Materials and Design 197 (2021) 109268

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

The incremental contour method using asymmetric stiffness cuts

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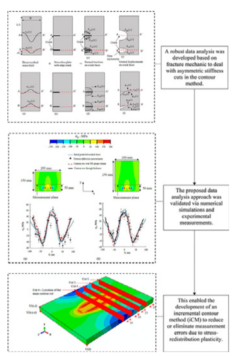
HIGHLIGHTS

- A new data analysis based on fracture mechanic was developed to deal with asymmetric stiffness cuts in the contour method.
- The data analysis to deal with asymmetric stiffness in the contour method was validated numerically and experimentally.
- An incremental contour method, leveraging the new capability, was developed to mitigate cutting-induced plasticity errors.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 August 2020
Received in revised form 15 October 2020
Accepted 24 October 2020
Available online 28 October 2020

Keywords:
Residual
Stress
Measurement
Asymmetric
Multi-cut
Plasticity
Superposition

ABSTRACT

An incremental Contour Method (iCM) of residual stress measurement is proposed where residual stresses in the body of interest are sequentially reduced by successive contour cuts and the risk of stress re-distribution plasticity is mitigated or eliminated. The cutting-induced plasticity is known to cause significant inaccuracies when trying to measure the near-yield residual stresses using a conventional single cut contour method. The iCM procedure implements a new displacement data processing approach for the general case of sectioning at an arbitrary plane where the cut parts do not possess mirror-symmetric elastic stiffness. The basis for the new asymmetric stiffness data analysis approach is presented and the accuracy of the new method demonstrated using both numerical and experimental case studies.

1. Introduction

Residual stresses introduced by manufacturing processes can combine with operational stresses and result in unexpected overload or premature failure of components. Alternatively, if residual stresses are engineered at the design stage they can lead to improved performance and enhanced product lifetime. In the former case, the distribution and magnitude of residual stress needs to be well characterised and allowed for in assessments supporting the safety operation and life extension of critical infrastructure. Whereas in the latter case, detailed knowledge is required to manipulate the residual stress field through careful design, controlled manufacture processes and lifetime management.

The contour method of residual stress measurement was invented at the turn of the century by Prime [1] and is being increasingly applied to

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https://doi.org/10.1016/j.matdes.2020.109268

map stresses in complex components. It is a destructive strain relief technique based on a variation of Bueckner's principle of elastic superposition [2]. The standard contour method involves: (i) sectioning a body into two mirror-symmetric halves along a plane of interest using wire electro-discharge machining (EDM), (ii) measuring the out-of-plane displacement of the created cut surfaces associated with the release of residual stress, (iii) processing the measured displacements to remove the effect of shear stress, any artefacts introduced by the wire EDM cutting process, and to smooth the scatter in the data, and (iv) applying the displacement "contour" as a surface boundary condition to a Finite Element (FE) model of one of the cut parts and conducting an elastic stress analysis to back-calculate the original (pre-cut) residual stress acting normal to the cut plane [3,4]. An introduction to the method and measurement guidelines can be found in [5,6] respectively.

An outstanding advantage of the contour method, compared with other strain relief techniques, is that it can provide a cross-sectional map of bulk residual stress using equipment available in many workshops. Although only one component of the stress tensor perpendicular to the cut surface is measured, the contour method can be extended to measure other stress components by combining with other techniques [7] or using multiple cuts [8].

Like any other technique, the validity and accuracy of the contour method is bounded by its assumptions and practical considerations [5]. In particular, stress errors arising from plasticity associated with stress re-distribution during cutting are important but difficult to manage [4]. The contour method assumes that stress re-distribution during cutting is linear elastic. However, cutting introduces a concentration of stress ahead of the cut tip which can be sufficient to cause local yielding and this directly influences the out-of-plane displacement profiles of the created cut surfaces resulting in errors in the back-calculated residual stress [9]. Recent work [10] has experimentally demonstrated how different cutting path configurations can be employed to minimise the amount of cutting induced plasticity and its effect on the accuracy of stresses determined by the contour method. But this approach is a costly and time-consuming process. An attractive alternative is to simulate the contour method cutting technique [11] where not only can the level of cutting induced plasticity be captured using numerical analysis, but process optimisation can be carried out to eliminate the costly battery of tests that would otherwise be required.

This paper sets out a novel approach for eliminating (or reducing) plasticity-induced error in residual stress measurement using the Contour Method. The idea is to repeatedly reduce the size of component, and magnitude of residual stress remaining in it, using successive contour cuts such that near zero plasticity occurs during any of the cuts. This proposed 'incremental Contour Method' (iCM) relies on the principle of superposition where out-of-plane displacements obtained by the standard contour method from the first cut are applied as a boundary condition to that cut face when determining residual stresses at the second cut face and so forth for subsequent cuts. Pagliaro et al. [8] first introduced the concept of using a second contour cut to determine residual stresses elsewhere in a body, but noted the approach assumes that the influence of (unknown) shear stresses at the first cut face on the normal stress distribution determined at the second cut face is negligible.

A further solid mechanics consideration for the proposed iCM, where a component may be "bread-sliced" several times, is that the relative elastic stiffness of the cut parts will be very different. In contrast the standard contour stress measurement method assumes that a body is cut into two parts having mirror-symmetric elastic stiffness. Whilst for some practical applications mirror-symmetry is a reasonable assumption, for others it can give rise to stress measurement errors that have received little attention in published literature [12]. Practical implementation of the iCM is not trivial because the plane and location of each cut must be chosen to avoid cutting plasticity, whilst ensuring that the relaxed residual stresses in the remaining part are sufficiently low for the next cut. And the more cuts that are performed, the greater the chance of introducing wire EDM cutting errors and risk of propagating error.

In this paper, we address the generic problem of dealing with contour cut parts having asymmetric stiffness (which is of potential relevance to many contour measurements of complex geometry components). A new data analysis approach is proposed and validated via numerical simulations of the contour measurement method and by experimental data including contour and neutron diffraction measurements on carefully designed benchmark steel specimens. Secondly, we demonstrate the efficacy of the proposed iCM approach in mitigating plasticity induced errors, compared with the standard contour method, via numerical simulation of an international residual stress round-robin benchmark specimen.

2. New data analysis approach for treatment of asymmetric stiffness

The contour method of residual stress measurement is based on the principle of elastic superposition that is best explained by reference to Bueckner's work on stress fields for structures having a crack or blunt notch [2,13]. His seminal lemma was that any crack or notch stress field problem can be reduced to one where the external load appears in the form of tractions distributed over the faces of the crack.

Consider a rectangular thin plate of length L and width W that contains an arbitrary residual stress field and is completely unrestrained at its boundaries. The distributions of direct residual stress, $\sigma_y(x)$, and shear stress, $\sigma_{xy}(x)$, along section AA' at mid-length of the plate and at an arbitrary located section BB' are indicated in Fig. 1a. If a crack is introduced into the plate (Fig. 1b) the resultant stress field can be defined by a new stress system in the form of tractions distributed over the crack faces that cancel the residual stresses in the plate acting on the crack faces. Both mid-length and offset crack cases are illustrated for normal tractions in Fig. 1c and for shear tractions in Fig. 1d. The normal and shear tractions applied to opposite crack faces are equal in magnitude and opposite in sense for both the mid-length and offset cracks: $F_{1A}(x) = -F_{2A}(x)$, $F_{1B}(x) = -F_{2B}(x)$ and $S_{1A}(x) = -S_{2A}(x)$ and $S_{1B}(x) = -S_{2B}(x)$.

The crack face displacements associated with the applied normal tractions are illustrated in Fig. 1e and the applied shear tractions in Fig. 1f. For the mid-length crack case, the elastic stiffness of the plate is mirror-symmetric about the crack line such that the applied normal tractions will give corresponding normal displacements $\delta_{1A}(x) = -\delta_{2A}(x)$ and the applied shear tractions will give corresponding shear displacements $\mu_{1A}(x) = -\mu_{2A}(x)$ and contribute to the normal displacement $g_{1A}(x) = g_{2A}(x)$. But for the offset crack, the elastic stiffness of the plate is asymmetric about the crack line. In this case the applied normal tractions will give asymmetric normal displacements $\delta_{1B}(x) \neq -\delta_{2B}(x)$ and the applied shear tractions will give asymmetric shear displacements $\mu_{1B}(x) \neq -\mu_{2B}(x)$ and contribute to the normal displacements $g_{1B}(x) \neq g_{2B}(x)$.

