Project No. 11-3117

Life Prediction of Spent Fuel Storage Canister Material

Fuel Cycle Research and Development

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Life Prediction of Spent Fuel Storage Canister Material

Final Report

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1.0 Project Description

1.1: Project Objectives

The original purpose of this project was to develop a probabilistic model for SCC-induced failure of spent fuel storage canisters, exposed to a salt-air environment in the temperature range 30-70°C for periods up to and exceeding 100 years. The nature of this degradation process, which involves multiple degradation mechanisms, combined with variable and uncertain environmental conditions dictates a probabilistic approach to life prediction. A final report for the original portion of the project was submitted earlier. However, residual stress measurements for as-welded and repair welds could not be performed within the original time of the project. As a result of this, a no-cost extension was granted in order to complete these tests. In this report, we report on the results of residual stress measurements.

1.2 Detailed Task Descriptions-No Cost Extension

Task 1: Neutron Diffraction Base Residual Stress Measurements: Additional residual stress measurements on additional sections of weld. Additionally, one of the weld sections used for the residual stress measurements will then undergo a “repair weld” in which a simulated repair weld will be performed followed by re-measurement of the residual stresses at the SAME locations (HAZ) of the previously measured residual stresses.

Task 2: Contour Based Residual Stress Measurements: In this task we will make use of the welds for which neutron diffraction based residual stress measurements have been made and perform residual stress measurements at the same locations as the neutron diffraction based measurements using the Contour method. Measurements will be made at three locations. The Open University (StressMap) in the UK, at Alto University in Finland and at MIT. The StressMap and Alto University laboratories are experts in this technique. The cost to the project will be 12K for the StressMap measurements and at no cost (except for travel costs and incidentals for the team members) for the measurements at Alto University. Data from both locations will be supplied to the MIT team in order that the MIT measurements can be calibrated.

2.0 Results

Neutron Diffraction Residual Stress Measurements

Neutron diffraction residual stress measurement campaign have been conducted at the Canadian Institute for Neutron Scattering (CINS) at the AECL Chalk River Nuclear Laboratory in Deep River, Ontario Canada.

The campaign focused on developing 3D stress measurements on a single sample but on 2 different planes for the as-welded conditions. Additional residual stresses were measured on a weld that had undergone a simulated weld repair.

Figure 1 shows a photo of the physical setup for the transverse/normal and longitudinal scans. Figure 2 shows the plate with the simulated weld repair. The weld repair was made assuming the following conditions:

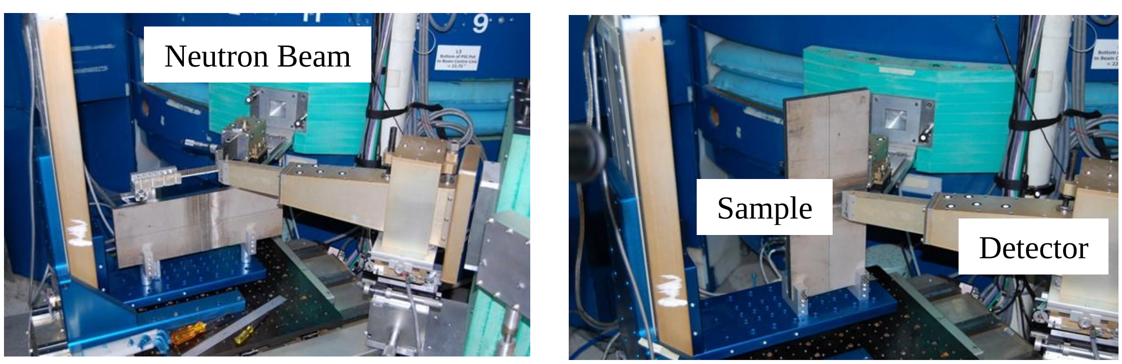
1. That a “defect” was present 1/3 of the way through the thickness and 25 mm in length.
2. The “defect” was ground out by removing material to a depth 1/3 through the plate weld by 55 mm long and 12 mm wide.
3. The weld repair was then made using the gas tungsten arc (GTA) technique.

Figures 3-5 present residual stress measurement results for one of the planes from the campaign sample. Figures 3-5 show the residual strains in the Transverse, Normal and Longitudinal directions respectively. Measurements were made at depths of 2.05, 6.15, 8.2, 10.25, and 14.35mm from the top surface. Stresses were measured at selected points at a specific depth over a region +/- 50 mm from the weld centerline.

It is clear that there is considerable variation of the stress through the wall and that compressive stresses will exist in many locations. The data from this campaign as well as from the first campaign is still being analyzed.

Figures 6-8 present residual stress measurement results from the weld repair sample. Results are presented for a plane through the center (axially) of the weld repair. Measurements were made at depths of 1.1, 2.05, 4.1, 6.15, 8.2, 10.25, 12.3, 14.35 and 15.3mm from the top surface. Stresses were measured at selected points at a specific depth over a region +/- 50 mm from the weld centerline.

The results presented have not been fully analyzed but it is clear that weld repair introduces very high tensile residual stresses.



(a) Transverse & Normal Scans　　(b) Longitudinal Scans

Figure 1. Photographs of neutron diffraction experimental setup. (a) for transverse & normal scans, (b) for longitudinal scans

(a)

(b)

Figure 2. Photographs of neutron diffraction experimental setup for weld repair sample. (a) for transverse & normal scans, (b) photo of simulated weld repair.

