z , giving $\phi_o(z, \theta)$. (3) A core of material concentric to the reference hole is removed by trepanning using an electric discharge machine (EDM). (4) The reference hole is re-measured at identical positions as step 2, giving $\phi(z, \theta)$. In the incremental iDHD technique [3], trepanning is interrupted at predetermined EDM depth increments to measure hole diametral distortions $\phi(z, \theta)$ at the bottom of trepanned core. The change in reference hole diameter $\delta\phi_i$ at each increment is normalised with ϕ_i to provide normalised diametral distortions, $u_{rr_i} = \delta\phi_i / \phi_i = (\phi - \phi_i) / \phi_i$.

At the end of each trepan step the change in core length along the axial direction is measured using a Linear Variable Displacement Transducer (LVDT). The strain in the axial direction, u_{zz_i} , at a particular increment, i , is the ratio of the axial change in core length, δL_i , to the depth increment, δz_i , and is written as $u_{zz_i} = \delta L_i / \delta z_i$.

The reference hole strains at each increment are related to the residual stress components in the plane normal to the reference hole axis, σ_{xx} , σ_{yy} , σ_{xy} and out-of-plane residual stress component σ_{zz} .

$$\begin{bmatrix} u_{rr1} \\ \vdots \\ u_{rr9} \\ u_{zzi} \end{bmatrix} = -\frac{1}{E} \begin{bmatrix} 1+2\cos 2\theta_1 & 1-2\cos 2\theta_1 & 4\sin 2\theta_1 & -\nu \\ \vdots & \vdots & \vdots & \vdots \\ 1+2\cos 2\theta_9 & 1-2\cos 2\theta_9 & 4\sin 2\theta_9 & -\nu \\ -\nu & -\nu & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \\ \sigma_{zz} \end{bmatrix} \quad \text{i.e. } \bar{u}_{rr3D} = -\frac{1}{E} [M_{3D}] \bar{\sigma}_{3D} \quad (1)$$

Finally the stresses are calculated using least squares method,

$$\hat{\sigma}_{3D} = -E [M_{3D}]^+ \bar{u}_{rr3D}$$

where, $[M_{3D}]^+ = ([M]^T \bullet [M])^{-1} \bullet [M]^T$ is a pseudo-inverse matrix.

Sources of uncertainty There are two sources of uncertainty associated with the standard DHD. These mainly relate to the uncertainty due to calibration of the airprobe, U_{AP} and uncertainty due to material constant, U_{MC} . An additional source of uncertainty is associated with the LVDT, U_{AX} used to measure axial distortion during the iDHD procedure. The measurement of the axial distortion at each trepanning increment requires the use of an LVDT that is calibrated using a standard micrometer with known linear displacements. The uncertainty arises from human error in reading the micrometer and in fitting the calibration data using a polynomial curve. Detail of uncertainty in air-probe, material and LVDT are provided in [4, 5].

A fourth source of uncertainty U_{RH} which is the main focus of the present paper includes the influence of the creation of the initial reference hole.

Uncertainty due to reference hole can only be estimated by utilising a finite element simulation of the DHD measurement. An FEA model of the ring welded circular disc, Fig. 1 was used to predict the initial residual stress due to welding. Detail of specimen and further FEA study are provided in [6]. The FEA model included provision to carry out the simulation of the deep-hole drilling procedure. The drilling simulation of the DHD process was carried out both elastically and plastically. The difference provided a quantitative indication of the influence of the reference hole on the DHD method, shown in Fig. 2.

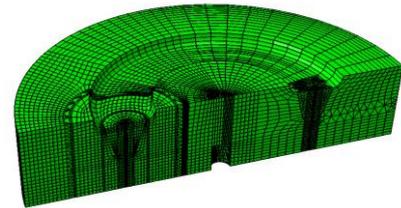


Fig. 1 Schematic of ring weld specimen

All these sources of uncertainty are considered to be independent of each other and are combined together using law of propagation [7] to define the total uncertainty.

$$U_{Total} = \sqrt{U_{AP}^2 + U_{MC}^2 + U_{AX}^2 + U_{RH}^2} \quad (2)$$

Application of error analysis Experimental data to test the error analysis method was taken from residual stress analysis of a ring welded circular disc manufactured from Essete stainless steel material. 2D-iDHD analysis was used for error analysis. The sample shown in Fig. 1 includes a circular disc of diameter 160mm, thickness 35mm. The sample was manufactured from an Essete stainless steel with initial diameter 185mm, thickness 52mm. The sample was heat treated at 1080°C followed by rapid water quenching to 100°C before machining to final dimensions. A circular excavation with a width 24mm, depth 24mm located 40mm away from centre of the disc was machined away where a ring weld was partially deposited.