2.1. Standard contour method (symmetric stiffness)

The fracture mechanics case for a crack at mid-length section AA' of the plate illustrates stress/displacement superposition for a contour method measurement where the cut parts have symmetric elastic stiffness. For this case the measured out-of-plane displacement profile from one side is reversed and the displacement data from both sides averaged to reduce scatter and eliminate the shear stress induced out-of-plane displacements, because $g_{1A}(x) = g_{2A}(x)$. The in-plane shear displacements $\mu_{1A}(x) = -\mu_{2A}(x)$ along the crack faces cannot be readily measured and are generally ignored [5]. The averaged out-of-plane displacement is then applied to an FE elastic model of one of the cut parts to back-calculate the normal stresses.

2.2. New approach for asymmetric stiffness contour method

The fracture mechanics case for the offset crack at section BB' of the plate can be used to explain the problems of using measured out-of-

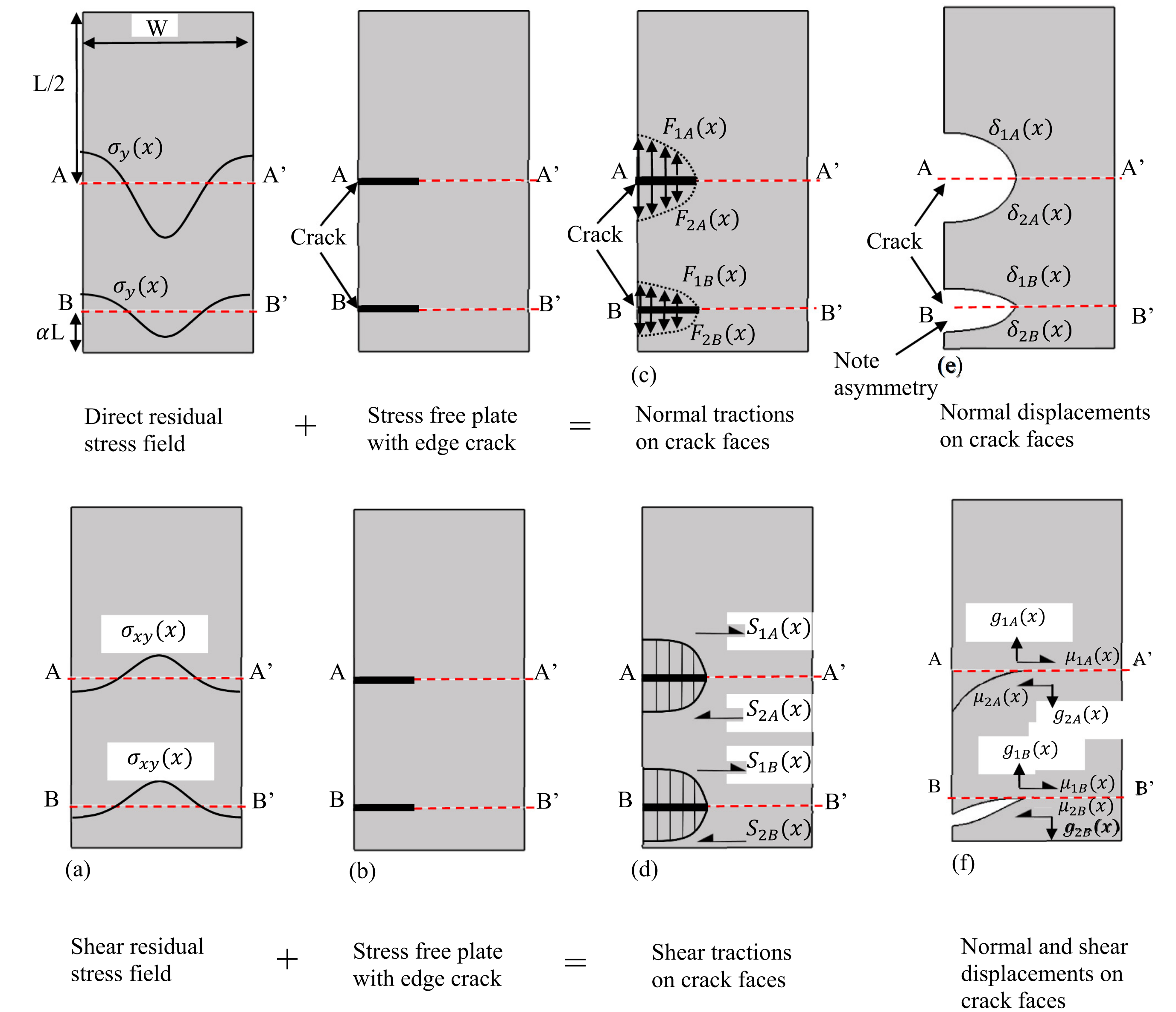

Fig. 1. Explaining elastic superposition in the Contour Method using the fracture mechanics lemma of Bueckner [2]: (a) rectilinear thin plate containing an arbitrary residual stress field with unrestrained boundaries, (b) the same plate, stress-free, with edge cracks located at mid-length section AA' and at an arbitrary section BB', (c) the distribution of tractions **F(x)** normal to the crack faces that cancel the distribution $\boldsymbol{\sigma_y}(\mathbf{x})$ of residual stress along the crack faces, (d) the same as (c) for shear tractions **S(x)**, (e) crack opening displacements arising from direct tractions **F(x)**, and (f) crack opening and shear displacements arising from shear tractions **S(x)**.

plane displacement data for asymmetric stiffness cut parts to determine the stress distribution at the cut face. Tractions applied normal to the crack faces, $F_{1B}(x) = -F_{2B}(x)$, will result in asymmetric displacements, $\delta_{1B}(x) \neq -\delta_{2B}(x)$ and shear tractions applied to the crack faces, $S_{1B}(x) = -S_{2B}(x)$, will contribute to normal displacements $g_{1B}(x) \neq g_{2B}(x)$. These out-of-plane displacement data can be processed (averaged) in the same manner as for the standard contour method, but this procedure will not eliminate the shear stress induced out-of-plane displacements because $g_{1A}(x) \neq g_{2A}(x)$. Moreover, application of such an averaged out-of-plane displacement boundary condition to an FE model of each cut side will give a different stress measurement solution, neither of which is correct.

The problem can be solved by implementing the measured out-of-plane displacement for side 1 in an elastic stress back-calculation using the correct stiffness for side 1 to give an estimate of the original crack face normal stress profile. But this estimate will include stress error associated with out-of-plane displacements $g_{1B}(x)$ included in the measurement data that have been introduced by shear tractions, $S_{1B}(x)$. Likewise, implementing the measured out-of-plane displacement of side 2, in a corresponding elastic stress back-calculation for side 2, gives a second estimate of the original crack face normal stress profile that also includes the stress error associated with out-of-plane displacements $g_{2B}(x)$ included in the measurement data that have been introduced by shear tractions $-S_{2B}(x)$. But since $S_{1B}(x) = -S_{2B}(x)$, the normal stress estimates from sides 1 and 2 can be averaged to eliminate the shear stress errors. However, like the standard contour method, the new asymmetric stiffness data processing approach ignores shear displacements and tractions acting along the crack face.

In summary, the standard contour method can be applied to a component that is cut into halves (having mirror symmetric stiffness) and eliminates shear stress errors by inverting and averaging measurement displacement data prior to stress back-calculation. The new asymmetric contour method can be applied to components where the stiffnesses of the cut parts are unequal (in the direction normal to the cut), and eliminates shear stress errors by averaging back-calculated stresses from the two cut parts where side-specific displacement boundary conditions

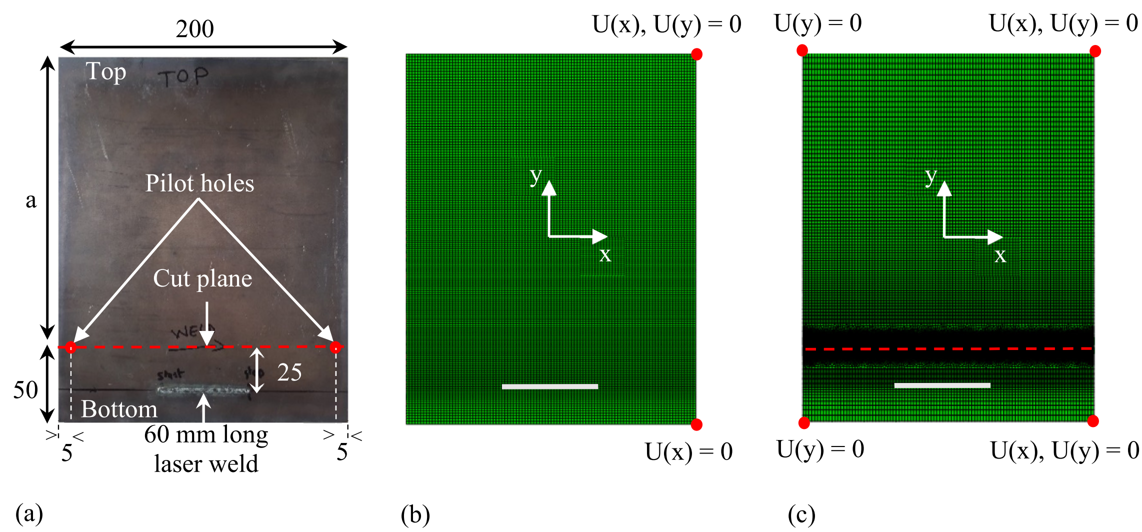

Fig. 2. (a) Photograph of test specimen design for asymmetric stiffness contour cuts showing a 60 mm long centred laser weld line at 25 mm from the bottom edge of the plate. The contour cut plane (marked in red) is located at 50 mm from the bottom edge of the plate. The dimension "a" marked on the plate can be changed to give different ratios of stiffness asymmetry of the cut parts. (b) The FE mesh and boundary conditions used to simulate the laser weld residual stress field. (c) The FE mesh and boundary conditions used for simulating the contour residual stress measurement for the specimen with a stiffness ratio of 4. Dimensions are in mm.

