# Residual stress measurements for aerospace structural integrity

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**Lloyd's Register Foundation Chair in Structural Integrity and Systems Performance**

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## Acknowledgements


- Dr Kashif Khan, Marco Pavan, Dr Niall Smyth, Professor Xiang Zhang (Coventry University)
- Dr Stefano Coratella (US Air Force Research Laboratory)
- Professor Phil Irving, Dr Supriyo Ganguly (Cranfield)
- Dr Burak Toparli (TÜBITAK SAGE)
- Dr Domenico Furfari, Dr David Liljedahl (Airbus)


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## Structural Integrity

- Structural integrity is about designing and operating products that are 'safe'
- Able to carry applied loads
- Remain structurally sound for their design lifetime
- Applies to single components and assemblies
- Often associated with failure investigation

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Structural integrity often focusses on failure investigations

## Structural integrity

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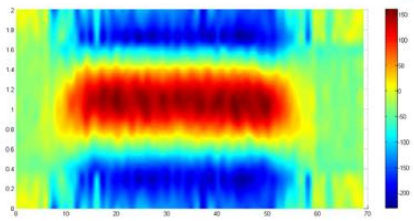
## Residual stresses

- In safety-critical and high-performance applications, need to know residual stresses
- Ideally, want to *measure* residual stress
- Can also *model* residual stress using computational methods
  - But then must validate the results



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## What do engineers want?

*Nondestr. Test. Eval.*, Vol. 5, pp 395–413
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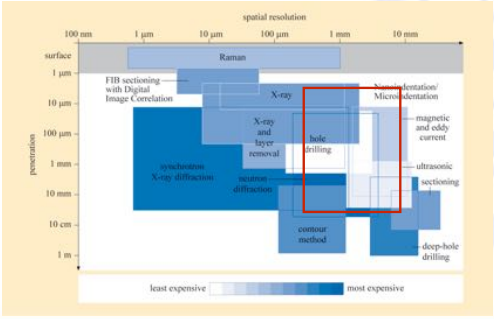
**NEUTRON DIFFRACTION MEASUREMENT OF RESIDUAL STRESS FIELDS—THE ANSWER TO THE ENGINEERS' PRAYER?**

MICHAEL T. HUTCHINGS
*Materials Physics and Metallurgy Division, Harwell Laboratory, Didcot, OX11 ORA*

*(Received 3 April 1990)*

**"A small meter placed on the surface of the component, on which one simply dials a position in the sample… and obtains a readout of the magnitude and direction of the stress would do nicely!"**




## Stress measurement techniques

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## Residual stress measurement

- Technique often depends on the value of the problem, or, more accurately, the budget available to solve the problem
  - £$10^2$
  - Can I stop using this production step that costs £1 per part?

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## Residual stress measurement

- Technique often depends on the value of the problem, or, more accurately, the budget available to solve the problem
  - £$10^3$
  - I have a new problem with components failing a residual stress acceptance criterion

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## Residual stress measurement

- Technique often depends on the value of the problem, or, more accurately, the budget available to solve the problem

  - £$10^2$
  - Can I stop using this production step that costs £1 per part?
  - £$10^3$
  - I have a new problem with components failing a residual stress acceptance criterion
  - £$10^4$
  - I have a critical residual stress problem on a product development path

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## Residual stress measurement

- Technique often depends on the value of the problem, or, more accurately, the budget available to solve the problem
  - £$10^5$
  - I have a major development programme where the residual stresses are critical
  - but the value could be.....
  - £$10^7$ - $10^8$
  - If I can't prove it's safe this power plant will be closed down / aircraft will be grounded or development stalled

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## Typical costs

- Surface X-rays £$10^2$ - £$10^3$
- Incremental hole drilling £$10^2$ - £$10^3$
- Neutrons, synchrotron X-rays, contour method Deep Hole Drilling £$10^4$ - £$10^5$

