Application of the Contour Method to NeT weld components

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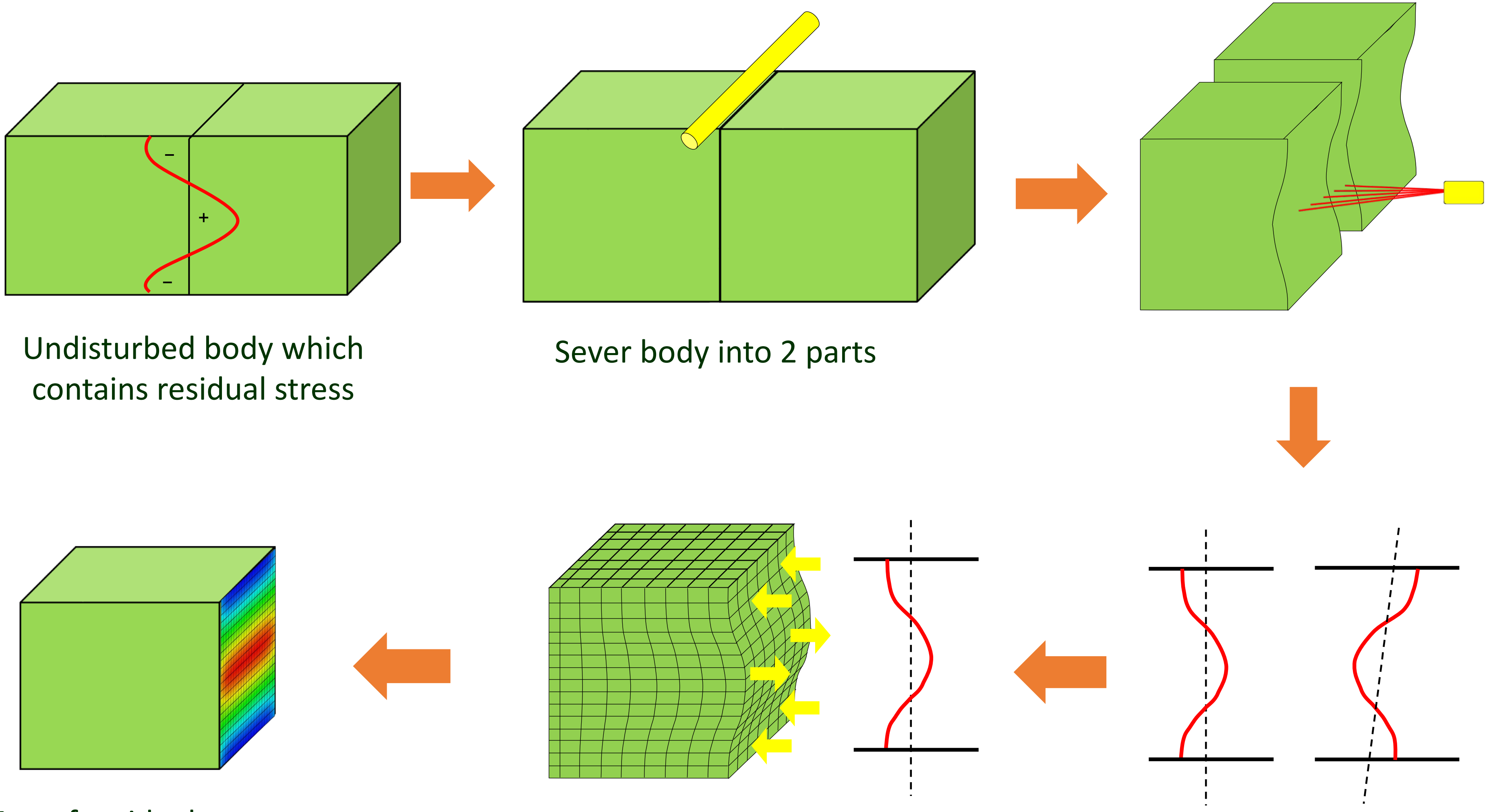
Life-changing Learning

THE CONTOUR METHOD

- **Invented** by Dr Mike Prime (Los Alamos): first presented at ICRS6 in Oxford, 2000 and published in J. Engng Mater. Tech., 2001
- **Wide range of applications:** welds, forgings, quenched plates, etc.
- **Advantages:** provides a full cross-sectional map of stresses, insensitive to microstructure, relatively time and cost effective, hybrid methods
- **Disadvantages:** destructive, sensitive to the cutting process, data processing dependent, susceptible to bulging and plasticity errors
- **Applied to Net Components:** TG1, TG4, TG5, TG6……

The Contour Method



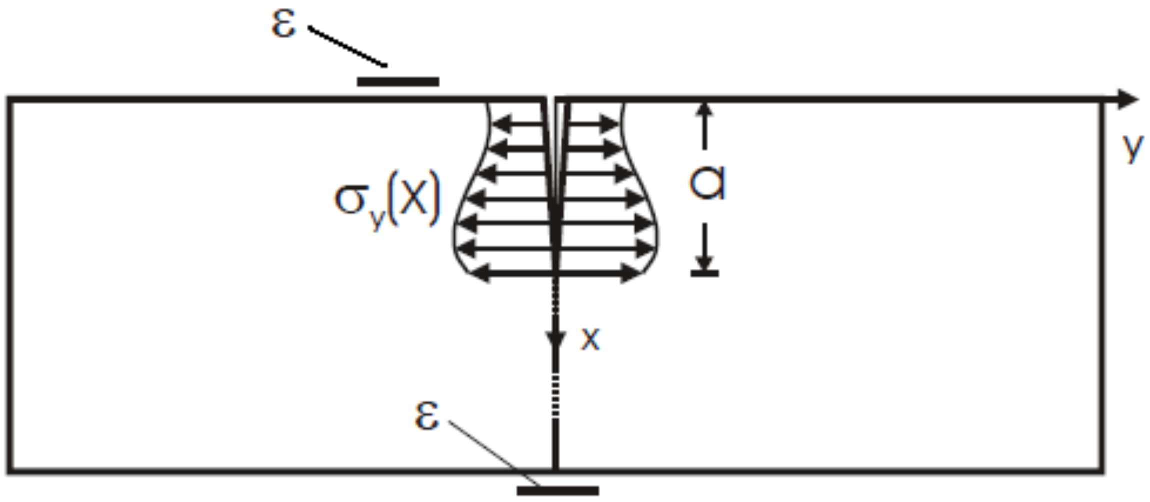
Undisturbed body which contains residual stress

Sever body into 2 parts

Map of residual stress on surface where severed

Data analysis

THE SLITTING METHOD



Assumptions

- Linear elastic stress re-distribution during cutting
- The slit behaves like a perfect edge-crack in 2D (constant width) structure (LEFM conditions)

- A slit is incrementally introduced into a part containing residual stress
- At each slit increment, a_i , strain relaxation on the bottom surface of the part is measured using strain gauges
- A fracture mechanics approach can be used to back-calculate the residual stress relieved giving width-averaged stress profile normal to the plane of the cut

Application to NeT TG5: Edge Welded Beam

- NeT Task Group 5 (TG5) studied the development of residual stresses in a simply supported beam (50.8 mm deep x 180 mm long x 10 mm thick) made from SA508 Gr 3 low alloy steel where a single autogenous weld pass was applied along the top surface.
- Two sets of test specimens were made using “Slow” and “Fast” welding speeds under carefully recorded conditions.
- Several NeT partners carried out computational weld mechanics analyses to simulate the development of the microstructure and final residual stress state.
- Other NeT partners undertook diverse residual stress measurements.
- The next few slides presents details of strain relief measurements carried out by The Open University using a **Hybrid-Slitting-Contour approach**.