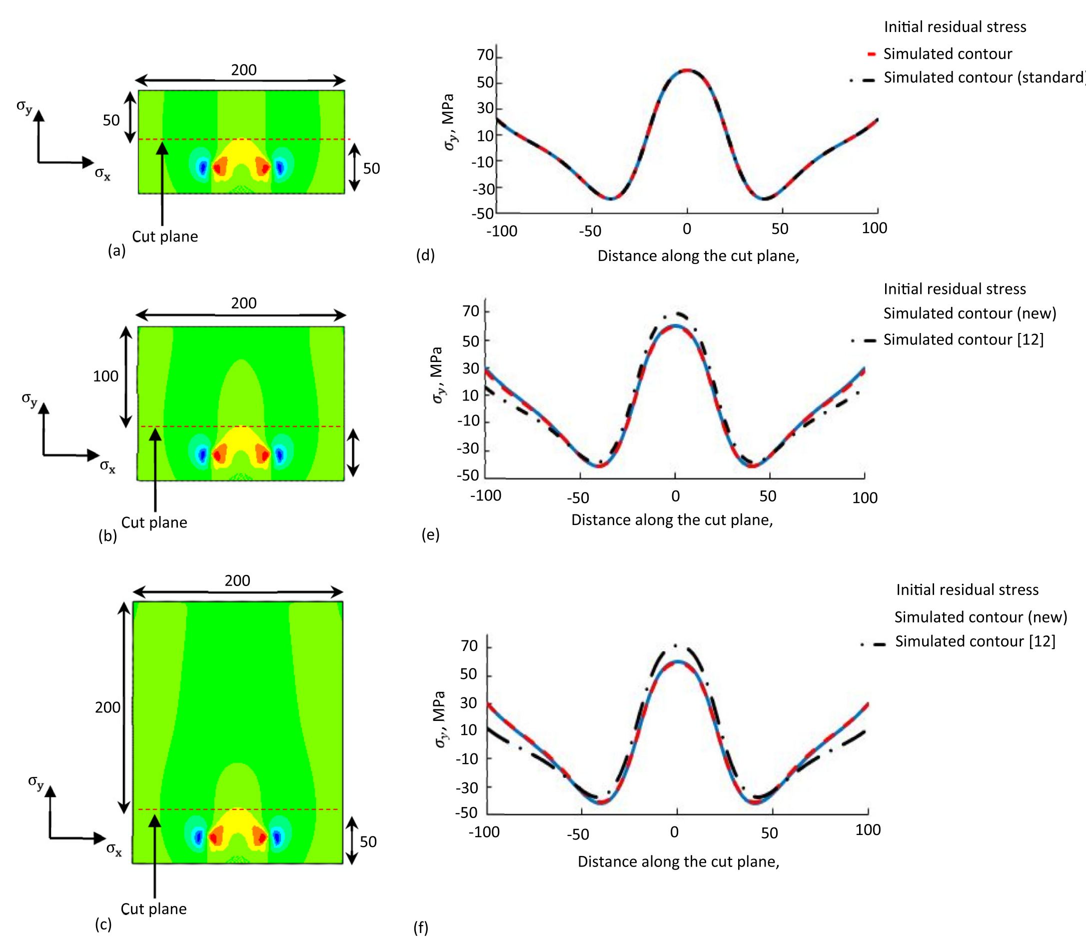

Fig. 3. Predicted weld residual stresses in test samples for (a) a symmetric stiffness contour cut, (b) an asymmetric stiffness (ratio of 2) contour cut, and (c) an asymmetric stiffness (ratio of 4) contour cut. The initial residual stress profiles at the cut line are compared with simulated contour method measurements for (d) the symmetric cut using the conventional and new data analysis approach and (e) and (f) asymmetric stiffness cuts using the new data analysis approach and alternative procedure reported in [12].

have been applied. The standard contour data processing approach is good for dealing with wire EDM cutting errors [4,6] and measurement scatter, but will give incorrect results for cuts where there is a significant mismatch between the elastic stiffnesses of the cut parts.

3. Experiment design for validating the asymmetric stiffness approach

The proposed data analysis approach for the asymmetric stiffness contour method is first explored by simulating the complete contour measurement process for a virtual test component containing a known residual stress field. This involves simulating the contour cut, collecting the out-of-plane displacements of the cut surfaces, applying them to respective FE models of the cut parts, averaging the reconstructed stresses from each side and then finally comparing the results with the initial stress field to demonstrate the accuracy of the approach. Secondly, real welded test components representing the virtual models are made and residual stresses measured non-destructively using neutron diffraction followed by destructive contour measurements on an asymmetric stiffness plane. The measured stresses determined from the asymmetric contour data processing method are then compared with the neutron diffraction measurements and predicted stresses from the virtual simulation.

3.1. Component design

A suitable test component was designed to ensure that: i) it contained an initial residual stress field large enough to be measured, and with some shear stress contribution, at an asymmetric stiffness plane by the contour method, ii) that the geometry could be reconfigured to study the effect of different levels of stiffness asymmetry, and iii) that the redistribution of residual stress during a contour cut at the asymmetric stiffness plane would be elastic.

The initial idea for the test component design was inspired by the PhD work of Traoré [9]. The dimensions and layout of the component required to meet the above requirements were selected by examining a number of design options for which the initial state of residual stress was predicted and the entire contour method measurement process simulated.

The final test component design is shown in Fig. 2. It comprises a rectangular steel plate of width 200 mm and length (50 + a) mm with a 60 mm long autogenous laser weld introduced parallel to and at 25 mm from one edge of the plate. The asymmetric stiffness contour cut plane lies parallel to the weld line and at 25 mm on the other side of the weld centre-line. The length of the plate, a, is variable (see Fig. 2a) allowing different asymmetric stiffness ratios to be studied.

3.2. Initial residual stress field

A residual stress field was introduced into the virtual test specimens by simulating a high energy autogenous (no added filler material) laser welding process using the ABAQUS FE package [14]. A two dimensional model with 8-node quadratic heat transfer quadrilateral elements (DC2D8) was used with a global mesh size of 2 mm and finer elements having a size of 1 mm in the weld and surrounding areas. An initial temperature of 1300 °C was applied to nodes in the weld region representing

