Stress Engineering for
Earth & Space

Measurement of Awkward Components using X-Ray Diffraction

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The Measurement of Residual Stress using Laboratory Based X-Ray Diffraction Instruments; the Positives, the Pitfalls and a Round Robin, 27 September 2023, NPL

www.stress-space.com

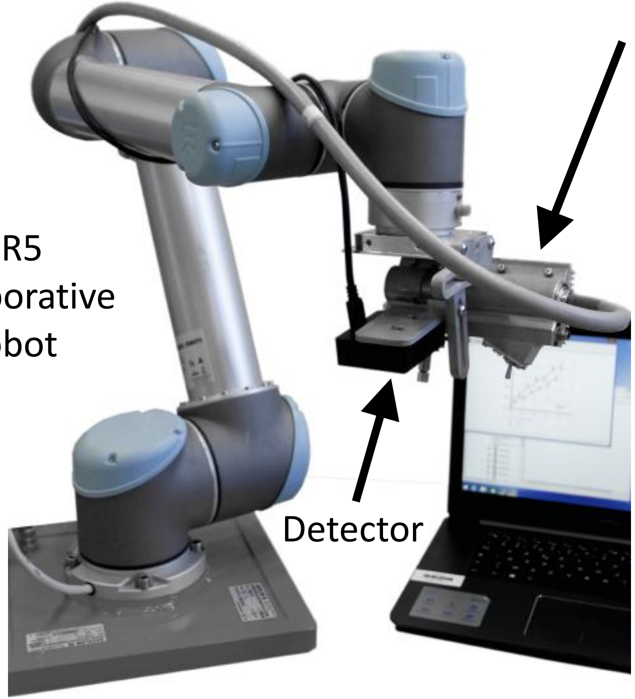
esa business incubation centre UK

Awkwardness

1. Geometric
    - Surface normal is not vertical
    - Curved surfaces
    - Limited X-ray goniometer access (including shading)
    - High stress gradients (positioning is critical)
    - Component too large or too heavy to fit on diffractometer test table
2. Material
    - Rough surface
    - Large grain size
    - Texture
3. Place
    - Installed infrastructure or plant
    - Production line (Industry 4.0 applications)
    - Hazardous environment

X-Raybot

A robotic X-ray diffractometer designed by MRX-rays for surface residual stress analysis

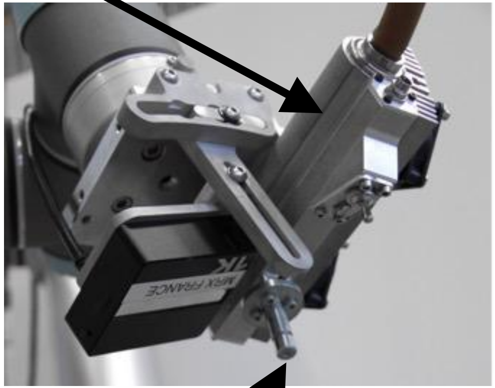


X-ray tube (20-25 kV, 1-2 mA))