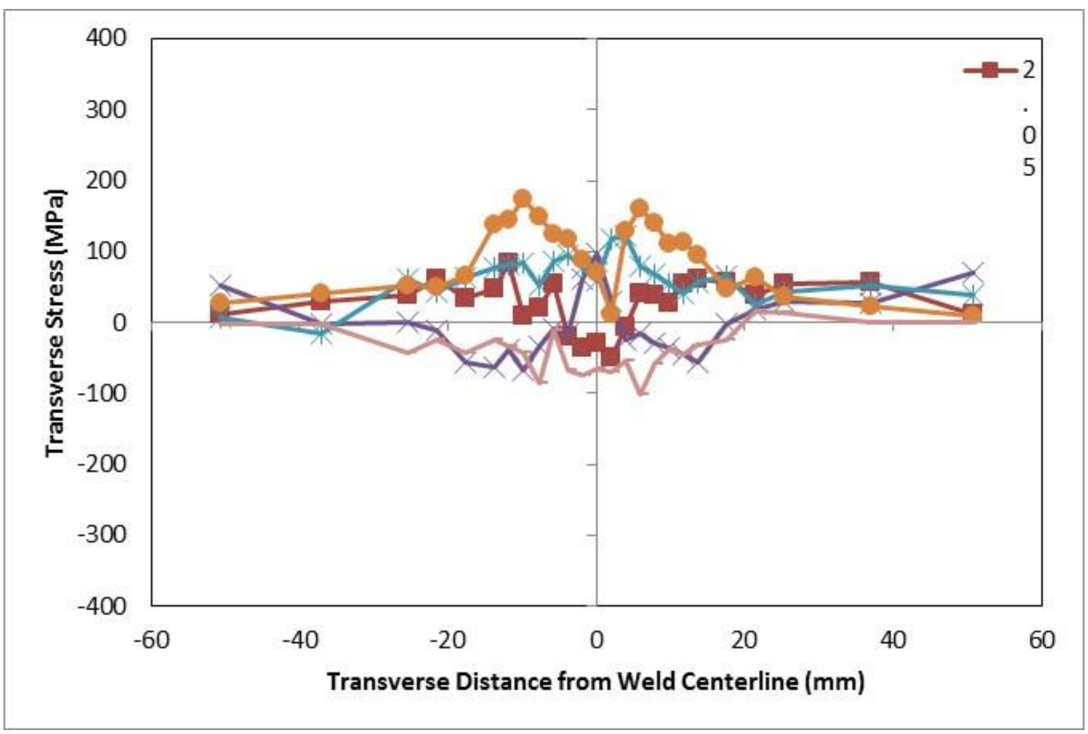


Figure 3. Transverse stresses measured on Plane #1

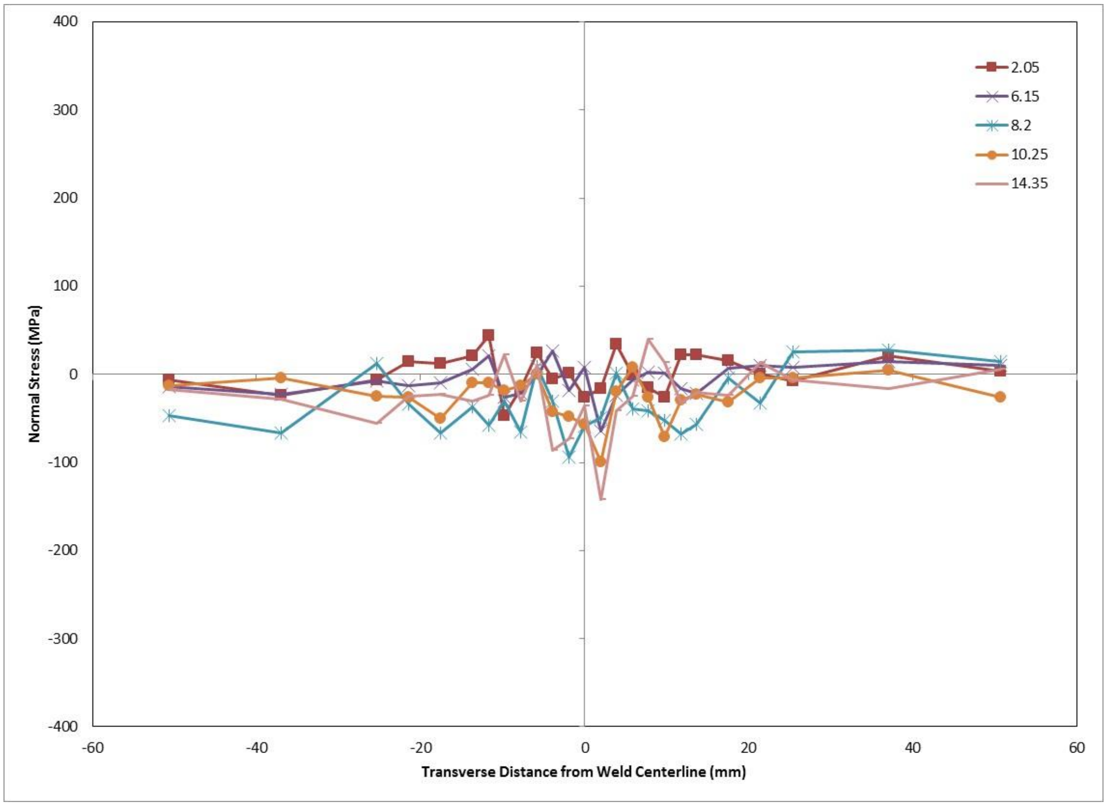


Figure 4 Normal stresses measured on Plane #1

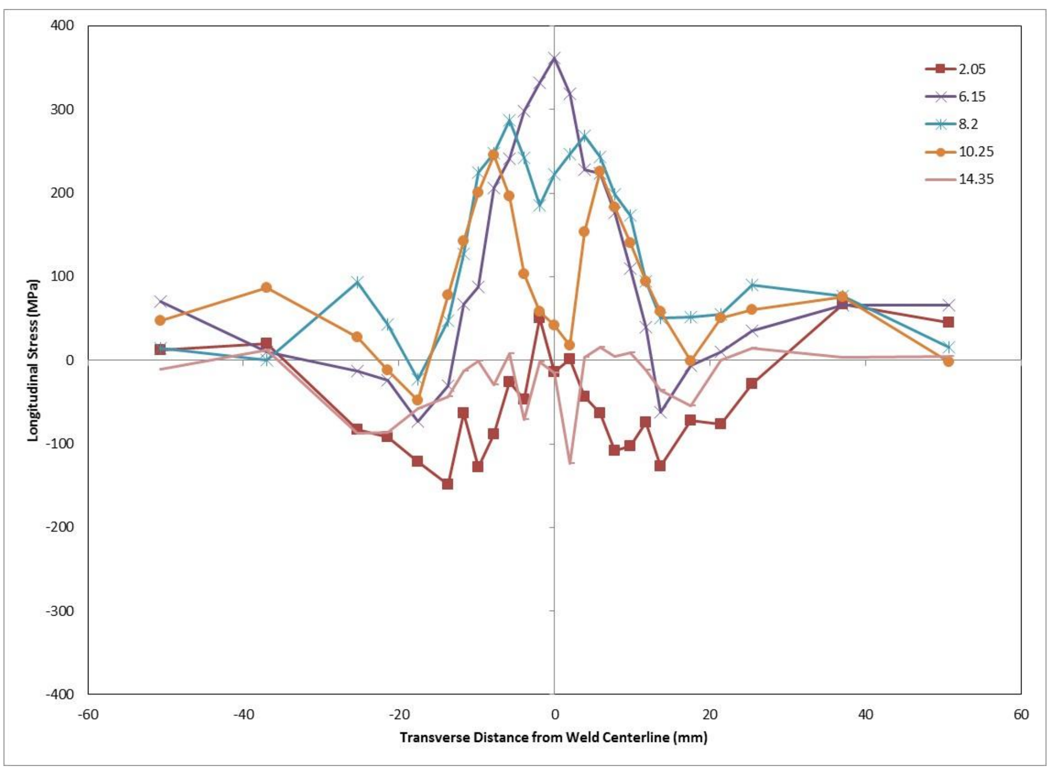


Figure 5. Longitudinal stresses measured on Plane #1.

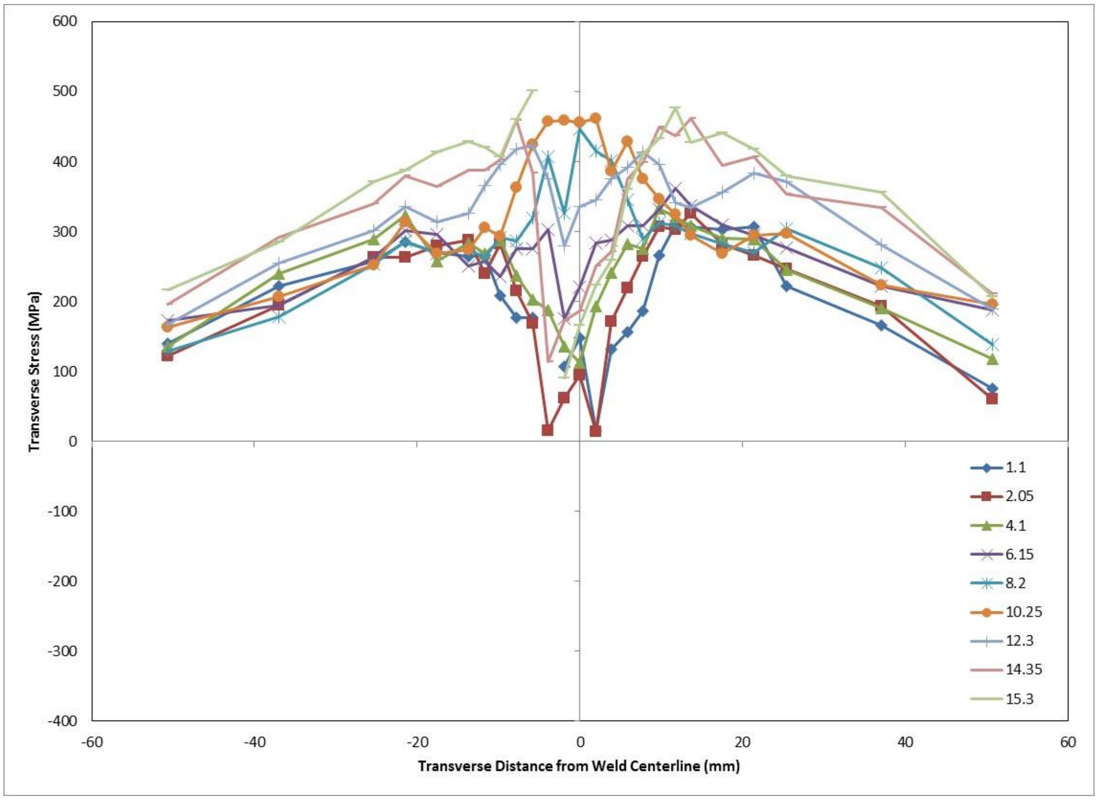


Figure 6. Transverse stresses measured on plane through the weld repair axial center.

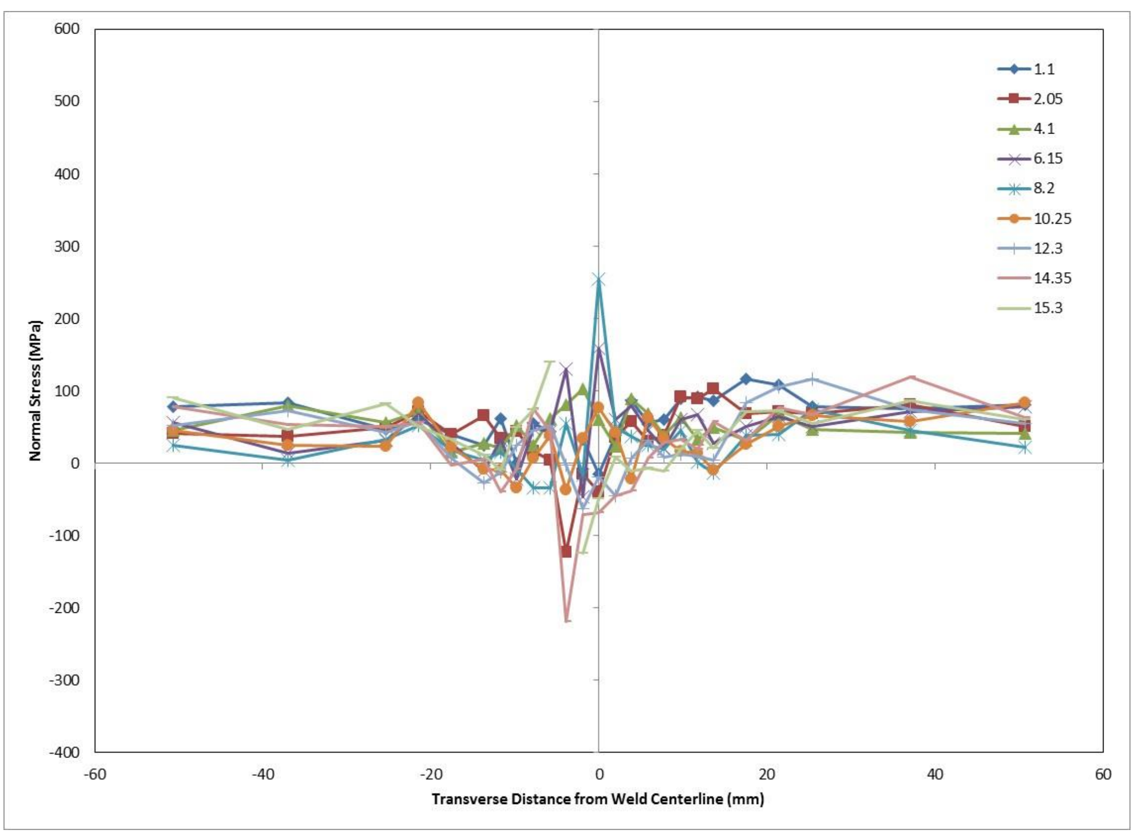


Figure 7. Normal stresses measured on plane through the weld repair axial center.

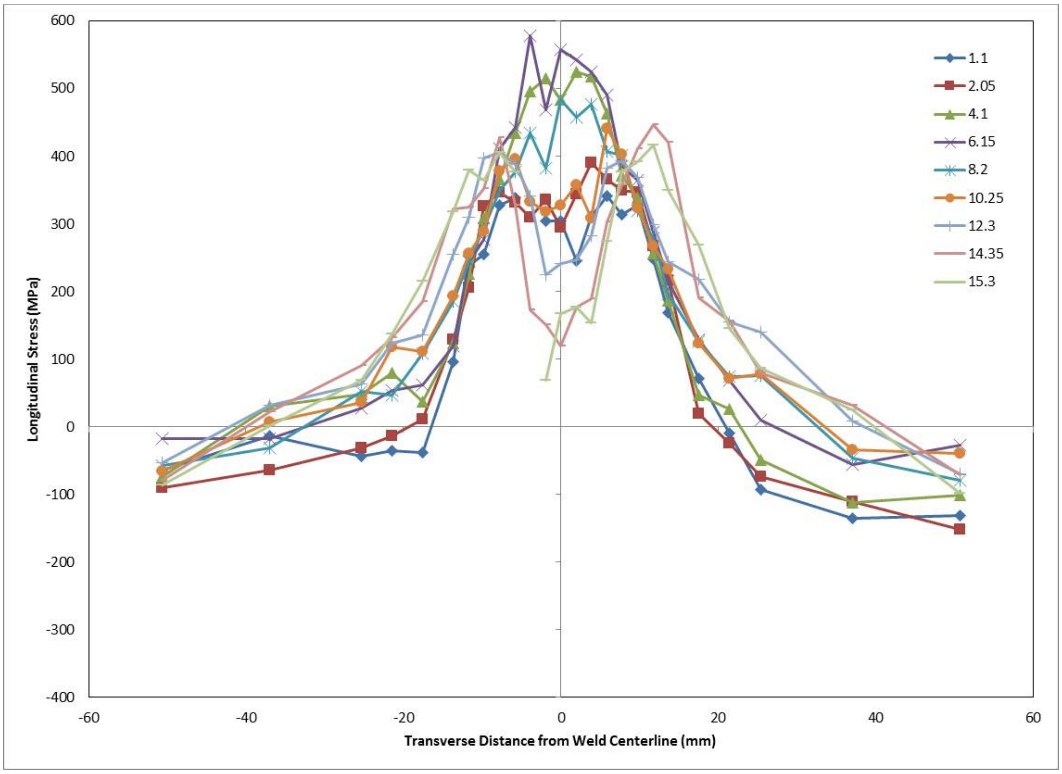


Figure 8. Longitudinal stresses measured on plane through the weld repair axial center.

Prototypic Canister Weld Measurements

In addition to prototypic plate weld residual stress measurements, resisual stress measurements we also made on a prototypic canister weld provided by a DOE program. Figure 9 shows a photograph of the actual canister weld installed in the neutron diffraction facility at Chalk River.