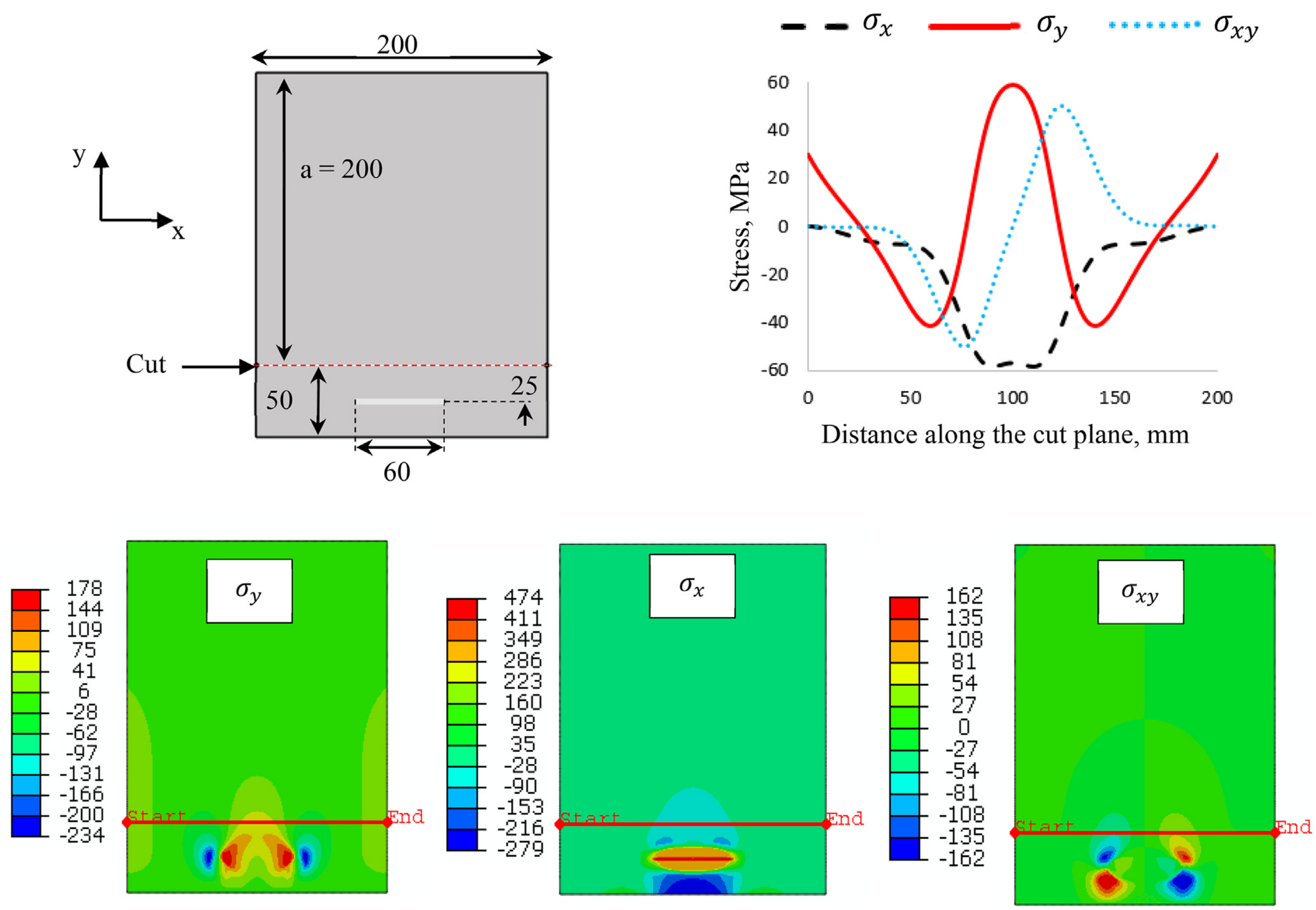

Fig. 4. The test plate design for an asymmetric stiffness contour cut (ratio of 4) showing predicted maps of transverse stress (σ_y), longitudinal stress (σ_x) and shear stress (σ_{xy}) line profiles at the cut location. Stress units are in MPa and dimensions in mm.

the melting point temperature of the material. Then cool-down to 20 °C was made in a transient thermal analysis with surface convective heat transfer losses of 7.9 W/m^2K for mild steel in air [15] and temperature dependent physical properties [16]. The nodal temperature history was then mapped onto a new FE model of the same design with reduced integration elements (CPS8R), temperature dependent mechanical properties [17] and displacement boundary conditions to stop rigid body motion (Fig. 2b) for the mechanical stress analysis. Three virtual test specimen geometries with a-dimensions equal to 25 mm, 50 mm and 200 mm that would give asymmetric stiffness ratios of mating contour cut parts of 1, 2 and 4 respectively were analysed. The predicted distributions of stress, σ_y, acting transverse to the welding direction are shown in Fig. 3.

3.3. Contour method measurement simulation

Simulation of a contour method measurement was carried out using a new FE model with a refined mesh (0.3 mm size) along the contour cut line. First the initial residual stress field and plastic strain were mapped onto a new model. Then the contour cutting process was simulated by sequentially removing 0.3 mm wide element sets along the cutting path in an elastic stress analysis. This width of cut represents a typical wire EDM cut using a 200 or 250 μm diameter wire, although the actual cut width modelled has an insignificant effect on contour method simulation [9].

To prevent rigid body motion, displacements were constrained in both the x and y-directions on the right corners of the plate and in the y-direction of the left corners (see Fig. 2c).

The predicted y-displacements normal to the cut line of each cut part were collected and processed using the new data analysis procedure described earlier; that is the displacement profile for each part was applied as a surface boundary condition to a new FE model of the corresponding cut part and elastic stress analysis back-calculations conducted, following which the resulting direct stresses at the cut line from the two parts were averaged.

The distributions of residual stress along the cut lines for the 3 case studies, as determined by simulated contour measurements using the new procedure, are compared with the initial weld residual stress profiles in Fig. 3. For the symmetric stiffness case (Fig. 3d), the simulated contour stress profiles based on the standard and new data analysis approaches perfectly match the initial weld residual stress profile. The simulated contour stress distributions for the asymmetric stiffness cases based on the new data analysis approach are also in excellent agreement with the initial weld residual stress profiles (see Fig. 3e and Fig. 3f), despite the presence of a high level of shear stresses along

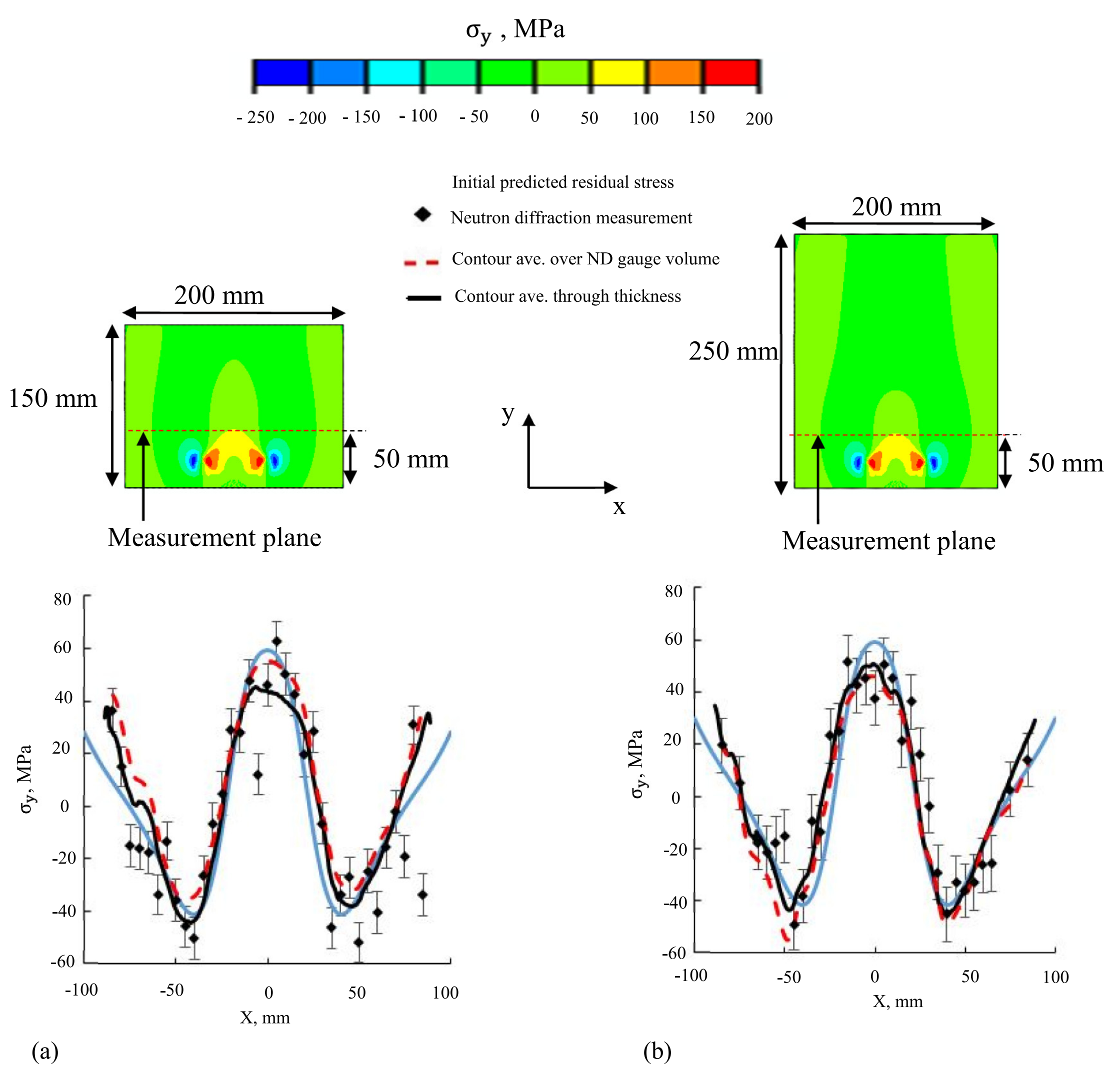

Fig. 5. Neutron diffraction residual stresses, along a line profile at mid-thickness of the welded samples, are compared with results from FE predictions and contour method measurements for the sample with (a) cut parts having stiffness ratio of 2 and (b) cut parts having stiffness ratio of 4. To compare the contour results with neutron diffraction (ND) measurements the contour results are averaged over neutron diffraction gauge volume. Likewise, for a fair comparison between the contour and FE prediction results the contour measurements are averaged through the thickness.

the cut line (Fig. 4). Note that the test components for asymmetric contour cut studies were deliberately designed to produce a significant level of shear stress along the contour cut plane. This was to demonstrate that the proposed approach correctly eliminates shear stress errors.

