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RESIDUAL STRESS MEASUREMENT IN A STAINLESS STEEL CLAD FERRITIC PLATE USING THE CONTOUR METHOD

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ABSTRACT
In pressure vessels stainless steel weld-overlay cladding is a widely used technique to provide a protective barrier between the corrosive environment and the ferritic low alloy base metal. While the cladding layers enhance corrosion resistance, the induced residual stresses due to the deposition of weld layers are of major concern. It is of paramount importance to understand how residual stresses interact with service loading when the vessel is pressurized. Therefore, knowledge of the initial residual stresses due to cladding is an essential input for structural integrity assessment of pressure vessels.

In the present paper the Contour Method was conducted to measure residual stresses in an austenitic steel cladded plate that was fabricated from a ferritic steel base plate with three layers of austenitic stainless steel weld metal cladding deposited on the top surface. The Contour Method was chosen for various reasons. First, it provides a full 2D variation of residual stresses over the plane of interest. Second, it is not limited by the thickness of components or microstructural variations and finally it should potentially capture the variation of residual stresses in each individual weld beads and due to the possible phase transformation in the ferritic base material. The map of longitudinal residual stresses was measured by sectioning the test component along a transverse plane at mid-length. The measured residual stresses were in good agreement with published results in the open literature.

INTRODUCTION
The reactor pressure vessel (RPV) of a light water reactor is made from ferritic low alloy steel with the inner surface clad using austenitic stainless steel to protect against crack initiation and growth by corrosion of ferritic steel exposed to reactor coolant water conditions. These two materials have different mechanical and thermal properties. The low thermal conductivity of the austenitic cladding material shields the inner surface of the RPV against thermal shock loading and development of excessive transient thermal stresses. However, residual stresses are introduced into the clad itself and ferritic base material during the cladding application process. These stresses are modified by post weld heat treatment (PWHT). This is typically carried out in the temperature range of 605-620 °C, usually for at least 10 hours [1]. Holding at the heat treatment temperature acts to relieve, but does not completely eliminate, high magnitude welding-induced stresses. When the temperature is decreased from the notionally “stress-free” heat treatment temperature of the vessel, additional residual stresses are introduced. The final distribution of such stresses in the clad component depends on many factors such as: the cladding and base material physical and mechanical properties; the cladding thickness; the cladding (weld) procedure; the PWHT, and how it is applied to the vessel. When ferritic base material is clad with layers of austenitic material, the peak tensile stresses normally occur in the cladding layer. The magnitude of these tensile stresses can reach the yield strength of the cladding material at room temperature [2]. For safety critical applications, such as nuclear power plants, it is important to quantify residual stresses in clad components as they can promote degradation and threaten the structural integrity of the plant. For example, they can encourage surface crack growth through the cladding, increase the rate of fatigue damage, stress corrosion, and under clad cracking. They can change fracture margins and contribute to brittle fracture [1].

Several different measurement techniques are available for characterising residual stresses in fabricated components [3]. These techniques can be categorized into three groups: non-destructive, semi destructive and destructive. Non-destructive techniques such as X-ray diffraction, neutron diffraction and synchrotron diffraction are limited to surface and near-surface residual stress measurements. For example, X-ray diffraction probes the material only down to a few microns below the surface. The higher energy X-rays from a synchrotron have a penetration depth up to several millimetres in steel and can be used to measure three-dimensional strain components [4]. Neutron diffraction can be used to measure strains within a distance of about 20 mm for steel components but there are some limitations, such as errors resulting from path length variations when measuring specimens with curved surfaces. Neutron diffraction is also an expensive technique [5]. Non-destructive methods are not capable of measuring through-thickness residual stresses in large engineering components (i.e. where the thickness exceeds 50 mm or so).

Semi-destructive and destructive techniques, such as deep hole drilling, layer removal, sectioning, slitting and the Contour Method are often used to measure type I residual stresses (continuum long-range). Destructive techniques are capable of measuring through-thickness residual stresses. The sectioning method in its simplest form provides a single component of the stress tensor [6]. However, it can give multiple stress components by performing multiple cuts but this is less accurate and very time consuming. Deep-hole drilling is a semi-destructive technique that is capable of measuring multiple stress components but provides only a 1D stress profile (depth profile) [7]. The Contour Method, which involves cutting the sample in two [8] yields a full cross-sectional map of the residual stress normal to the cut surface [9]. Other traditional relaxation techniques such as layer removal, incremental hole drilling and slitting (crack compliance), commonly give a depth profile and provide a single component of stress.