- However, access to neutron and synchrotron facilities is <u>not</u> prohibitively expensive because
  - Possible to collaborate with the facilities or university groups to study the engineering science underpinning an application problem
  - Staffing associated with sample preparation, characterization, experimentation and analysis are often the highest costs, even for "simple" measurements

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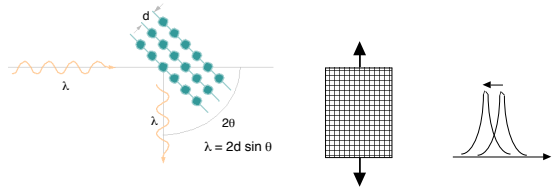
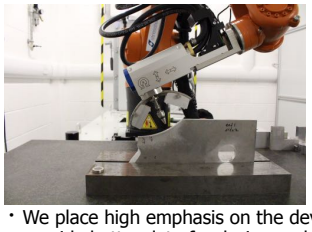
Use diffraction of X-rays or neutrons from the atomic lattice to measure the strain in the material.




As the strain changes, the diffraction peak can be observed to move and the strain can be calculated

## Diffraction techniques

- Laboratory X-ray diffraction
- Synchrotron X-ray diffraction
- Neutron diffraction

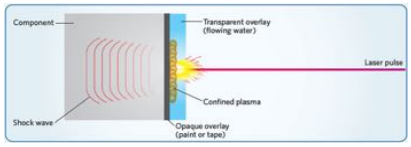


- We place high emphasis on the development of novel techniques to provide better data for design and lifing calculations

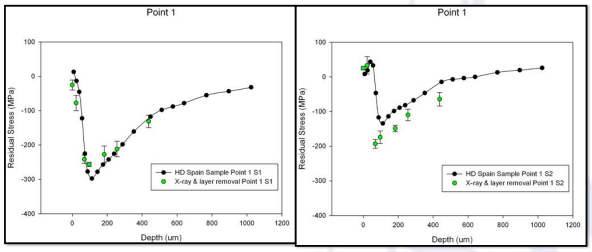
## The research tools

## Example: Laser shock peening

- Novel method for introducing beneficial compressive residual stresses
- Use high-intensity laser pulse to produce a stress wave that deforms the material
- Applied to aeroengine components, we are investigating applications in airframe assemblies




Comparison of XRD and incremental hole drilling: laser peening surface treatment



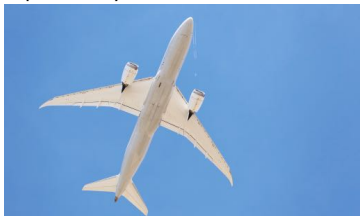

## Validation

## Residual stress in aircraft structures

- Aerospace structures are highly safety-critical
- Structures are designed using damage-tolerance methodologies
  - Need accurate characterization of residual stress
- New designs place greater reliance on integral structures
  - Fewer natural crack-stoppers
  - Stiffening straps for crack retardation
- Future design and manufacture routes will introduce new challenges in residual stress assessment


## Damage tolerance

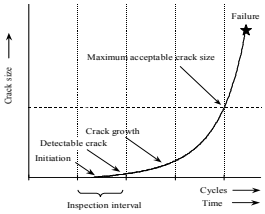
- Accepts that structure will experience fatigue cracking or other damage
- Need accurate knowledge of crack growth kinetics and critical crack sizes
- New technologies such as welding are treated conservatively, particularly if residual stresses are unknown



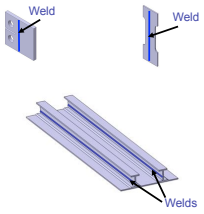
## Damage tolerance

- …is not fail-safety. Lusaka accident in 1977 showed the shortcomings of a fail-safe concept alone