An alternative data processing approach for asymmetric stiffness contour cuts has been suggested in [12] where the out-of-plane displacements of the cut parts are averaged (as per the standard method), then this profile is applied to a FE model of each of the cut parts to determine part related stresses, which are then averaged to give the resulting pre-cut profile. The rationale for this approach is not clear and it gives the wrong answer, see Fig. 3e and Fig. 3f.

3.4. Component manufacture

Test components with cut parts' stiffness ratios of 2 and 4, as shown in Fig. 3b and Fig. 3c, were manufactured from 200 mm wide, 6.5 mm thick bright steel plate (Fig. 2a) designated in British Standard BS 970:1991 as 080A15. One of the plates was 150 mm long and the other was 250 mm long. After machining, the plates were stress relief heat treated at 600 °c for 10 h and air cooled. A 3 kW CO_2 fibre laser source (type IPG YLR-8000 CW) with a 1 mm diameter welding spot was used for introducing a fully penetrating autogenous weld 60 mm long in each plate. The keyhole [18] welding mode was used to promote deep penetration whilst minimising the width of the heat affected zone.

3.5. Neutron diffraction stress measurement

Neutron diffraction residual stress measurements along the proposed contour cut planes of interest in both plates were carried out using the ENGIN-X instrument at the ISIS Neutron and Muon Source (UK). Over 30 points at mid-thickness of each plate were measured using a nominal gauge volume of $2 \times 2 \times 2$ mm^3 in three orthogonal directions x, y and z. Stress-free lattice parameter measurements were

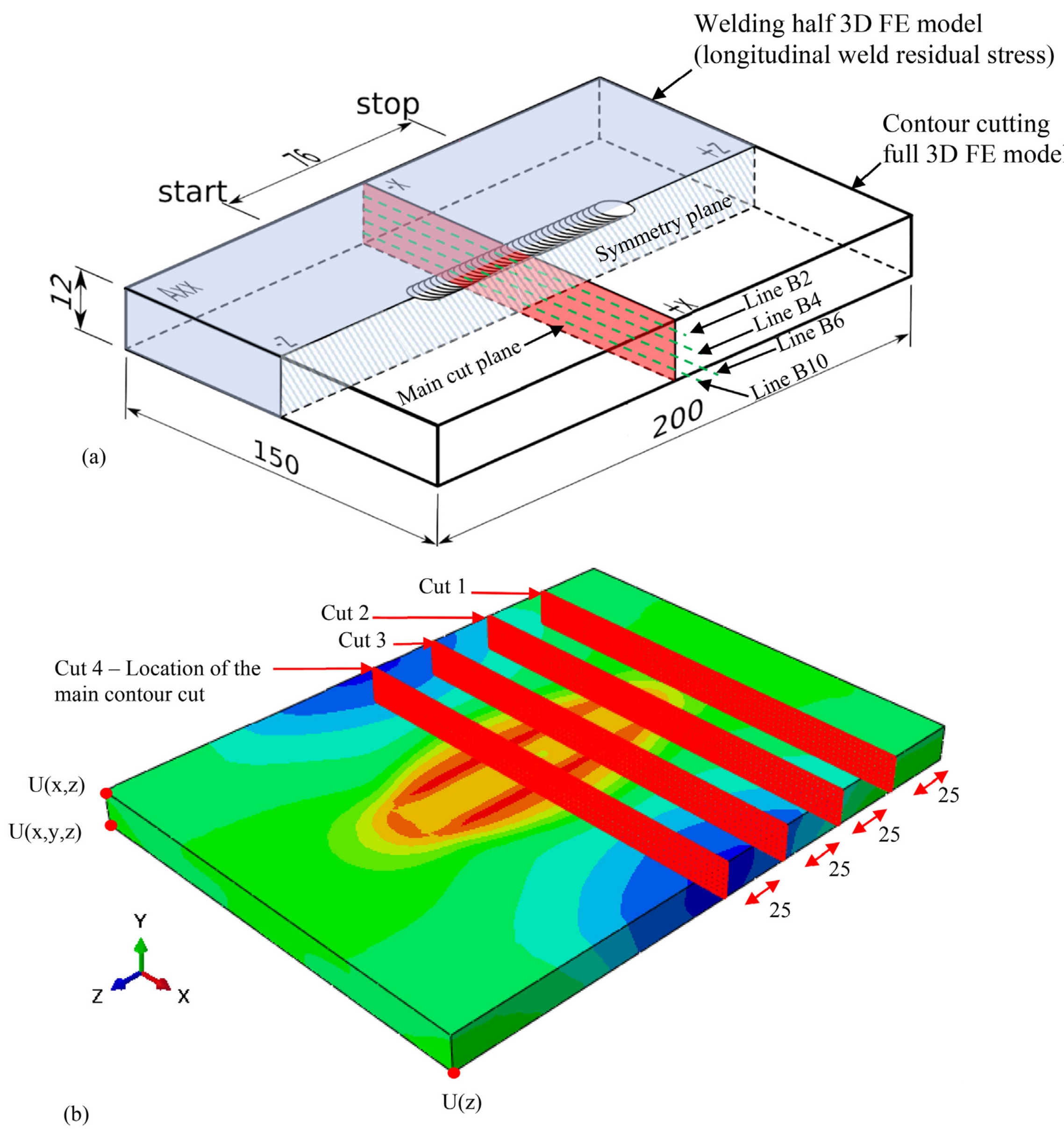

Fig. 6. (a) Schematic of the NeT TG6 benchmark specimen, showing the weld start/stop, main cut plane and B2, B4, B6 and B10 line locations. (b) 3D FE prediction of weld residual stresses for the benchmark specimen showing the location of contour cuts for the incremental contour method. X = transverse direction; Y = normal direction; Z = longitudinal direction. A set of pin constraints to prevent rigid body rotation was applied to the model during the weld simulation (shown here by red dots).

made at the extreme ends of the plates (i.e. remote from the influence of the weld) at 3 locations and the results averaged to give directional dependent values. The diffraction data analysis was performed using a full-spectrum Rietveld refinement [19] with the General Structure Analysis System [20].

The stresses measured by neutron diffraction are compared with the FE predictions described earlier in Fig. 5. In both cases the measured stresses closely follow the "W" shaped predicted profiles. The scatter in the measured data (±10 MPa) is judged to be exceptionally good for this application where the peak to valley stress range of interest is about 100 MPa.

3.6. Contour method stress measurements

Experimental contour method measurements were conducted on the two manufactured test plates after neutron diffraction measurements. The components were prepared by bonding 3 mm thick sacrificial layers to the top and bottom surfaces of the plates at the cut lines to shield them against wire entry and wire exit cutting artefacts [6] and drilling 1.5 mm diameter pilot holes, 5 mm from the edges of the plate, at the start and finish of the proposed cutting path, as shown in Fig. 2a. The main cut joining the pilot holes was performed with the intact ligament at the start end providing cut-opening restraint. Then the ligaments were severed. This 'embedded cutting strategy' provides self-restraint during cutting that reduces the risk of plastic deformation caused by stress re-distribution [10,11]. In addition, the samples were 'finger-clamped' to the EDM bed to prevent rigid body motion during cutting.

Prior to cutting, the test plates and fixturing were left in the wire EDM tank of deionised water to reach thermal equilibrium conditions. The contour cuts were conducted using an Agie Charmilles CUT 1000 wire EDM machine with a 50 μm diameter tungsten coated wire at a cutting speed of 1 mm per minute. This smaller than usual wire size was selected in order to achieve a lower surface roughness and thereby reduce surface displacement noise and improve the stress measurement resolution.

The displacements of the cut surfaces were measured in a metrology laboratory using a Zeiss Eclipse coordinate measuring machine, fitted with a Micro-Epsilon triangulating laser probe and a 4 mm diameter ruby-tipped Renishaw PH10M touch trigger probe. The latter was used to measure the perimeter of the cut faces at 1 mm pitch. The out-of-plane deformation of the cut surfaces was measured using the triangulating laser probe on a 25 μm × 25 μm grid.

The new data analysis approach was used for both test components, as both feature asymmetric stiffness cut parts. The displacements of each cut part were smoothed using quadratic bivariate splines following the optimisation approach outlined in [3]. The smoothed data were then inverted and applied as boundary conditions to a 3D FE model of the corresponding cut part. Additional boundary conditions were applied to prevent rigid body motion. Following elastic stress analysis for each part, the normal components of stress at the cut surfaces of the pair of parts were averaged giving the required contour stress measurement result. A line profile at mid-thickness of each plate determined from this contour measurement approach is presented in Fig. 5.

