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Prediction and Measurement of Through Thickness Residual stresses in Large Quenched Components

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Abstract— Although there are many simulations of residual stresses in quenched steel components there is little validation of these predictions particularly when the components are large. This is not surprising bearing in mind that the application of the through thickness measurement techniques (mechanical strain relief techniques) are problematic when the components exhibit high levels of residual stresses or triaxial stress state. This paper examines the application the incremental deep hole drilling technique (IDHD) to measure through thickness residual stresses in the quenched solid and hollow steel cylinders. The measured residual stresses are compared with FE predictions.

Index Terms— **Quenching process, Residual stress, Deep hole drilling, Plasticity.**

I. INTRODUCTION

Residual stresses are inevitably introduced during manufacture of engineering components. For example, heat treatment and machining create residual stresses. There is limited evidence that shows there is a complex interaction between the initial internal stresses and imposed loading when the components are in service [1, 2] .This evidence suggests that the presence of residual stresses is one of the primary factors influencing the durability of the components in service [1, 2]. Furthermore, it is claimed [3, 4] that the presence of residual stresses is one of the major contributing factors in delaying failure (in the case of compressive residual stresses) or promoting internal failure (from tensile residual stresses).

Quenching is one of the most common heat treatments to produce components with desirable properties [5]. Cooling from a certain temperature can decisively affect the resulting material properties and internal stress levels [6]. Induced residual stresses in the quenching process can affect the performance life of the components; they can be beneficial or detrimental depending on their interaction with service loadings. There is substantial evidence that very often, in the absence of phase transformation, quenching the components culminate in compressive residual stresses on the surfaces and with balancing tensile residual stresses in the centre [5, 7, 8]. However, knowledge of the magnitude of surface residual stresses does not provide evidence for the magnitudes of the tensile stresses [9]. Therefore, a reliable integrity assessment of the engineering components relies on how accurate the operating and residual stresses are estimated throughout the region of interest. Very often it is possible to determine accurately the service loadings by means of analytical, numerical methods and finite element simulations. It is the residual stresses that are difficult to predict [10]. However in many cases it is only the measurement that can be used to validate the numerical and analytical predictions.

Simulations of the quenching help to design the process, control and evaluate the distribution of the residual stresses [5]. Nevertheless, results from computer simulations are dependent on the accuracy of input data [11]. Therefore, the first step in developing a more fundamental understanding of the nature of the residual stresses is to generate experimental data. In this paper we first summarize the range of techniques available for measuring the residual stresses in quenched components, together with a brief review of earlier work. This is followed by a description of our recent studies to measure through thickness residual stresses in quenched solid and hollow steel cylinders.

II. RESIDUAL STRESS MEASUREMENT METHODS

A wide variety of techniques are available for measurement of residual stresses particularly in steels [10, 12]. The methods can be classified as non- or semi- and fully destructive methods. The non-destructive techniques are those where a beam or a wave penetrates into the material and include methods such as diffraction (conventional X-ray, synchrotron X-ray and neutron diffraction), ultrasonic and magnetic methods. These methods are confined to relatively near surface measurements only. Although the neutron diffraction and synchrotron X-ray methods can penetrate a few centimeters in depth, they are limited to relatively small samples that are to be taken to specialized facilities and require reference samples that are assumed stress free. Nevertheless, X-ray and neutron diffraction methods have been extensively used to measure quench residual stresses. However, they were all limited to surface measurements and in cases where through thickness residual stresses were obtained the examined samples were relatively small [13-15]. There are a variety of strain relaxation methods using for

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residual stress measurement. They can be either semi- or fully destructive. In ether case material removal relaxes residual stresses and the residual stresses are obtained through associated monitored strains. Although techniques such as layering [16] and inherent strain [17] methods can be used for through thickness measurements of large samples, they completely destroy the specimens. Semi-destructive methods such as centre hole drilling [10], deep hole drilling [18] and ring coring [19] involve in limited degree of material removal, enabling further measurement to be made at different locations. However, due to limited strain sensitivity the measurement depths of the centre hole drilling and ring coring methods are roughly equal to the hole or trepan diameter.

There are a number of measurements reported to validate the predicted residual stresses created during quenching [14, 20, 21] using Sach's method, material removal and incremental centre hole drilling techniques.