The hypothesis underlying the present work is that the Contour Method can be applied to characterise manufacturing residual stresses in thick section ferritic components that have been clad with layers of stainless steel weld metal (see figure1). Moreover, it was envisaged that this measurement method might have the potential to resolve weld-to-weld bead variations and local phase transformation effects. This paper describes how the Contour Method was applied to a 50 mm thick ferritic steel plate clad with a 10 mm thick layer of stainless steel. The challenges associated with implementation of the method and how these were dealt with are described. The accuracy of the measurement results is assessed using sensitivity studies and by comparison with unpublished neutron diffraction measurements on the identical component, as well as published analytical [1] and experimental studies on other clad components [10,11].

FIGURE 1: REPRESENTS THE 3D VIEW OF THE CLAD PLATE

THE CONTOUR METHOD

The Contour Method is based on cutting the test components in two halves. The cut surfaces deform owing to the relaxation of residual stresses. The deformation of the cut surfaces is measured and input as the boundary conditions in a finite element analysis to back-calculate the 2-dimensional map of original residual stresses normal to the plane of the cut. The cutting step in the Contour Method is very important in that it provides the raw data on which all the subsequent steps are based. Any artefacts introduced here therefore feed through to the final results.

Wire Electro-Discharge Machining (EDM) has been identified as the best choice for the cutting step [12]. There are several assumptions associated with the Contour Method and in particular about the cutting step of the technique. Crucially, the cutting must be done in such a way that it does not introduce any new stresses. The cut should be flat with a constant kerf width. The ideal cut would have zero width, induce no stresses and allow no plasticity at the tip of the cut [13].

TEST SPECIMEN

A clad test component for the present study was supplied by Rolls-Royce. The test specimen was fabricated from a 300 mm long by 180 mm wide by 50 mm thick ferritic base plate of SA508 Grade 3 steel. Three layers (totalling 10 mm thick) of austenitic stainless steel weld metal cladding were deposited on the top surface as shown in Figure 2. The first clad layer was 309L stainless steel to minimise dilution effects and the final two layers were 308L stainless steel. A mechanical hot wire TIG welding clad process was used with stringer beads having an approximately 50% overlap. The welding parameters recorded are given in Table 1.

The welding procedure for the clad plate specimen included a hydrogen bake-out phase after completion of welding. The specimen was held at the pre-heat temperature of 170 °C for a minimum of four hours. This is done to minimise the risk of hydrogen cracking in the heat affected zone (HAZ). No PWHT was applied, thus the specimen supplied for measurement was in the as-welded condition.

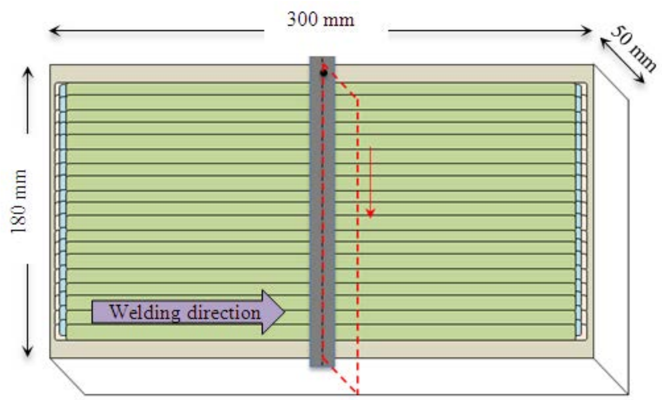

FIGURE 2: SCHEMATIC IMAGE FOR THE CLAD PLATE

TABLE 1: CLAD WELDING CONDITIONS

		Layer 1	Layer 2	Layer 3
Material of the band electrode		Type 309L	Type 308L	Type 308L
Current (A)	**Primary**	315	315	315
	Background	180	180	180
Voltage (V)		12	12	12
Inter pass Temperature (°C)		250	250	250
Pre-heat (°C)		170	170	170
Travel speed (mm/min)		150	150	150
Number of passes		19	19	19

MEASUREMENT CHALLENGES

The specific challenges associated with implementing the Contour Method were:

- The specimen should be rigidly and symmetrically clamped on the EDM table to constrain movement caused by the relief of residual stresses during cutting. Secure clamping can reduce the risk of plasticity. The specimen can be clamped onto the EDM table with fitted bolts and by introducing pilot holes at start and at end of the cut. The use of pilot holes enables an uncut portion of the specimen at each end of the cut to remain, thus providing resistance to the opening or closing of the cut as it progresses.