## Damage tolerance

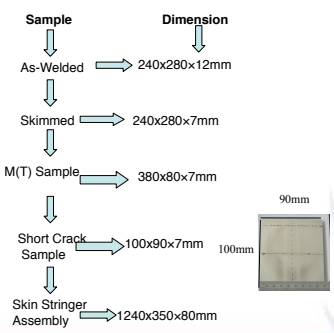


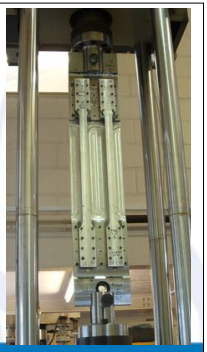

- Is additional to safe-life design calculations
- Assumes that initial flaws are present
- Implement systems of inspection and monitoring to prevent failure
- Inspection intervals are designed to ensure multiple inspections before failure




- Two welding processes: VPPA & MIG
- 2024-T351 & 7150-T651 (Lower and upper wing materials)
- Wide range of samples:
  - Small 3-point bend
  - Compact tension, CT
  - Mid-crack tension, M(T)
  - Skin-stringer panels
- Evaluate similitude of residual stresses in experimental and prototype samples

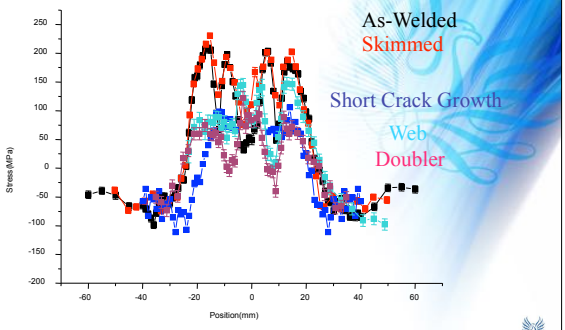
**Stresses evaluated in welded coupons and components: WELDES project**

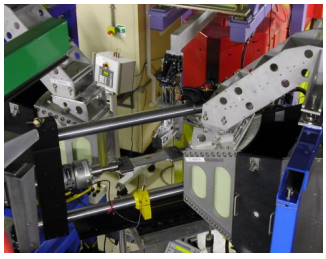


**Test matrix: VPPA welded Al**

## Residual stress evolution

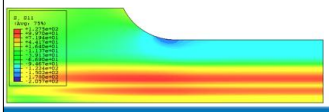


Sample fatigued *in situ* at ENGIN-X

**Measuring weld stress evolution**

Measure the residual stress with neutron diffraction; model with finite element analysis



## Simulation and modelling

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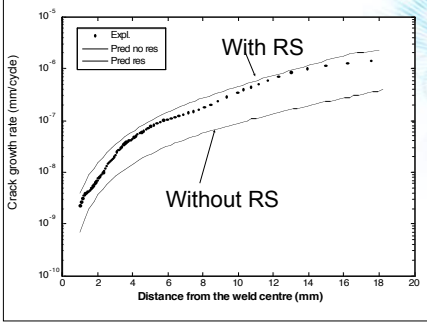
## Residual stress evolution

## Predicted crack growth

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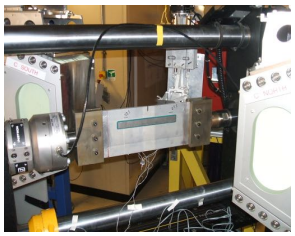
## Welded structures and crack retarders



- Bond local stiffening 'straps' to the structure
- Provides crack retardation
- Bonding line prevents passage of crack into the strap, and the strap gives additional 'crack bridging' effects once crack has grown beyond the strap
- But, bonding the strap induces additional residual stresses

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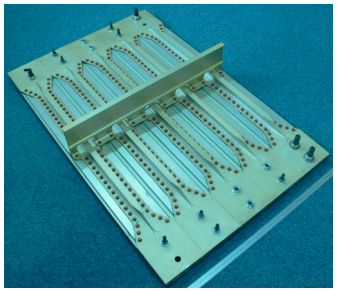
CURRENT TESTING