In contrast to the fully destructive methods, one method capable of semi-destructively measuring through thickness residual stresses deep within large scale engineering components is the deep hole drilling (DHD) technique. Since the early work of Beaney [22] and Zhadanov and Gonchar [23] the deep hole drilling technique has undergone considerable improvement. The versatility and accuracy of the technique has been demonstrated by performing the method on a variety of complex and large engineering components [24, 25]. Recently the method has been measured successfully the full residual stresses in a series of large scale engineering vertical sleeves [26].

Still it is worth bearing in mind that all the material removal techniques are based on the theory of elasticity which assumes that the corresponding change in the strains during material cutting is elastic. Hence, the residual stresses are directly related to the measured changes in strains. This underlying assumption would be no longer valid if the residual stresses are close to the yield stress and there is likelihood of plasticity during material removal. Severely quenched components are expected to exhibit high levels of residual stresses close to the yield stress of the material and with three principal stress components. None of the material removal techniques, except the deep hole drilling method, is capable of measuring all three stress components. The problem of accurate measurement is also more complicated when there is material removal in a highly triaxial residual stress field.

To account for the influence of plasticity created during material removal Mahmoudi and his co-workers [27, 28] proposed a modification to the DHD method, called the incremental deep hole drilling technique (IDHD). The present paper discusses the problems of full residual stress measurement in quenched solid and hollow steel cylinders, using the conventional deep hole drilling technique and the application of the IDHD technique for quenched components was investigated. The following section describes the conventional and incremental deep hole drilling techniques.

III. DEEP HOLE DRILLING TECHNIQUE

Standard DHD method

The deep hole drilling technique for measuring the through thickness distribution of in-plane residual stresses uses four steps. Fig. 1 shows the required steps schematically. First a reference hole is drilled through the thickness of the specimen using a self-aligning gun drill (Fig 1a). The diameter of the reference hole is measured accurately using an air probe at different angles around the reference hole and at equal intervals through the thickness of the sample (Fig. 1b). Then a core coaxial to the reference hole is trepanned using an electro discharge machining in metallic components (Fig 1c). Finally the reference hole diameter is remeasured at the same angular positions and depth intervals used before trepanning (Fig. 1d). The distortion of the reference hole diameter in the plane normal to the reference hole axis is used to determine the in-plane residual stress field.

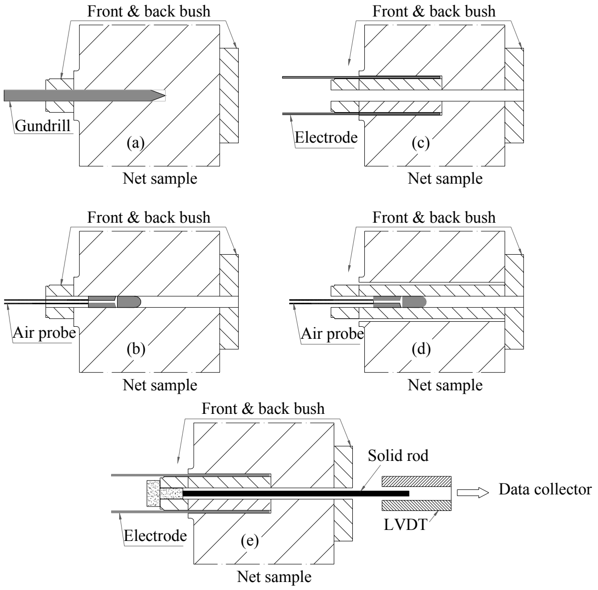

Fig. 1 A schematic diagram illustrating the procedures in the deep hole drilling technique: a) drill reference hole; b) diametral measurement of the reference hole; c) trepanning; d) remeasure the reference hole; e) axial strain measurement.

It is assumed that the introduction of the reference hole is a stress free procedure and the residual stresses are elastically relaxed in the trepanned core. Further details of the DHD technique are available [18, 29]. Measurement of the reference hole diameter before and after trepanning, $d(\theta)$ and $d'(\theta)$, are made at m angular positions, $\theta_1,...,\theta_i,...,\theta_m$, around the reference hole and at a number of equal intervals in depth to determine the through thickness of residual stress distributions in the component. The change in the reference hole diameter, $\Delta d(\theta) = d'(\theta) - d(\theta)$, may then be used to determine the residual stresses. The normalized diametral distortion, $\bar{u}_{rr}(\theta)$, is related to the residual stress field, σ_{xx}, σ_{yy}, σ_{xy} and σ_{zz} by