NeT TG5:- Acknowledgements

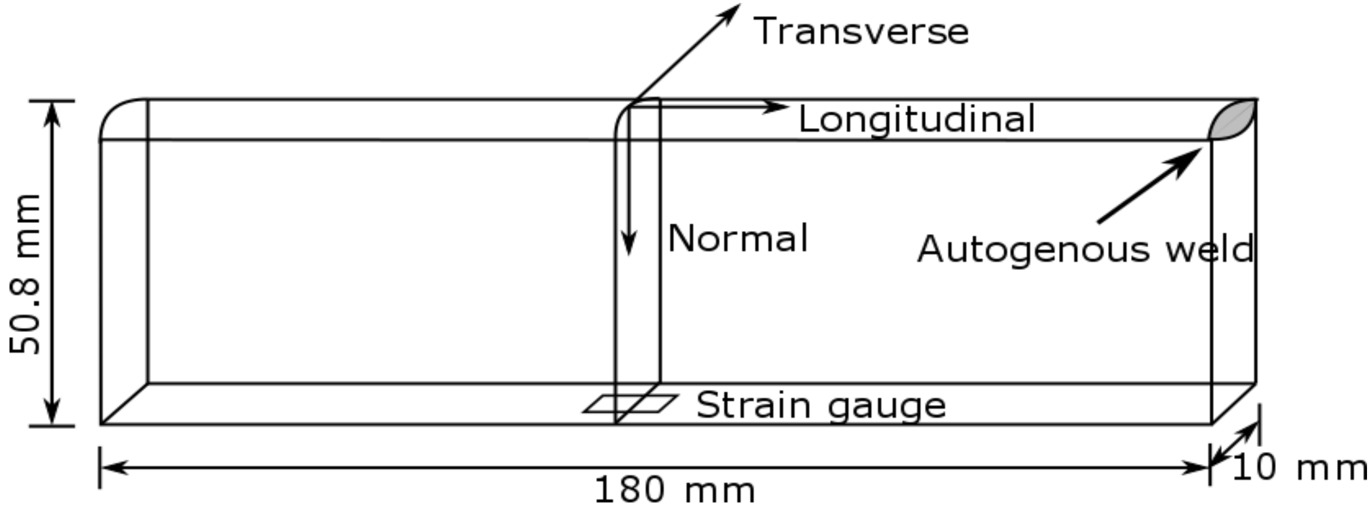
- NeT Task Group TG5 was led by Steve Bate (Jacobs)
- The following organisations contributed to TG5
  - Joint Research Centre (JRC), Petten
  - FRM II, TU München
  - Helmholtz-Zentrum Berlin (HZB)
  - The Australian Nuclear Science Technology Organisation (ANSTO)
  - The Open University (OU)
  - The University of Manchester
  - Jacobs
  - IHI Corporation

TG5: TEST COMPONENT

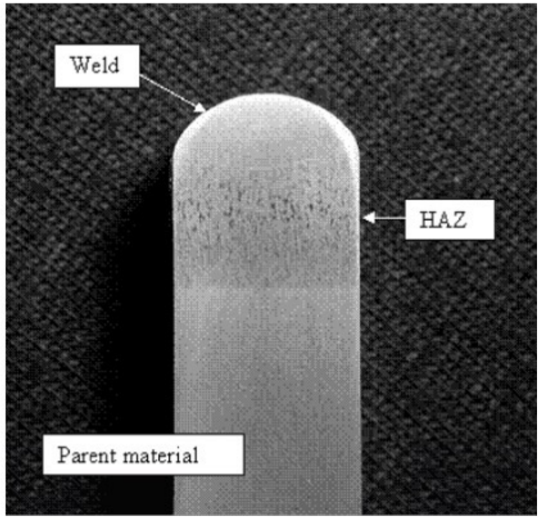
Welded edge

Photograph of SA508 ferritic edge-welded beam benchmark specimen from *[1]*

- Material: SA508 Gr. 3 C1.1 ferritic steel.
- Single-pass autogenous TIG weld was applied with 'slow' welding parameters.
- Run-on and run-off tabs used to create "steady-state" welding along the beam



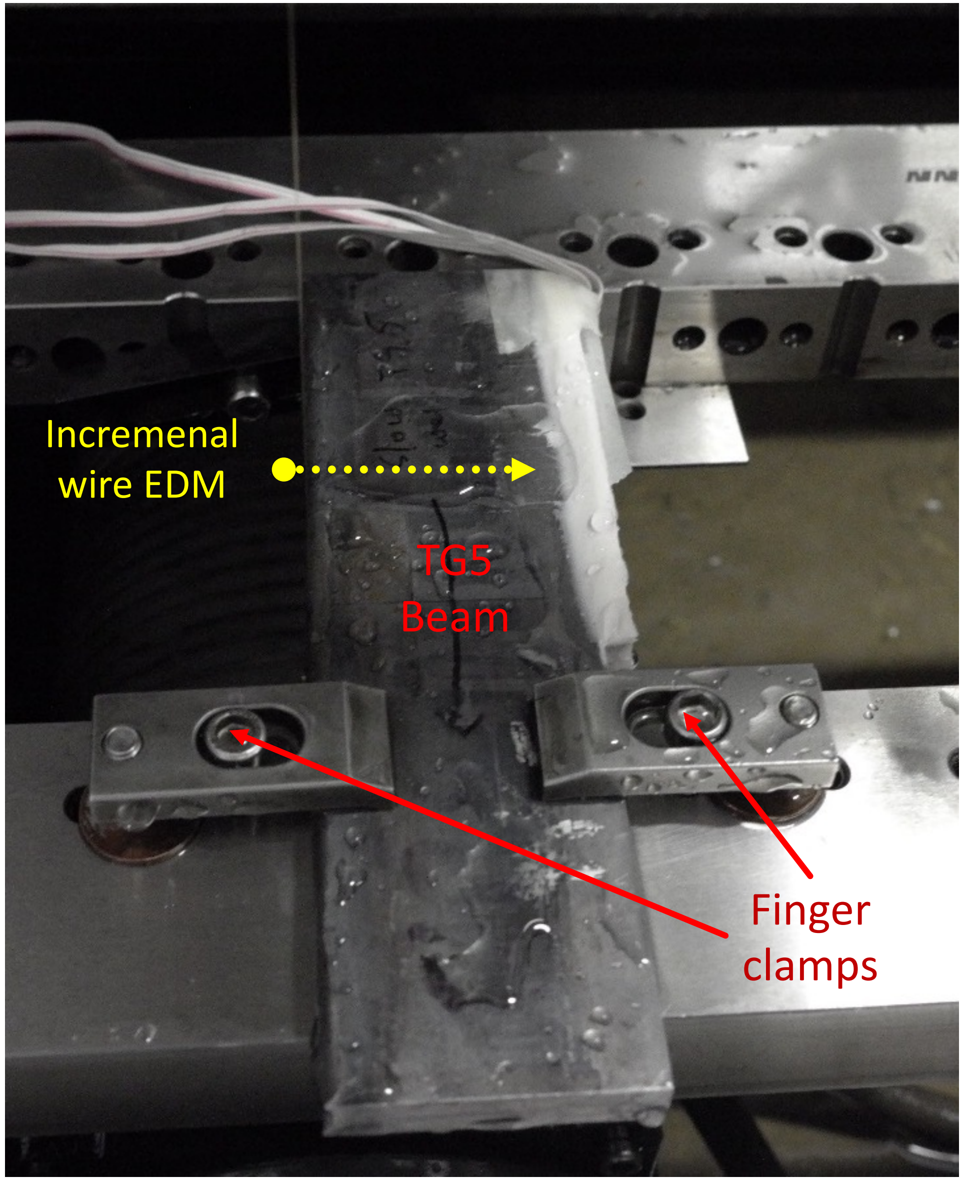
Schematic diagram of geometry and coordinate system of the specimen



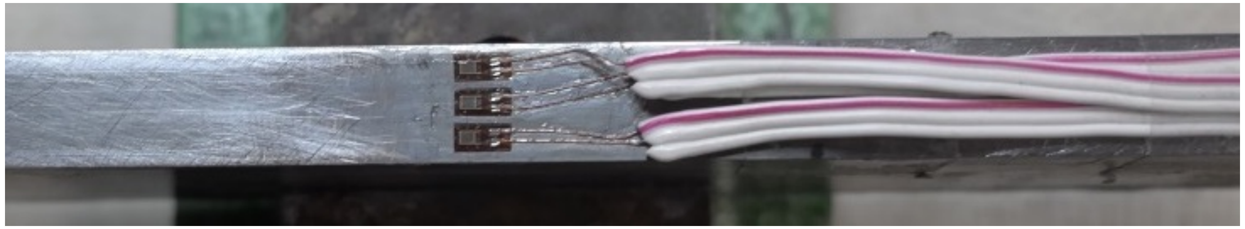
Weld macrograph from *[1]*

[1] Smith MC, Bate SK, Bouchard PJ. In: ASME 2013 pressure vessels & piping conference, Paris, France, 2013; p. 15.