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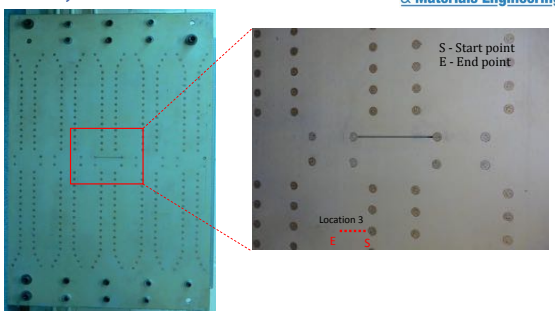
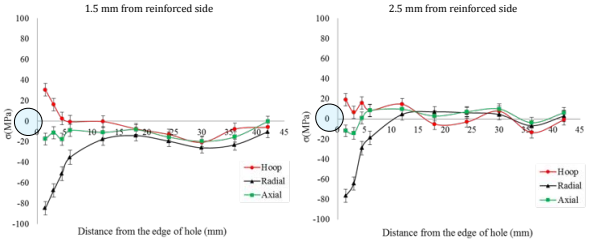



Mock-up panel with BCR, Location 3




**Mock-up panel with BCR, Location 3**

Representing bolted hole

## LASER SHOCK PEENING

- In aerospace applications, LSP may be required to be applied to thin sections if it is to be used to enhance fatigue life
- Typical fuselage skin has thickness of ~ 2 mm
- Peening may be applied selectively: e.g., along the line of a joint overlap, rather than on a large patch
  - Challenges in selecting appropriate peen parameters
  - Uniform stress field difficult to obtain

## INITIAL RESULTS

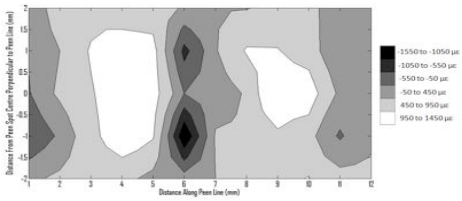
Single Peen Coverage

3 GW/cm$^2$ with 5% overlap

5 mm x 5 mm spot

Large variation in the peened area

Tensile residual strain at the centre of each peened spot, compressive residual stress at the overlap

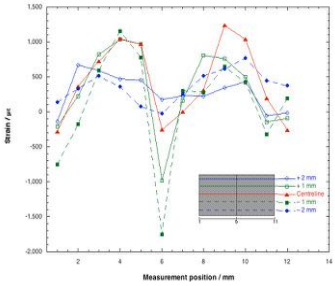



## CORRELATION WITH FATIGUE CRACK PROFILES

Single Peen Coverage

Crack acceleration from centre of peen spots, retardation at overlap

Life reduction for this treatment, though lower power density did show life improvement



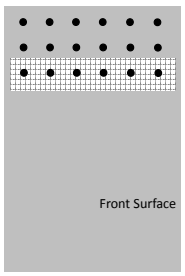

*M. Dorman, M. B. Toparli, N. Smyth, A. Cini, M. E. Fitzpatrick, P. E. Irving,* ***Measurement of residual stress and fatigue life of laser-peened clad 2024 aluminium sheet containing scribe defects****, Mater Sci Engng.*

## USE OF PEENING IN JOINT REINFORCEMENT

LSP parameters:

- Double side peening
- ≈2 Joules per pulse
- 10 ns pulse duration
- Spot Diameter 2.5 mm

2024-T351 Aluminium clad sheet, 144 mm x 250 mm x 2.5 mm




# Test facility and Methodology

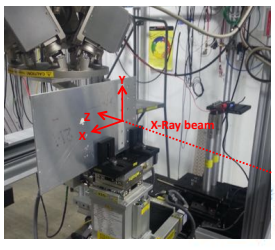
The measurements were carried out with Angle Dispersive XRD – ADXRD at the **Advanced Photon Source (Chicago, USA)**.