UR5
Collaborative
Robot

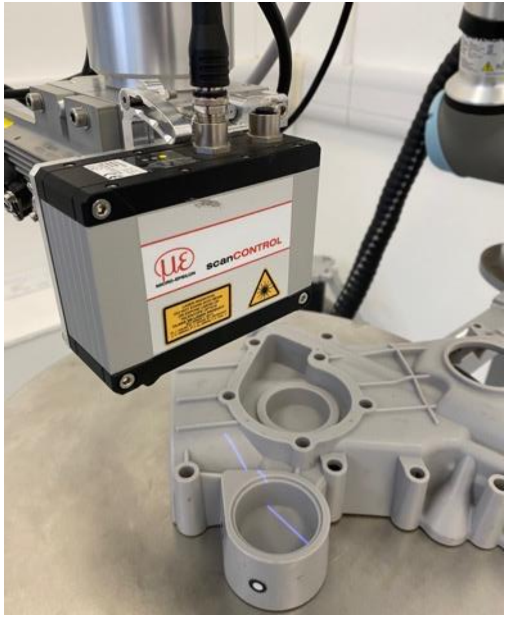
Detector

Remote
control
console



Collimator

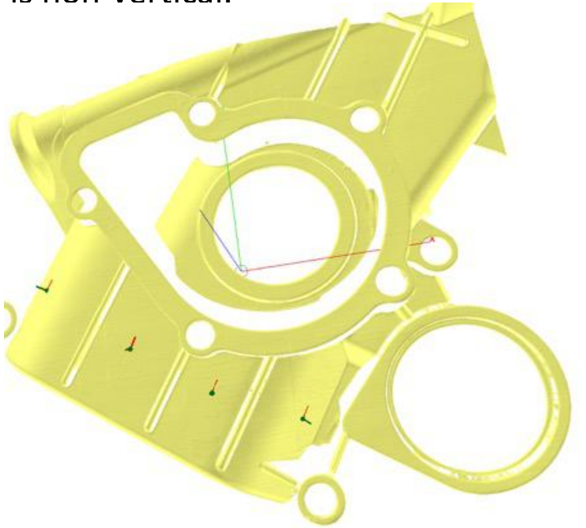
Vision-guided X-Raybot



Stress-Space Ltd developed an Adaptive X-Raybot System (2021)

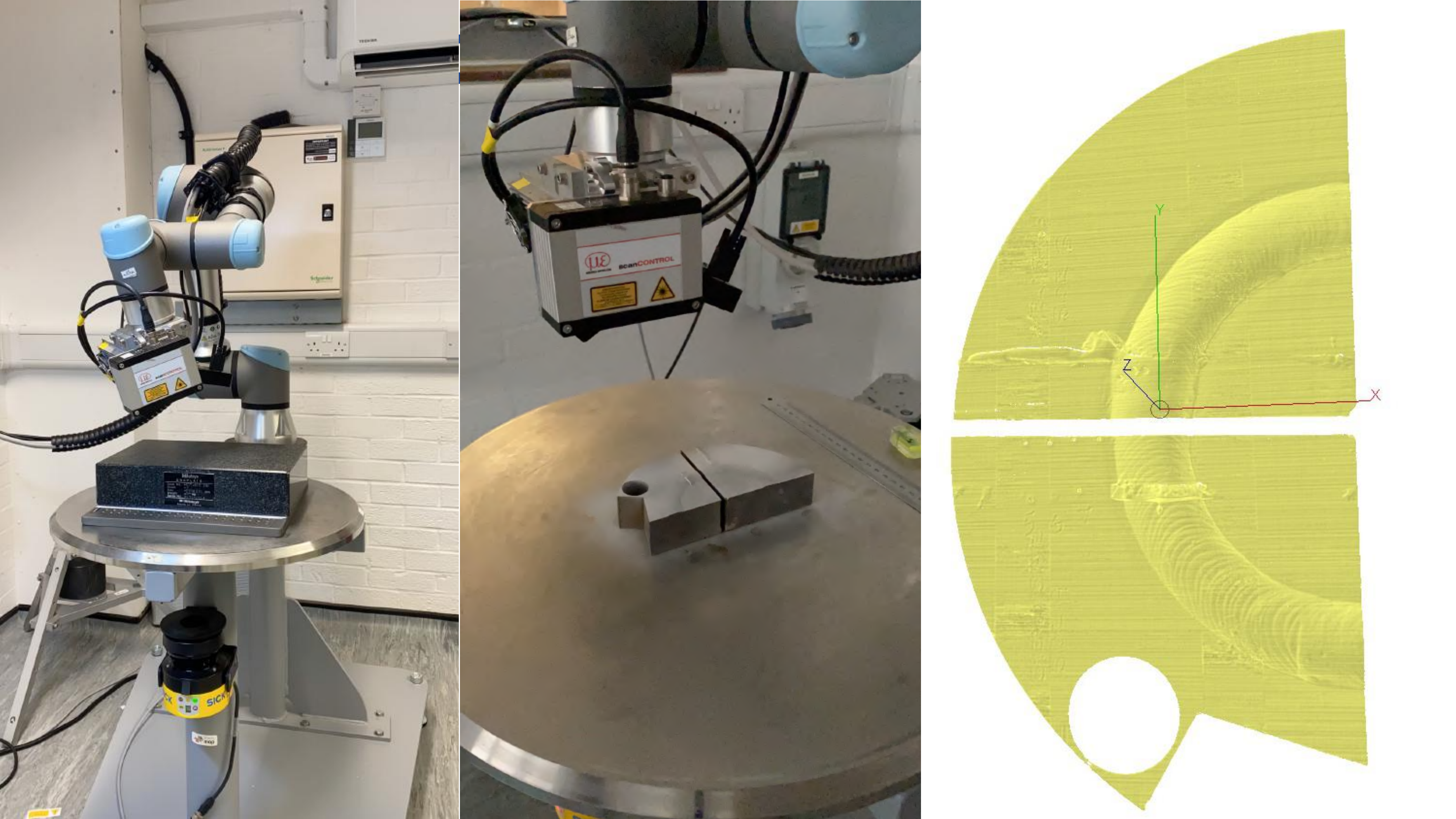
- Laser scans the surface geometry of interest (to within $\pm$ 25 μm)
- Positions the measurement lateral coordinates (to within 100 μm)
- Defines the measurement surface normal & direction vector
- Adapts to curved surfaces where the normal is non-vertical.