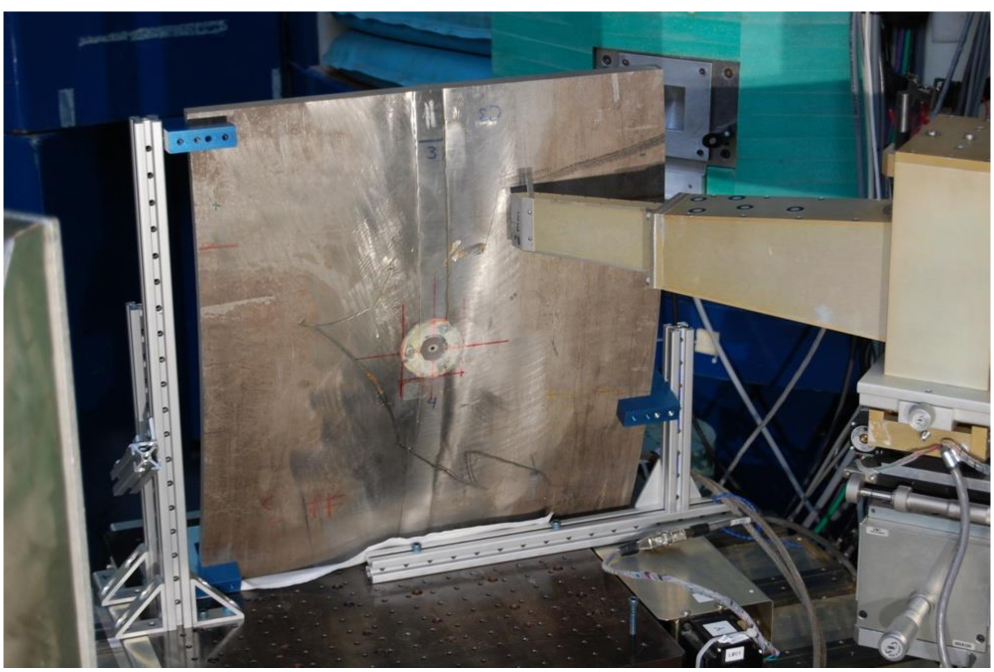


Figure 9. Prototypic canister weld installed in residual stress fixture at NRU (Chalk River). Note that hole in center is from previous stress measurements using hole drilling.

Figure 10 shows the resulting longitudinal residual stress.

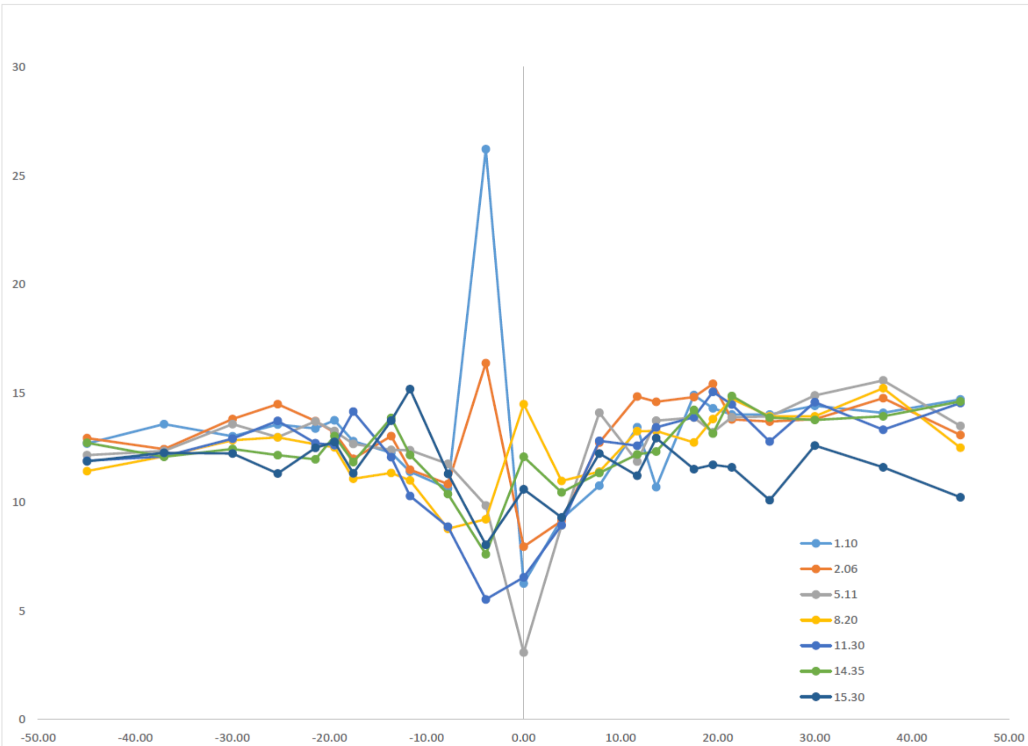


Figure 10. Longitudinal stress component of the weld residual stress for prototypic canister weld. The horizontal axis shows the distance on either side of the weld centerline in mm. The vertical axis shows the longitudinal stress in MPa.

Contour Based Residual Stress Measurements.

In addition to neutron diffraction based residual stress measurements, residual stresses were measured using the Contour method by the StressMap company in the UK. The residual stress measurements were made at the same locations as that of the neutron diffraction based measuremsnts. Figures 11, 12 show selected results. A detailed report of the Contour measurements is included in Appendix 1. In general, the Contour results are consistent with the neutron diffraction based results. This includes the effect of w weld repair.

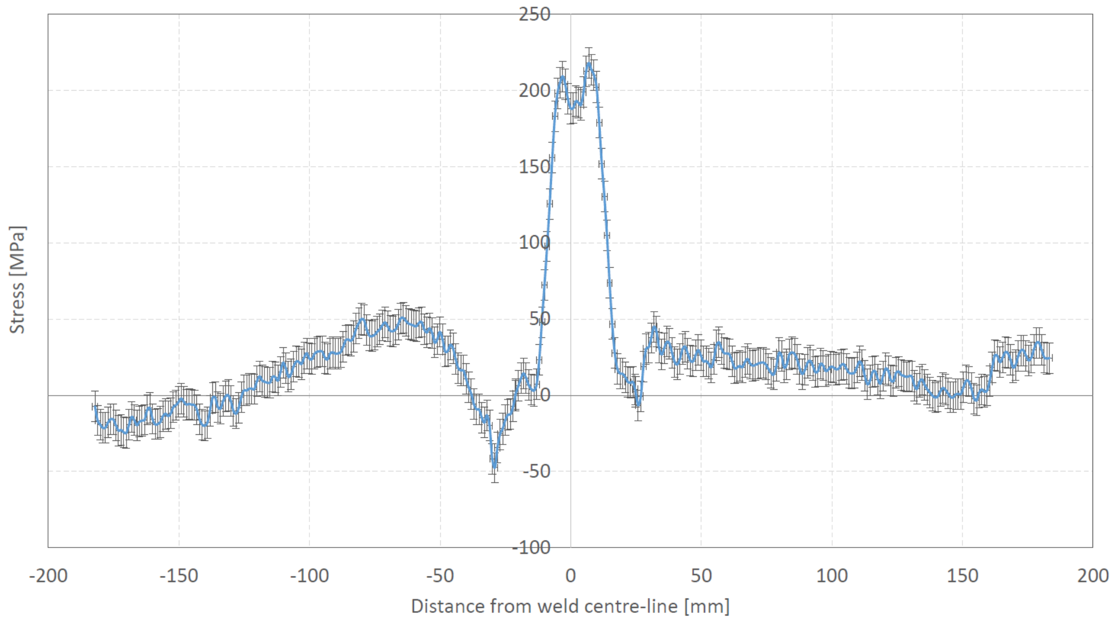


Figure 11. Preliminary results for longitudinal residual stress measurements using the Contour method. Location is near mid-plane of as-welded sample used for neutron diffraction measurements.

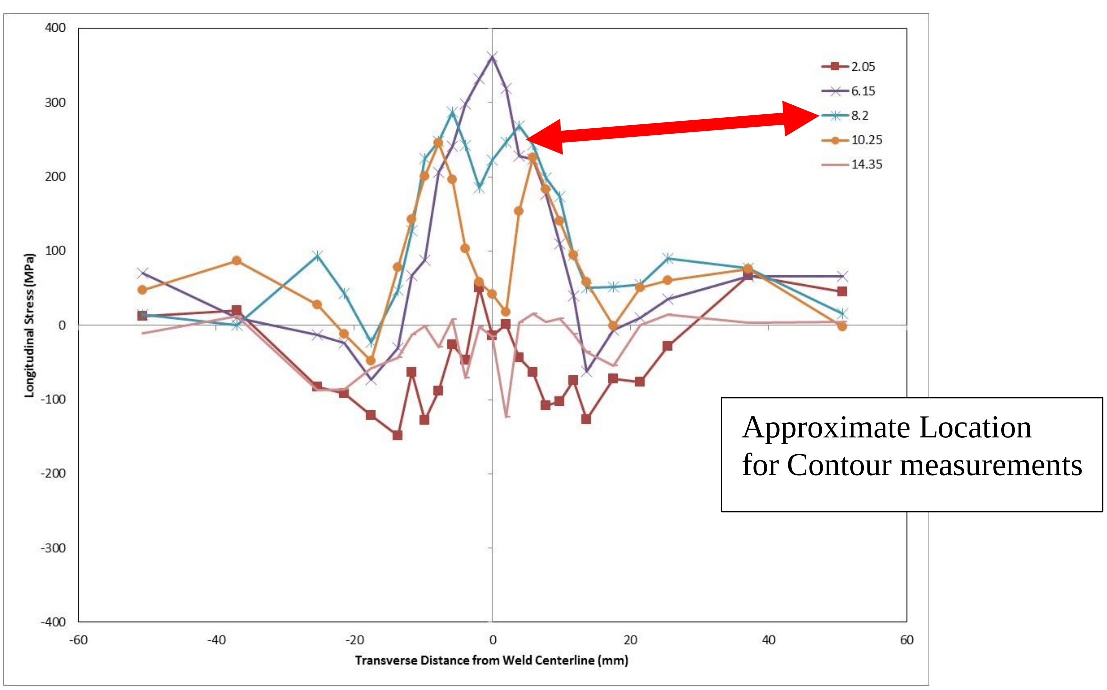


Figure 12. Neutron diffraction based residual stress measurements for plane on which Contour measurements were made.

3.0 Conclusions

Neutron diffraction based residual stress measurements were made for prototypic double-V stainless steel dry storage canister weld. These welds included: (1) welds made in plate material used for the construction of typical dry storage canisters, including repair welds, and (2) a prototypic canister weld made from the same plate material used for (1). In addition, Contour-based residual stress measurements were made on exactly the same welds for which the neutron diffraction based residual stresses were made.

The results of the comparison indicate that Contour and neutron diffraction based measurements are comparable, showing the same trends and the same residual stresses on average. The neutron diffraction based measurements are of higher resolution.

The results of the investigation suggest that, for a double-V canister weld, the residual stresses become compressive at some thickness in the heat affected zone of the weld. Thus suggests that crack propagation based on an assumption of constant, tensile, residual stresses will greatly under estimate the time to a through wall crack due to stress corrosion cracking. However, for the case where a weld repair has been made, the residual stresses are tensile through wall which justifies the assumption of through wall tensile stresses for modeling purposes.

The implications of the effect of weld repairs on canister welds is that weld repairs should be made only under conditions where there is a clear reason to do so. The only reason to do so would be if a significant defect is present and that breaks the surface. Under these conditions, stress mitigation techniques should be considered to relieve/remediate the stresses. Additionally, other “repair” techniques, including application of corrosion resistant coatings (pure nickel plating, etc.) should also be considered.

Lastly, while not examined in this project, single-V welds are likely to result in tensile residual stresses through wall and should this not be considered for canister welds.