- For best practice, trial cuts should be performed on a stress-free sample. These trial cuts are used establish the best EDM cutting parameters for the specimen shape and size and material [14, 15]. When the specimen contains more than one material, for example, stainless steel weld metal on a ferritic component, the best EDM cutting parameters are not necessarily those established for each material alone, and a trial cut can be helpful in establishing the optimum parameters.

- A small diameter EDM cutting wire can be used to improve the surface finish and thereby the stress resolution of the technique. However, this carries an increased risk of wire breakage.

- To deal with surface displacement errors arising from wire EDM cutting artefacts, particularly at wire entry, wire exit, at the start and at the end of the cut, sacrificial layers can be attached at the top and bottom faces of the plate as well as at the start and at the end of the cut[15].

- To avoid introducing thermal expansion errors, the deformation of the cut surface should be measured in a temperature-controlled room, held at the same temperature as the EDM bath temperature (usually 20° °C).

EXPERIMENTAL PROCEDURE

In order to determine the longitudinal stress, the cut was performed along the centreline of the plate, in a direction perpendicular to the weld beads. Before specimen cutting, a 1.5 mm diameter pilot hole was introduced 5mm from the edge of the plate in the plane of the cut. This provided self-restraint and edge clamping of the plate during cutting. An Agie Charmilles FI 440 CCS Wire Electro Discharge Machine (EDM) was used to perform the cut. Running cutting trials was impossible for this sample case because there was no stress free material available exactly similar to the clad specimen. Therefore, cutting parameters were chosen based on past experience. The first attempt at cutting was carried out using one of the thinner wire diameters: 0.15 mm brass wire. Stable cutting conditions for this component could not be achieved with this wire, which broke at the start of the cut. Therefore, a thicker wire (0.25mm diameter brass wire) was chosen to perform the cut. This limited the surface finish achievable and thereby the stress resolution length-scale. To avoid wire entry, exit, and the cut start and end effects, sacrificial layers were placed. These were of carbon steel having a cross-section of 5mm x 10mm (see figure 3). They were placed at the top and bottom of the plate along the plane of the cut and at the start and at the end of the cut. However, special consideration was given to obtain a close fit between the wavy clad surface and the attached layer, and silver-loaded epoxy resin was used to prevent any gaps.

FIGURE 3: CLAD PLATE MOUNTED ON EDM TABLE SHOWING SACRIFICIAL PLATES AND CLAMPING ARRANGEMENT

The clad specimen is a combination of two different materials; therefore, to avoid introducing thermal expansion errors, the deformation of the cut surface was measured in a temperature controlled room, held at the cutting bath temperature of 20 °C. After completion of the EDM cutting, the cut surfaces were inspect by eye for any obvious cutting artefact and the sacrificial layers were removed. The contours of the created cut surfaces were measured using a Mitutoyo Crysta Plus 547 coordinate measuring machine (CMM). For this measurement, a 3 mm diameter Renishaw PH10M touch trigger probe was used. The three spatial coordinates of each point on a 0.5 mm square grid pattern on the cut surface were measured. During the EDM cut debris, in the form of tiny particles of metal, is formed and deposited onto the cut surfaces. The thickness of the debris layer may be a few microns and if left in place may affect the contour measurements. The cut surface should therefore be free from these dust deposits. Removal of these deposits was done using a rubber eraser (see figure 4). The cut surfaces were re-measured using a hybrid laser-CMM system with finer measurement pitch. A 0.125 x 0.125 mm point spacing with 2 mm s^{-1} measuring speed was used. The laser CMM system comprises a Zeiss Eclipse CMM to which a Micro-Epsilon triangulating laser probe is fitted. The laser sensor has a resolution of 0.15 µm at its maximum sample rate of 10 000 per second and without averaging.

