



HAL
open science

A correction method for measuring residual stress of irregular cross-section weldments with the contour method

Zhe Cai, Jan Roman Hönnige, Matthew Roy

► **To cite this version:**

Zhe Cai, Jan Roman Hönnige, Matthew Roy. A correction method for measuring residual stress of irregular cross-section weldments with the contour method. ICRES 11 - The 11th International Conference of Residual Stresses, SF2M; IJL, Mar 2022, Nancy, France. hal-03998015

HAL Id: hal-03998015

<https://hal.science/hal-03998015v1>

Submitted on 20 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - ShareAlike 4.0 International License

A CORRECTION METHOD FOR MEASURING RESIDUAL STRESS OF IRREGULAR CROSS-SECTION WELDMENTS WITH THE CONTOUR METHOD

Zhe Cai^a, Jan Roman Hönnige^b, Matthew Roy^a,

^a*Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, M13 9PL, Manchester, United Kingdom*

^b*Premium AEROTEC GmbH, Riesweg 151-155, 26316, Varel, Germany*

ABSTRACT

Reliable evaluation of residual stress (RS) is essential in structural integrity assessment for critical components such as welded joints. Being able to provide a 2D cross-sectional stress map over a cutting plane, the contour method (CM) is often used for assessing butt-welds and other components with rectangular cross-sections. For components such as T-sections, sacrificial material is often employed to render a rectangular cutting path to prevent cutting artefacts. This is because artificial stresses can appear in back-calculated results when there are sudden changes in cutting length during wire electro discharge machining (WEDM). Sacrificial material can be used to compensate, but this may be impractical for large or irregular components, where a perfect match between sacrificial material and the original component cannot be easily achieved. We demonstrate a new technique for CM analysis employing a stress-free sample, realised on welded Ti-6Al-4V T-sections to evaluate cutting artefacts (CAs) and the proposed correction method. It will be shown that back calculated stress calculated based on stress-free samples can be considered as artificial stresses introduced during WEDM process. A correction on a conventional CM analysis has been achieved by subtracting these artificial stresses from original CM results. The total artificial stress introduced by cutting a variable cross-section component will be presented, along with a discussion on this effect on quantifying stresses at weld roots employing the CM. It has been found that this technique is capable of mitigating cutting artefacts, especially when applied to components with complicated profile where changes in cutting length exist.

Keywords: Contour Method; Residual Stress; Irregular components; WEDM; Cutting Artefacts

1. Introduction

The contour method has proven viable for nearly 20 years. Based on an elastic superposition principle, the CM can generate a stress map normal to a measurement surface with minimal resources [1]. The implementation is relatively easy compared to some diffraction methods, and it can provide much more information on stress distribution than conventional destructive techniques. It can be performed in any laboratory with access to WEDM and coordinate-measuring machine (CMM) facilities. The operating principle is to reconstruct the internal stress normal to a plane of interest with finite element analysis (FEA) tools using the measured out-of-plane displacement as boundary condition. This assumes that the out-of-plane stresses can

* Corresponding author. zhe.cai@manchester.ac.uk

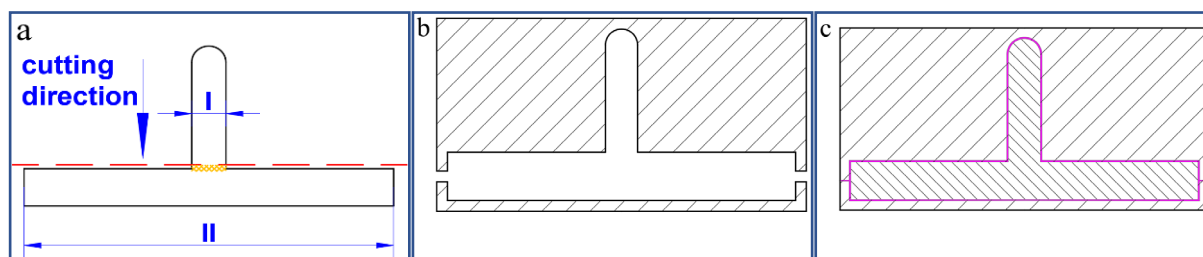


Fig. 1 (a) A non-rectangular specimen to be cut by WEDM, cutting length changes dramatically as the wire (red dashed line) moves from I to II; (b) sacrificial material; (c) assembly with conductive epoxy.