TG5: Prep for Slitting/Contour Measurement

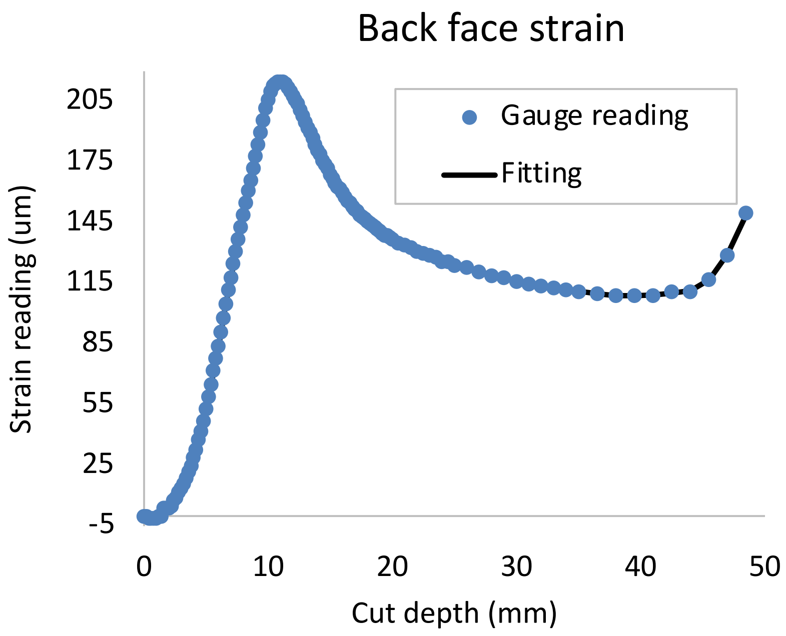


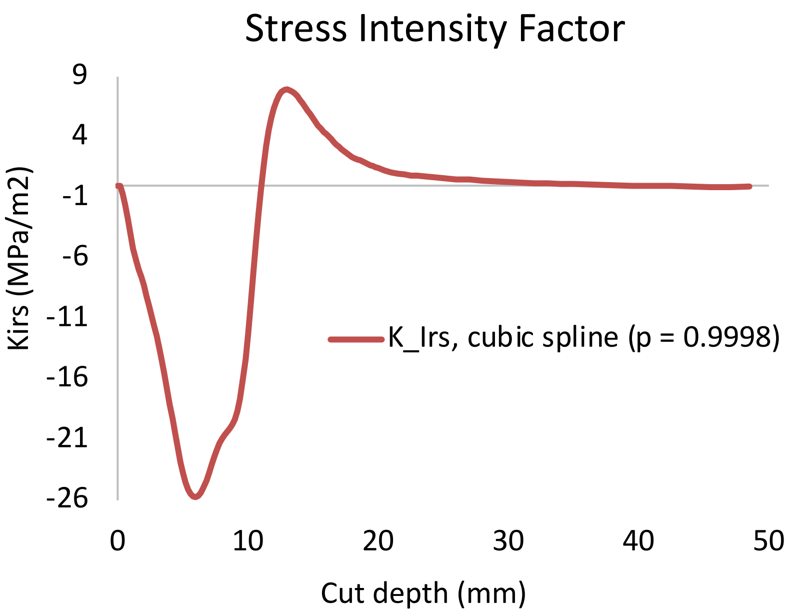
- 3 strain gauges fitted to base of beam ahead of cut

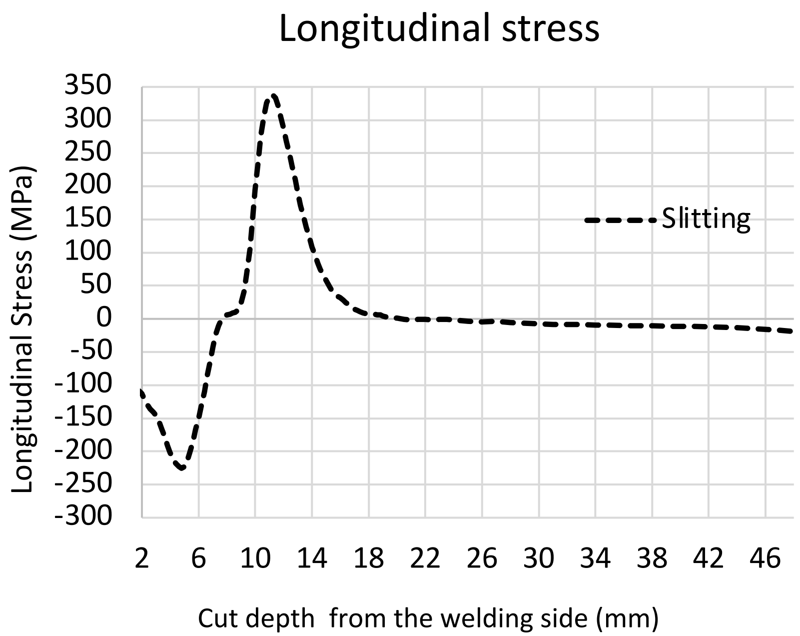


- Wire EDM set-up for cutting is shown (left)
- Wire diameter: 0.15 mm brass
- Specimen was finger clamped on one side of the cut (not ideal for contour cut)
- Cut increments varied from 0.1 mm near the weld crown to 1 mm deep within the beam
- Strains were recorded after the readings stabilised to within 1-2 microstrain
- The final ligament (2mm) of the sample was fractured

SLITTING METHOD DATA ANALYSIS





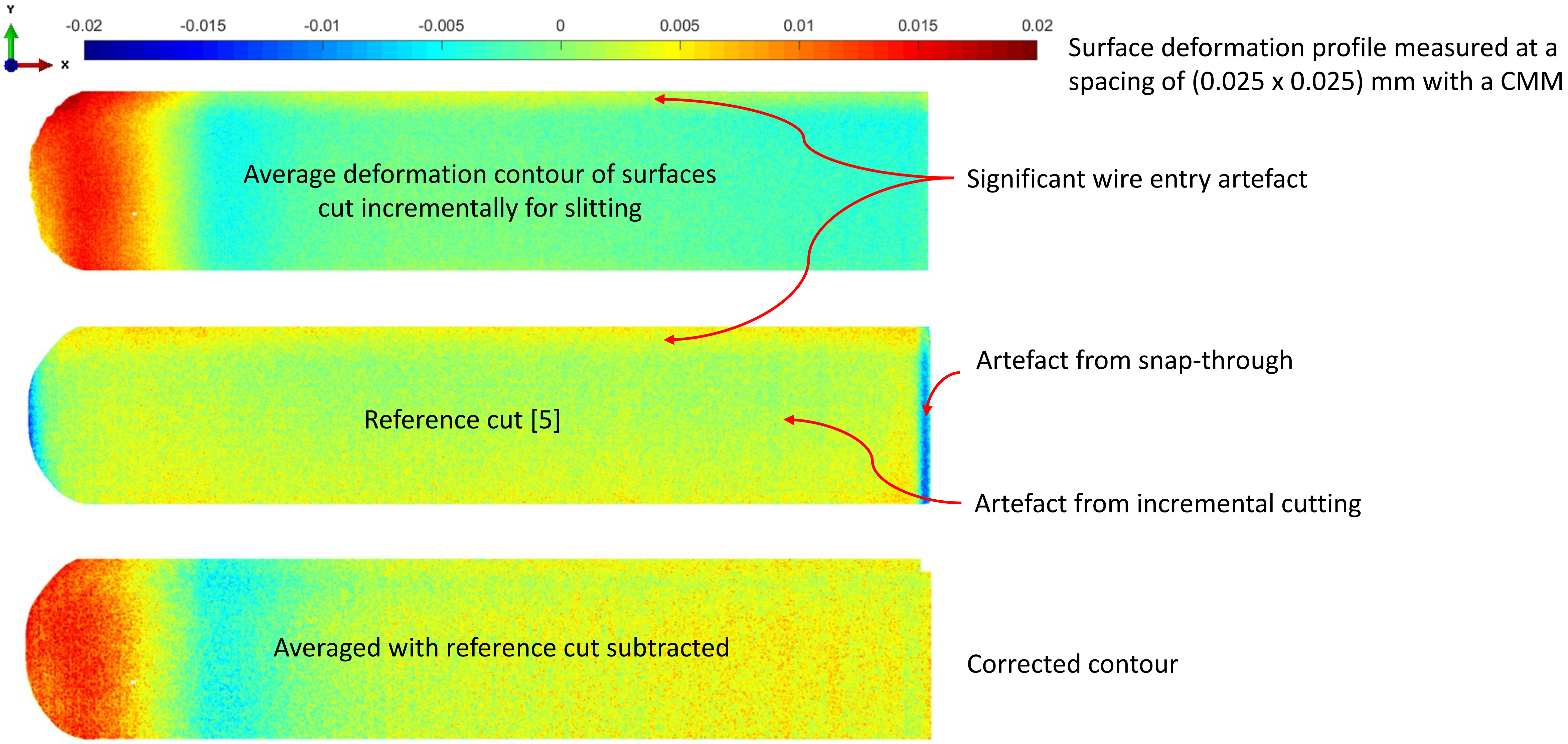


$$K_{Irs}(a) = \frac{E'}{Z(a)}\frac{d\epsilon}{da}$$ [2]

$$K_{Irs}(a) = \int_{a_0}^{a} h(x,a)\sigma_y(x)dx$$ [2,4]

*[2] Schindler, H.J., W. Cheng, and I. Finnie,. Experimental mechanics, 1997. **37**(3): p. 272-277.*
[3] F. Hosseinzadeh, M. B. Toparli, and P. J. Bouchard, J. Press. Vessel Technol. ASME, vol. 134, no. 1, Feb. 2012
[4] Fett, T, D. Munz, Stress Intensity factors and Weight functions. 1977, Southampton UK and Boston USA: Computational Mechanics Publications