DATA PROCESSING

The two sets of measured surface deformation data, the first from the touch probe scan and the second from the laser probe survey (after cleaning with a rubber) were analyzed independently. Each set of data contained measurements of the left and right hand cut surfaces. These data were processed into a suitable form to get the original map of the residual stresses with the FE model. For data analysis the surfaces were mapped from the measured coordinates using MATLAB 7.10. The basic steps for data processing are:

FIGURE 4: EDM CUT AFTER CLEANING WITH RUBBER

- alignment of the two data sets with one another, by translating and rotating the data in the x-y plane,
- removal of noise and outliers in the raw data of the surface contours. These outliers are easily identified as single data points markedly above or below the average height of the adjacent measurements. They must be removed as they cause errors in the measurements of residual stresses
- averaging of the left and right side measurements points (this is required to avoid the effect of shear stresses and anti-symmetric cutting artefacts)
- smoothing by fitting to a cubic spline function, with a suitable knot spacing

Further details about the data processes sets are published elsewhere [16].

RESIDUAL STRESS CALCULATION

Residual stresses are calculated for touch probe CMM data points and laser CMM data points using ABAQUS finite element (FE) code, and linear elastic analysis was performed. For building the 3D model, one half of the plate was built by extruding the measurements of the perimeters of one half of the plate. The measured displacements on the cut surface were very small. Therefore; the created cut surface was modelled as a flat surface. Initially, to avoid the complexities during the analysis, the same material properties were applied for the clad and base materials ($E = 210$ GPa and $\vartheta = 0.3$). For analysis the cut surface was meshed with 1 mm × 1 mm linear hexahedral elements (type C3D8R) within the clad material and 10 mm below the clad region, and 3 mm × 3 mm linear hexahedral elements (type C3D8R) were defined far from the clad region. Boundary conditions normal to the cut plane were defined in the FE model, which is in the opposite direction to the deformation. Finally, elastic finite element analyses were performed to obtain the residual stress distribution for the created cut surface. In order to critically evaluate the actual stress map, the laser CMM data points were reanalyzed with the more exact material properties (E = 171 GPa and $\vartheta = 0.3$ and E = 209.125 GPa and $\vartheta = 0.3$) were used for ferritic base plate and stainless steel weld metal cladding respectively. Finally, the Contour Method results were compared with neutron diffraction results.

RESULTS AND DISCUSSION

A map of the longitudinal residual stresses using touch probe CMM data points is shown in figure 5. Longitudinal stresses normal to the cut plane (at mid length of the clad plate) are tensile in the cladding region and extend down to a depth of a few millimetres within the ferritic base metal, Compressive stresses are found immediately below the tensile area. Figure 6 shows the comparison of the line profile of longitudinal stresses obtained from the touch probe CMM data points and the laser probe CMM data points. For the laser CMM survey, a finer measurement density was used than with the touch probe CMM. The stress profiles match each other except for their peaks, which are at slightly different heights and very slightly shifted. The stress profile of the laser CMM measured data points produced smooth peaks (such as at around 25mm and 55mm region). In contrast, the touch probe measured data points produced sharper peaks in the same region. This is most likely to be because of the higher density of the laser CMM measurements.

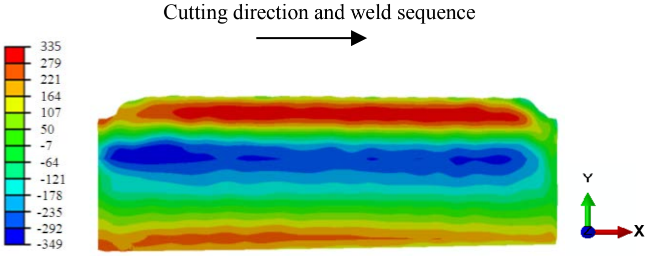

FIGURE 5: MAP OF THE LONGITUDINAL RESIDUAL STRESSES ACTING ON THE TRANSVERSE PLANE CALCULATED FROM TOUCH PROBE CMM DATA POINTS (STRESSES ARE IN MPA)