be elastically released by cutting process with no further stress introduced, which is usually achieved with WEDM. There are a range of previous studies regarding applying the CM to regular components such as rectangular [2] and tubular [3] weldments, with good agreement with other RS measurement techniques and FEA predictions.

Irregularities in cutting length will generate cutting artefacts (CAs) due to the characteristic of WEDM process. Here, the cutting length is defined as the total length of instantaneous interaction between the wire and workpiece. More energy is imparted to the workpiece when the cutting length increases from position I to II as marked with yellow mesh in Fig. 1a. WEDM control architecture is usually independent of the part which is being cut, and therefore transitions between thin and thicker cutting lengths can lead to being misinterpreted as out-of-plane displacement and create artefacts in back-calculated CM stresses.

The sacrificial material approach [4] has been proscribed to reduce CAs by compensating the profile changes with similar materials and conductive epoxy (Fig. 1b), rendering a continuous cutting length (Fig. 1c). Sacrificial material has also been applied at entry/exit position of contour cuts [5] to avoid entry/exit irregularity errors. However, this approach can be time-consuming, and the design/ manufacture of sacrificial parts can be challenging, with increasing effort required when the cross-section of the specimen is complicated.

There has been some discussion on cutting a thin layer off [6] (thin wafer strategy) next to the original cut plane, assuming such thin structure contains no stresses therefore to separate the effects of CAs from original stress profiles. This stress-free (SF) reference cut approach has yet to be demonstrated in practice. The thin wafer strategy was tested in this research, but it was found the deformation that resulted in the 'stress-free' sample generated more problems than it solved without further relief of out-of-plane stresses. Due to these findings, we present a method to produce CM results for irregular and inhomogeneous specimens by accounting for cutting introduced artefacts. A new routine to create a SF reference sample and separate CAs from a cut plane that can be easily implemented has been discussed and demonstrated by experiments.

2. Theory and assumptions

Diffraction measurements require a sample of SF material to acquire a datum for subsequent measurements [7] (i.e., crystallographic plane spacing d_0 in the absence of stress). Here we adopt the same principle to capture the effect on resolved stress due to variations in the cutting process as a datum. In this experiment, a comb-grid stress relaxing cutting configuration was examined, followed by a contour analysis on the SF sample which showed the artificial stresses caused by cutting through a changing cross-section only. These artificial stresses were then subtracted from previously calculated stress results to reduce the errors of CM analysis introduced by discrepancies in cut length.

3. Experiments

3.1. Specimen preparation

Two groups of specimens manufactured with different methods and materials were examined in this research. The first group contains two Ti-6Al-4V alloy specimens (A1 and A2) prepared with wire + arc additive manufacturing (AM) in same T-shaped configuration as shown in Fig. 2a. These two specimens have been described previously [8]. Specifically, a side-rolling process has applied on specimen A1, while A2 remained in the as-deposited state, therefore the level of residual stress in A1 and A2 are different. Another two specimens (B1 and B2) to test a sacrificial material approach were extracted from a 400mm long mild steel MIG weldment in a T-shape configuration similar to A1 and A2, as shown in Fig. 2b.

3.2. Residual stress analysis using contour method

An Agie-Charmilles FI440CCS WEDM machine with a 250 μm diameter brass wire was used for all cuts using slightly modified 'E2' finish cut parameters for subsequent contour analysis. A contour cut was applied on A1, A2 and B1 to separate each specimen into equal halves according to the direction shown in Fig. 1a, with the presence of CAs expected due to the varying cutting length during WEDM process. Sacrificial material was applied on B2 intended to provide a stress map without the presence of CAs, however this cut was not successful therefore the subsequent stress analysis is mainly based on A1 and A2. The failure of sacrificial material approach will be discussed in later sections. Rigid clamping was applied using a customised fixture during the cutting process which isolated each half of the workpiece throughout.