Appendix 1 Contour Based Residual Stress Measurements Report

Materials Engineering

RESIDUAL STRESS MEASUREMENT ON AS-WELDED AND REPAIR STAINLESS STEEL WELDED PLATES USING THE CONTOUR METHOD

OU/MatsEng/0122, Draft

By: Sanjooram Paddea

Date: August 2017

DOCUMENT INFORMATION

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Confidentiality:	Commercial-in-confidence		
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Approved by:		Signature:	
Date Approved:			
Contact Information:	Materials Engineering, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK. http://materials.open.ac.uk Tel: + 44 (0)1908 332461; Fax: + 44 (0)1908 653858		

QUALITY ASSURANCE

Measurements have been carried out by qualified and experienced staff at the Open University with reference to published experimental procedures for the contour method [1]–[4].

The outcomes and report have been reviewed by the Verifier and Approver. The records relating to this report will be held on the Penelope server at the Open University.

SUMMARY

The longitudinal residual stress has successfully been measured on two austenitic stainless-steel plates comprising an as-welded and a repair plate. A multiple cut approach i.e. superimposing relaxed stresses to measured stresses was used to measure the longitudinal stress on a 2nd plane of each plate. In general, tensile stresses were observed in the weld which was noticeably higher in the repair plate. The results at the 2nd cut plane of the repair plate was different to that measured at the 1st cut plane and may have been influenced by the fact that it was located in close proximity to the repair start/stop position.

CONTENTS

1 INTRODUCTION

This report presents contour method [3] measurements performed to quantify the level of longitudinal residual stresses in two welded plates. The contour method involves cutting the component of interest into two parts along a plane on which the distribution of normal direct residual stresses are to be quantified. Here, the contour method test procedures are described and the results of the measurements discussed.

2 TEST COMPONENT

The test components comprised of two austenitic stainless steel (Grade 304) plates with a multi-pass weld (Grade 308) across the entire width at mid-length. Plate 1 was supplied in an ‘as welded’ condition and the second plate had a repair weld. A schematic illustration of the test components and the contour cut locations are shown in **Figure 1**. Both the parent and the weld material was assumed to have homogeneous isotropic elastic properties with a room temperature Young’s modulus of 200 GPa and Poisson’s ratio of 0.3.

3 THE CONTOUR METHOD

The contour method is increasingly being used to measure residual stresses in engineering components. The method is particularly attractive for providing a 2-dimensional map of residual stress over a cross-section of a component using a single cut. Unlike diffraction techniques, the contour method is not sensitive to microstructural variations and has been successfully applied to various weldments [5]–[8]. Furthermore, the contour method is not limited by the geometry and thickness of the test components and has been applied to large and complex geometries [5], [9]. Recently the ability of the technique has been extended to measure more than one component of the stress tensor by using multiple cuts and by combining it with other residual stress measurement techniques [5], [10]–[12].

The method involves making a cut in the test component of interest, at the plane on which residual stresses will be measured. The created cut surfaces deform owing to the relaxation of residual stresses that existed within the component prior to the cut. The topography of the newly created surfaces is measured precisely and elastic finite element (FE) modelling used to determine the cross-sectional distribution of undisturbed residual stresses that were acting normal to the plane of the cut [8], [13]. The main steps of the contour method are: test component cutting, surface contour measurement, data analysis and FE modelling which are now described in further detail.

3.1 Test component Cutting

Cutting the component of interest is the most critical step in the contour measurement procedure as all the following steps depend on the quality of the cut faces created. Several assumptions are made concerning the cutting step in the contour method [14]. In particular, a straight cut having a constant minimal width must be performed, additional material should not be removed from already cut surfaces and the cut should not cause plastic deformation or introduce significant additional residual stresses.

Wire electric discharge machining (EDM) is the cutting technique that best meets the ideal cutting conditions required for the contour method. Unlike conventional machining processes that require high cutting forces for material removal, wire EDM is a non-contact technique that uses an electrically charged thin moving wire where the energy contained in a spark is used to remove material. In the “finishing” or “skim” mode of EDM cutting operations, a relatively low energy is used where changes in material properties due to the cutting process and residual stresses introduced are negligible [15]; that is they are confined to a thin near-surface layer.

The topography of the created cut surfaces may possess both symmetric and anti-symmetric geometric features [8]. Anti-symmetric surface contour features can arise due to the presence of a shear component of residual stress, or when a crooked cut is made, or when the body is asymmetrically restrained during cutting. These anti-symmetric features can be all, or partly, removed by averaging the surface displacement contours of the two cut halves.

The relaxation of residual stresses normal to the plane of the cut results in symmetric features in the deformation contours of the cut surfaces. It is these “mirror image” surface contours that must be measured and used to back-calculate the undisturbed residual stresses that existed prior to the cut. However, other factors can introduce symmetric surface deformation features which contribute to errors in the contour stress measurement; for example elastic bulging or plasticity during cutting [8], both of which are mainly dependent on the original state of residual stress that exists within the component. Other undesirable symmetric features can arise from the cutting process itself including surface roughness, longer range surface waviness, wire entry and wire exit artefacts giving flared edges, bowed surfaces, cut entry transitions, wire breakages etc. These symmetric deformation cutting artefacts are not cancelled out by averaging and therefore contribute directly to uncertainties and errors in residual stresses measured using the contour method [2].

It is important to restrain the test component firmly and symmetrically across the cutting plane during wire EDM machining. This is to prevent movement of the component relative to the cutting path during machining, to restrain cut face opening/closure (which can help to control the risk of plasticity and bulging errors [8], [16]) and to promote development of symmetrically deformed cut surfaces.

3.2 Surface Contour Measurement

After wire EDM cutting, the distorted contours (out of plane shapes) of the newly cut faces are measured. A coordinate measuring machine (CMM) is the most widely used system for measuring the cut faces [8]. The two halves of the test component being measured are placed side by side in the CMM workspace. Either a touch trigger probe or an optical probe is used and the CMM programmed to perform a dense array of measurements covering each of the cut faces. The outlines of the cut parts are also measured and used in the data analysis step of the contour method.

3.3 Data Analysis

The presence of noise and outliers in the measured raw data from the CMM is inevitable. Sources include cutting artefacts, surface roughness or random errors in measurements. The noise and outliers can result in large errors in the calculated stresses. Hence, the raw data have to be processed prior to their application as displacement boundary conditions in the FE analysis step. In addition, the raw data are not at the same locations as the nodes of the subsequent FE model used to calculate the stresses. The most important steps of data analysis are: the alignment of measured data from both cut faces; averaging of the two sets of measurements in order to remove shear stress effects and cutting imperfections; removal of noise and outliers; and finally smoothing the averaged data [13].

3.4 FE Modelling

A three-dimensional FE model of the cut part is created. As the deformations are small and the stress relaxation process is elastic, the deformed face is modelled flat. Once meshed, the opposite of the measured displacement is applied as a boundary condition to the cut face. The corresponding residual stress acting normal to the cut face is obtained from a linear elastic FE analysis [8].

4 EXPERIMENTAL PROCEDURE

4.1 Contour Method

4.1.1 Test component Cutting

A commercial wire EDM machine fitted with a 0.15 mm diameter brass wire was used for all cutting operations. The cutting parameters were based on previous experience of cutting similar plates and were optimised for a single, ‘best finish’ cut which minimised symmetric artefacts. Prior to cutting, the test components and clamping fixtures were left to reach thermal equilibrium conditions within the EDM water tank. The dielectric medium within the EDM water tank was deionised water.

EDM *wire entry* and *exit* from the test component can introduce cutting artefacts that affect near surface measurements. *Wire entry* refers to the top face of the test component where the running wire enters the test component. *Wire exit* relates to the bottom face of the test component where the running wire leaves the test component. To mitigate *wire entry* and *exit* cutting artefacts, stainless steel sacrificial layers were bonded on the top and bottom faces of the plate in the vicinity of the cut plane [12]. The test components were securely clamped to the EDM table to avoid opening and closure of the cut kerf as well as to restrain any free movement during cutting. To measure longitudinal stresses, the test components were cut across planes normal to their longitudinal direction i.e. on a transverse plane. The wire EDM cutting process is shown in **Figure 2**.

Following wire EDM cutting, the sectioned parts were cleaned, dried and left in a temperature controlled laboratory to reach thermal equilibrium within the laboratory environment before starting surface profile measurements. The normal deformation contours of the opposing cut surfaces were measured using a Zeiss Eclipse co-ordinate measuring machine (CMM), fitted with a Micro-Epsilon laser probe and a 2 mm diameter ruby-tipped Renishaw PH10M touch trigger probe. The resolution of the Micro-Epsilon laser triangulation displacement sensor is 0.15 μm. The measurement point spacing adopted was on a 0.1 mm grid. Furthermore, the perimeters of the cut parts were measured with the touch probe to define the geometry of the surfaces for the data processing step. The surface measurements process is shown in **Figure 3**.

4.1.2 Data Analysis and Stress Calculation

The contour cut data analysis was undertaken using a modified standard approach [13] to account for geometrical asymmetries with respect to the cut planes. Noise in the measured surface contour is unavoidable due to the nature of the EDM cut surfaces and uncertainty in surface measurements. Because the stress calculation magnifies the noise in the data, it is important to smooth the surface deformation data. For this study, data smoothing was conducted using a local regressive polynomial filter with window sizes between 1.5 to 5.0 mm.

A three-dimensional finite element model based on the measured perimeter of the cut parts was built for each test component using the ABAQUS code [17]. To reduce computing time, linear hexahedral elements with reduced integration (C3D8R) were used to mesh the models.

The meshes used for both test components are shown in **Figure 4**. Previous work has shown that linear elements are appropriate where a relatively simple linear elastic model is used [18]. For this study, the materials were assumed to have homogeneous isotropic elastic properties with a room temperature Young's modulus of 200 GPa and Poisson's ratio of 0.3.

Smoothed displacement data were evaluated and applied as boundary conditions, with reverse sign, at the cut surface nodes of the FE models. Additional constraints were imposed on the FE models to avoid rigid body motion. Linear elastic stress analyses were performed to calculate the residual stresses normal to the cut faces.

For the multiple cut analyses (i.e. the 2nd cuts on each plate), the relaxed stresses (an output of the 1st cut analyses) were superimposed on the newly measured stresses to give the undisturbed residual stress at the 2nd cut plane (as if the 1st cuts were not conducted).

Errors were determined for each of the analyses using the method detailed in [13] and were of the order of 10 MPa. It is important to note that this is just a fitting error to help determine the optimum smoothing level.

5 RESULTS AND DISCUSSION

Figure 5 through to Figure 8 show longitudinal stress maps measured at the 2 cut planes of the 2 plates. All the maps show tensile stresses in the weld region followed by compressive/low tensile stresses away from the weld. It is also clear that the stress pattern within the weld was different when comparing the as-welded and repair plate, where the former showed a 'turned v' tensile stress profile and the latter showing a 'U shaped' profile. Whilst the trends at the 2 cut planes of the as-welded plate were very similar, the results at the 2 cut planes of the repair plate were slightly different showing a concentration of tensile stresses in the top portion of the weld at the 2nd cut plane. On closer inspection of the repair plate, it appears that the 2nd cut plane was in close proximity to the repair weld start or stop, which could explain the apparent difference in the profile.

Figure 9 through to Figure 12 show line profiles from the four stress maps extracted along a transverse line (spanning the parent material and the weld material) and a drill down at the weld centre-line, starting from the top of the weld. The line profile extracted from the as-welded plate show tensile stresses of the order of ~225 MPa in the weld at both cut planes and relatively low tensile/compressive stresses elsewhere. The line profiles extracted from the repair plate show much higher tensile stresses ~450 MPa at the 1st cut plane and ~275 MPa at the 2nd cut plane. Compressive/low tensile stresses were measured near the top of the weld of the as-welded plate and the 1st cut plane of the repair plate. At the 2nd cut plane of the latter, tensile stresses of the order of ~300 MPa were measured. As highlighted earlier, the difference in the results at the 2 cut planes of the repair plate may be associated with the repair start/stop.