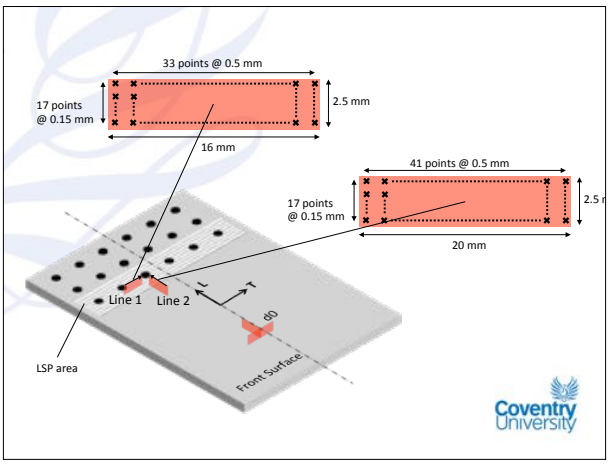
**Setup:**

- Conical slit setup
- Gauge volume 50 x 50 x ~210 μm$^3$
- Monochromatic x-ray beam:
  - Energy 54.998 keV
  - Wavelength 0.2254 Å

**Data Analysis:**

- {111} reflection plane
- Plane Stress




33 points @ 0.5 mm
17 points
@ 0.15 mm
2.5 mm
16 mm
41 points @ 0.5 mm
17 points
@ 0.15 mm
20 mm
Line 1
Line 2
L
T
dD
LSP area
Front Surface
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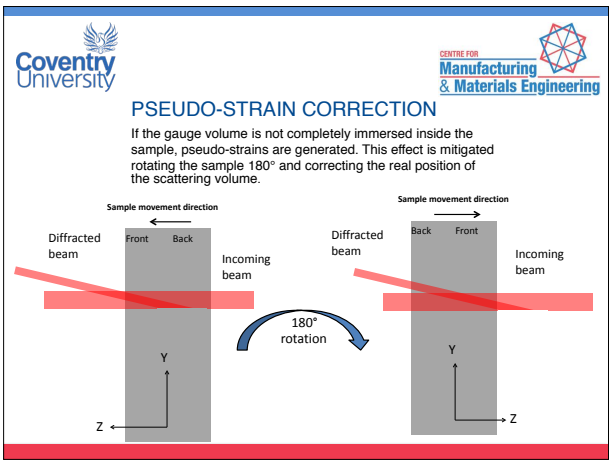
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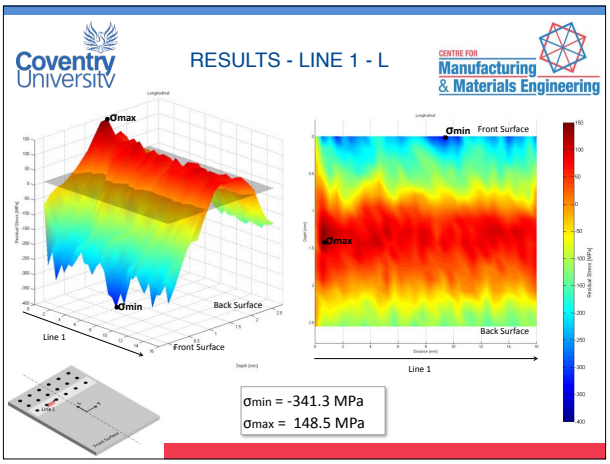
PSEUDO-STRAIN CORRECTION
If the gauge volume is not completely immersed inside the sample, pseudo-strains are generated. This effect is mitigated rotating the sample 180° and correcting the real position of the scattering volume.
Sample movement direction
Diffracted beam
Front
Back
Incoming beam
180° rotation
Y
Z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RESULTS - LINE 1 - L
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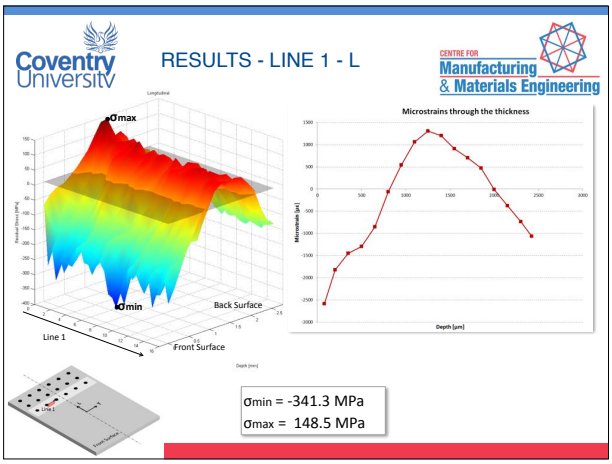
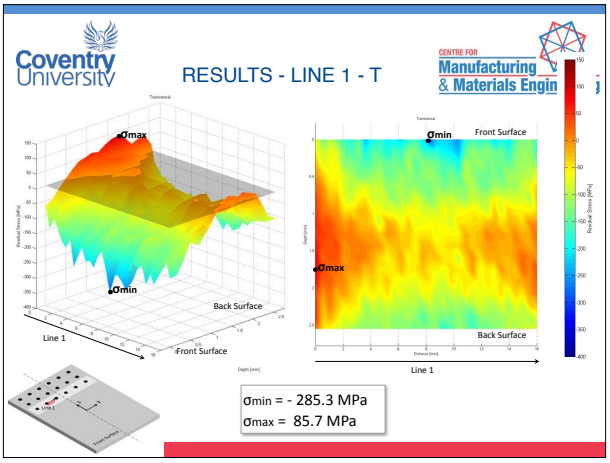
σmax
σmin
Back Surface
Front Surface
Line 1
σmin = -341.3 MPa
σmax = 148.5 MPa