$$\bar{u}_{rr}(\theta) = \frac{\Delta d(\theta)}{d(\theta)} = -\frac{1}{E}\times \left[f(\theta)\sigma_{xx} + g(\theta)\sigma_{yy} + h(\theta)\sigma_{xy} - \upsilon\sigma_{zz}\right] \tag{1}$$

where $f(\theta) = 1 + 2\cos 2\theta$, $g(\theta) = 1 - 2\cos 2\theta$ and $h(\theta) = 4\sin 2\theta$. E and υ are the Young' modulus and Poisson's ratio. Very often only the in-plane residual stresses, σ_{xx} , σ_{yy} and σ_{xy} are measured using the conventional DHD technique. The temperature of the sample substantially increases during the electro discharge machining. Therefore, traditionally the axial strains were measured using thermocouples attached on the sample to exclude the effect of thermal strains in the core length changes [16, 25, 30]. However, often the out-of-plane stress is assumed as zero.

When measurements are made at m angular locations the above equation can be expressed in matrix form

$$\bar{u}_{rr} = -\frac{1}{E} M\sigma \tag{2}$$

Consequently at a specific location along the reference hole axis equation (2) can be rewritten as

$$\begin{bmatrix} \bar{u}_{rr}(\theta_1) \\ \bar{u}_{rr}(\theta_2) \\ \vdots \\ \bar{u}_{rr}(\theta_m) \\ \Delta\varepsilon_{zz} \end{bmatrix} = -\frac{1}{E}\times \begin{bmatrix} f(\theta_1) & g(\theta_1) & h(\theta_1) & -\upsilon \\ \vdots & \vdots & \vdots & \vdots \\ f(\theta_i) & g(\theta_i) & h(\theta_i) & -\upsilon \\ \vdots & \vdots & \vdots & \vdots \\ f(\theta_m) & g(\theta_m) & h(\theta_m) & -\upsilon \\ -\upsilon & -\upsilon & 0 & -1 \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \\ \sigma_{zz} \end{bmatrix} \tag{3}$$

and $\Delta\varepsilon_{zz}$ is the out-of-plane strain as the core is trepanned. Then a least squares fit to the diametral strain can be used to determine the stresses [18, 31]

$$\hat{\sigma} = -EM^{*}\bar{u}_{rr} \tag{4}$$

where

$$M^{*} = (M^{T}M)^{-1}M^{T} \tag{5}$$

M^{*} is the pseudo-inverse of matrix M, M^{T} is the transpose of matrix M and $\hat{\sigma}$ is the optimum stress vector that best fits the measured diametral distortions.

Incremental DHD method

All the mechanical strain relaxation measurement methods, including the DHD technique, rely on an underlying assumption that stresses during cutting are relaxed entirely in an elastic manner. However this assumption does not always exist. If high initial residual stresses are present, removing the material may result in elastic-plastic unloading. Consequently the simple relationship between relaxed strains and residual stresses would be no longer valid.

To understand this problem Mahmoudi and his co-workers [27, 28] conducted a finite element study. It was found that if the trepanning is carried out incrementally rather than in one step plastic deformation starts to grow while cutting and results in deviation of the measured stresses using the conventional DHD. Basically it was shown that the incremental trepanning in the presence of high stresses modifies the profile of the reference hole. A new technique was proposed that uses intermediate diameter data at each increment of trepanning rather than the hole diameter before and after trepanning in one cut. In the incremental DHD technique the trepan is stopped at certain depths and the maximum hole deformation is recorded. The stresses are then calculated from the difference between the deformation of the hole after a certain trepan depth and when the trepan cut is complete.

The incremental nature of the technique also allows the measurement of the out-of-plane strain without having to use thermocouples as used in the conventional DHD technique. The outcomes of the simulations were validated experimentally using the modified technique and a significant improvement in the measured residual stresses was achieved when compared to the conventional method [27, 28].

In cases where the out-of-plane stress component is to be counted a special configuration is required using the incremental DHD technique to keep the alignment of the cutting and measurement procedures through the entire of the experiment. This set up is shown in Fig 1e. and employs a linear variable differential transducer (LVDT) to record the change in the core length on completion of each trepan increment. The average out-of-plane strains after each step is used to calculate the stresses using equation (3).