6 CONCLUSIONS

1. The contour method has been successfully applied to measure longitudinal residual stress on two stainless steel plates comprising an as-welded and a repair plate.
2. The multiple cut contour method was used to measure longitudinal stress on a second plane on each plate. The relaxed stresses due to the first cut was superimposed to give the undisturbed longitudinal stress at the 2nd cut plane.
3. The pattern in the longitudinal stress maps showed a clear 'turned v' tensile stress profile within the weld of the as-welded plate and a 'u shaped' tensile stress profile in the repair plate.
4. The results on the as-welded plate showed tensile stress of the order of 225 MPa in the weld and low tensile/compressive stress near the top of the weld.
5. The results on the repair plate showed higher tensile stress of the order of 450 MPa in the weld, although the stresses at the 2nd cut plane of the repair plate was closer to 275 MPa. The 2nd cut plane was located in close proximity to the repair start/stop which could explain the difference observed at the 2 cut planes.

7 REFERENCES

[1] M. B. Prime, M. R. Hill, A. T. DeWald, R. J. Sebring, V. R. Dave, and M. J. Cola, “Residual Stress Mapping in Welds Using the Contour Method,” in *Proceedings of the 6th International Conference:Trends in Welding Research*, 2002, pp. 891–896.

[2] F. Hosseinzadeh, J. Kowal, and P. J. Bouchard, “Towards good practice guidelines for the contour method of residual stress measurement,” *J. Eng.*, 2014.

[3] M. B. Prime and A. R. Gonzales, “The Contour Method: Simple 2-D Mapping of Residual Stresses,” *Proc. 6th Int. Conf. Residual Stress.*, vol. 1, pp. 617–624, 2000.

[4] M. B. Prime and A. T. DeWald, “The Contour Method,” in *Practical Residual Stress Measurement Methods*, G. S. Schajer, Ed. 2013, pp. 109–135.

[5] F. Hosseinzadeh and P. J. Bouchard, “Mapping Multiple Components of the Residual Stress Tensor in a Large P91 Steel Pipe Girth Weld Using a Single Contour Cut,” *Exp. Mech.*, vol. 53, no. 2, pp. 171–181, May 2012.

[6] Y. Traore, S. Paddea, P. J. Bouchard, and M. A. Gharghouri, “Measurement of the Residual Stress Tensor in a Compact Tension Weld Specimen,” *Exp. Mech.*, vol. 53, no. 4, pp. 605–618, 2013.

[7] F. Hosseinzadeh, M. Burak Toparli, and P. John Bouchard, “Slitting and Contour Method Residual Stress Measurements in an Edge Welded Beam,” *J. Press. Vessel Technol.*, vol. 134, no. 1, p. 11402, Dec. 2011.

[8] M. B. Prime, “Cross-sectional mapping of residual stresses by measuring the surface contour after a cut,” *J. Eng. Mater. Technol.*, vol. 123, pp. 162–168, 2001.

[9] M. B. Prime, “Contour Method Advanced Applications: Hoop Stresses in Cylinders and Discontinuities,” in *Proc. of the Soc. for Exp. Mechanics Series*, 2011, vol. 836, pp. 13–28.

[10] P. Pagliaro *et al.*, “Measuring Inaccessible Residual Stresses Using Multiple Methods and Superposition,” *Exp. Mech.*, vol. 51, no. 7, pp. 1123–1134, Nov. 2010.

[11] P. Pagliaro, M. B. Prime, H. Swenson, and B. Zuccarello, “Measuring Multiple Residual-Stress Components using the Contour Method and Multiple Cuts,” *Exp. Mech.*, vol. 50, no. 2, pp. 187–194, 2010.

[12] F. Hosseinzadeh, P. A. 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.

[13] M. B. Prime, R. J. Sebring, J. M. Edwards, D. J. Hughes, and P. J. Webster, “Laser surface-contouring and spline data-smoothing for residual stress measurement,” *Exp. Mech.*, vol. 44, no. 2, pp. 176–184, 2004.

[14] M. B. Prime and A. L. Kastengren, “The Contour Method Cutting Assumption: Error Minimization and Correction,” in *SEM Annual Conference & Exposition on Experimental and Applied Mechanics*, 2010.

[15] W. Cheng, I. Finnie, M. Gremaud, and M. B. Prime, “Measurement of Near Surface Residual Stresses Using Electric Discharge Wire Machining,” *J. Eng. Mater. Technol.*, vol. 116, no. 1, pp. 1–7, Jan. 1994.

[16] Y. Traore, P. J. Bouchard, J. A. Francis, and F. Hosseinzadeh, “A Novel Cutting Strategy for Reducing Plasticity Induced Errors in Residual Stress Measurements Made with the

Contour Method - PVP2011-57509," in *American Society of Mechanical Engineers, Proceedings of the ASME, Pressure Vessels and Piping Division*, 2011.

[17] ABAQUS, "ABAQUS/Standard Documentation Version 6.10.2," 2010.

[18] Y. Traore, "Controlling plasticity in the contour method of residual stress measurement," Ph.D. Thesis. The Open University, UK, 2013.

8 FIGURES

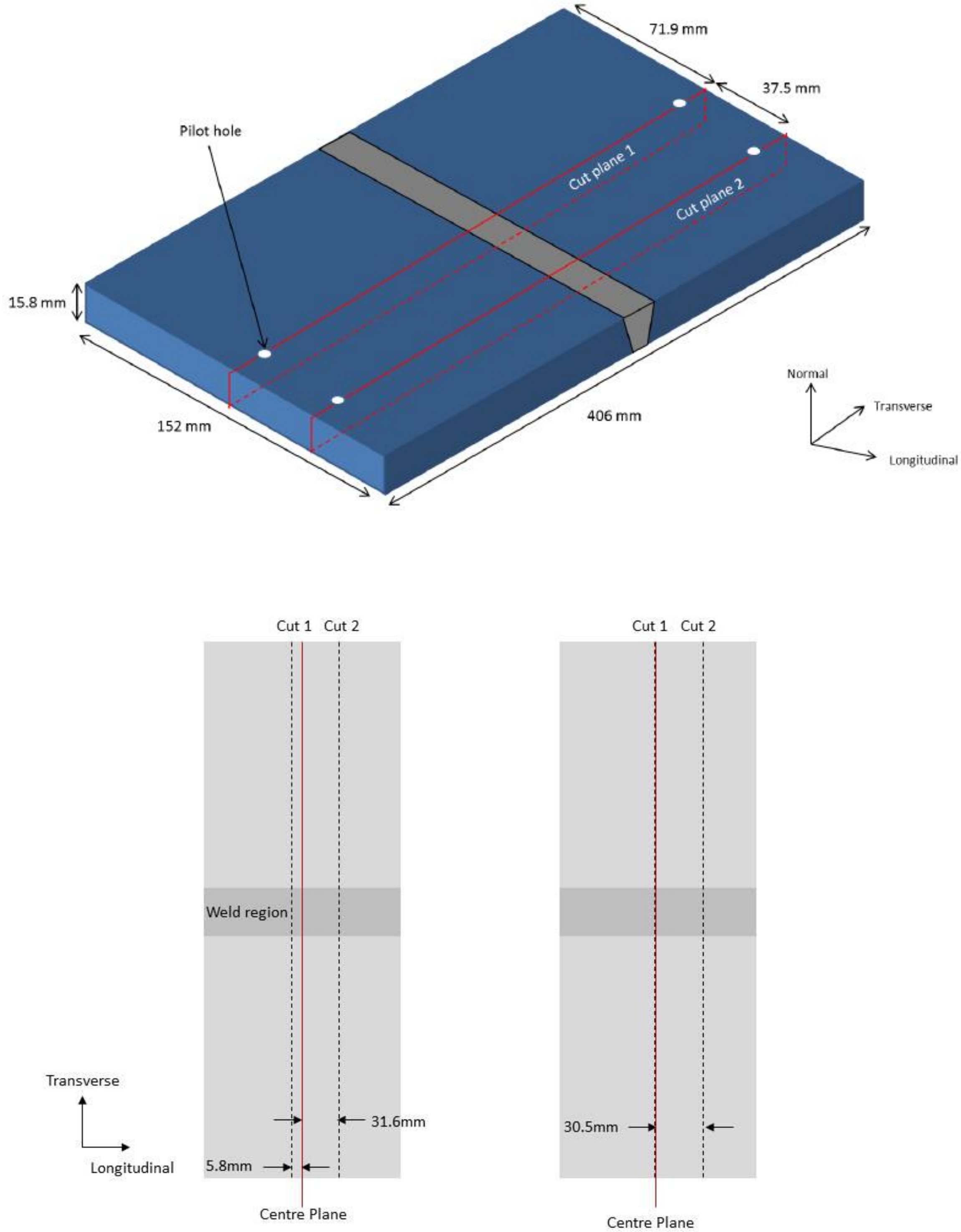


Figure 1: Schematic illustration of the 'as-welded' (left) and repaired (right) components with cut planes. Pilot holes were positioned approximately 5 mm from the end of each cut plane.

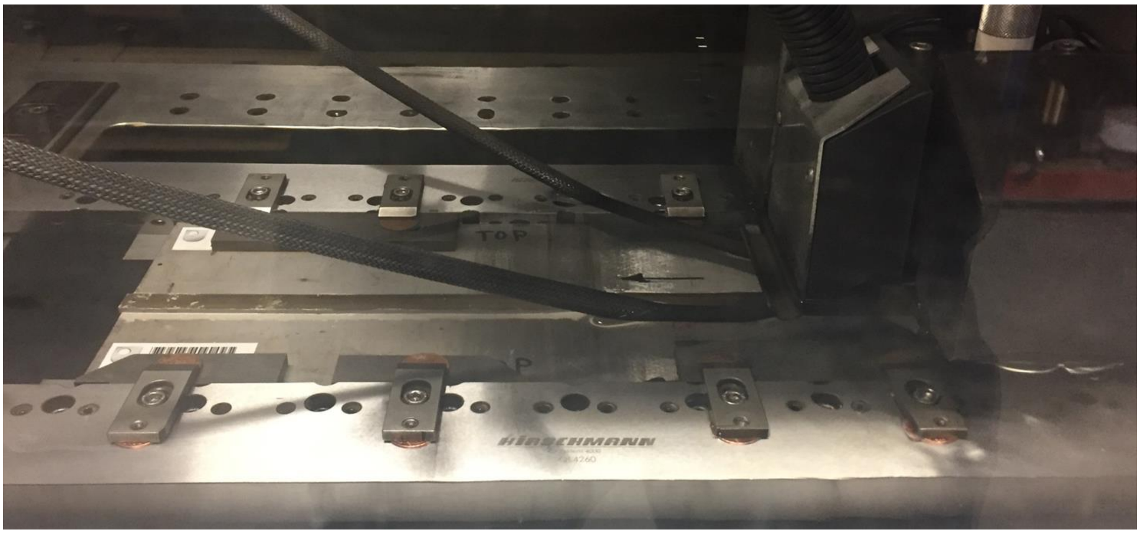


Figure 2: Picture showing wire EDM cutting operation.