- Remote control of measurements
- Over 10x faster set-up
- Input CAD/externally scanned model
- Audit trail with graphics

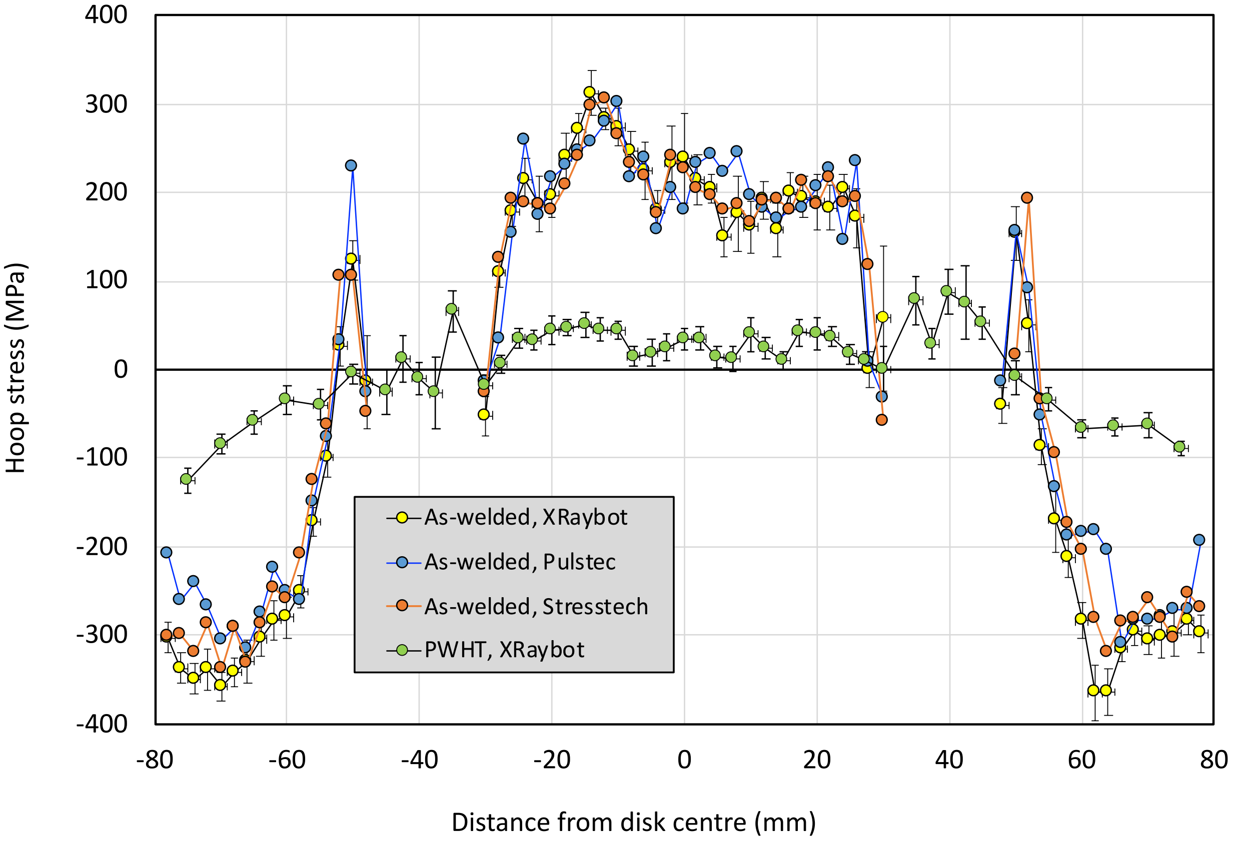


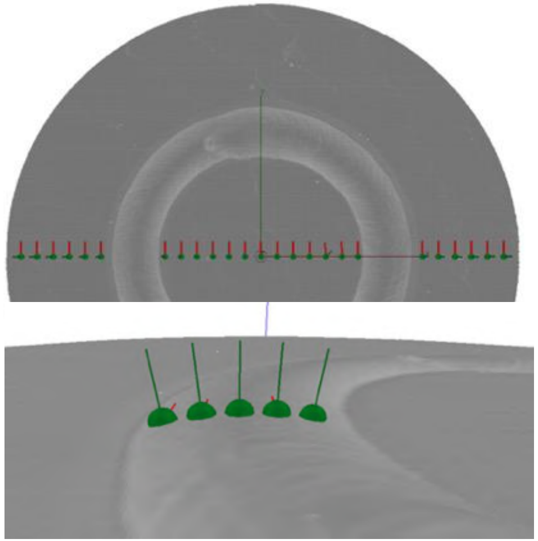
