APPLICATION OF THE CONTOUR METHOD TO VALIDATE RESIDUAL STRESS PREDICTIONS

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Abstract

Welding is the most widespread method employed to join metallic components in nuclear power plants. This is an aggressive process that introduces complex three-dimensional residual stresses of substantial magnitude into engineering components. For safety-critical applications it can be of crucial importance to have an accurate characterisation of the residual stress field present in order to assess plant lifetime and risk of failure. Finite element modelling approaches are being increasingly employed by engineers to predict welding residual stresses. However, such predictions are challenging owing to the innate complexity of the welding process [1] and can give highly variable results. Therefore, it is always desirable to validate residual stress predictions by experimental data. This paper illustrates how the contour method of measuring residual stress can be applied to various weldments in order to provide high quality experimental data. The contour method results are compared with data obtained by other well-established residual stress measurement techniques such as neutron diffraction and slitting methods and show a very satisfactory correlation.

Keywords: Residual stress, measurement techniques, weldments, contour method.

1 Introduction

Safety cases for high integrity components in operating nuclear power plants must demonstrate very low risk of failure, especially where systems are experiencing degradation mechanisms. This can be achieved by undertaking structural integrity and lifetime assessments of critical engineering components that account for both expected and unexpected degradation. Such assessments require detailed knowledge of residual stresses introduced by welding and other fabrication processes; for example when considering the risk of stress corrosion cracking at dissimilar metal welds in pressurised water reactor pipe-work, or susceptibility to reheat cracking in weldments operating at high temperature.

Although numerical methods for simulating welding residual stress have improved in recent years, it is imperative that predictions are validated by experimental data, particularly for safety-critical applications in nuclear power plant [2]. There is a wide range of techniques available for measurement of residual stresses in engineering components. Most non-destructive techniques are limited to near-surface measurements or are experimentally complex and expensive [3]. For instance, although neutron diffraction is non-destructive and provides multi-axial components of stress, its application is constrained by the size and geometry of the sample, microstructural factors, the feasibility of taking the component to a neutron source, high costs and the availability of specialists to undertake the experiment and interpret measured data. Among the destructive techniques that are capable of measuring through-thickness residual stress, the relatively novel contour method offers significant advantages [4]. It provides a two-dimensional map of residual stress on the cut surface, it can be implemented in the laboratory with widely available cutting and measurement equipment and is not limited by microstructure or the thickness of the component.

The aim of this paper is to demonstrate how the contour method can be applied to various weldments for the purpose of providing measured residual stress data that can be used to validate numerical predictions. In particular we will demonstrate the accuracy of the contour method by comparing its results with those obtained from independent measurement techniques, namely neutron diffraction and the slitting method. Results for three welded austenitic stainless steel samples are presented: an edge-welded beam containing well-defined residual stresses, a Compact Tension (CT) specimen extracted from a mock-up thick section butt weld, and a three-pass slot weld in a flat plate.

2 The Contour Method

The contour method is a relatively new residual stress measurement technique which is capable of providing a cross-sectional map of residual stresses on a cut flat plane intersecting a body [4, 5]. It is a strain relaxation method that is conceptually and experimentally simple, inexpensive, and uses equipment available in most engineering workshops. The method involves cutting the sample in two halves along the plane where residual stresses, normal to the cut surface, are desired to be determined. The created cut surfaces locally deform owing to the relaxation of any residual stresses present before cutting. These deformations can be measured and then used to calculate the residual stresses that were present prior to the cut. The contour method is implemented by undertaking four steps: specimen cutting, contour measurement, data processing and stress calculation using finite element (FE) analysis.

In the present work specimens were cut by wire electro discharge machining using a 0.25 mm wire diameter and “skim cut” parameters. The profiles of the cut surfaces (the contours) were measured using a Mitutoyo Crysta Plus 574 co-ordinate measuring machine, equipped with a 4 mm diameter ruby-tipped Renishaw PH10M touch trigger probe. Each cut surface was measured with a point spacing of 0.5 mm $\times$ 0.5 mm. The measured profiles were then processed using Matlab analysis routines and a FE analysis undertaken, using the deformed surface contour as an applied boundary condition, to calculate the residual stresses.