Figure 7 shows a map of the measured longitudinal residual stresses across the cut plane (at mid-length of the clad plate). The stresses are tensile in the clad itself but rapidly reduce to compression in the ferritic base metal before rising to tension towards the bottom surface. The maximum tensile stress of 321 MPa and maximum compressive stress of -285 MPa are located at approximately 3 mm and 25 mm respectively below the top of clad surface. The stresses reduce in magnitude approaching the left and right ends of the plate, as expected. There is little evidence of weld bead-to-bead variations in stress but the clad metal tensile stresses do increase with weld pass position up to about 30 mm from the edge of the plate before reaching an essentially constant level. This is illustrated more clearly by the through-thickness line profiles shown in Figure 8.

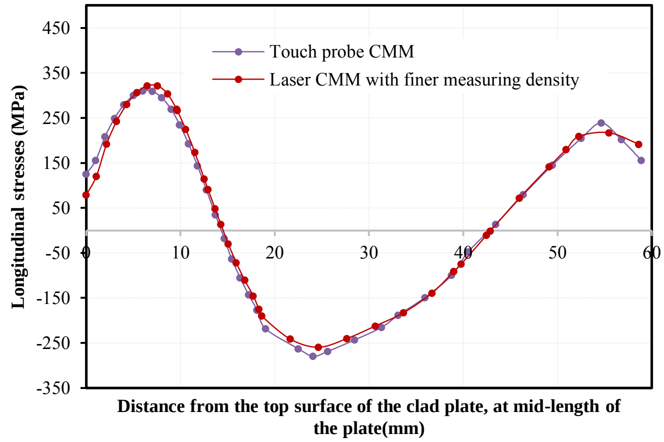

FIGURE 6: RESIDUAL STRESSES ALONG MID-THICKNESS LINE-COMPARISON OF TOUCH PROBE AND LASER CMM WITH SAME MATERIAL PROPERTIES

These profiles give no indication of any local stress fluctuations in the ferritic base material adjacent to the clad interface. This suggests that any phase transformation effects that might be present in this region do not have a significant influence on the residual stress profile.

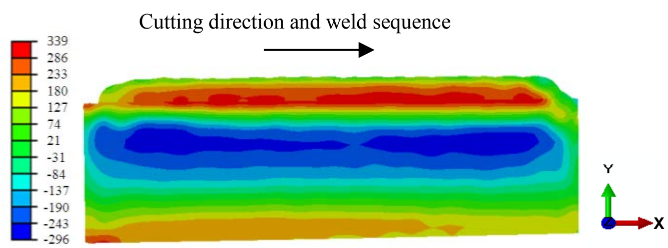

FIGURE 7: MAP OF THE LONGITUDINAL RESIDUAL STRESSES ACTING ON THE TRANSVERSE PLANE CALCULATED FROM LASER CMM DATA POINTS (STRESSES ARE IN MPA)

A sensitivity analysis was carried out on the effect of the knot spacing of the smoothing function. Two knot spacings, 7 mm and 5 mm, were used. The choice between these knot spacings was based on a comparison of the cubic spline fits and the raw measured data along the mid-thickness and across the width of the specimen. It was seen that the fitted spline corresponding to the 7 mm knot spacing follows the trend of the raw data more closely (due to limited space these charts are not included here). Figure 9 shows the calculated residual stress for the two knot spacings along the mid-thickness of the plate. The stress line profiles are very similar to each other, though not identical. To optimize the exact knot spacing, the present work is continuing, with an extended sensitivity study. Mike Prime's approach [15] is being used to optimize the knot spacing and evaluate the uncertainties in the calculated stresses.