In order to compare the contour results with neutron measurements on a fair basis, the contour stresses are averaged over the neutron diffraction gauge area. Likewise, for a fair comparison between the contour and 2D FE prediction results the contour measurements are averaged through the thickness. It is evident from Fig. 5 that the stresses measured by the asymmetric stiffness data processing approach are in excellent agreement with both the neutron diffraction measurements and 2D FE predictions of the initial residual stress state.

A disadvantage of the new data processing approach is that the accuracy of the measured results can be compromised by any anti-symmetric feature of the cut, scatter in measured surface deformation data and wire EDM cutting artefacts. These effects are either eliminated or mitigated to some extent by the standard data processing approach where the out-of-plane displacement data from the two cut surfaces are averaged. Therefore, when implementing the asymmetric approach extra care should be taken in the wire EDM cutting step of the technique in order to produce high quality cut surfaces. In the work presented above, a 50 μm wire diameter was used producing cut surfaces with a surface roughness R_a of 0.98 μm.

4. The incremental contour method (iCM)

Having found a robust method for dealing with asymmetric stiffness contour cuts, we can now investigate the incremental Contour Method (iCM) as a means of eliminating (or at least reducing) plasticity-induced error in residual stress measurement using the Contour Method. The concept is to repeatedly reduce the size of component, and magnitude of residual stress remaining in it, using successive contour cuts such that near zero stress re-distribution plasticity occurs during any of the cuts. Relaxed stresses at the location of the second cut face owing to the initial contour cut are determined and superimposed to the remaining stresses at the second contour cut plane following the method of Pagliaro et al. [8], and so forth for a series of subsequent cuts until stresses at the final cross-section of interest have been determined. The method requires a judicious choice of location for each cut to avoid cutting plasticity, whilst ensuring that the relaxed residual stresses in the remaining part are sufficiently low for the next cut. Ideally some priori knowledge of the residual stress field present is required. If significant shear stresses are present on one or more of the cut planes, then this may introduce stress errors. And the more cuts that are performed, the greater the chance of introducing wire EDM cutting errors. Given that several cuts may have to be performed there is also a risk of propagating error.

Nonetheless a numerical approach is applied here to explore the feasibility of the iCM for measuring residual stress and determine its efficacy in mitigating plasticity-induced stress errors. We will examine the NeT TG6 Welded Benchmark Specimen (Fig. 6) that contains high magnitude residual stresses and for which application of the standard contour stress measurement technique is known to give significant stress errors owing to cutting plasticity. The proposed iCM approach for this test specimen involves conducting the following steps:

(i) Select the plane of the first contour cut where the maximum level of residual stress normal to the plane is estimated to be lower than a target threshold; for example 50% of the yield strength of the material (see Fig. 6).

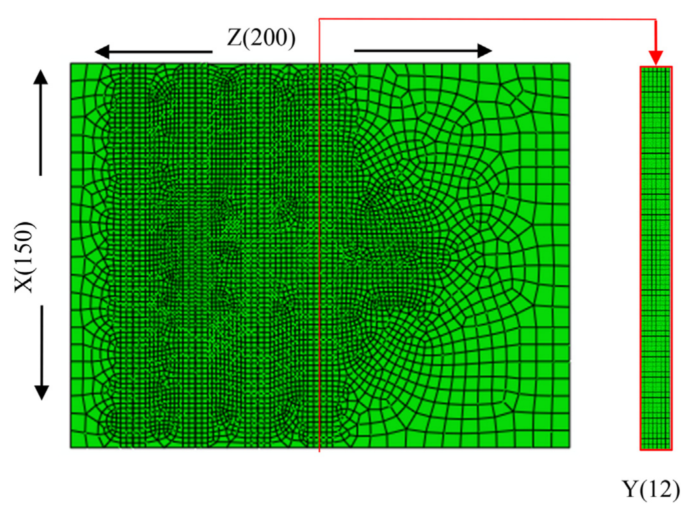

Fig. 7. Design of 3D finite element model of the TG6 benchmark specimen for contour residual stress measurement simulations. Dimensions are in mm.

(ii) Estimate the extent of stress relaxation that would occur in the remaining larger cut part as a result of the cutting process.
(iii) Select the plane of the next contour cut where the maximum level of remaining residual stress is estimated to be lower than the target threshold.
(iv) Repeat steps (ii) and (iii) until the final contour cut is located on the plane of interest.
(v) Use the asymmetric stiffness contour cut data processing method for all cuts when back-calculating the residual stresses.
(vi) Apply the multiple-cut approach to take into account the stress relaxation caused by each cut on the location of the following cut and on the final plane of interest.

The above iCM approach is applied to the TG6 Weldment by simulating the contour measurement steps for a FE prediction of the initial weld residual stress field. The simulated iCM measured stresses are compared with the initial weld residual stress field predicted by FE analysis and also simulated measured stresses based on application of the standard contour method.

4.1. TG6 welded benchmark test specimen

The European Network on Neutron Techniques Standardisation for Structural Integrity (NeT) is working on the development of state-of-the-art experimental and numerical techniques for the reliable characterisation of residual stress in structural welds. The experimental methods used include neutron diffraction, synchrotron diffraction, laboratory X-ray diffraction, deep hole drilling and the contour method. Each benchmark problem examined by the network is tackled by creating a dedicated Task Group (TG) comprising researchers from universities, central scientific facilities and industry, which undertakes measurement and modelling round robin studies and interprets the results. Task Group 6 (TG6) was formed to study residual stresses in a benchmark problem where three superimposed weld beads are laid in a finite length slot in an Alloy 600 nickel alloy plate (see Fig. 6). Quantifying the residual stress field in the longitudinal direction across the transverse plane at mid-length of the specimen is of particular interest for application of the iCM approach. In particular, we shall be examining stresses along measurement lines B2, B4, B6, and B10 that are positioned 2 mm, 4 mm, 6 mm, and 10 mm respectively below the top surface of the sample (see Fig. 6).

4.2. Weld residual stress model

Weld residual stresses in the NeT TG6 benchmark specimen have been predicted using well-established sequentially coupled thermo-mechanical FE analysis, whereby the numerical solution from the thermal analysis is used as an input in the mechanical analysis [21] . A 3D half-model comprising 179,077 hexahedral quadratic elements took advantage of the specimen and process symmetry about the weld centreline (Fig. 6), thus significantly reducing computational time. The thermal analysis used quadratic heat transfer elements (DC3D20), while mechanical analysis use reduced-integration quadratic stress

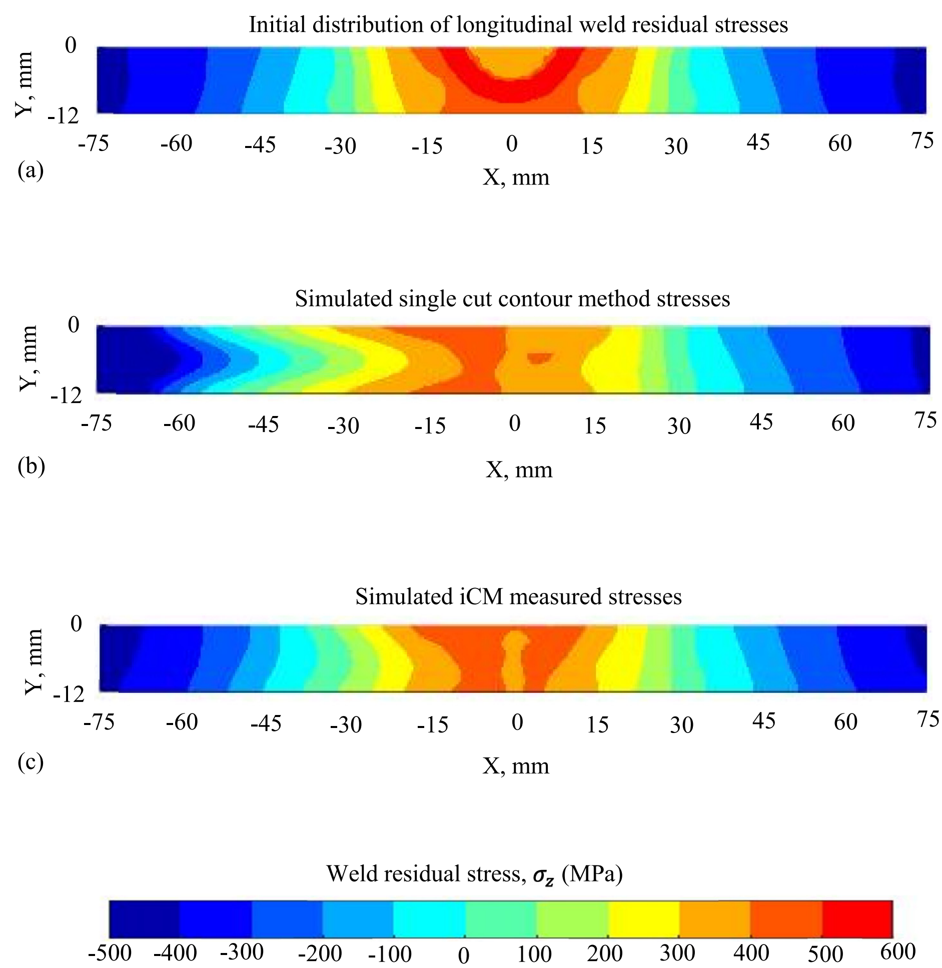

Fig. 8. 2D maps of the longitudinal residual stress acting across a plane located at mid-length of the TG6 benchmark specimen: (a) predicted initial weld residual stress field, (b) simulated standard single cut contour measurement, and (c) simulated incremental contour method (iCM) measurement.