3 Other Residual Stress Measurement Techniques

Two diverse residual measurement techniques, neutron diffraction and the slitting method, were chosen to provide independent residual stress measurement data against which to compare the contour method results. Neutron diffraction relies on measurement of atomic lattice spacing and is a well-established residual stress measurement technique [6], that has been applied to weldments, for example see [7, 8]. Slitting is a strain relief measurement method that involves introducing a narrow slot of progressively increasing length into the component, see [9] for details. This has the effect of both relaxing the residual stress at the cut surfaces and redistributing the residual stress field throughout the body of the component. The strain change at any arbitrary location in the body contains information about the released stresses at the cut plane. These strain changes can be measured at suitable locations by strain gauges and the data analysed to determine the distribution of transverse direct stress along the cut surface. Different approaches can be employed to analyse the data, such as the fracture mechanics approach [10] and the series expansion method [11]. The results in this paper have been derived using the fracture mechanics approach.

4 Application of the Contour Method to Various Weldments

The first two weld examples show contour method results that are validated by comparison with neutron diffraction measurements from [12] and slitting residual stress measurements undertaken simultaneously with the contour method cuts. The third example compares contour results for a 3-pass slot welded plate with neutron diffraction results from [13], and forms part of Task Group 4 (TG4) round robin studies organised by the European NeT network [14].

4.1 Example 1: Edge-Welded Beam

A narrow beam, welded along one edge using an autogenous process, is a very simple test specimen that has been selected as a benchmark for residual stress simulation. The welded beam design is 50 mm deep, 10 mm thick and has a length varying from 110 mm to 250 mm. Several specimens have been made from AISI Type 316H austenitic stainless steel and residual stress measurements undertaken using neutron diffraction [12] and the contour and slitting measurements reported here.

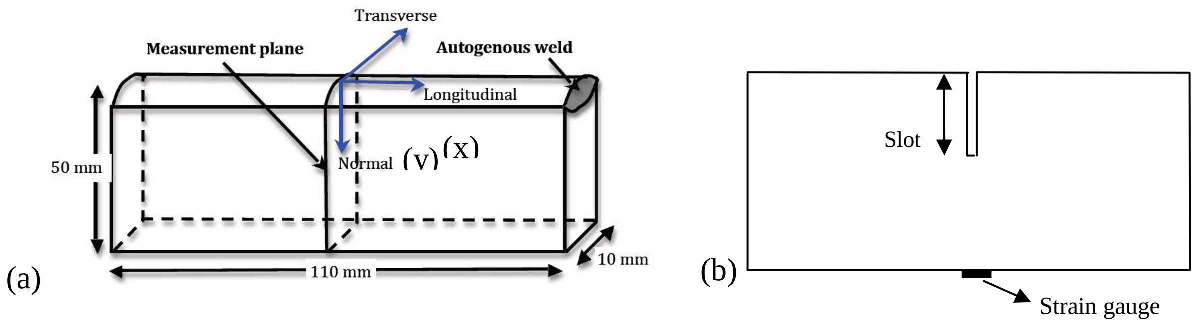

Figure 1: Schematic drawing of the edge-welded beam showing the dimensions, line and plane of measurement, co-ordinate system and the location of weld.

The dimensions of the beam studied using the contour and slitting methods are illustrated in Figure 1(a). First the sample was instrumented with a uniaxial strain gauge on the back face as shown in Figure 1(b) and cut for the slitting method, see [15] for details. The strain gauge readings were then used to determine the distribution of longitudinal residual stress, averaged across the thickness, along the beam cut plane. Following the slitting measurement, the normal deformation of both cut surfaces of the beam was measured and a map of the normal stresses obtained using the contour method.