The surface profiles were measured with a laser profilometer ($\mu\text{Scan NanoFocus}$) with a resolution of 30 μm for both x and y direction. The data processing was carried out with code adapted from pyCM [9]. The measured displacements from two cut halves of specimen A1 were first averaged to remove the effect of shear stress. Then a bivariate spline surface was fitted to the averaged point cloud with a knot spacing of 1.5mm and 4mm in x and y direction respectively, and a spline order of 3 for both x and y directions. A 3-D mesh was generated from the 2-D profile with 148,242 nodes defining 33,500 C3D20 elements. Displacement boundary conditions on the front face of the mesh were imposed directly as defined by the fitted spline as well as to prevent rigid body movement as shown in Fig. 3. These rigid body boundary conditions were applied to restrict all movement in y-direction (DOF 2) on one corner of the baseplate and also in x & y-direction (DOF 1&2) on the other corner. Similar process was applied on specimen A2, the elastic material properties imposed throughout were a modulus of elasticity of 113.8 GPa and Poisson's ratio of 0.342. The results of the FEA generated by Abaqus for specimen A1 and A2 were post-processed to show out-of-plane stress components in contour plots as in Fig. 4. A scan of stresses along central line will be shown in later section when compared with CAs.

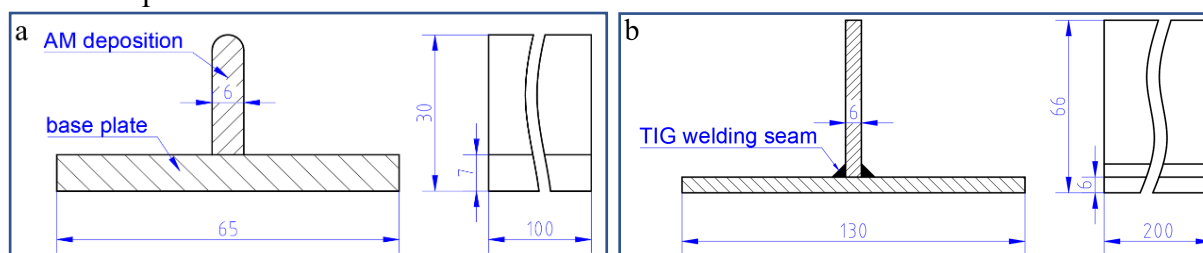


Fig. 2 (a) schematic of specimen group A; (b) schematic of specimen group B