Acknowledgements

ESA BIC UK incentive funds	*Dr Stephen Nneji*
STFC B4I grant	*Dr Graham Appleby*


scanCONTROL
SICK
Y
Z
X

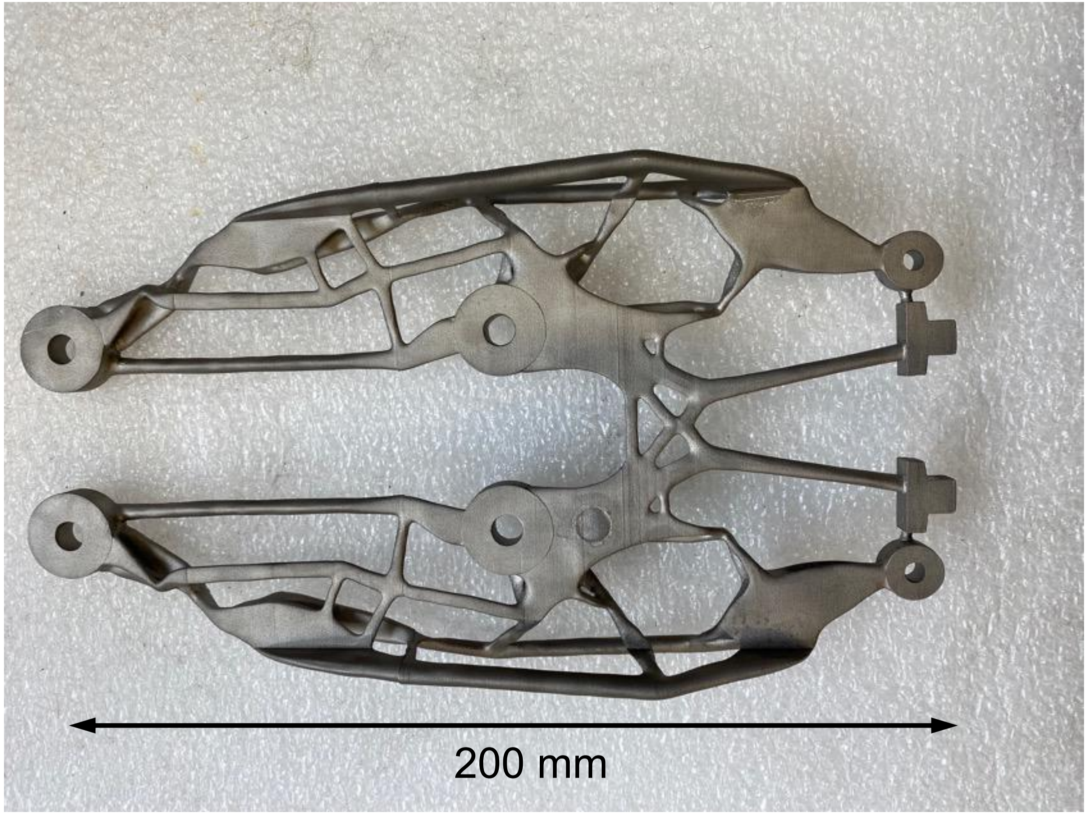
Ringweld residual stresses measured by XRD