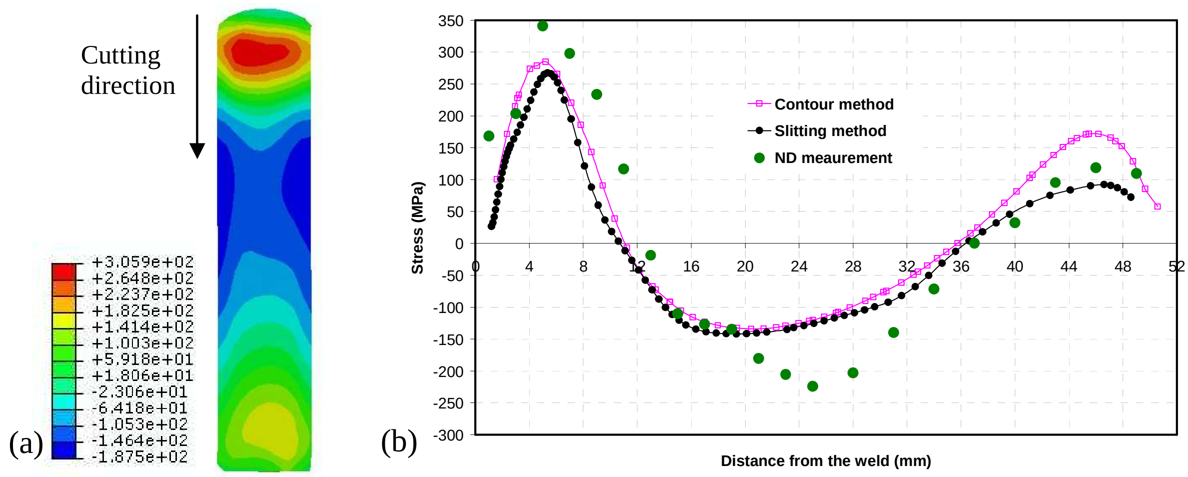

Figure 2 (a) A map of longitudinal stresses normal to the cut plane from the contour method measurement, (b) comparison between the contour stresses with those from neutron diffraction [12] and slitting measurements.

A map of longitudinal stresses normal to the cut plane from the contour method measurement is shown in Figure 2(a). The stresses change from tension (beneath the weld) to compression well away from the weld. The maximum measured tensile and compressive stresses are about

305 MPa and -187 MPa respectively. Figure 2(b) compares the contour method results with the stresses obtained from slitting and neutron diffraction [12]. All the line plots are at the mid-thickness of the beam on the cut plane and are referenced relative to the top edge. There is good agreement between the three measurements. But it should be noted that we are comparing measurements here based on different sampling areas: the contour results are from local points along the mid-thickness, the slitting stresses relate to average stresses across the thickness and the neutron diffraction measurements sampled a gauge area of $(2.8 \times 2.8)\ mm^2$ along a line at mid-width of the specimen.

4.2 Example 2: CT Welded Specimen

Residual stresses have been measured by the contour method, slitting and neutron diffraction in a welded CT specimen blank of dimensions 64.2mm x 62.8mm x 25mm, that is in a welded block of material prior to machining the CT loading holes and notch, see Figure 3(a).

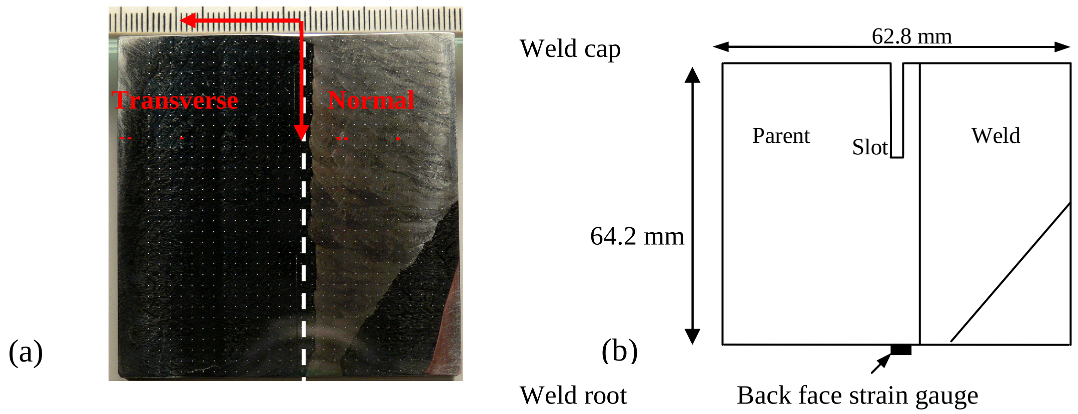

Figure 3: (a) Photo of the supplied block showing the neutron measurements line, (b) schematic drawing of the CT blank for the slitting method showing the location of strain gauge and the cut.