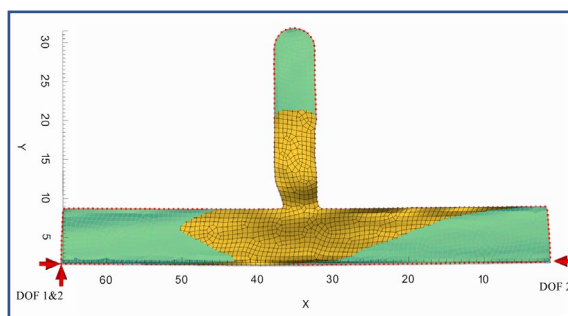


Fig. 3 example of FE mesh and boundary condition

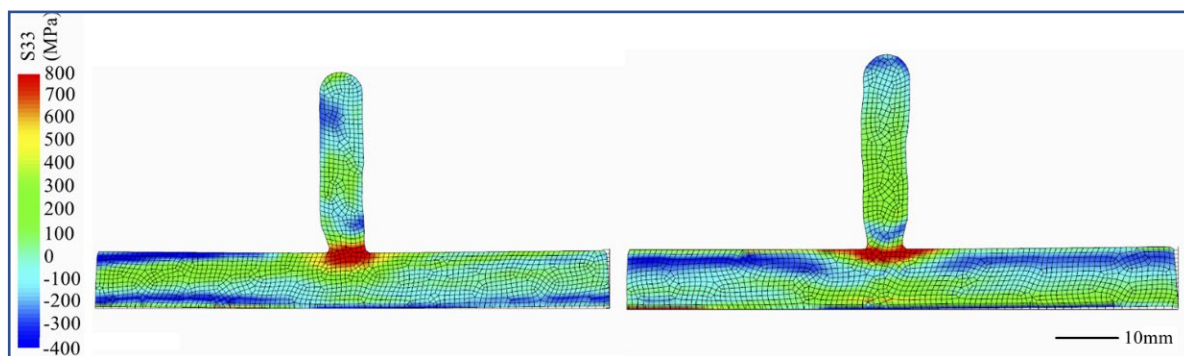


Fig. 4 contour method residual stress plot of A1 (left) and A2 (right) in out-of-plane direction

3.3. Cutting artifacts correction with stress-free reference samples

3.3.1 Thin wafer strategy

A ‘thin wafer’ strategy (Fig. 5a) was initially tested on specimen A1 and A2 by cutting off a 1 mm thick wafer from the previous contour cut plane with the exact same WEDM parameters as the previous contour cut to recreate the local cutting errors. However, the wafer showed visible global distortion induced by the release of out-of-plane stresses (Fig. 6). The effect of cutting length change is a localized phenomenon, which coincides with changes in cutting length which is then masked by this global distortion. Therefore, the thin wafer strategy cannot reliably provide a SF reference to separate the CAs without the further relief of out-of-plane stresses. The artificial stresses presupposed by these thin wafers were not further considered.

3.3.2 Annealing & thin wafer strategy

Specimens A1 and A2 were then annealed to reduce the overall deviatoric residual stresses and reprocessed with the thin wafer strategy. The surface profiles of two new cut planes from the wafer and its mating base part were measured in same configuration as the cut surfaces of previous contour analysis and the two point-clouds appeared to be flat. At this stage it was