Coventry University
RESULTS - LINE 1 - L
CENTRE FOR Manufacturing & Materials Engineering
Microstrains through the thickness
Depth [μm]
σmax
σmin
Back Surface
Front Surface
Line 1
σmin = -341.3 MPa
σmax = 148.5 MPa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RESULTS - LINE 1 - T
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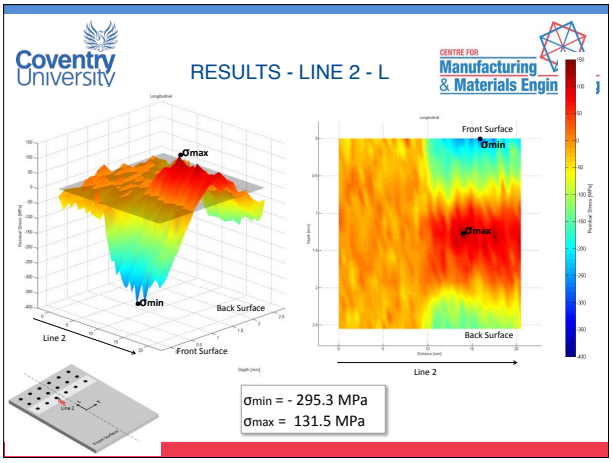
σmax
σmin
Back Surface
Front Surface
Line 1
σmin = - 285.3 MPa
σmax = 85.7 MPa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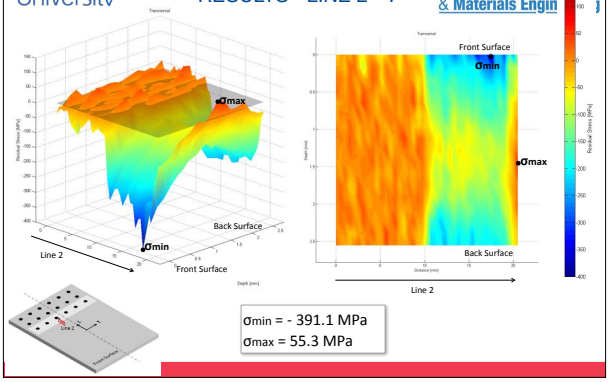
RESULTS - LINE 2 - L
CENTRE FOR Manufacturing & Materials Engin
σmax
σmin
Back Surface
Front Surface
Line 2
σmin = - 295.3 MPa
σmax = 131.5 MPa