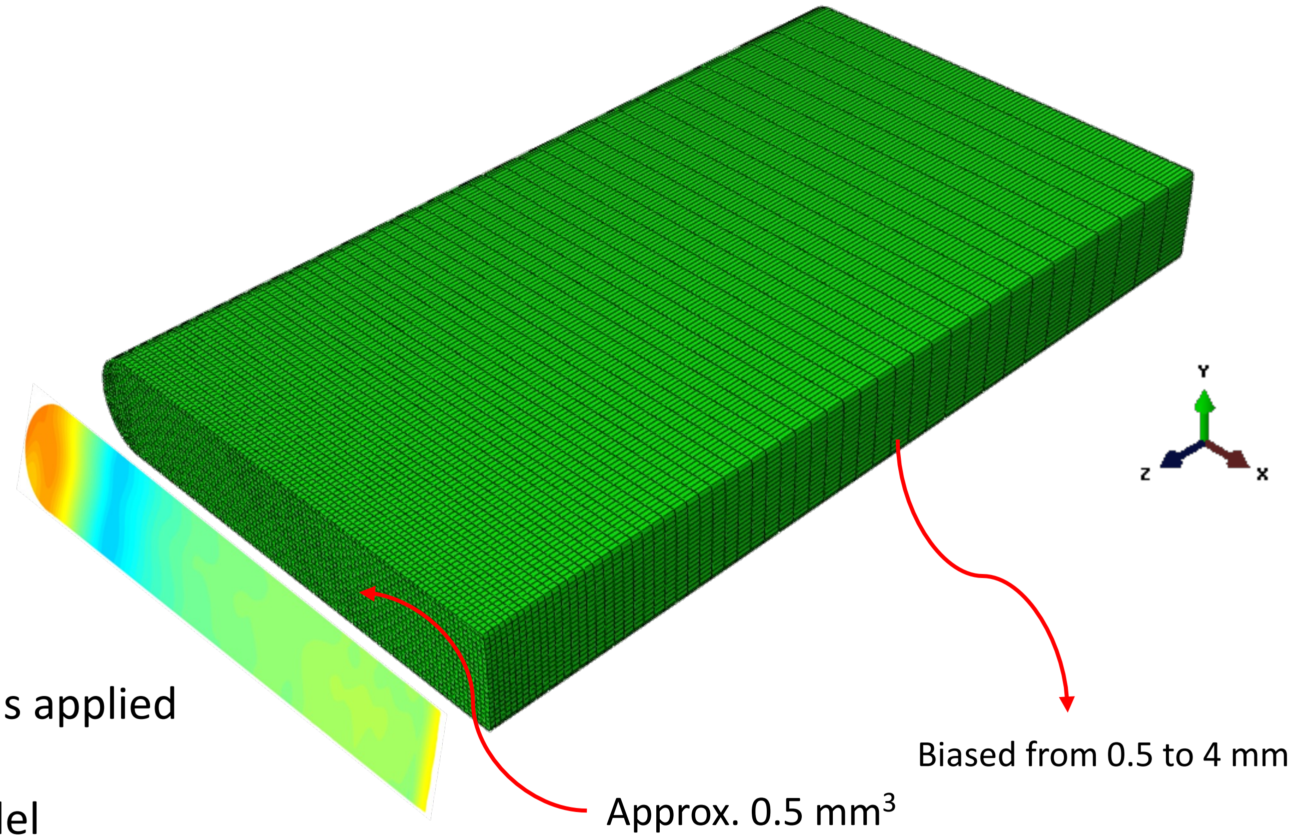
TG5 Contour Method Deformation Results



[5] Prime, M.B., Journal of engineering materials and technology, 2001. ***123****(2): p. 162-168*

TG5 Contour Smoothing

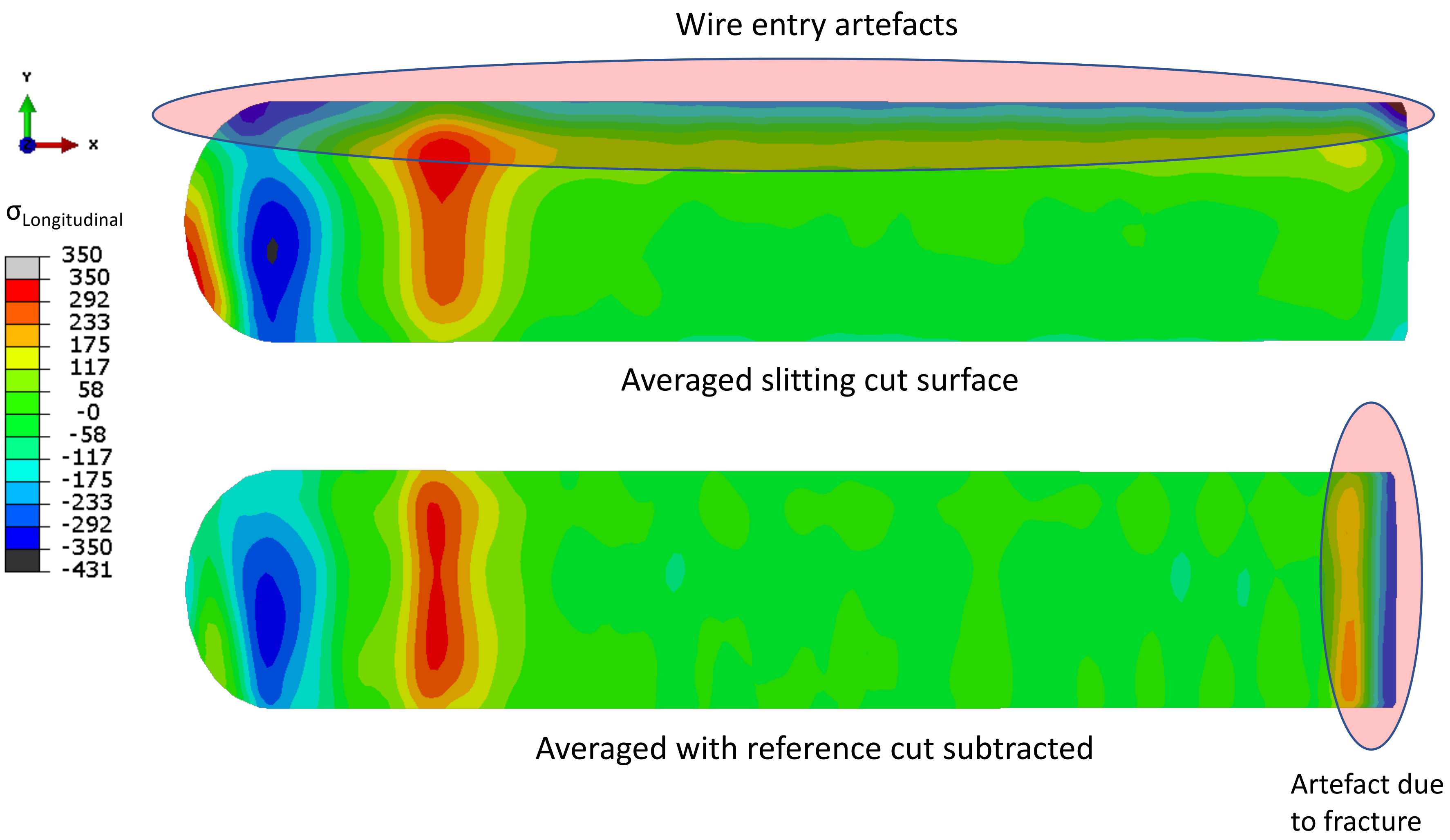
- Median smoothing (StressMap proprietary method [6]) is used with the mask size of 1.5 mm x 3 mm
- Total of about 107,400 hexahedral elements with reduced integration were used to generate mesh (C3D8R).
- Homogeneous isotropic elastic properties assumed: Young's modulus: 199 GPa and Poisson's ratio: 0.29



Smoothed displacement data was applied as boundary conditions on the corresponding surface of FE model

[6] J Araujo de Oliveira, J. James, A. Achouri, S. Paddea, Y. Traore, B. Stewart,F. Hosseinzadeh, and P. J. Bouchard "Contour method data analysis case study" in proc on 10th Int Conf on Residual Stresses (Presentation), 2016, Sydney, Australia.