IV. COMPONENTS

Through thickness residual stresses were studied in quenched solid and hollow steel cylinders. The material was a Type 316L stainless steel and a full description of the physical, thermal and mechanical properties are available in [32]. Schematic drawings of the components along with the measurement line and orientation of the measured stresses are shown in Fig. 2. The solid cylinder [13] was 60 mm in diameter and length. The deep hole drilling technique was carried out along the axial axis from top to the bottom face.

The outside and inside diameters of the hollow cylinder were 100 and 50 mm respectively with 50 mm long. The residual stresses were measured along a radial line in the midsection from the outer to the inner surface of the specimen.

A test rig was designed to quench the cylinders and consisted of a furnace, cooling chambers, a water-tank and a quick release mechanism. The quenching procedure for both samples was basically the same. The cylinders were heated up to $850^{\circ}C$ in the furnace. Once the components had attained the required temperature throughout, they were quickly released into the cooling chamber where water was pumped through spray nozzles over the specimens from different directions.

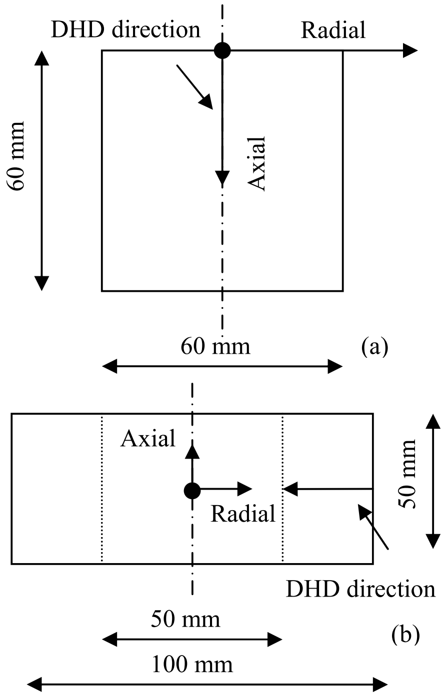

Fig 2. Schematic drawing of the components indicating the measurement line: (a) solid cylinders, (b) hollow cylinder.

V. FE MODELS OF QUENCHING

To achieve a preliminary insight into the created residual stresses created finite element analysis of the quenching process for both components were carried out. Basically quenching is rapid cooling of a specimen from a high uniform temperature to room temperature by a coolant medium. During cooling, heat dissipates via free faces and a non-uniform temperature gradient develops through the entire volume of the specimen. The temperature gradient is a key parameter in determining the residual stress field and distortion in the quenched component. Therefore the process can be considered as a transient heat conduction problem with convective boundary conditions. The simulation is strongly dependent on reliable boundary conditions as input data and the surface heat transfer coefficient is an important parameter.

To simulate the quenching process a sequential thermal-stress analysis was conducted in ABAQUS/Standard. This type of analysis is performed when the stress and deformation fields are dependent on temperature but the temperature field can be obtained independently. Hence an uncoupled heat transfer analysis using heat transfer elements was performed to determine the temperature field all over the entire of the specimen during cooling process. Nodal temperatures were saved in the heat transfer output data file as a function of time. Then a stress/deformation analysis was carried out. The recorded temperature-time history was then used as input to the stress analysis [33].

Axisymmetric models were created for the solid and hollow cylinders. A schematic drawing of the model for the hollow cylinder with applied boundary conditions is shown in Fig. 3. Symmetry in the Y direction simplified the model. The finite element model included approximately 650 axisymmetric elements DCAX4, 4-nodelinear heat transfer quadrilateral and CAX8R, 8-node biquadratic quadrilateral for the heat transfer and stress analyses respectively. Kinematic material hardening was assumed. Mechanical and physical properties of Type 316L stainless steel were defined in the ABAQUS input file by tabulating the material data as a function of temperature. Phase transformation during quenching was assumed not to occur for stainless steel.

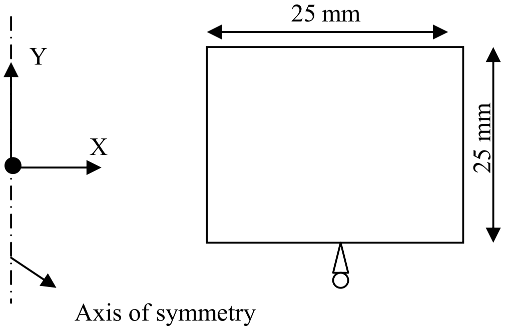

Fig.3 Axisymmetric model of the hollow cylinder.