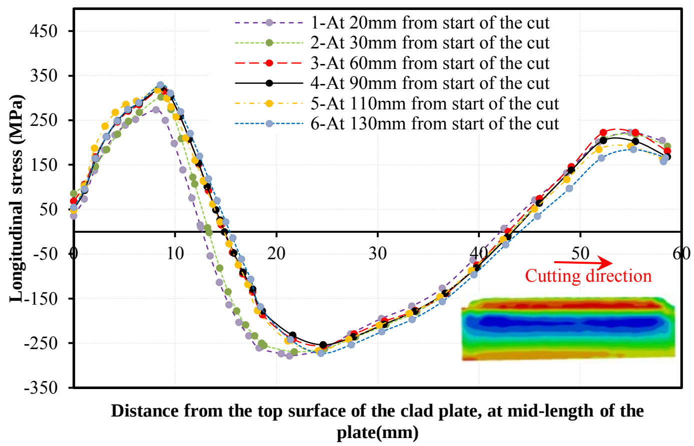

FIGURE 8: THROUGH THICKNESS STRESS LINE PROFILES AT DIFFERENCT DISTANCES FROM START OF THE CUT

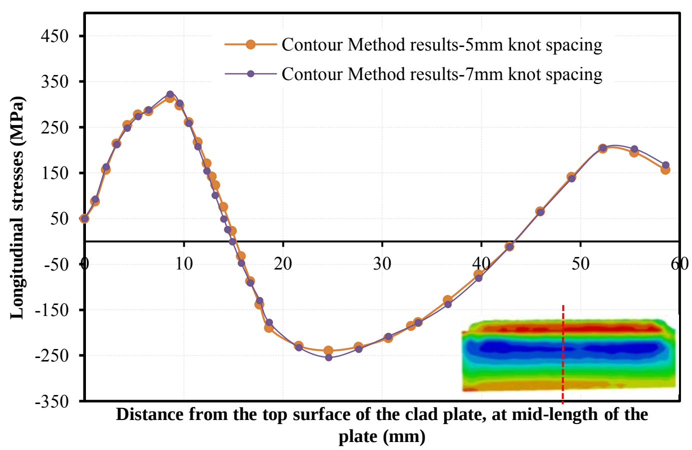

FIGURE 9: RESIDUAL STRESSES ALONG MID-THICKNESS LINE WITH DIFFERENT KNOT SPACING

The Contour Method results presented here are compared with neutron diffraction measurements made on the same specimen. These were carried out by researchers from Manchester University and Rolls Royce at ISIS. A rectangular window was cut in the underside of the plate to reduce the beam path length and count time. Results from these studies have not been published elsewhere.

Figure 10 shows a comparison of the longitudinal residual stress distributions obtained by the Contour Method and by neutron diffraction. The stress distribution is plotted along a line located at the 90 mm mid-length of the plate, extending from top to bottom. It can be seen residual stresses distribution from both techniques follow a similar trend and are in reasonably good agreement with one other.

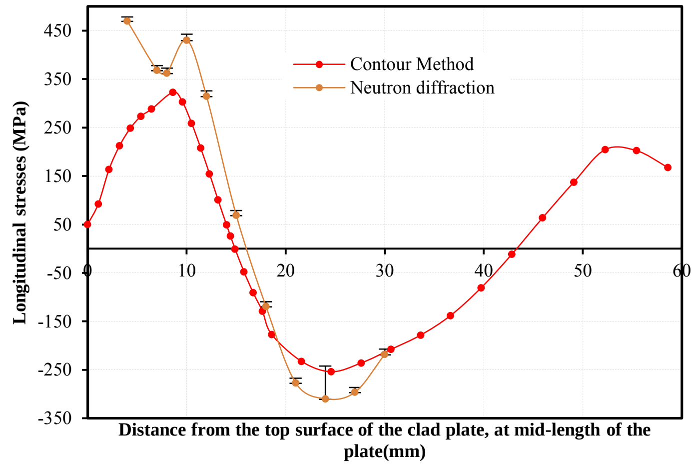

FIGURE 10: RESIDUAL STRESSES ALONG MID-THICKNESS LINE-COMPARISON OF NEUTRON DIFFRACTION RESULTS WITH THE CONTOUR METHOD RESULTS

CONCLUSIONS

- The Contour Method results are reasonably well in agreement with the neutron diffraction results.
- A maximum tensile stress value of 321 MPa and a maximum compressive stress value of 289 MPa were determined using the Contour Method.
- The stress distribution is similar in form and magnitude to published data from other measurements and predictions for similar clad ferritic material [10 - 11].
- The residual stress distribution shows that the tensile stress in each weld bead is slightly greater than in the preceding one. This is most likely to be because of the longitudinal tensile residual stress generated by the preceding weld

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