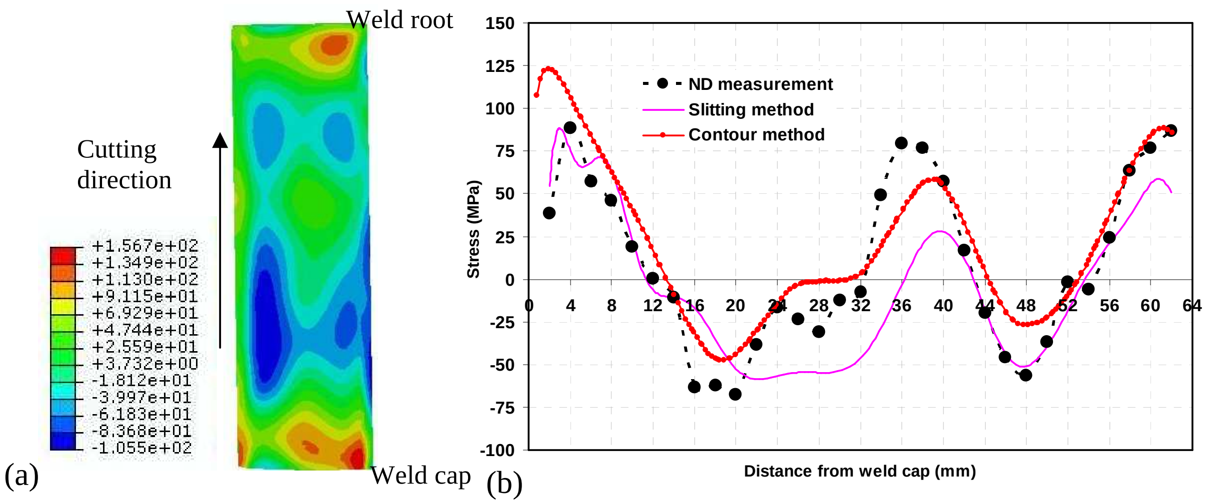

Figure 4 (a) A map of longitudinal stresses normal to the cut plane from the contour method measurement, (b) comparison between the contour stresses with those from Neutron diffraction and slitting measurements.

The specimen had been extracted from a thick section cylindrical butt weld made by joining together two sections of an AISI Type 316H stainless steel ex-service pressure vessel with a manual metal arc multi-pass weld. The elastic material properties assumed for parent material at room temperature were $E = 195.4\ GPa$ and $\upsilon = 0.294$. First, the residual stress field in the heat affected zone (HAZ) centred on a plane about 2 mm from the fusion boundary, see Figure 3(a) was measured using neutron diffraction (non-destructive) at the FRMII facility in

Munich. Secondly a slitting method measurement was undertaken along the same plane to provide greater understanding and confidence in the results, see [16]. Figure 3(b) shows the specimen dimensions, plane of the cut and the location of the strain gauge for the slitting method. Finally the normal deformation of both cut surfaces of the CT specimen was measured and a map of the normal stresses obtained using the contour method. A map of transverse stresses obtained by the contour method over the plane of cut is shown in Figure 4(a) and the contour method results are compared with the stresses obtained from slitting and neutron diffraction method in Figure 4(b). The contour stresses are in good agreement with the neutron diffraction and slitting results showing transitions in sign of stress at three matching depths. Again the different sampling areas of these measurements must be allowed for when comparing line profiles (see the edge-welded beam discussion above).

4.3 Example 3: Three-pass Slot Welded Plate (TG4)

This specimen, referred to as TG4, has been designed by the NeT European collaborative network for residual stress simulation and measurement round robin studies which are aimed at improving methods for characterising of residual stresses in weldments [14]. The TG4 specimen is a rectangular plate, 194 mm x 150mm x 18 mm, made from AISI grade 316L austenitic steel, with a three-pass TIG weld deposited in a shallow finite length slot. A schematic drawing of the test specimen is shown in Figure 5(a).