In the heat transfer analysis the specimen was initially defined as a uniform temperature of $850^{\circ}C$. In practice the hub was quenched from $850^{\circ}C$ by spraying water. In the model the cooling procedure was simulated by applying boundary conditions on the free surfaces. This was done by performing an interaction for all surfaces of the hub with ambient conditions. A surface film condition with a film coefficient of 7000 W/m^2°C and sink temperature of $20^{\circ}C$ was defined in the finite element model. Using thermocouples in five locations in laboratory samples during quenching the temperature against time was recorded. Then several trials by means of finite element simulations with different heat transfer coefficients as boundary condition were conducted to achieve the identical temperature history for the same points. Eventually a heat transfer coefficient of 7000 W/m^2°C was found to best match the experimental temperature profiles. On completion of the heat transfer analysis, a stress analysis was carried out by reading the resulting time-history from the heat transfer analysis as input data.

VI. RESIDUAL STRESS MEASUREMENTS

Conventional and incremental DHD measurements were carried out along the measurements lines shown in Fig 2. A gundrill of 3 mm was used for drilling the reference hole. A 10 mm diameter core coaxial to the reference hole was trepanned using an electro discharge machining. Accurate measurement of the reference hole diameter were carried out using a calibrated air probe. The diameters were measured at nine angular positions and 0.2 mm intervals through the thickness of the components.

The measured in-plane residual stresses using the conventional DHD technique are compared with FE predictions for the solid and hollow cylinders in Figs. 4 and 5 respectively. In figure 4 the direction of the DHD measurement is from left to right while in figure 5 it was from right to left. Initially the conventional DHD method was able to measure near surface compressive residual stresses.

However, at greater depths it is evident that the results from the conventional DHD technique began to deviate significantly from the expected residual stresses provided by the FE analysis.

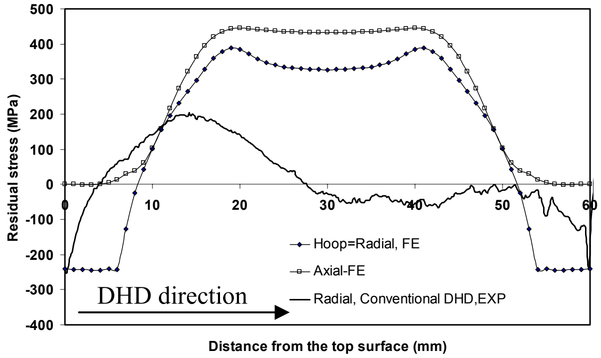

Fig. 4 Residual stresses predicted using FE for the solid steel cylinder and results obtained from the application of the conventional DHD technique.

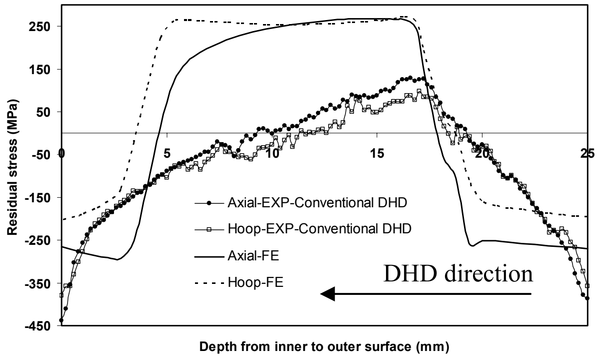

Fig. 5 Residual stresses predicted using FE for the hollow steel cylinder and results obtained from the application of the conventional DHD technique.

The incremental deep hole drilling technique was then used to measure residual stresses in the solid and hollow cylinders. Using modifications to the conventional DHD apparatus trepanning was implemented incrementally and the reference hole diameter and the changes in the length of the core (for solid cylinder) were measured on completion of each step. The final results for the two cylinders are shown in Figs. 6 and 7. In both cases the application of the incremental DHD method significantly changed the measurements compared to the conventional DHD measurements shown in Fig 4 and 5.