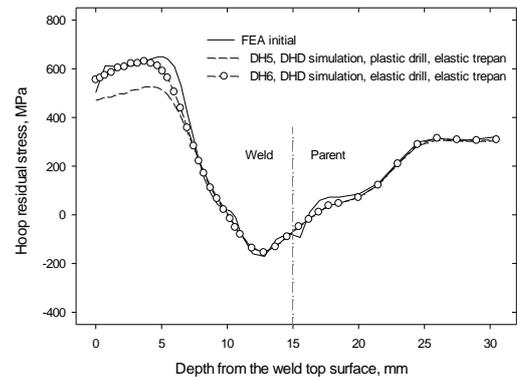


Fig. 2 Uncertainty due to reference hole drilling

A 1.5mm diameter reference hole was drilled at the centre of the partial weld along the through-thickness, i.e. the axial (Ax), direction of the disc. A core having a diameter of 5mm was trepanned using EDM in 12 depth increments with depths ranging from 1 to 3.6mm.

Results and discussion The residual stress distribution measured along through-thickness using the 2D-iDHD technique is shown in Fig. 3. Also shown are the combined uncertainties calculated using the error propagation, Eq. 2. For clarity, only the hoop stress is shown. The focus of this study has been on determining the uncertainty in the DHD analysis of components having triaxial stresses due to welding. Uncertainty analysis based on propagation of errors from various sources was adopted. The advantage of using an analysis based on propagation of errors is that it reveals which element of the system provides the greatest error. Uncertainty due to reference hole was found to be the highest of the four sources of uncertainties.

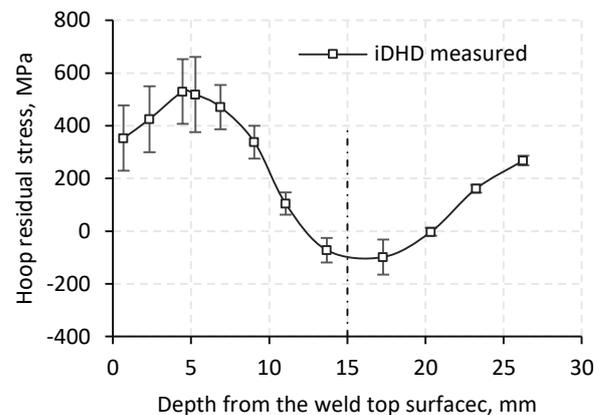


Fig. 3 Measured hoop with combined error

References

- [1] D. George, E. Kingston, and D. J. Smith, Measurement of through-thickness stresses using small holes, *Journal of Strain Analysis*, vol. 37, pp. 125-139, 2002.
- [2] E. Kingston, *Advances in the Deep-Hole Drilling technique for Residual Stress Measurement*, PhD Thesis, University of Bristol, 2003.
- [3] A.H. Mahmoudi, S. Hossain, C.E. Truman, D.J. Smith and M.J. Pavier, A New Procedure to Measure near Yield Residual Stresses Using the Deep Hole Drilling Technique, *Experimental Mechanics*, v 49, n 4, p 595-604, 2009.
- [4] D.M. Goudar, S. Hossain, C.E. Truman, E.J. Kingston, D.J. Smith, Uncertainties in Triaxial Residual Stress Measurements, *Materials Science Forum*, ISSN: 1662-9752, Vol. 681, pp 498-503, 2011.
- [5] D.M. Goudar, S. Hossain, C.E. Truman, D.J. Smith, Uncertainty in residual stress measurements, *Proceedings of PVP*, 2008.
- [6] Zheng, G, Hossain, S, Kingston, E, Truman, CE & Smith, DJ, An optimisation study of the modified deep-hole drilling technique using finite element analyses applied to a stainless steel ring welded circular disc, *International Journal of Solids and Structures*.2017.
- [7] J. R. Taylor, *An introduction to Error Analysis*, University Science Books, vol. second edition, 1997.