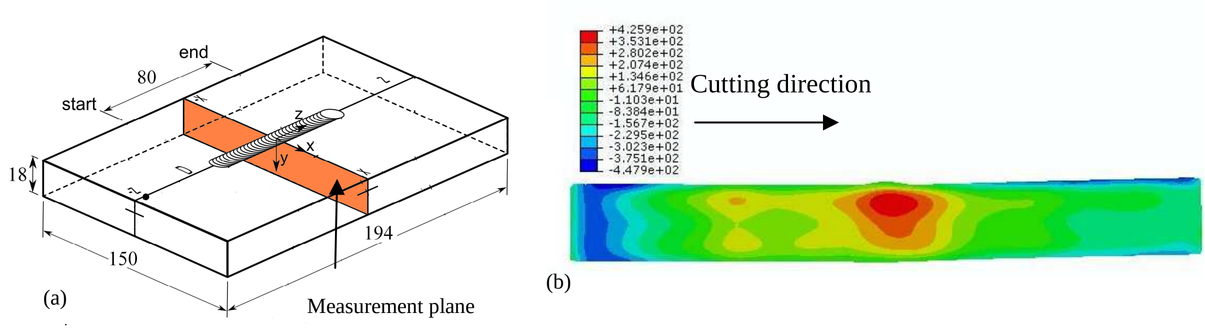

Figure 5 (a) Schematic drawing of the slot welded plate showing the measurement plane, and b) longitudinal residual stresses measured by the contour method.

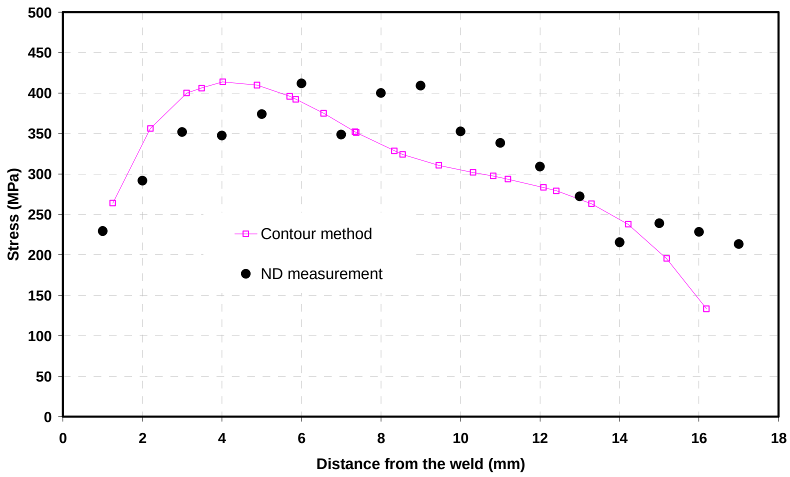

Figure 6 Comparison between longitudinal stresses measured by the contour method and neutron diffraction, from [13]. The results are plotted along the y-axis from the top of the weld through the thickness at mid-length of the cut plane.

Figure 5(b) shows a map of longitudinal stresses (that is stresses parallel to the welding direction) obtained by the contour method. High tensile residual stresses are indicated in the region of the weld balanced by compressive stresses in the parent material away from the weld region. However, the map suggests an asymmetry in the stress field with high compressive stresses where the cut starts. The reason for this unexpected pattern of stress is most likely to be associated with development of local plasticity as the stresses re-distribute during the cutting process, for example see discussion in [17]. This phenomenon is a subject of a continuing research at the Open University [18]. Nonetheless, the measured distribution of longitudinal residual stress through the thickness at mid-length of the weld from the contour method correlates remarkably well with neutron diffraction measurements from [13], see Figure 6.

5 Concluding Remarks

Generally good agreement has been found between contour, neutron diffraction and slitting method residual stress measurements in three welded test specimens. This evidence demonstrates that the contour method can produce reliable full field maps of residual stresses over the entire cross-section of welded components. The contour method has the advantages of being simple, cost effective and insensitive to microstructural variations. However, further research is required to investigate and mitigate plasticity effects.

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