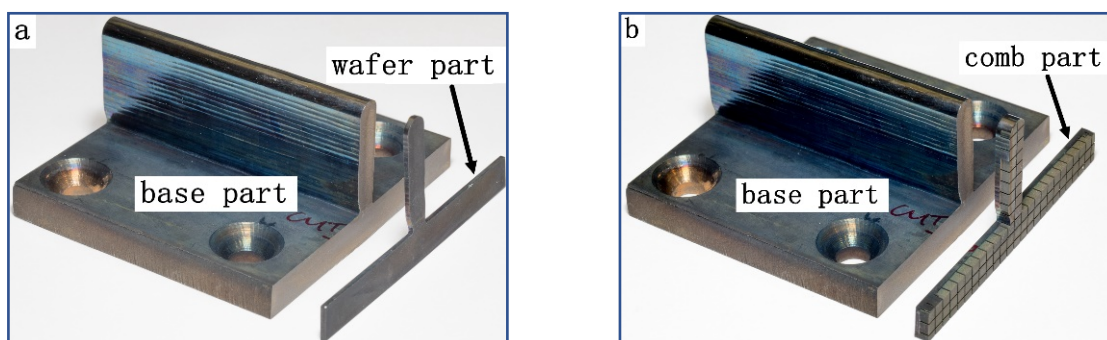


Fig. 5 (a) thin wafer cut; (b) comb grid cut

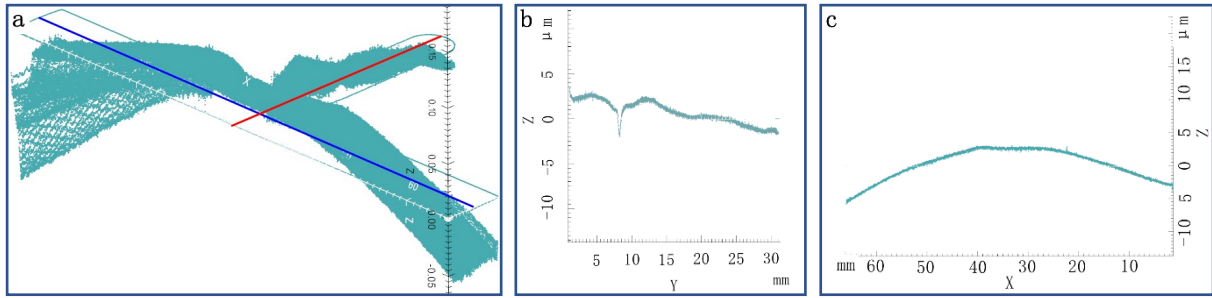


Fig. 6 (a) point cloud averaged from two halves of thin wafers cut; (b) Z-Y plot of surface contour (sampled along red line in Fig. 6a); (c) X-Z plot of surface contour (sampled along blue line in Fig. 6a)

assumed that there was no stress relaxed during this wafer cut, and the back calculated stress should be the artificial stress introduced by cutting process. The measured datasets were then processed in the exact same way as datasets of A1 and A2 to generate analytical surfaces and applied to the same FE model under same parameters as in previous CM analysis. When compared the back-calculated ‘artificial stress’ of thin wafer cut of annealed A1 and A2 evaluated at the central line of specimen ranging from 3 mm away from bottom surface to 2 mm away from the crown (Fig. 7), namely from $Y=3$ to $Y=28$, and same range applied to all stress line plots in following sections. The stress magnitude was very different with more ‘artificial stress’ present in specimen A2, which has higher magnitude of stress in its as-deposited state. However, A1 and A2 share similar geometrical configuration, which means the effect of cutting length variation should be comparable, and a similar level of artificial stress should be observed at corresponding location if the wafer cut was truly ‘stress-free’. Therefore, it cannot be assumed the thin wafer cut can be a reliable way to mitigate the CAs even if annealing is applied.

3.3.3 Annealing & comb-grid strategy

A further strategy to achieve a higher fidelity SF reference sample was tested inspired by the use of a stress-free comb sample as employed for diffraction techniques. Specifically, a series of stress relaxing cut were arranged for further stress relaxation, then this comb region was cut off from original specimen 1mm away from the root of comb teeth as illustrated in Fig 5b with same WEDM settings as previous contour cut. The cut halves were then processed in the same routine as annealed thin wafer cut mentioned in section 3.3.2 to generate a stress result.