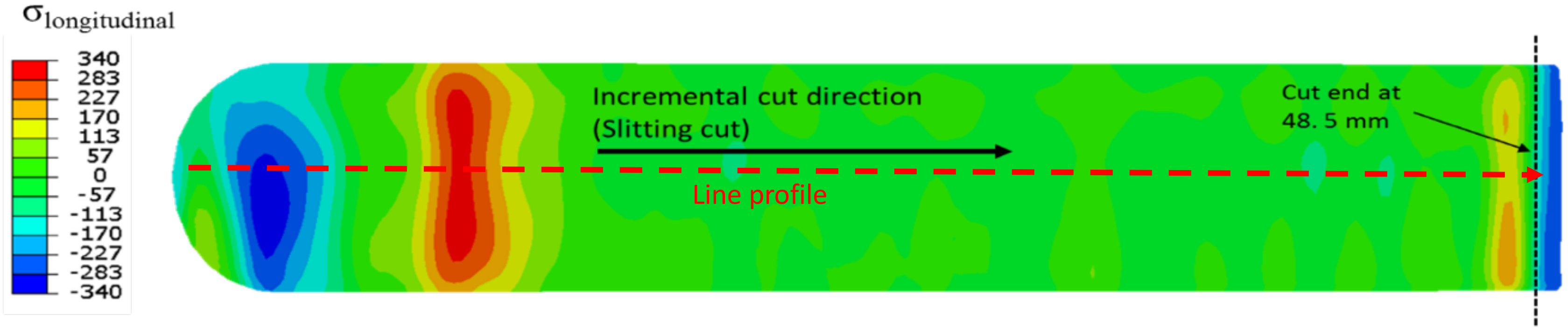
TG5 Contour Method Results

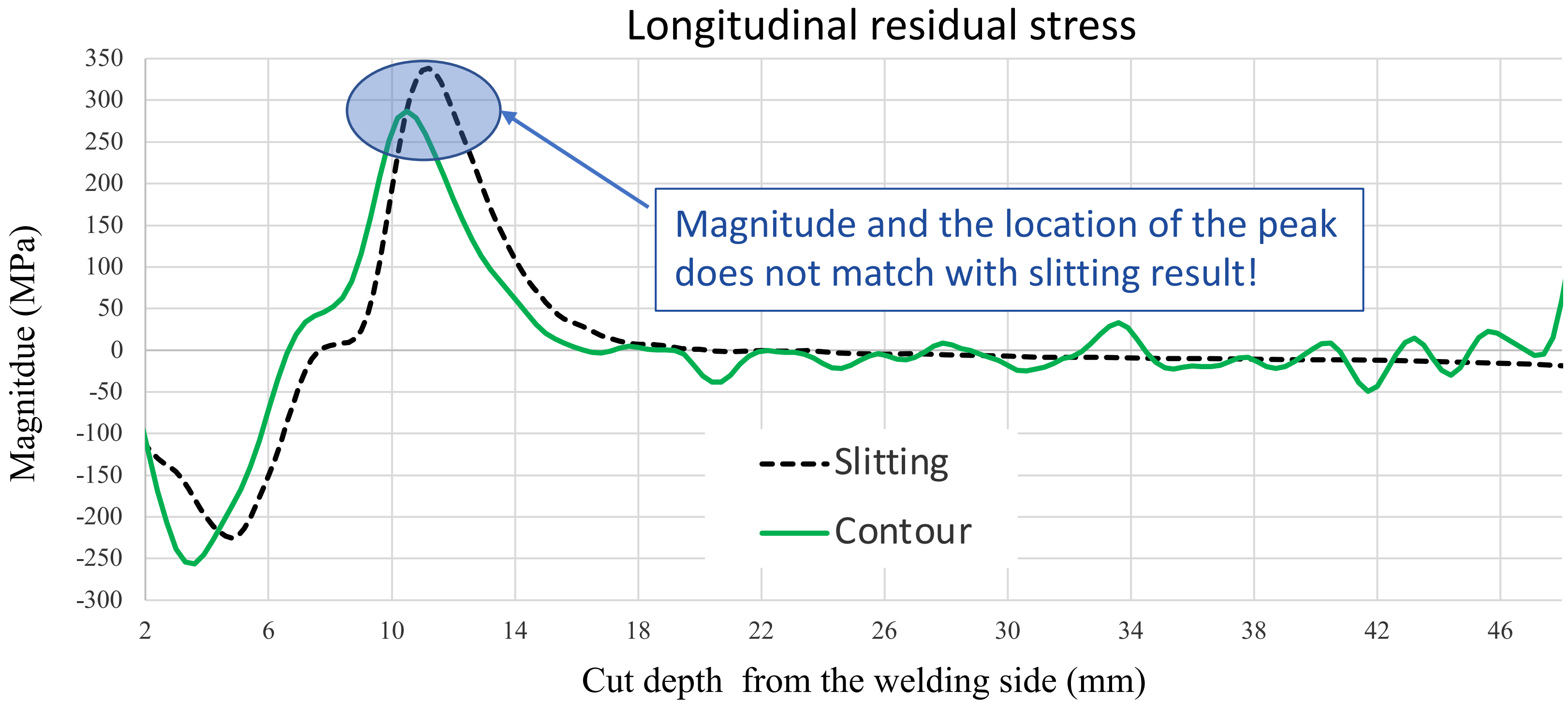


Wire entry artefact errors has been mitigated by using a reference cut analysis

Significant errors observed at the end of the EDM cut where the specimen was broken open.

TG5 Contour Method Results





- Generally agreed well with neutron diffraction results
- The peak tensile stress was 335 MPa from slitting.

CONTOUR METHOD BULGE ERROR

- **Cutting assumption**: the width of the cut is constant, when measured relative to the state of the body prior to cutting.
- However, the width of the cut is affected by the stress concentration at the cut tip that elastically stretches or contracts the material about to be cut, called 'bulge error'.
- This error can be estimated and corrected for by simulating incremental cutting of constant cut width [7].
- A new analytical solution, based on K_{Irs}, has been proposed to simplify the process of correcting for bulge error in contour method measurements.