Stresstech and Pulstec results courtesy of the Open University

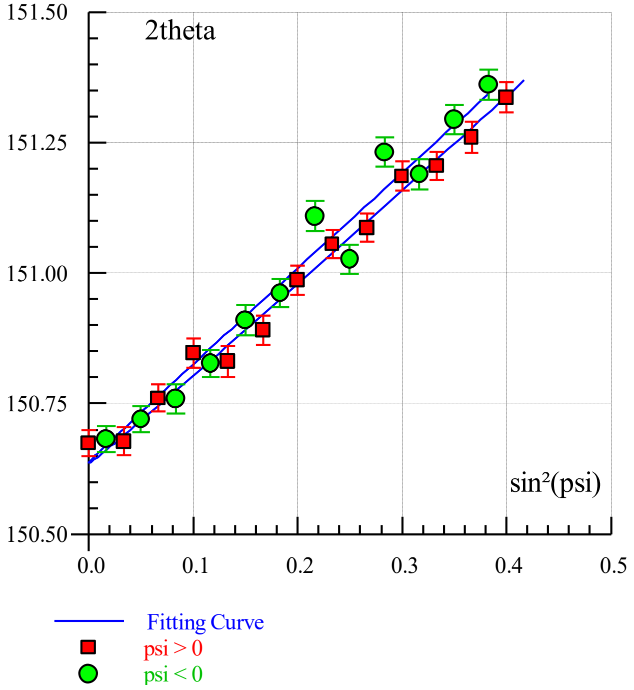
Awkward Geometry: AM Bracket

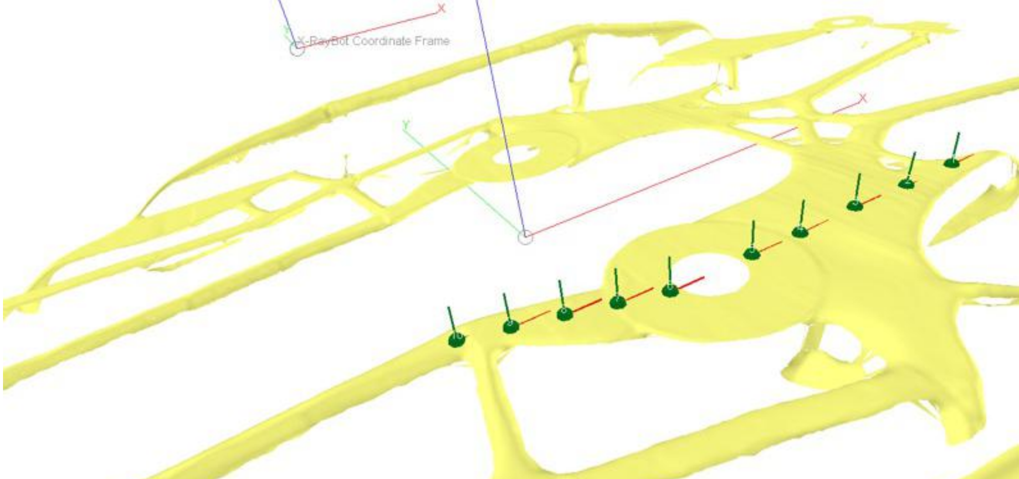


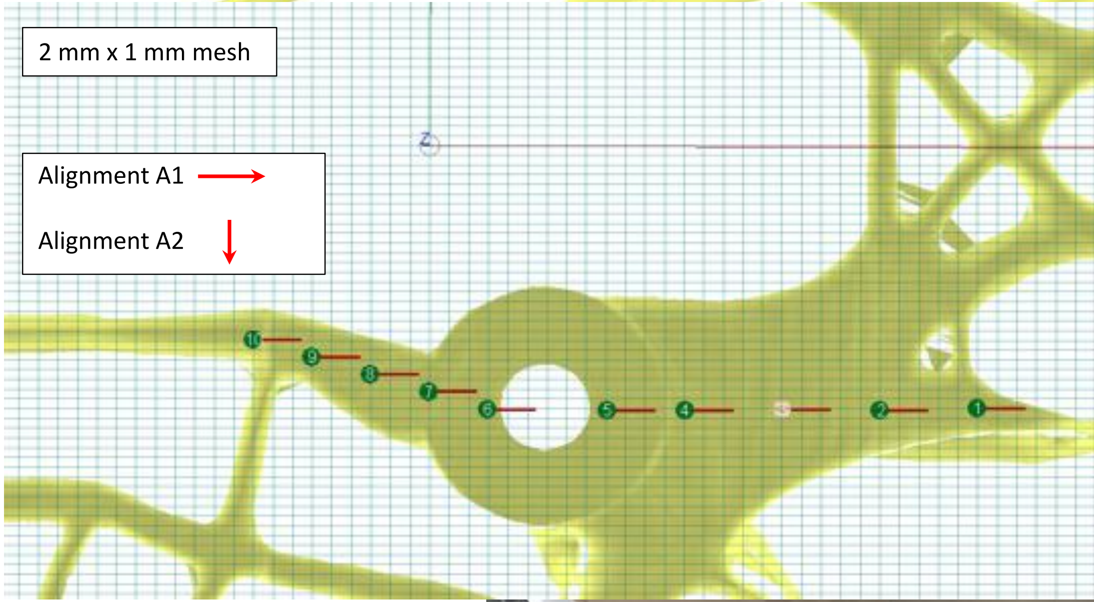
1. Complex geometry
2. Non-planar surfaces
3. Positioning
4. Surface roughness ?
5. Grain size ?
6. Texture ?

Acknowledgements: Architectural bracket supplied for residual stress studies, UCL