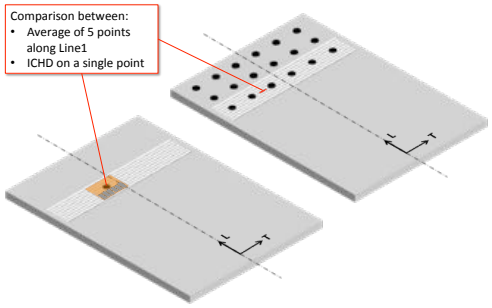
## RESULTS - LINE 2 - T



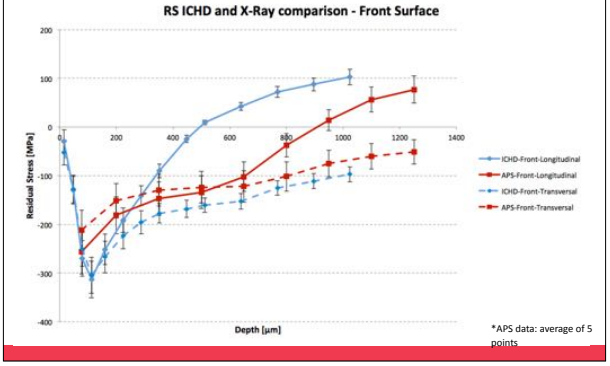

σmin = - 391.1 MPa
σmax = 55.3 MPa

## ICHD AND X-RAY COMPARISON

Comparison between:
- Average of 5 points along Line1
- ICHD on a single point

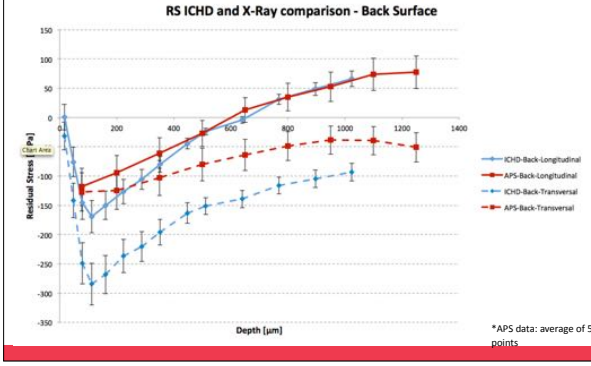


## RS ICHD and X-Ray comparison - Front Surface




*APS data: average of 5 points

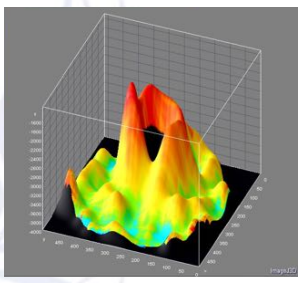
## RS ICHD and X-Ray comparison - Back Surface

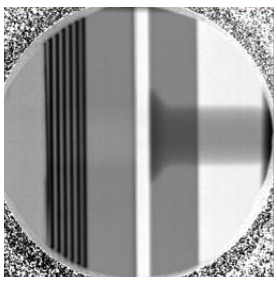



*APS data: average of 5 points

## Neutron transmission

- High-resolution through-thickness average of residual strain. Phase-selective imaging also possible;





## Summary

- We now have a range of tools for the determination of residual stress for structural integrity calculations.
- None is the "answer to the engineer's prayer", but some come close.
- Neutron and synchrotron X-ray diffraction are valuable tools in the box.
- Neutron transmission has immediate potential.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