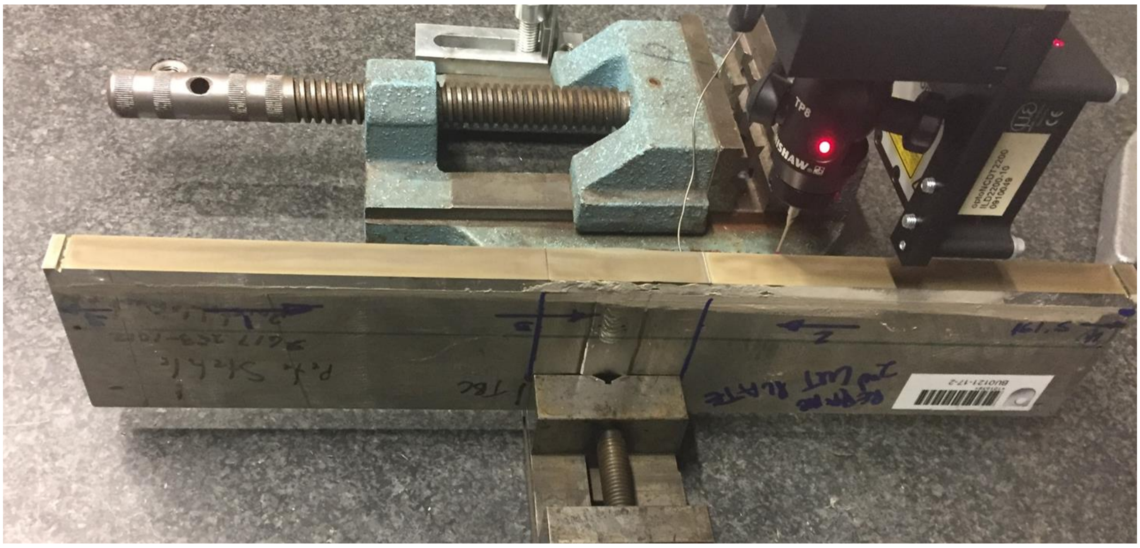


Figure 3: Picture showing surface measurements using a laser hybrid CMM.

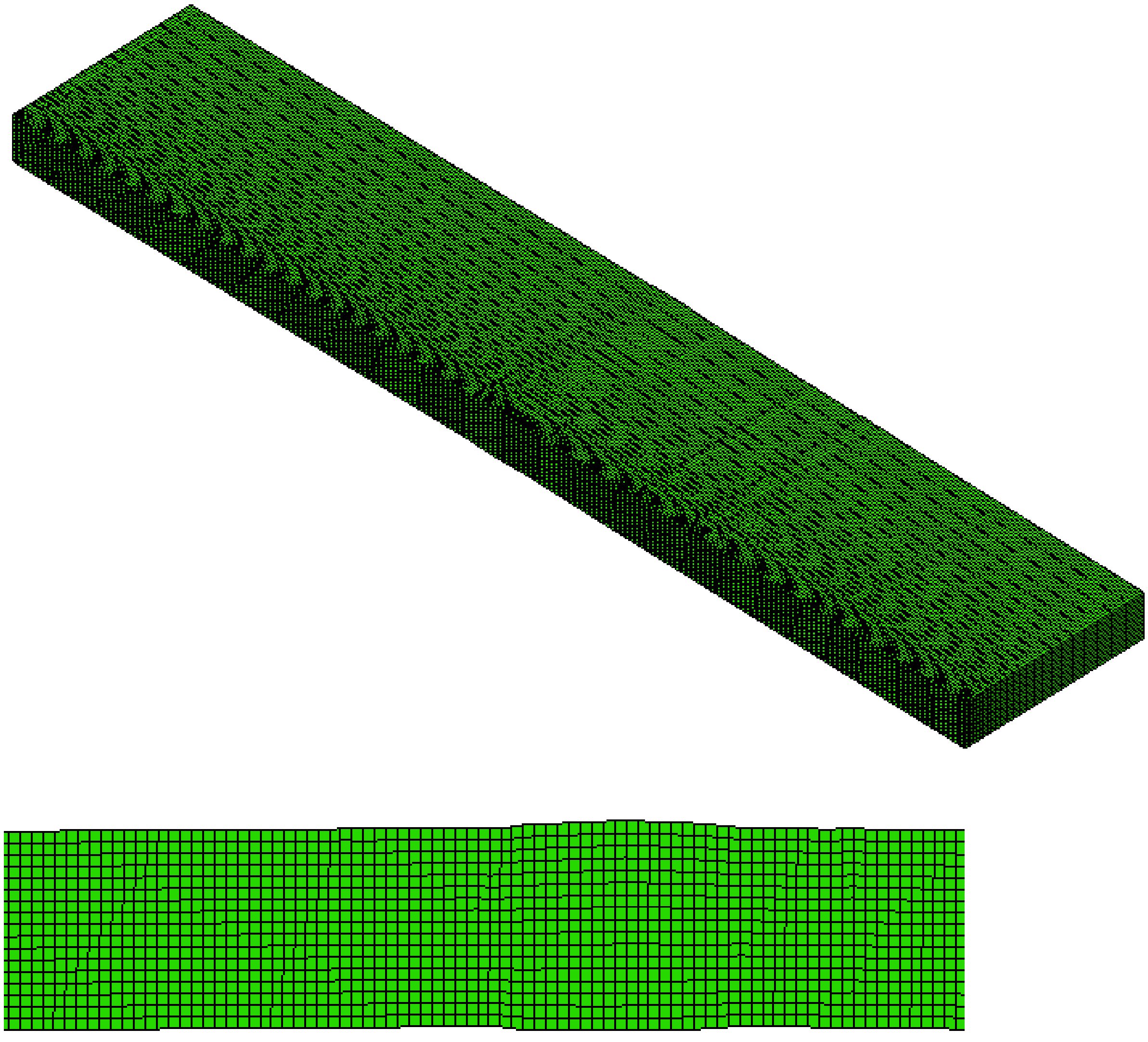


Figure 4: Finite element model mesh for the as-welded and repaired plate. A uniform mesh size of 1 mm was used on the cut face with a bias in the extrusion direction.

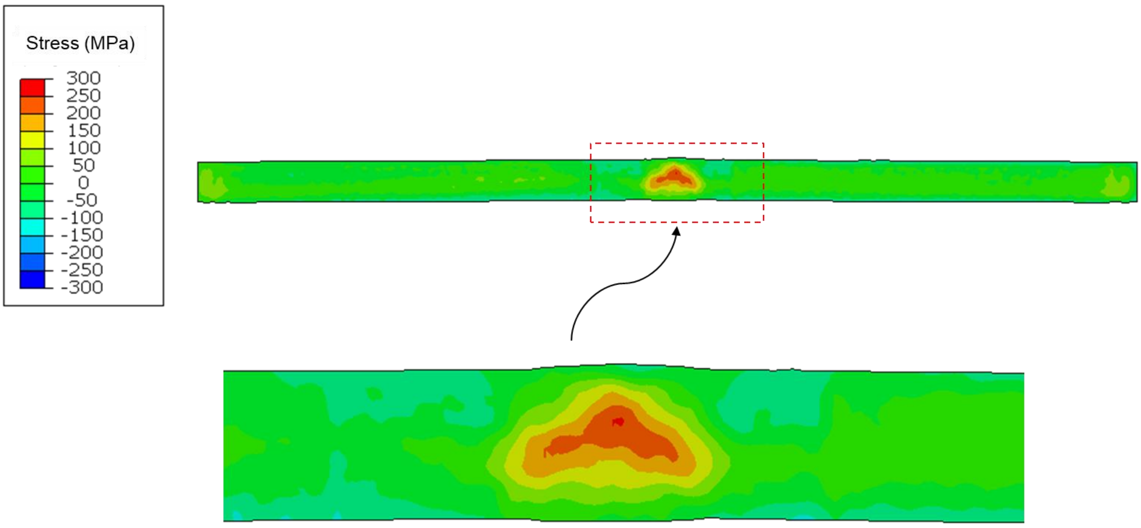


Figure 5: Longitudinal stress map for cut 1 in the ‘as-welded’ plate.

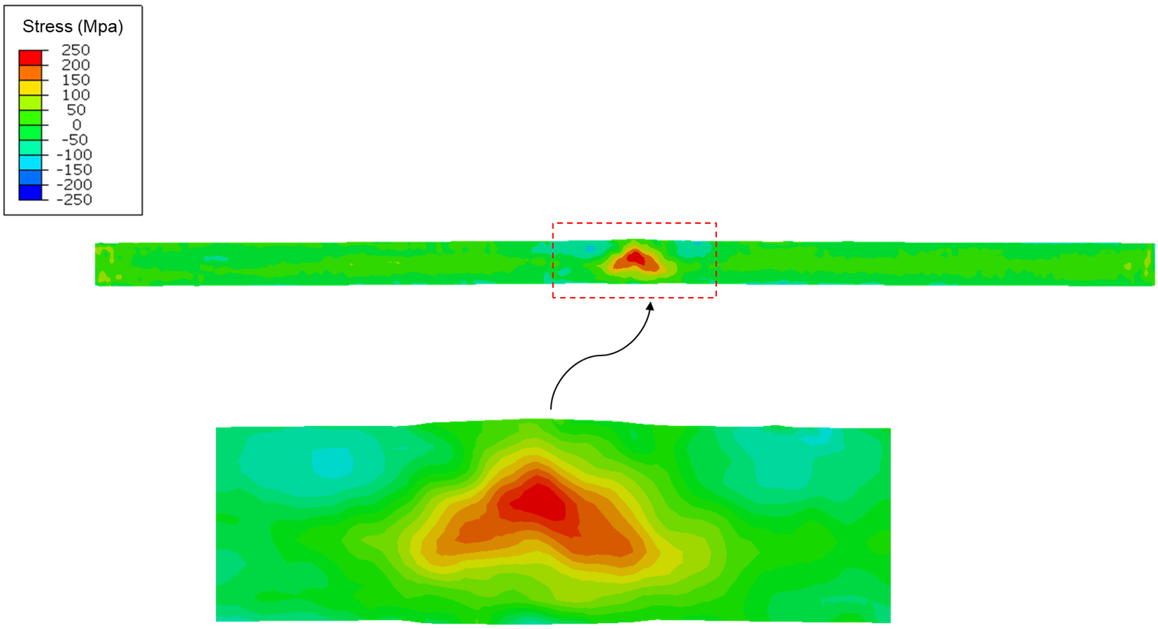


Figure 6: Longitudinal stress map for cut 2 in the ‘as-welded’ plate.

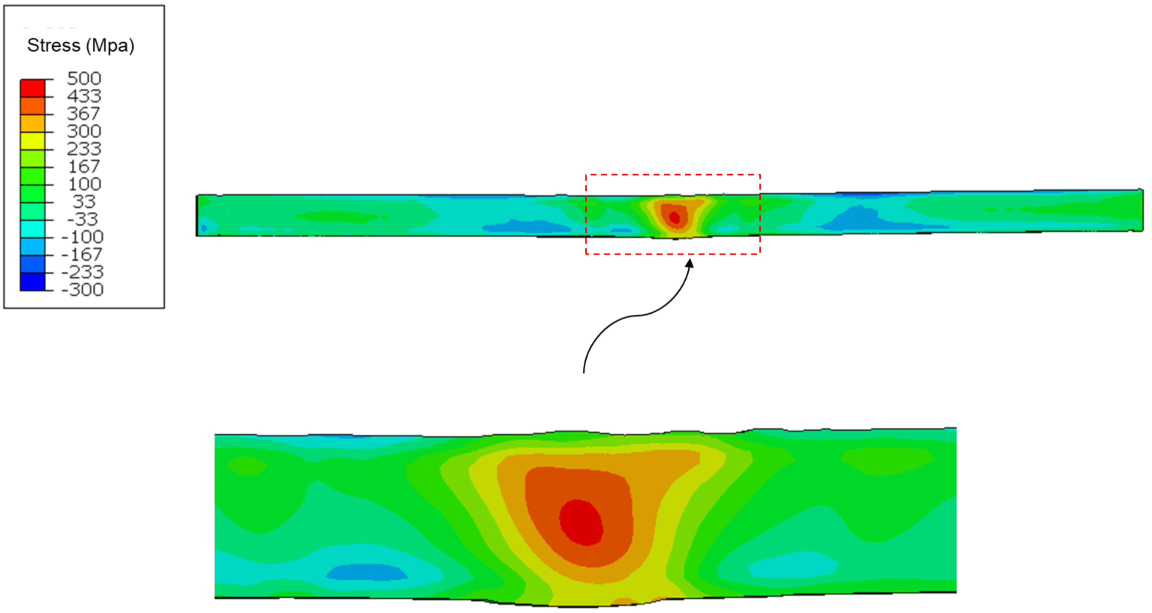


Figure 7: Longitudinal stress map for cut 1 in the repaired plate.