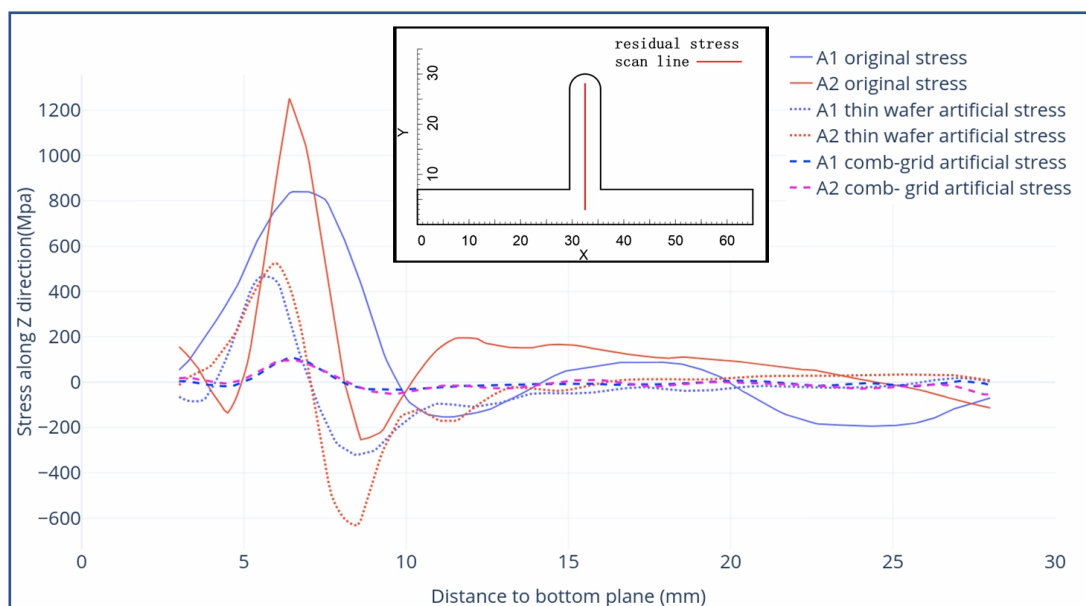


Fig. 7 Out-of-plane stress of A1&A2 plotted along scan line: original residual stress and artificial stresses calculated with annealed thin wafer and comb-grid strategy.

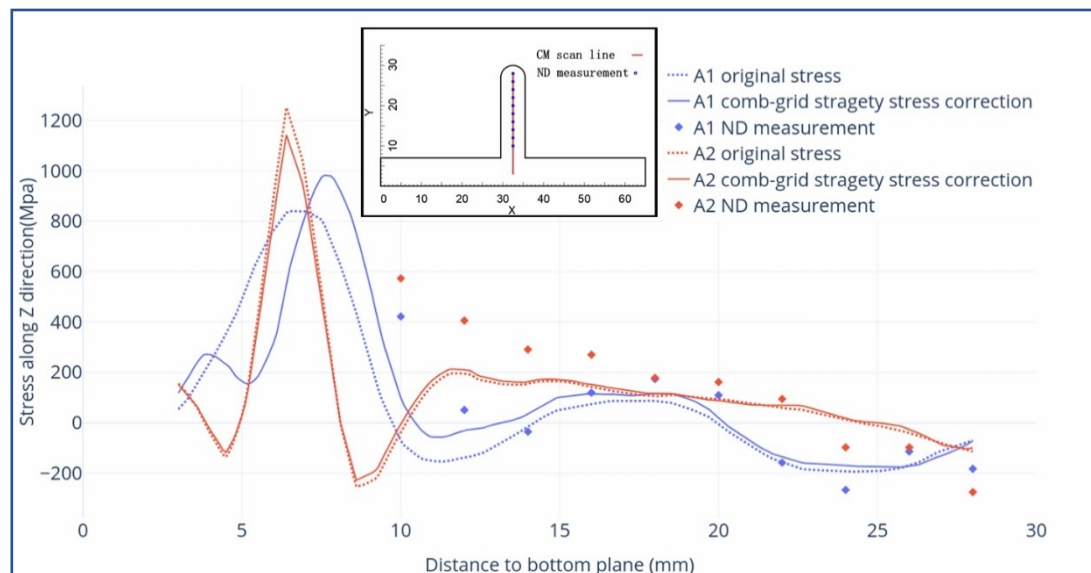


Fig. 8 residual stress correction with annealed comb-grid reference sample

The back-calculated stresses were interpreted as artificial stresses introduced by cutting through a varying cross-section. A tensile artificial stress region was observed near the root of T-sections (transition plane at $Y=7\text{mm}$) in the result of stress-free cut of all specimens. The artificial stress showed good consistency between specimens A1 and A2, whose geometrical configurations are similar but the original stress fields are different. This shows that the CAs are related to the physical profile of specimen, not the original stress state. The artificial peak tensile stresses measured along the axis of symmetry of T-section were 100 MPa with a compressive stress field of minimum -50 MPa balanced on the opposite side as shown in Fig. 7. A correction on the results of original contour method analysis can be achieved by subtracting the artificial stresses from original stress profile.

The corrected stress plot at the centre line of A1 and A2 were shown in Fig. 8. When compared with the published ND results measured in previous research [8], it can be seen that the CAs correction tend to facilitate a better agreement between CM results and ND measurements.