elements (C3D20R). A dedicated welding heat-source modelling tool (FEAT-WMT) [22] was used to calibrate moving heat source. Calibration was performed using cross-weld fusion boundary information, as well as thermocouple data acquired during the welding [21]. Once the heat source was calibrated, the transient thermal solution was imported from FEAT-WMT to ABAQUS in the form of time- and spatially-resolved volumetric power density data (via the ABAQUS DFLUX subroutine). The solution of performed ABAQUS thermal analysis was then imported into ABAQUS mechanical analysis. This used the Lemaitre-Chaboche isotropic-kinematic plasticity model [23] to accurately capture the welding-induced cyclic hardening of both parent and weld metals during the welding process. In addition, the high-temperature annealing (i.e. the loss of accumulated isotropic plasticity at high temperatures) was controlled using a single-stage annealing in ABAQUS, where annealing temperature was set to 1050 °C. The solution of performed ABAQUS mechanical analysis was then validated by a direct comparison of predicted weld residual stresses with those measured using neutron diffraction [24].

4.3. Contour cutting model

Unlike the welding process, the contour cutting procedure is not symmetric across the weld centre-line and therefore, requires a full 3D model. Thus the results of the half-model welding solution had to be mirrored about the symmetry plane and mapped onto the full 3D model. The full tensor values of weld residual stress and plastic strain were then mapped from the weld residual stress model onto the new contour cutting model. Note that the welding-induced distortion was omitted from the analysis in order to simplify the cutting model geometry. The latter was achieved by running an additional mechanical analysis step after the weld simulation wherein the nodal displacements were not recorded, thus removing all welding-induced distortion information. It has been confirmed that this simplification has a negligible effect on the magnitude and distribution of predicted weld residual stress and plastic strain [11].

The number of incremental cuts and the selection of cut positions in the component depends on a judgemental assessment of several factors including the risk of plasticity associated with the expected stress distribution across each (incremental) cut face, minimising the number of cuts (to avoid error propagation) and ensuring that each slice is wide enough to be rigidly clamped. The first cut plane for the iCM simulation was pitched at 75 mm from the mid-length of the plate (see Fig. 6b) where the predicted stress magnitudes were much lower than the yield stress of the material, thereby reducing the risk of stress redistribution plasticity during cutting. The amount of stress relaxation in the remaining part predicted by the contour simulation (as a result of the first cut) was used to identify a candidate location of interest for the next cut, and so forth. A compromise was made between the number of cuts, amount of relaxed stress at the location of interest after each cut and the practical requirement for ensuring that the width of each

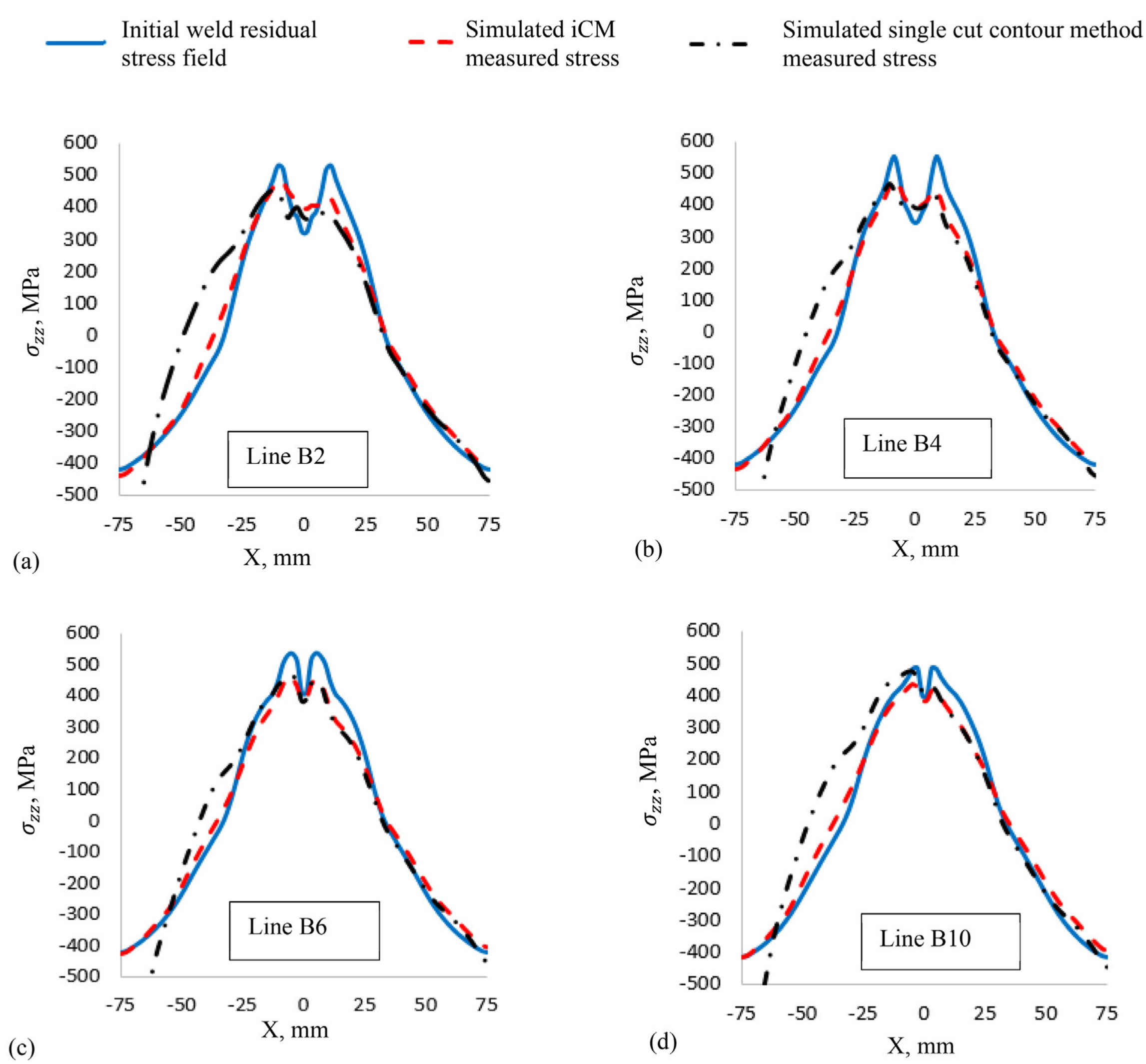

Fig. 9. Comparison of the initial and simulated contour method measurements of cross-weld residual stress profiles along lines B2, B4, B6 and B10.