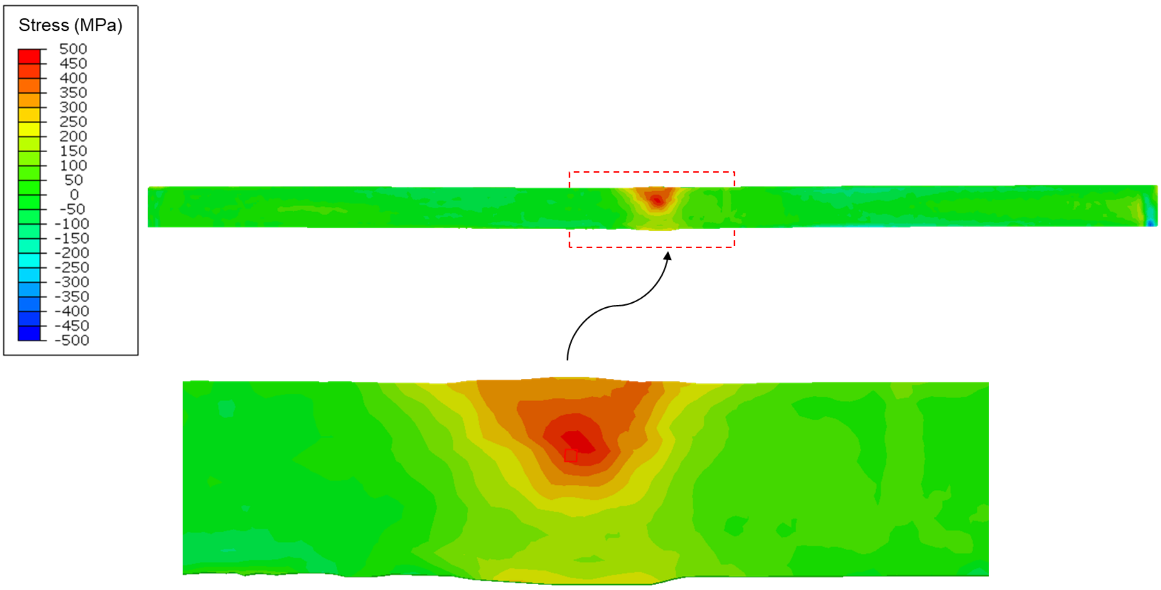


Figure 8: Longitudinal stress map for cut 2 in the repaired plate.

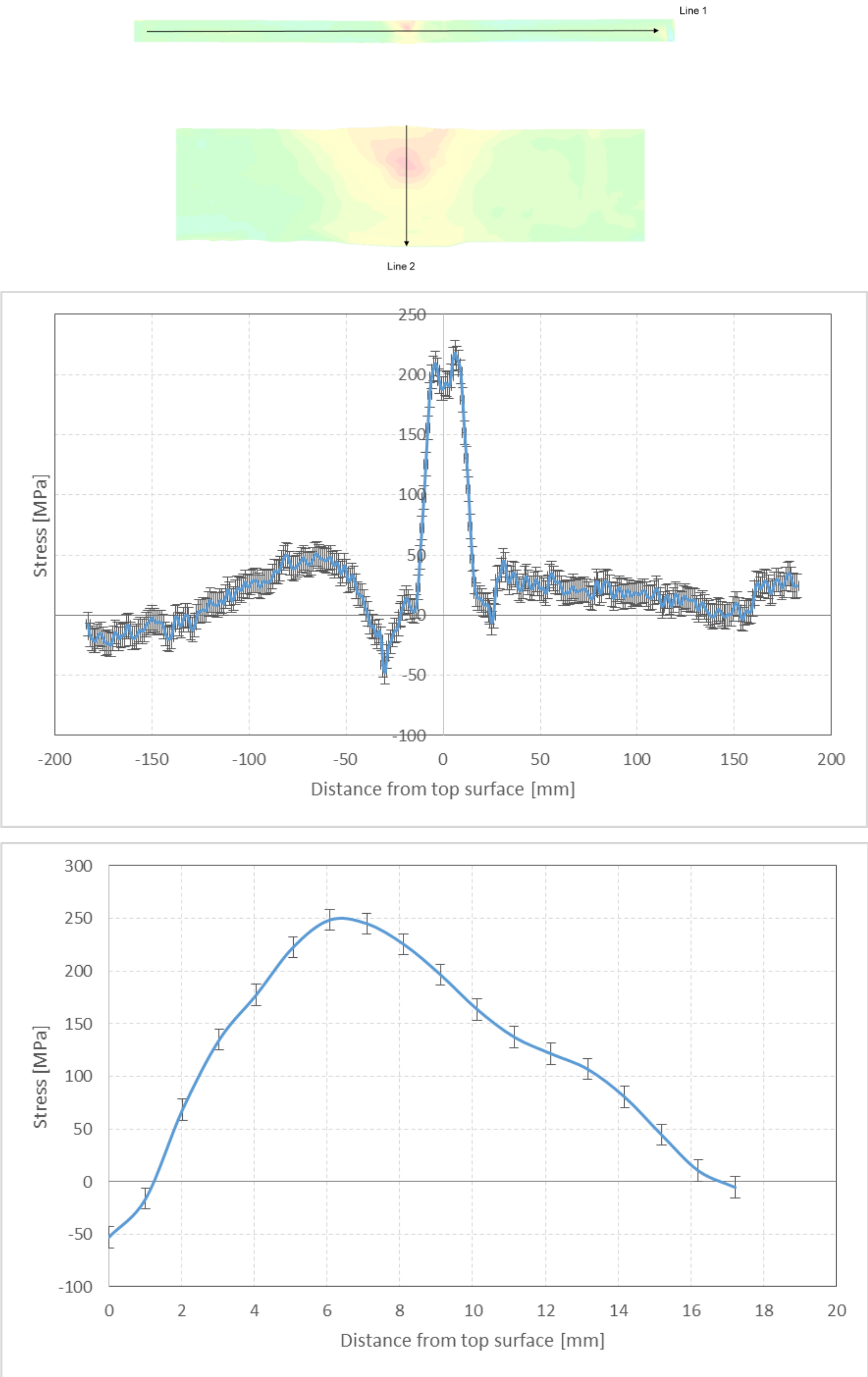
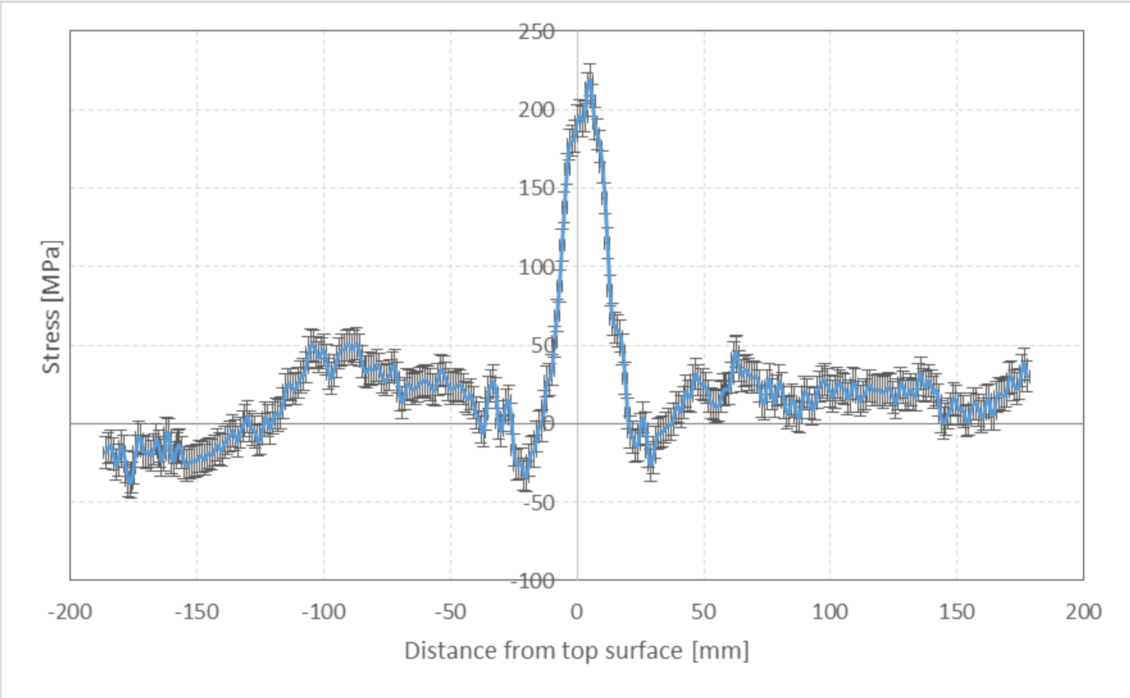


Figure 9: Line profile of longitudinal residual stress extracted from cut 1 in the 'as-welded' condition; Line 1 (top) and Line 2 (bottom).