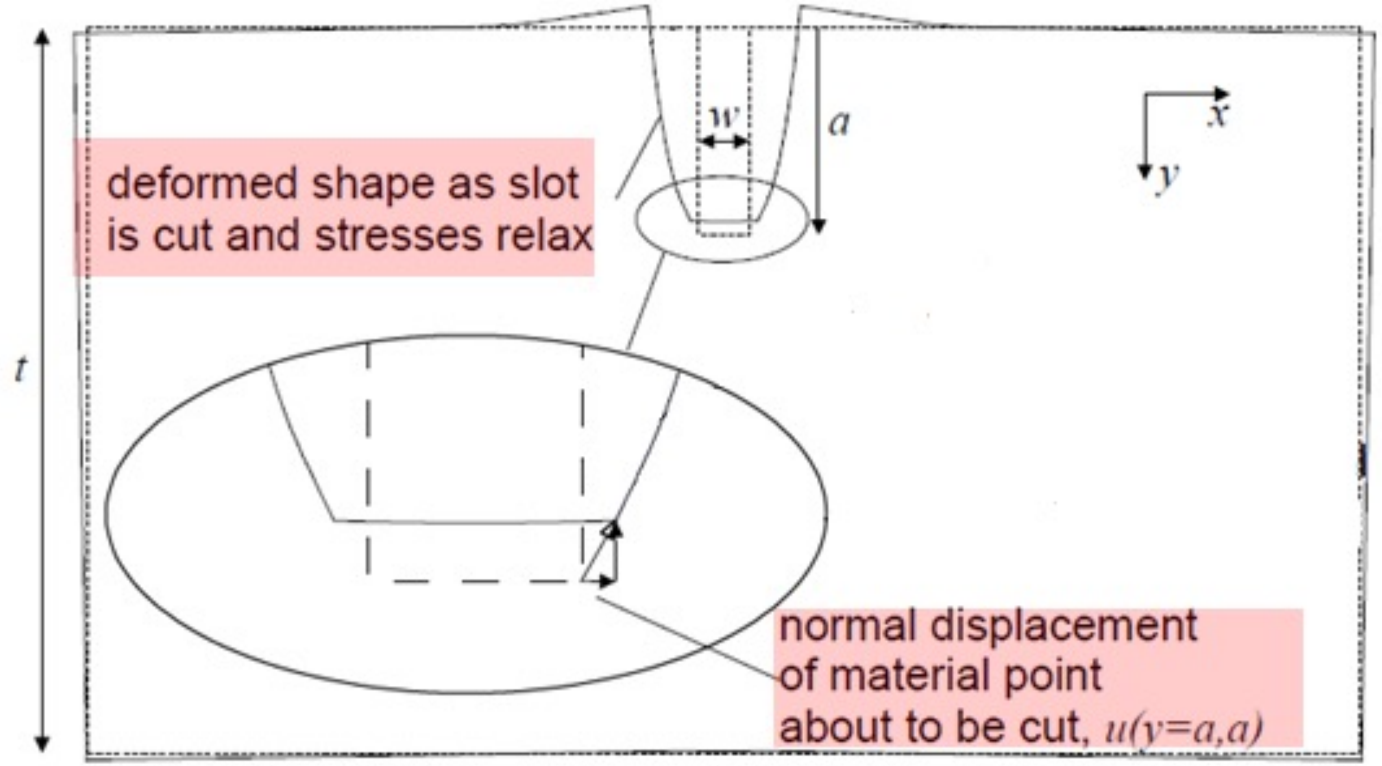
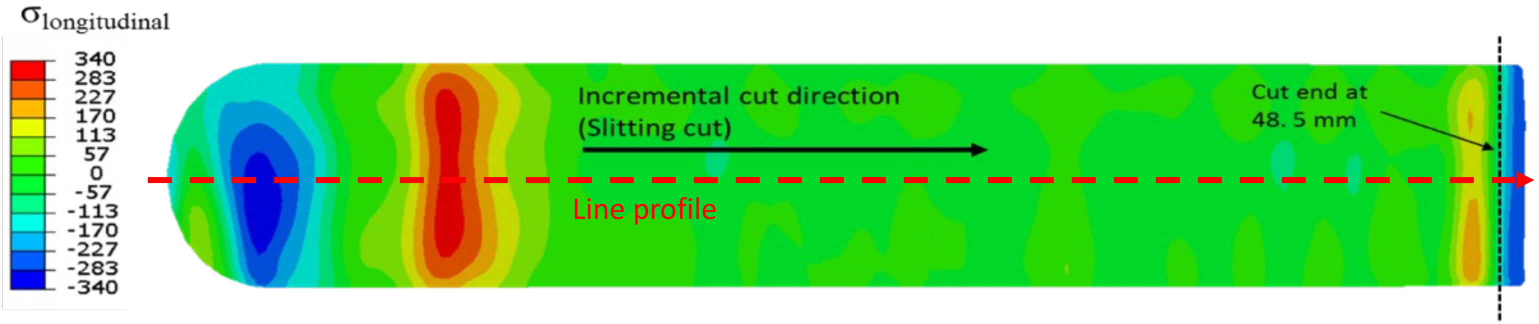
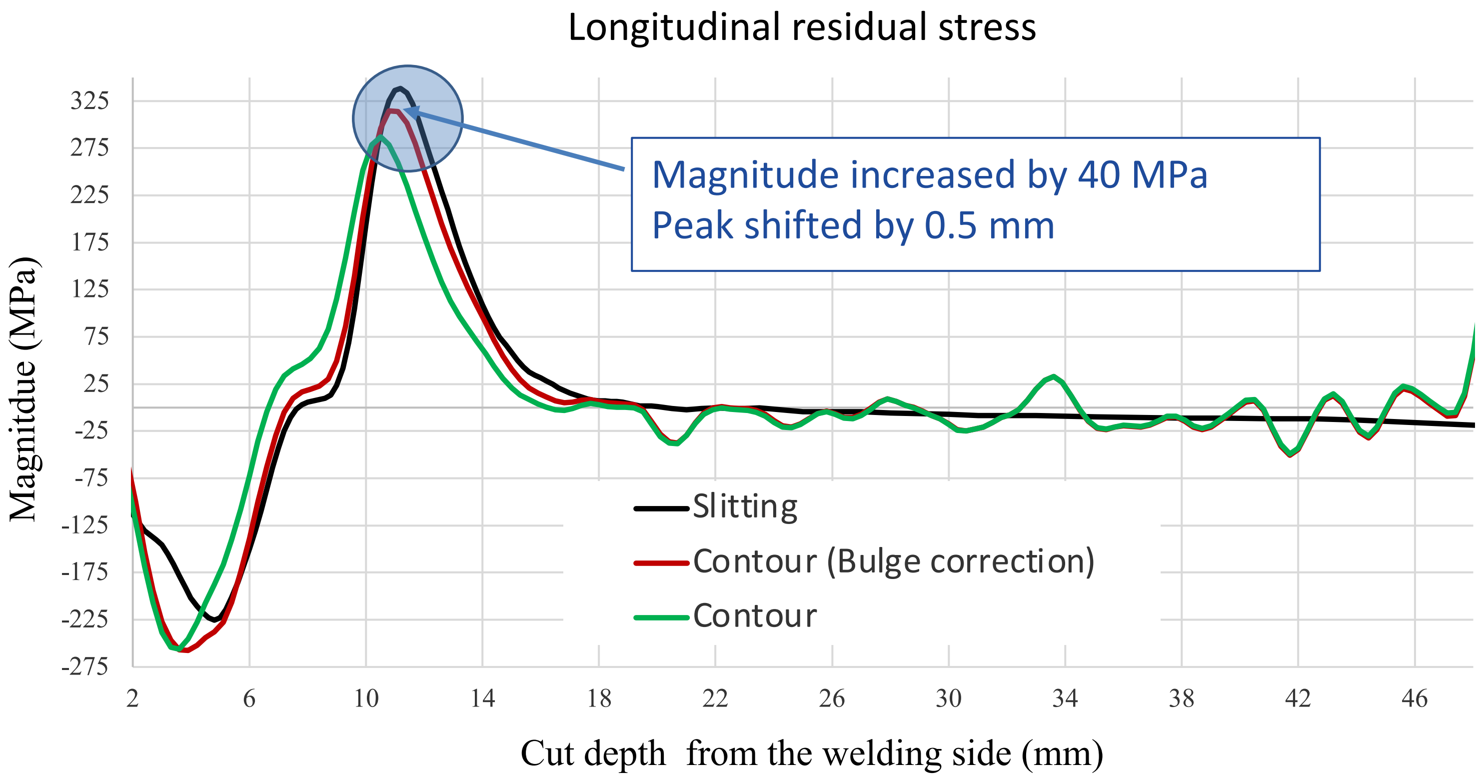


Fig: Schematic of 'bulge' error *[7]*

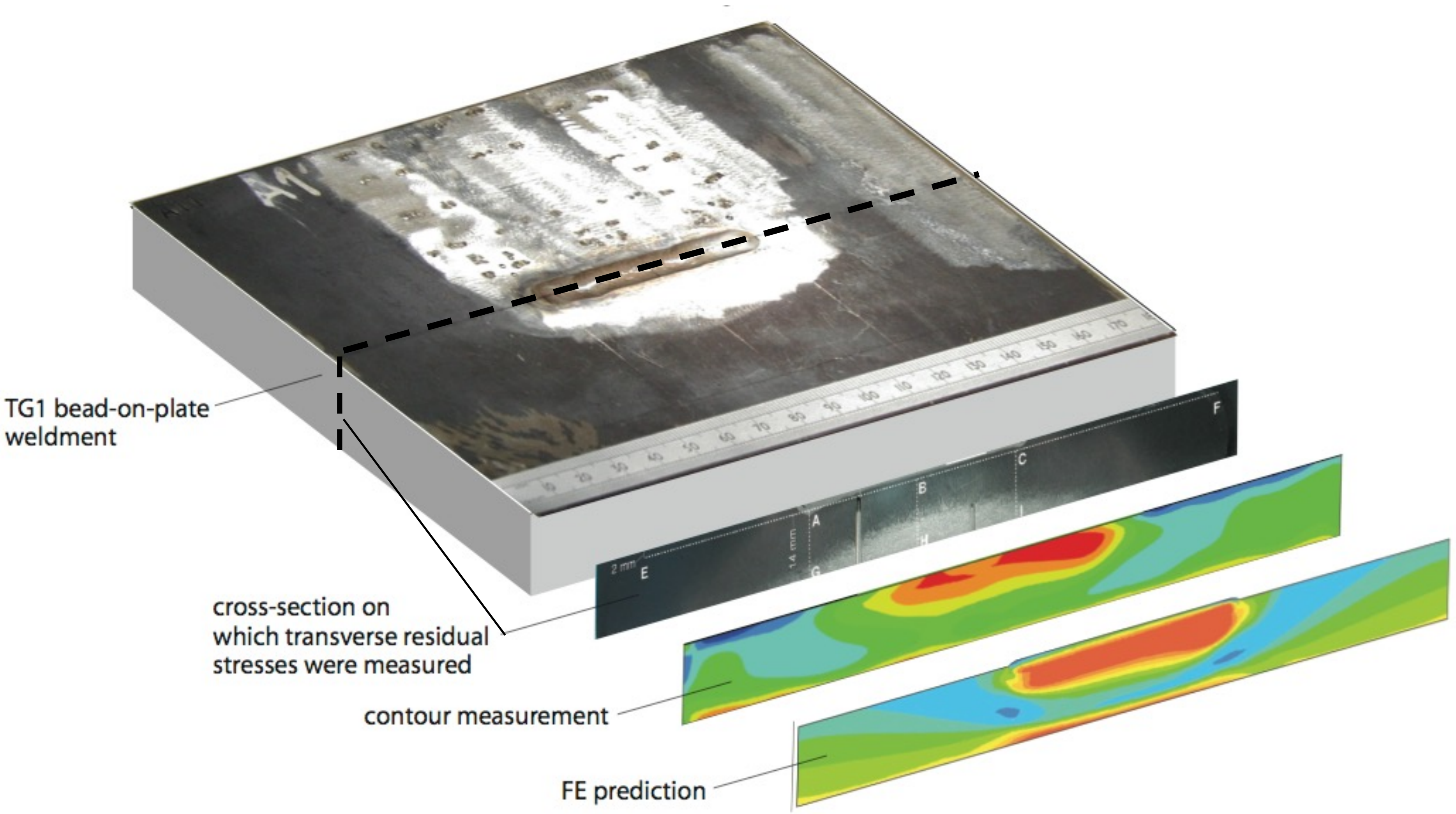
[7] M.B. Prime. and A.L. Kastengren. The Contour Method Cutting Assumption: Error Minimization and Correction. in SEM Annual Conference. 2011. Indianapolis, Indiana USA: Experimental and Applied Mechanics.