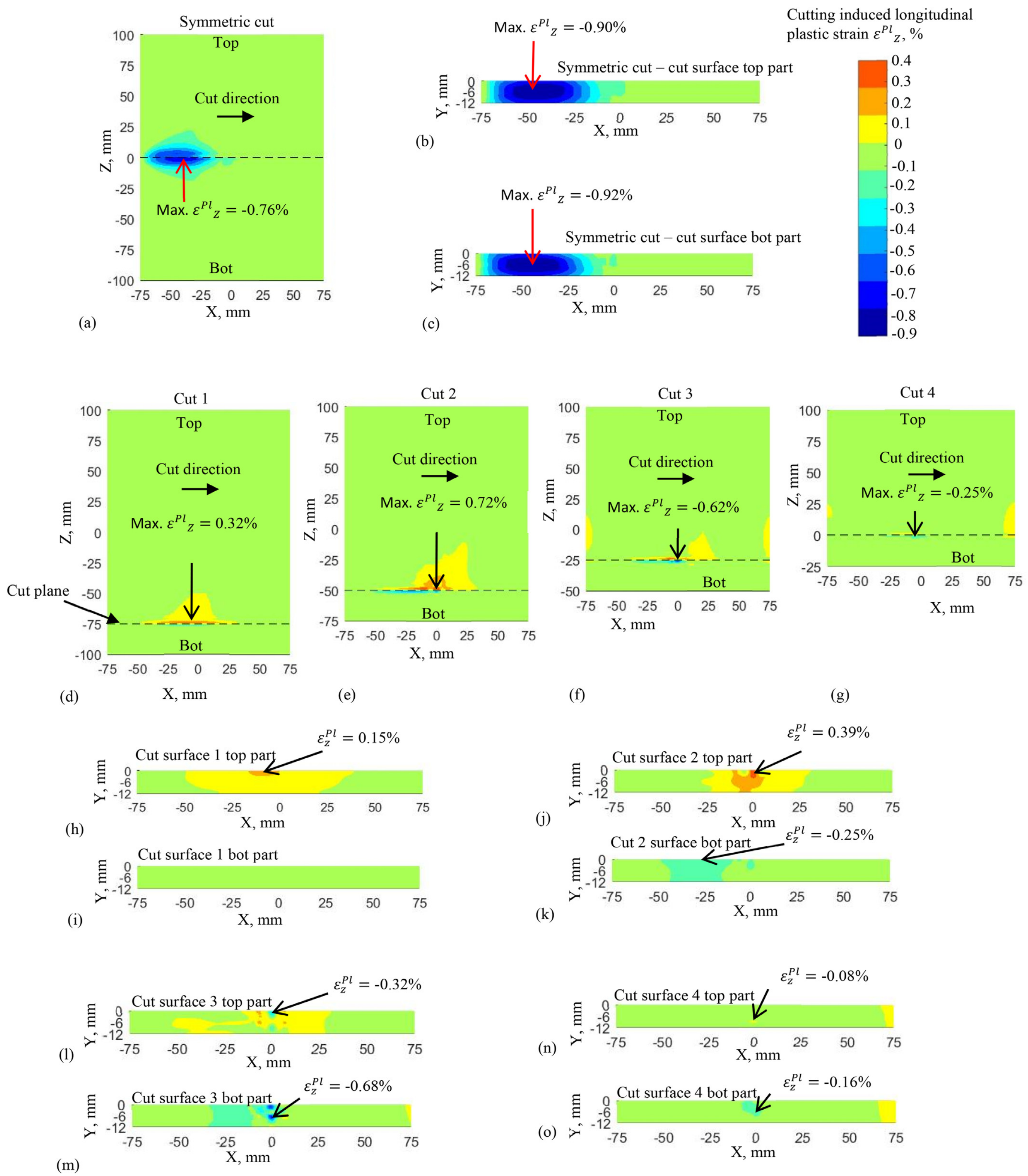

Fig. 10. Maps of predicted distributions of the longitudinal component of cutting induced plastic strain (a–c) for a standard single cut contour method measurement, and (d–o) for the iCM. (a) and (d) – (g) present the top view of the sample, and (b)–(c) and (h)–(o) present the cross-weld cut surfaces of the corresponding cut parts.

slice was sufficient for clamping in practice. A total of three asymmetric cuts were finally chosen prior to the 4th cut at the plane of interest (i.e. mid-length of the welded plate) as illustrated in Fig. 6 a–b.

The 3D FE model for the contour simulation differed from the weld simulation in several respects. In particular, the mesh was significantly refined in and near the contour cut regions (Fig. 7), but coarsened in the weld region and the weld bead geometry simplified (flattened) giving a total of 36,085 C3D8R elements. Each wire EDM cut was simulated by sequentially removing element sets (0.3 mm × 0.3 mm × 12 mm) along the cutting planes in an elastic-plastic analysis with rate independent material properties. The element removal rate was chosen to ensure FE analysis stability and had no physical relationship to the actual wire cutting speed. The same 3D FE mesh was also used to simulate a standard contour method measurement by implementing a single contour cut at mid-length of the plate.

The predicted out-of-plane displacement data for the standard contour method cut at mid-length were collected, averaged and applied as a boundary condition to a new 3D FE model of one of the cut parts in order to elastically back-calculate the original weld residual stresses. For the incremental contour method, out-of-plane displacement data for each sequential cut were processed using the new asymmetric stiffness and the multiple-cut superposition principle was applied following the approach outlined in [8].

Fig. 8a shows a map of the initial predicted distribution of longitudinal residual stress across the transverse plane at mid-length of the welded benchmark specimen. Fig. 8b and c present simulated measurements of the stress field from the standard single cut contour method and the iCM respectively. It is evident that the iCM measurement approach gives a closer prediction of the initial residual stress field than the conventional single cut case.

The success of the iCM approach can be confirmed by inspecting the detailed residual stress profiles along lines B2, B4, B6 and B10 shown in Fig. 9. Looking in more detail at the results, both contour approaches fail to capture the stress peaks adjacent to $x = 0$ mm and under-measure tensile stresses in the region between $x = 0$ and 37.5 mm. But the standard single cut contour measurement stresses have significant errors from $x = -75$ mm to $x = 0$ mm whereas the iCM gives an accurate measurement in this region.

The predicted stress re-distribution plasticity for each contour cut was evaluated by subtracting the initial welding-induced plastic strain in the longitudinal direction. The longitudinal plastic strain results for each cut are presented in Fig. 10. The results for the standard single contour cut (Fig. 10 a–c) illustrates how wide-spread plastic strain has been introduced over the first half of the cut through the entire thickness of the sample. Fig. 10 d–o demonstrates that some plasticity also occurred during all of the iCM contour cuts, but of lower magnitude and with isolated peaks (>0.2%) than for the standard single cut case; for example, for cut 1 and cut 4 the maximum longitudinal plastic strain was less than 0.16%. Thus the iCM approach has successfully reduced the level of stress re-distribution plasticity and delivered a more accurate contour stress measurement.

The accuracy of the simulated contour stress measurements was evaluated using a root mean square (RMS) approach:

RMS Error: $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(|WRS_{i,pc}|-|WRS_{i,bc}|\right)2}$.where $WRS_{i,pc}$ represents the initial (pre-cut) weld residual stress at a given nodal position i; and $WRS_{i,bc}$ represents simulated contour residual stress measurement at the corresponding nodal position i.

The RMS error between the initial weld longitudinal residual stresses and the simulated measurement was 118.5 MPa and 40.8 MPa for the standard single cut and iCM measurement methods respectively. This corresponds to normalised RMS errors (based on the total stress range) of 12.2% and 4.2%. This measure of error demonstrates again how the new iCM approach can be highly effective in reducing stress re-distribution plasticity and improving the accuracy of contour measurements.

4.4. General observations

It could be argued that the TG6 benchmark specimen is particularly suited to application of the iCM approach because the central embedded weld introduces a varying stress along and across the sample. But even in a full length butt welded plate, residual stresses acting in the longitudinal direction die will away to zero at the free end-faces of the plate and the characteristic decay distance can be used to select the position of the first and subsequent cuts. The iCM approach has been assessed using relatively thin welded plates (6.5 mm and 12 mm), but in principle the method can be applied to any thickness of test component that can be cut by wire EDM. Evidently the more cuts that are performed, the greater the chance of introducing wire EDM cutting errors and risk of propagating error. Overall, implementing an iCM approach requires careful planning, a priori information about the residual stress field, good quality wire EDM cuts and ideally an absence of shear stresses on the selected cut planes.

5. Conclusions

An incremental Contour Method (iCM) residual stress measurement procedure is proposed where residual stresses in the structure of interest are sequentially reduced by successive cuts and the risk of stress redistribution plasticity is mitigated or eliminated. It is shown that application of the iCM approach to the NeT TG6 weld benchmark specimen using a sequence of four cuts significantly reduces the measurement stress error compared with a conventional single cut. The iCM procedure relies on implementation of a new displacement data processing approach for the general case of sectioning at an arbitrary plane where the cut parts do not possess mirror-symmetry. The basis for the new asymmetric stiffness data analysis approach has been presented and the accuracy of the new method demonstrated by both numerical and experimental case studies.

Data availability

The processed data required to reproduce these findings are available to download from [https://data.mendeley.com/datasets/2xt62mc5tr/draft?a=3da99f0a-d8ac-4247-8398-b7a34acec28b].

Declaration of Competing Interest

None.

Acknowledgements

The authors are grateful for detailed discussions with Dr. Mike Prime of Los Alamos National Laboratory. Dr. Anas Achouri would like to acknowledge funding support from the Open University and Rolls-Royce for his PhD. Dr. Foroogh Hosseinzadeh is grateful for support from EPSRC Grant EP/M018849/1. The support from Dr. Supriyo Ganguly at University of Cranfield for laser welding benchmark test specimens is highly appreciated.

Residual stress measurements and weld simulations produced under the auspices of the NeT programme via Task Group 6 have significantly advanced best-practice guidelines for treatment of weld residual stress and post-weld plastic strain which has added considerable value to the present work.

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