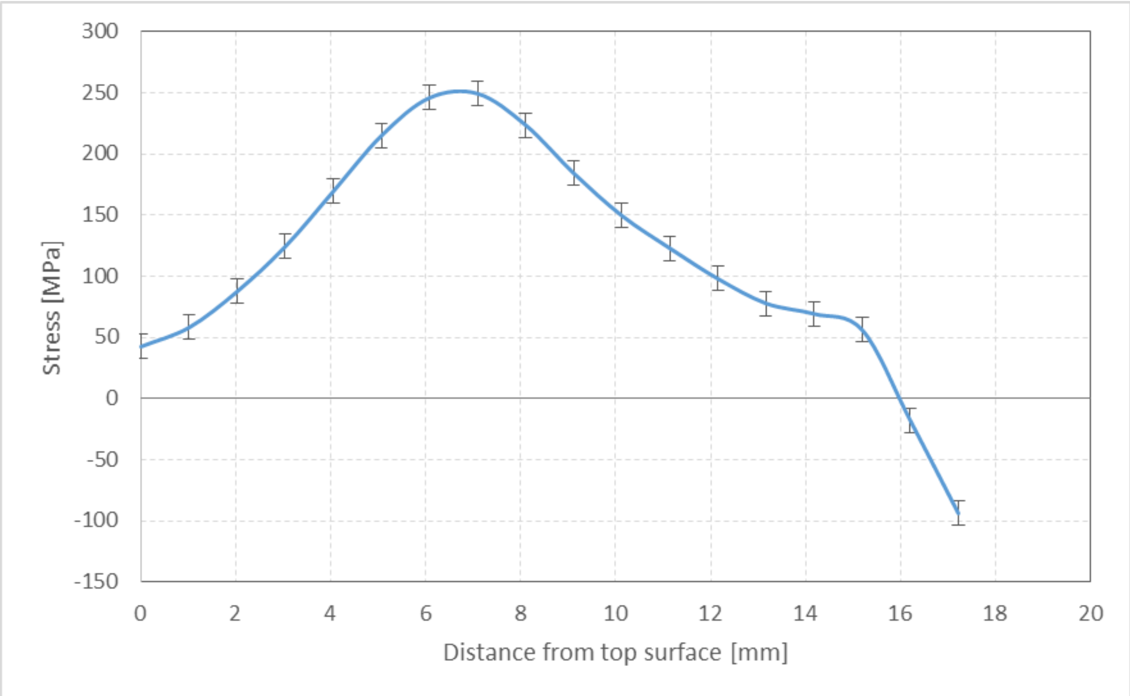
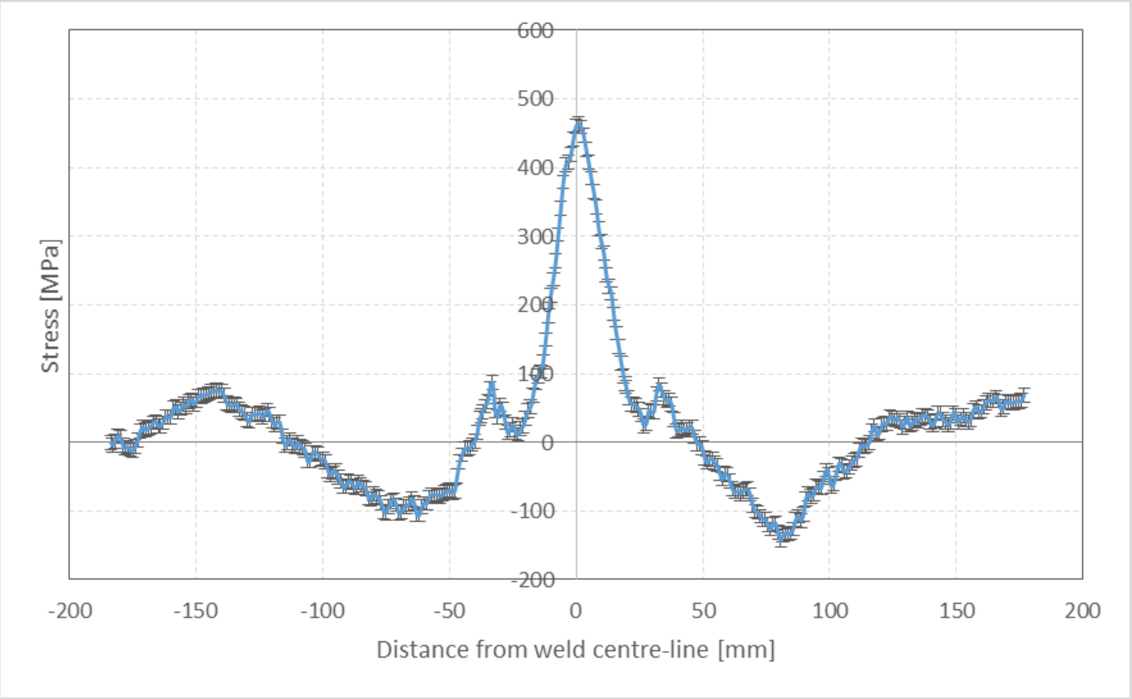


Figure 10: Line profile of longitudinal residual stress extracted from cut 2 in the ‘as welded’ condition; Line 1 (top) and Line 2 (bottom).



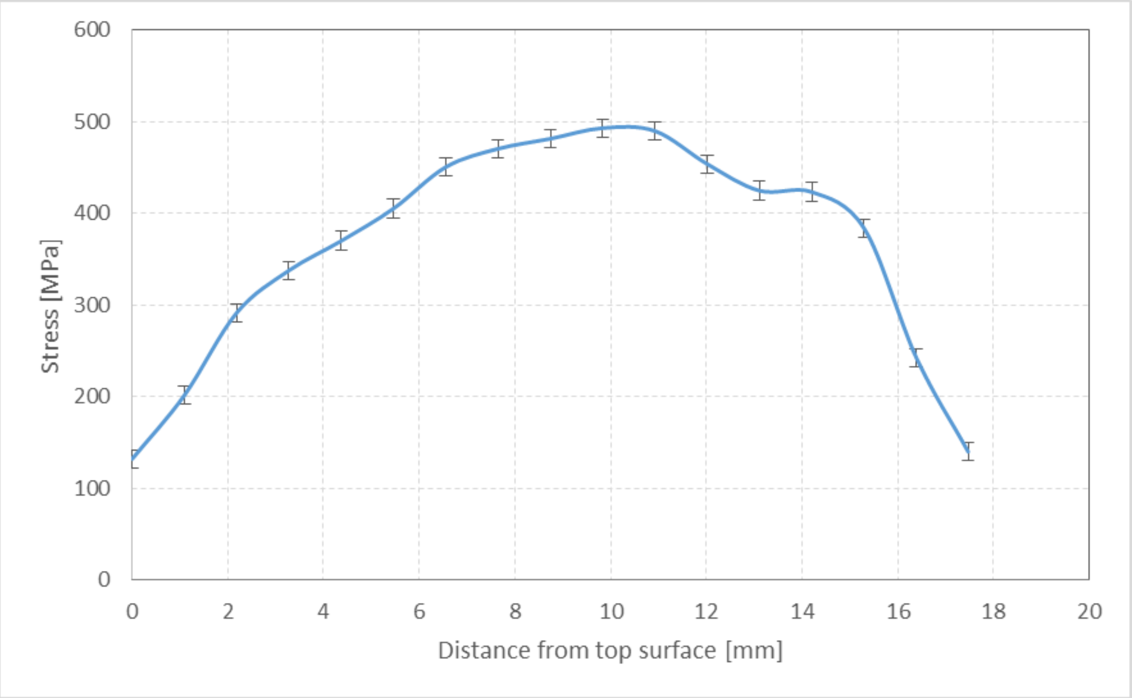
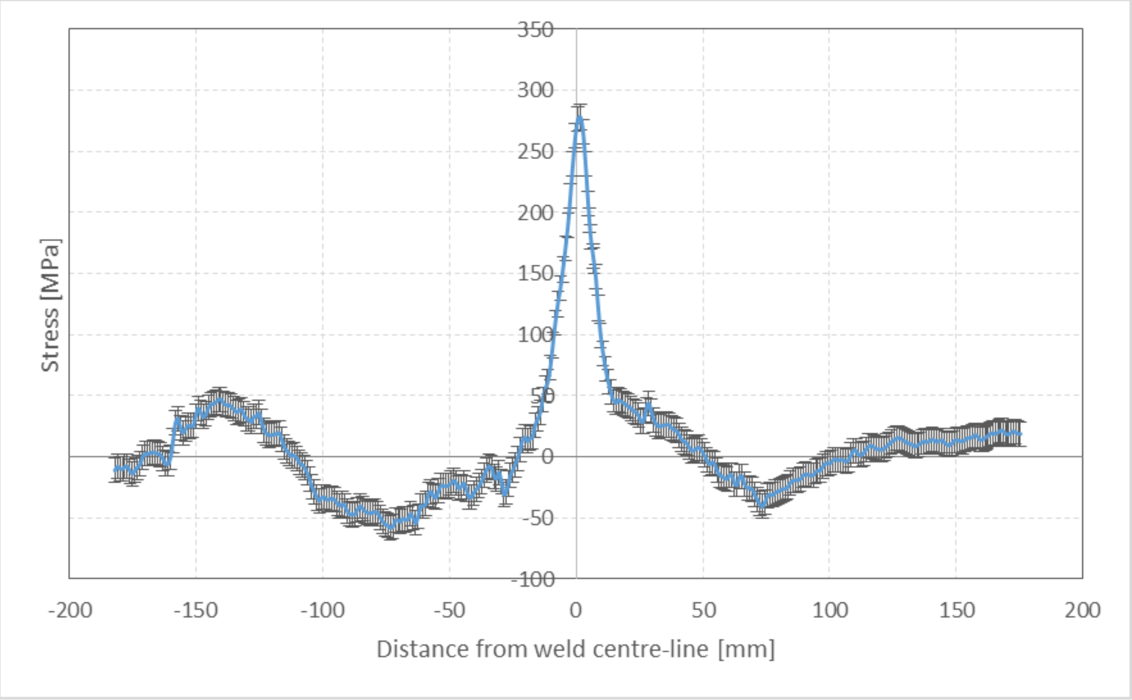


Figure 11: Line profile of longitudinal residual stress extracted from cut 1 in the 'repaired' condition; Line 1 (top) and Line 2 (bottom).



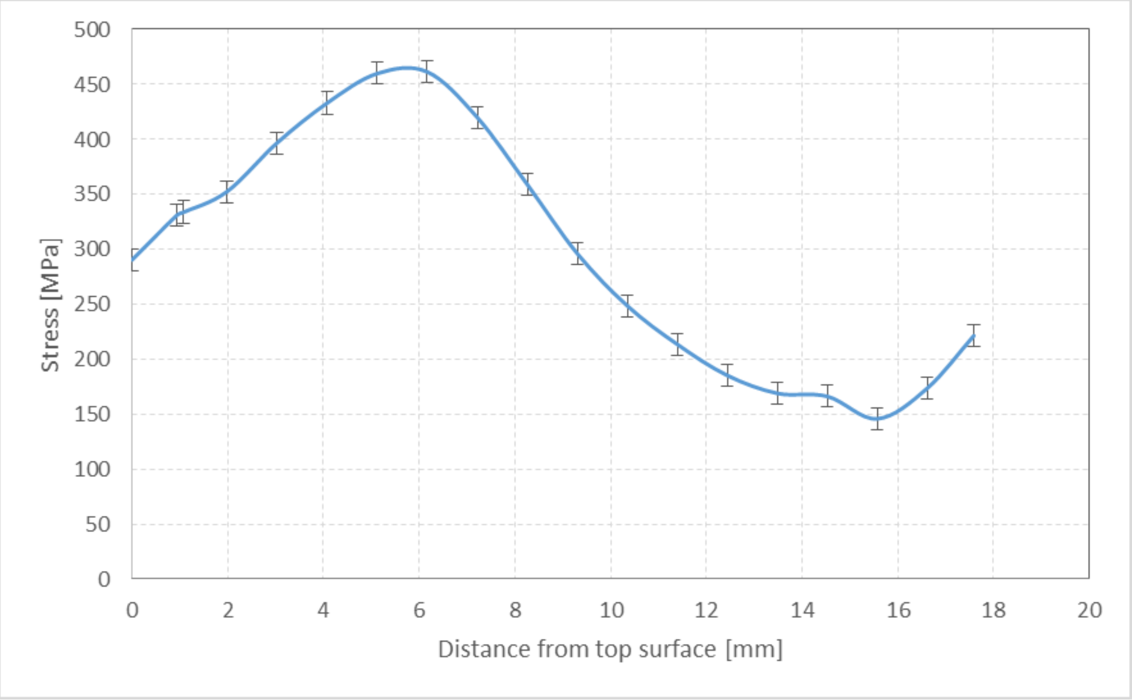


Figure 12: Line profile of longitudinal residual stress extracted from cut 2 in the 'repaired' condition; Line 1 (top) and Line 2 (bottom).