TG5 Contour Method Results

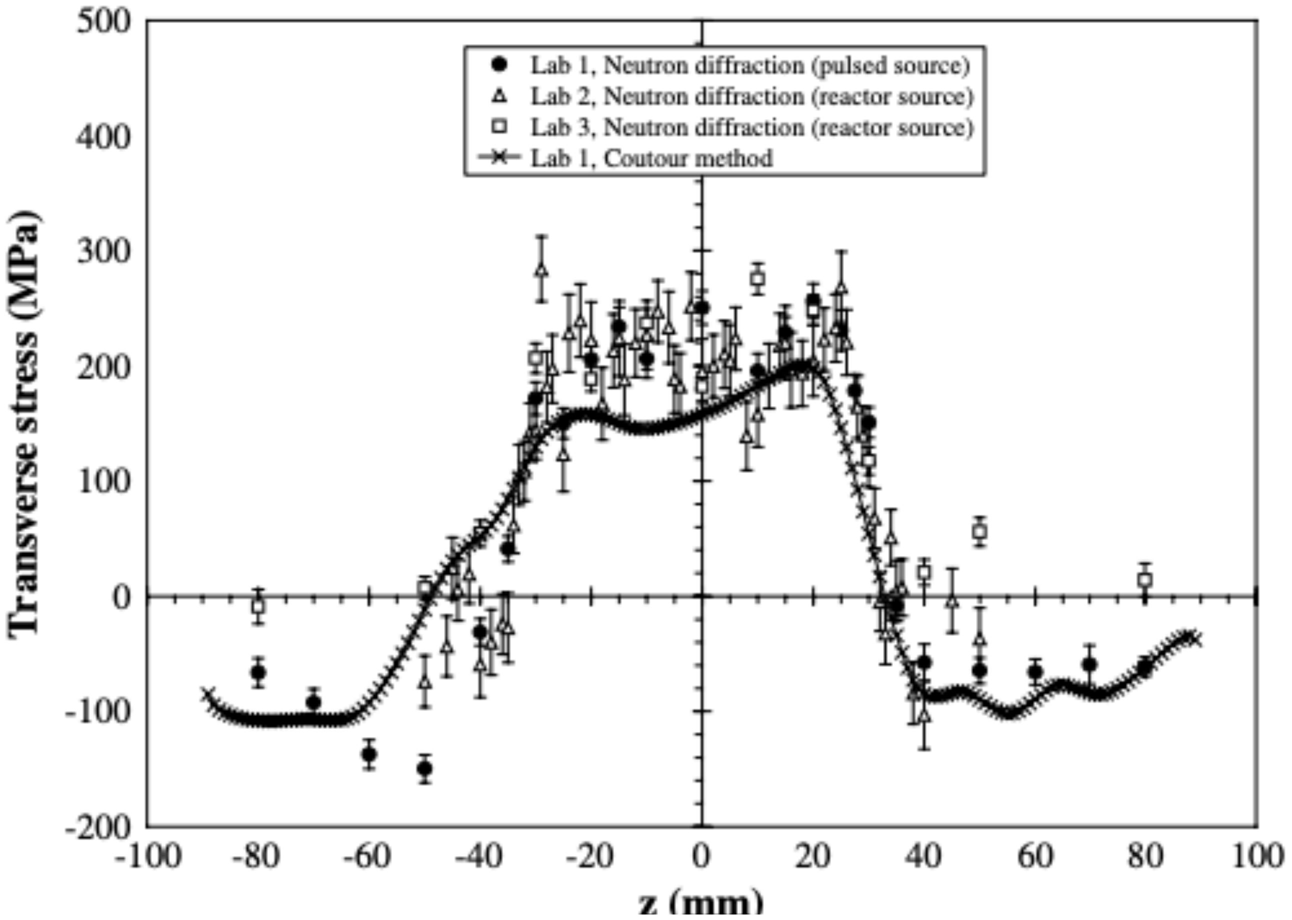


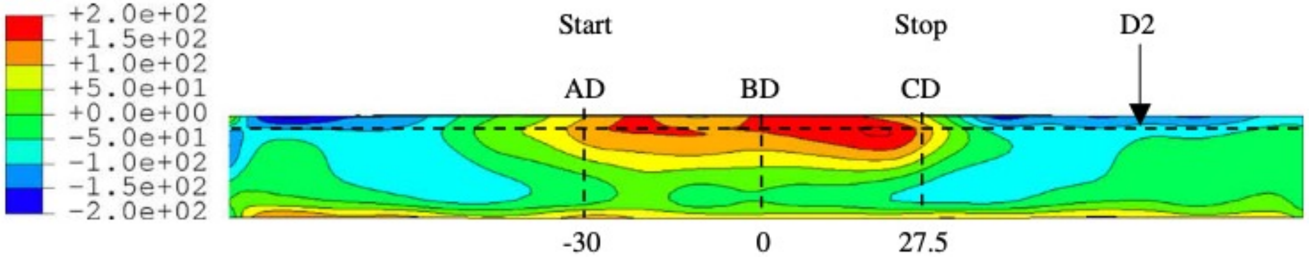


NeT TG1: Single Weld Bead-on-Plate



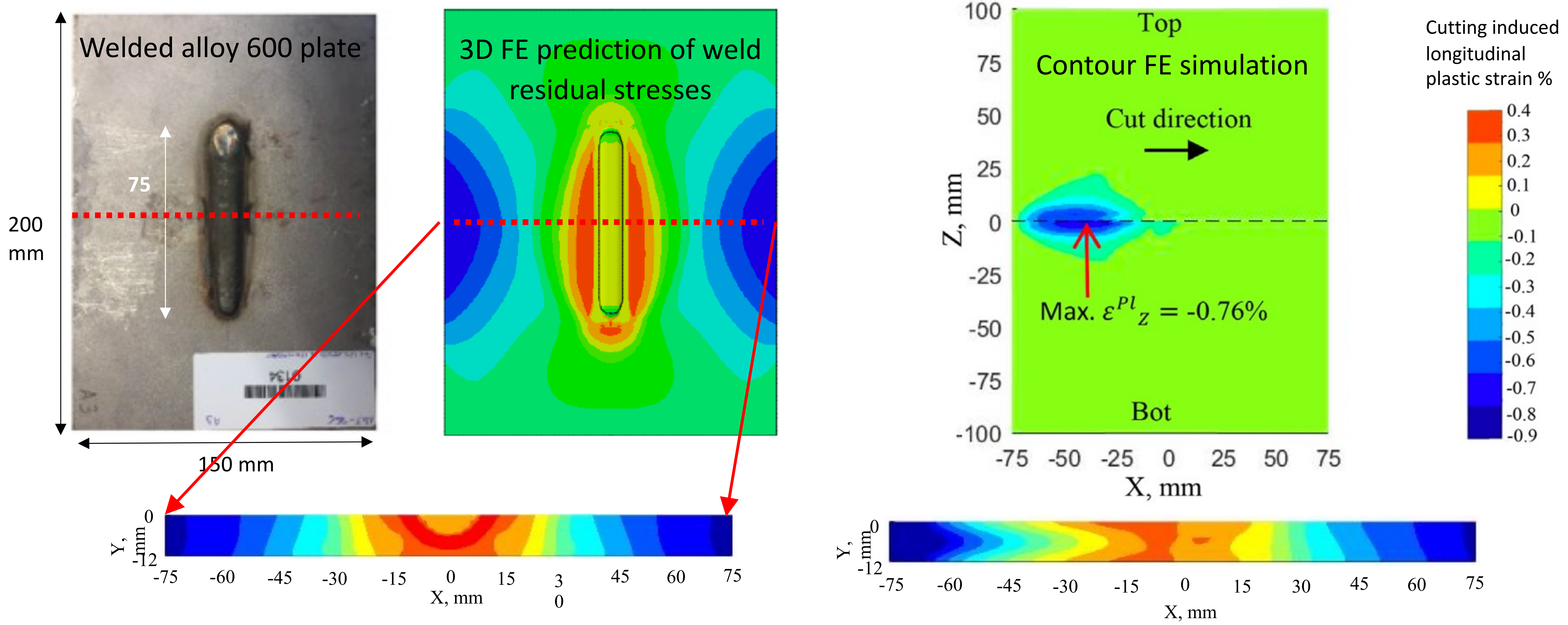
NeT TG1: Single Weld Bead-on-Plate





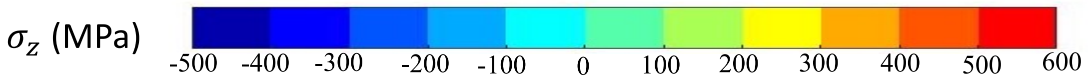
NET TG6 : APPLICATION OF THE CONTOUR METHOD

Three superimposed weld beads laid in a finite length slot in an Alloy 600 nickel plate.