3.3.4 Comb-grid stress relaxation cutting without annealing

Further experimentation employing the use of a comb-type stress relaxation was carried out on specimen B1 in as-welded state to investigate whether the comb cut alone is sufficient to provide a stress-free reference. The result is similar to thin wafer cut on A1 before annealing, which shows an unacceptable level of deformation on the cut-off parts due to stress relaxation. Therefore, heat treatment should be considered to minimize the effect of residual stress in CAs mitigation for the stress magnitudes found in the samples considered. Comb samples are typically employed to provide SF samples to provide d_0 data for diffraction measurements, but the extent to which stresses can be relieved with this approach can vary. As heat treatment can only be applied in certain circumstances with a compatible underlying microstructure, it is recommended that for components with high residual stresses the best outcome to arrive at a SF sample is to employ a combined annealing and mechanical stress relief.

3.4. Sacrificial material approach

Sacrificial parts were applied on specimen B2 in a 2-piece arrangement, intended to minimize the effect of CAs by rendering a rectangular cutting path. Those parts were acquired by scanning the cross-sectional profiles using CMM machine, then cut the compensational parts out of the

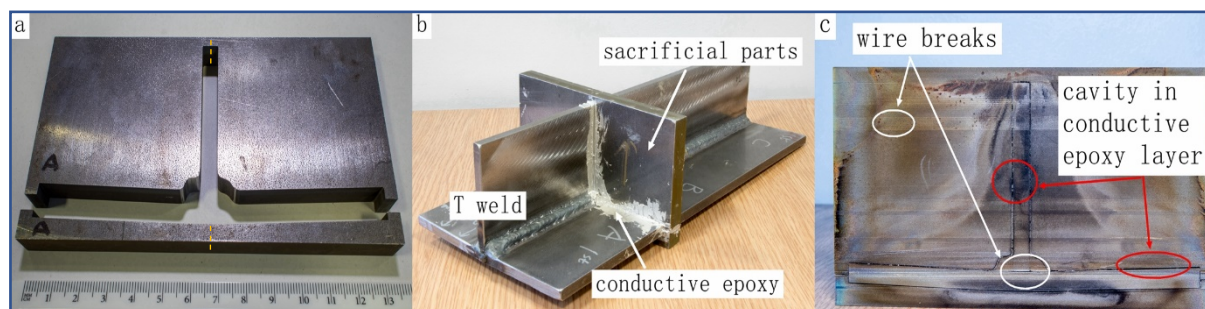


Fig. 9 (a) sacrificial material; (b) sacrificial material contour cut assembly; (c) issue with sacrificial material cut same grade of material as specimen B2 with WEDM (Fig. 9a). MG chemical 8331 conductive epoxy was used to fill the gap between sacrificial parts and original weldment conductively, as well as providing mechanical bonding during cutting process. The assembly (Fig. 9b) was then treated as a uniform steel plate for WEDM cutting with the same E2 settings for steel.

During the sacrificial material contour cut, several wire breaks occurred, and these affected the final surface (Fig. 9c). Potential causes are a weak bonding between sacrificial parts and weldment, and the epoxy was partially flashed out during cutting resulted in cavities. Later a 4-piece arrangement was used for easier application of epoxy by split the two pieces of sacrificial parts along the yellow dash line in Fig. 9a, with the hope of better bonding quality. However, the bonded sacrificial parts detached during cutting process and the cutting quality was not ideal. This is potentially due to by separating the sacrificial parts into smaller pieces, the integrity of the sacrificial assembly was insufficient to hold the assembly with the progression of WEDM process.

It was also observed that the wire tends to break when cutting into the epoxy layers parallel to wire direction, as the property of conductive epoxy mixture is still different from original steel weldment despite having the same conductivity. More investigation on the behaviour of conductive epoxy mixture under WEDM should be carried out to make this approach a reliable way to mitigate cutting artefacts.

4. Result summary and discussion

A summary of experiments and primary findings is provided in Table 1.