VII. DISCUSSION

As expected from earlier studies on quenching [32], quenching the solid and hollow cylinders introduced high compressive residual stresses on the surfaces. Finite element analysis as shown in Figs. 4 and 5 demonstrated that both samples exhibiting high compressive residual stresses on the surfaces that are balanced by high tensile residual stresses through the thickness. The FE prediction demonstrated a high state of triaxiality through the thickness of the solid cylinder (Fig. 4). Although not shown in fig. 5, the radial stress (out-of-plane stress component) was relatively small through the thickness of the hollow cylinder. In both cylinders the levels of induced residual stresses were substantially high, close to the yield stress of the material. However, while the compressive stresses would be beneficial when the components are subjected to surface tensile stresses the high interior tensile stresses may be detrimental. There is the potential for crack initiation when they are combined with through thickness imposed tensile stresses. Furthermore the surface residual stresses can not be utilized to evaluate the high tensile through thickness residual stresses. Hence, through thickness knowledge of the residual stresses in quenched components are necessary if we wish to obtain a reliable integrity assessment.

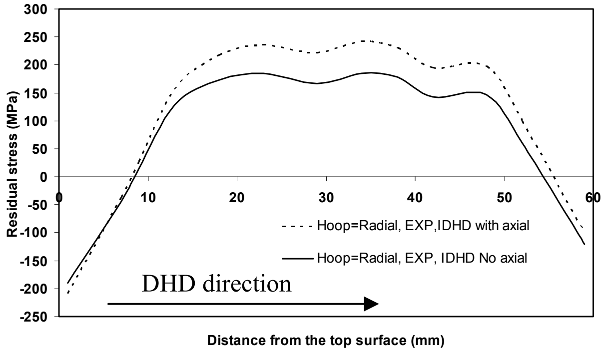

Fig. 6 Experimental results obtained from the IDHD technique for the solid cylinder, with and without the axial strain component.

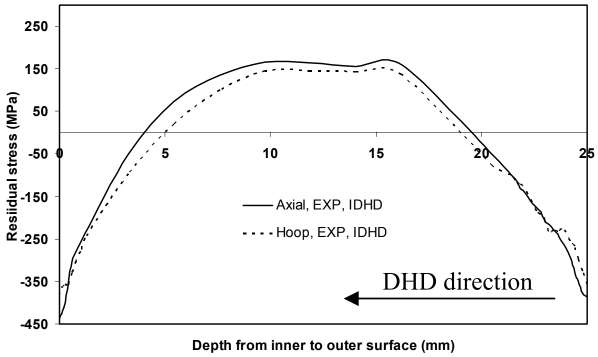

Fig. 7 Experimental results obtained from the IDHD technique for the hollow cylinder.

To achieve this, the deep hole drilling technique was employed to obtain experimental data of through thickness residual stresses in these components. For the hollow cylinder the measured stresses, hoop and axial stresses, were close to the yield stress of the material hence material removal through the thickness culminated in plasticity during cutting. For the solid cylinder, not only were the measured stresses substantially high but also there was a state of high triaxiality through the thickness.

To deal with plasticity effect and also to include the out-of-plane stress in the solid cylinder the incremental DHD technique was employed. The IDHD results in Figs 6 and 7 are indicative of a significant improvement in the measured stresses compared to the conventional DHD method. Not only were the measured stresses corrected but also the axial stress was obtained for the solid cylinder. Fig. 6 demonstrates that considering the out-of-plane stress improved the magnitudes of the hoop and radial measured residual stresses.

Nevertheless, there are some differences between the measured and predicted stresses. First, the IDHD measured through thickness stresses are lower than the FE results in both solid and hollow cylinders. Second higher compressive stresses were measured on the surfaces of the hollow cylinder. Third, the measured values change sign (compressive to tensile) at a lower depth than the predictions does. There are a number of explanations for all these. The lower level of through thickness measured stresses in the solid cylinder were in excellent agreement with the neutron diffraction results obtained previously by Hossain et al [8]. Higher compressive surface residual stresses had been previously observed by ICHD measurements on a quenched cylinder [8]. The different depths where the measured and predicted stresses change their sign were also seen previously [34].

VIII. CONCLUSIONS

Finite elements predictions of quenching of solid and hollow steel cylinders revealed high levels of residual stresses close to the yield stress of the material. Also the results indicated the presence of high triaxiality through the thickness of the solid cylinder. The conventional DHD technique measured incorrectly residual stresses due to the evolution of plastic unloading while trepanning the material to relax the stresses.

The application of the incremental DHD technique in both component resulted in a significant improvement in the measured residual stresses compared to the conventional method.

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