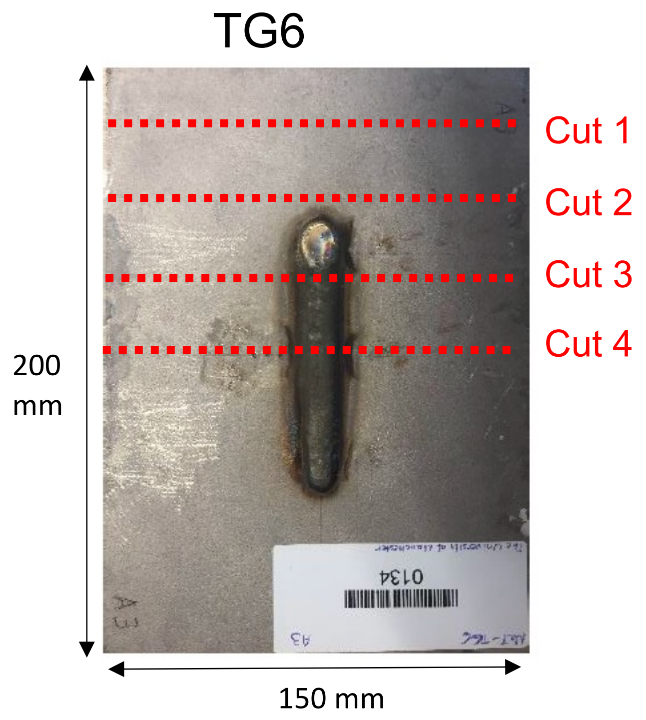
Mid-length X-sectional map of longitudinal weld residual stresses

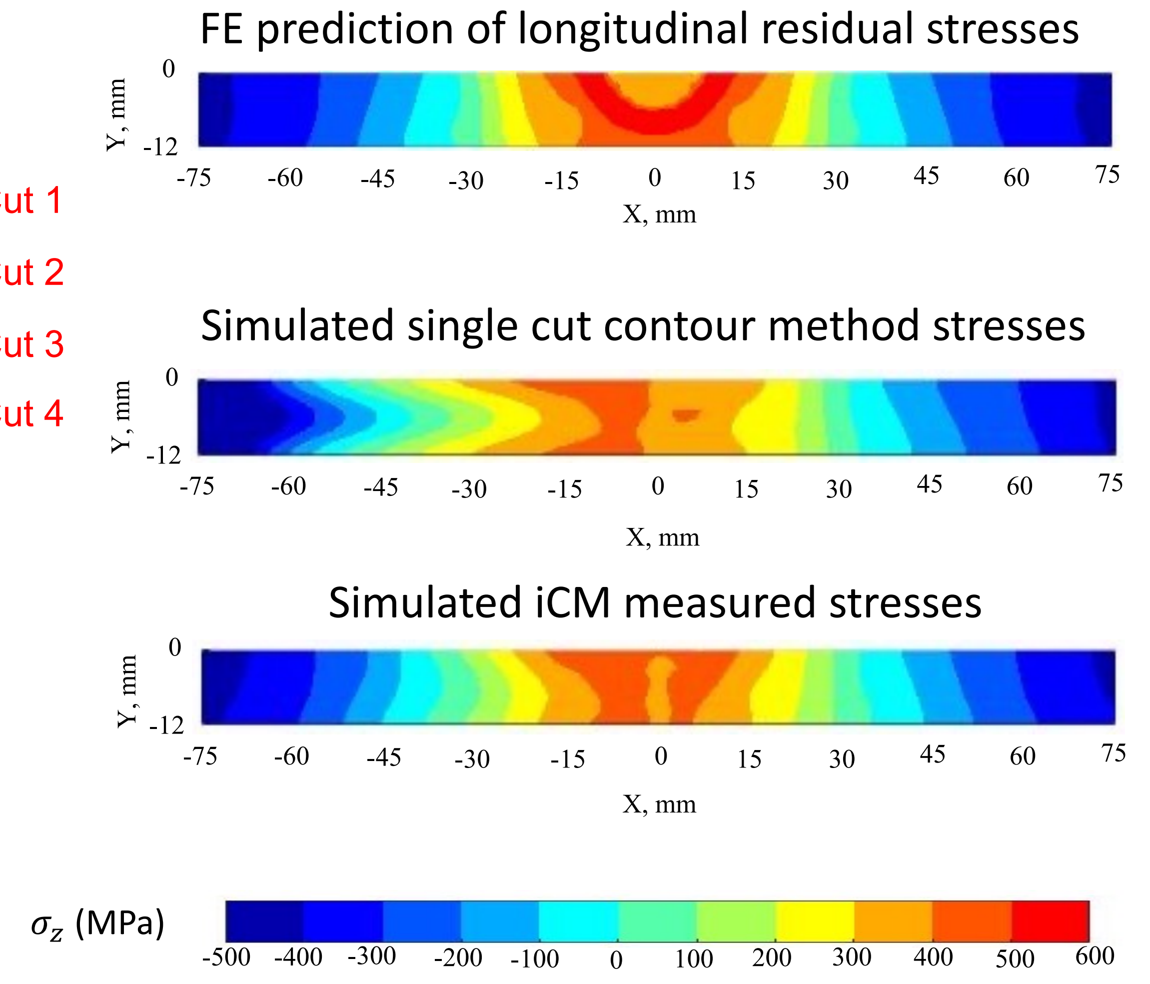
Simulated single cut contour residual stresses

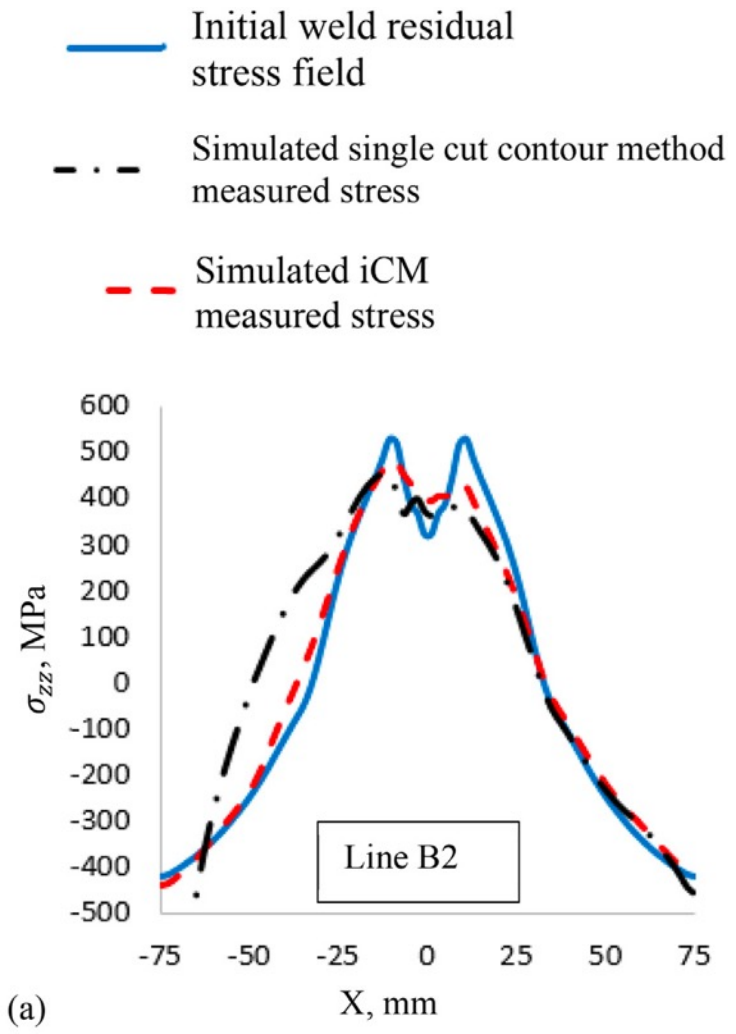


TG6: iNCREMENTAL CONTOUR METHOD (iCM)

Mitigating plasticity errors using iCM







TG5 CONCLUSIONS

1. Longitudinal residual stress distribution in the NeT TG5 Sa508 Gr. 3 C1.1 ferritic steel test specimen was successfully measured by a hybrid slitting/contour method.

2. Slitting provided a profile of width-averaged longitudinal residual stress through the depth of the beam

3. The contour method provided a 2D map of the longitudinal residual stress on the cut surface.

4. A reference cut correction technique was applied to mitigate cutting artefacts in the contour residual stress determination.

5. A new bulge correction technique was applied to mitigate cut finite width errors in the contour residual stress determination

6. The measured longitudinal residual stress profile from the contour with bulge correction and slitting method agreed very well with each other and also results from the neutron and synchrotron diffraction techniques (not shown in presentation).