Table 1. Results of different cutting artefacts correction methods

Specimen	Material	Manufacturing	CAs mitigation	Results
A1 & A2	Ti-6Al-4V	wire + arc AM	Thin wafer	Obvious global deformation
A1 & A2	Ti-6Al-4V	wire + arc AM	Annealing + thin wafer	Less global deformation; No consistency between A1 & A2.
A1 & A2	Ti-6Al-4V	wire + arc AM	Annealing + comb-grid	No obvious deformation; Good consistency between A1 & A2.
B1	Mild steel	TIG welding	comb-grid	Obvious global deformation.
B2	Mild steel	TIG welding	Sacrificial material	Several wire breaks; Low quality of cut surfaces; Sacrificial parts detached.

The idea of creating a stress-free reference part to separate the artificial stress introduced by cutting through a changing cross-section from original stress results of a contour method analysis is achievable, but the selection of stress-relaxing approach needs to be considered. For the samples considered in the present study, the thin-wafer approach is not effective in providing a wholly stress-free reference and a combination of residual stress reduction methods are required in order to reliably separate artificial stress from a cut plane. The comb-type stress relaxation method after heat treatment showed the best result and demonstrated that cutting artifacts are not related to original stress distribution but are geometrical, which means several attempts can be made as long as the geometrical configuration remains unchanged by stress relaxing cut. This is a main advantage of this proposed technique compared to sacrificial material approach, which has to be arranged during a contour analysis WEDM cut, meaning it is a one-off application.

5. Conclusion

The proposed CAs mitigation strategy is capable of capturing artificial stresses caused by cutting through a changing cross-section. Those artificial stresses are independent to original stress state but related to physical profiles of specimen. Corrected residual stress can be achieved by subtracting the cutting artefacts from previous CM results which reduces the error in contour method analysis of this type, but the reliability of this technique needs to be further examined.

Sacrificial material can be difficult to apply when the cross-sectional profile of specimen is complicated, and the possibility of a wire break cannot be ignored if the conductive epoxy has to be applied over large regions. Therefore, it is recommended to perform a full-sized test cut with sacrificial material applied, or the proposed CAs mitigation strategy can be an alternative approach.

References

- [1] M. B. Prime, D. J. D. J. Hughes, and P. J. P. J. Webster, "Weld application of a new method for cross-sectional residual stress mapping," *Soc. Engineering Mech. Annu. Conf. Expo.*, vol. 836, pp. 1–5, 2001.
- [2] M. B. Prime and M. R. Hill, "Residual stress in a thick steel weld determined using the contour method," vol. 2001, no. October, 2001.
- [3] D. W. Brown *et al.*, "Critical comparison of two independent measurements of residual stress in an electron-beam welded uranium cylinder: Neutron diffraction and the contour method," *Acta Mater.*, vol. 59, no. 3, pp. 864–873, 2011.
- [4] X. Duan, D. Sun, A. Glover, and S. Paddea, "Experimental study of the weld residual stress in manually and mechanically fabricated dissimilar metal weld," in *Proceedings of the ASME 2018 Pressure Vessels and Piping Conference*, 2018, vol. 6B-2018, pp. 1–13.
- [5] F. Hosseinzadeh, P. Ledgard, and P. J. Bouchard, "Controlling the Cut in Contour Residual Stress Measurements of Electron Beam Welded Ti-6Al-4V Alloy Plates," *Exp. Mech.*, vol. 53, no. 5, pp. 829–839, 2013.
- [6] M. B. Prime and A. L. Kastengren, "The Contour Method Cutting Assumption: Error Minimization and Correction," in *Experimental and Applied Mechanics, Volume 6*, 2011, pp. 233–250.
- [7] M. T. Hutchings, Philip J. Withers, Thomas M. Holden, and T. Lorentzen, *Introduction to the Characterization of Residual Stress by Neutron Diffraction*, vol. 112, no. 483. 1966.
- [8] J. Honnige *et al.*, "Residual Stress Characterization and Control in the Additive Manufacture of Large Scale Metal Structures," *Residual Stress. 2016*, vol. 2, no. January 2017, pp. 455–460, 2016.
- [9] M. J. Roy, N. Stoyanov, R. J. Moat, and P. J. Withers, "pyCM: An open-source computational framework for residual stress analysis employing the Contour Method," *SoftwareX*, vol. 11, p. 100458, 2020.