AM Bracket

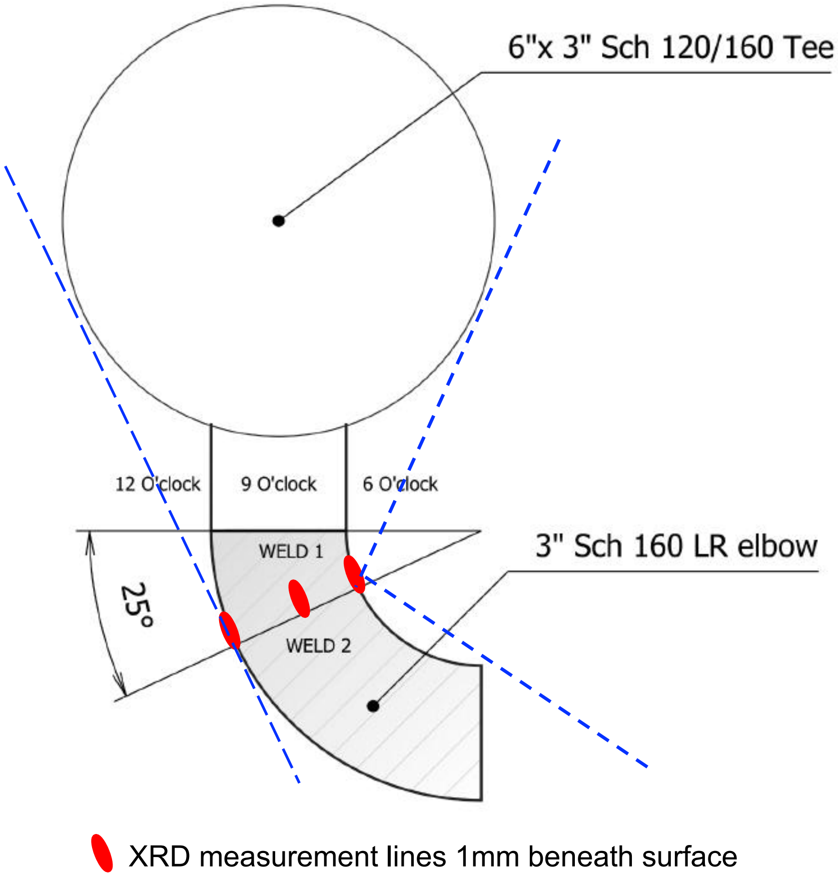






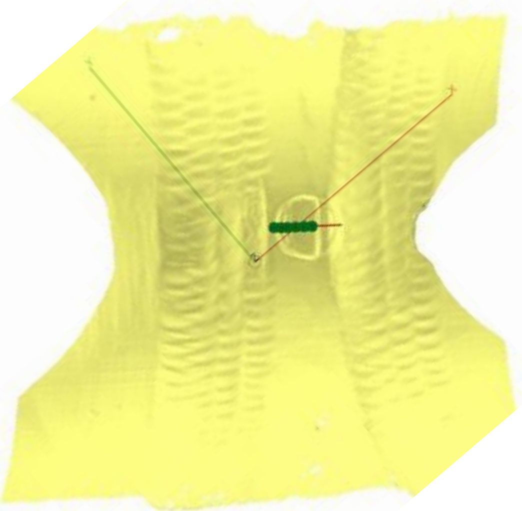
Laser guided adaptive system applied to define the X-ray optics for the positions and directions of interest

Awkward Geometry: Tee – Elbow Weld

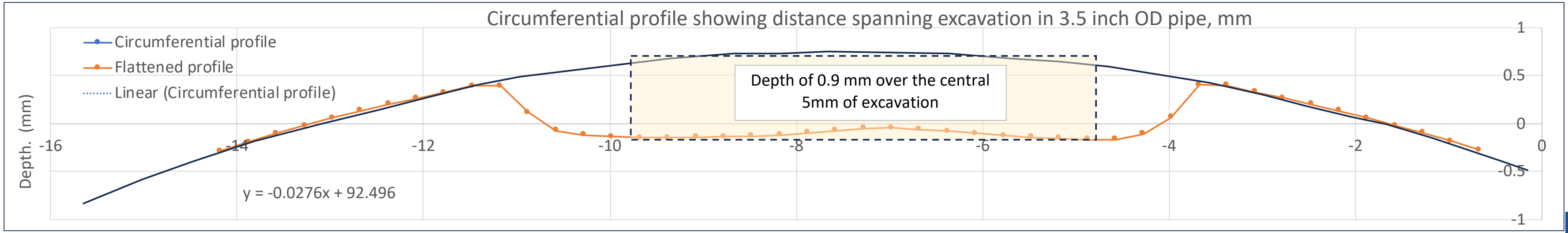


1. Restricted angular access for XRD goniometer
2. 1 mm sub-surface line scans defining stress profile up to fusion boundary required
3. Hoop & axial curvature plus weld cap features

Tee-Elbow Electro-polishing



- Laser system measured profile of ECM excavation
- Measurement positions located to within about 0.25 mm of the edge of the weld bead.
- Double curvature of Tee to Elbow captured together with uneven weld topography.



Tee-Elbow XRD Goniometer Access

6 o'clock position (left)

$-40\ to\ 0^o\ \psi$ range for axial

$\pm\ 30^o\ \psi$ range for hoop

Used 25 ψ tilts

X-Raybot source stand-off is 120 mm which helps access

9 o'clock position (right)

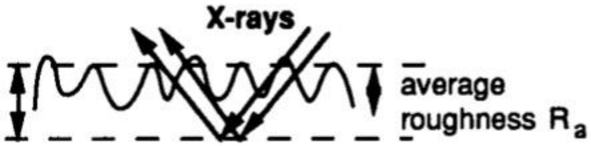
$-40\ to\ 0^o\ \psi$ range for axial

No restriction for hoop

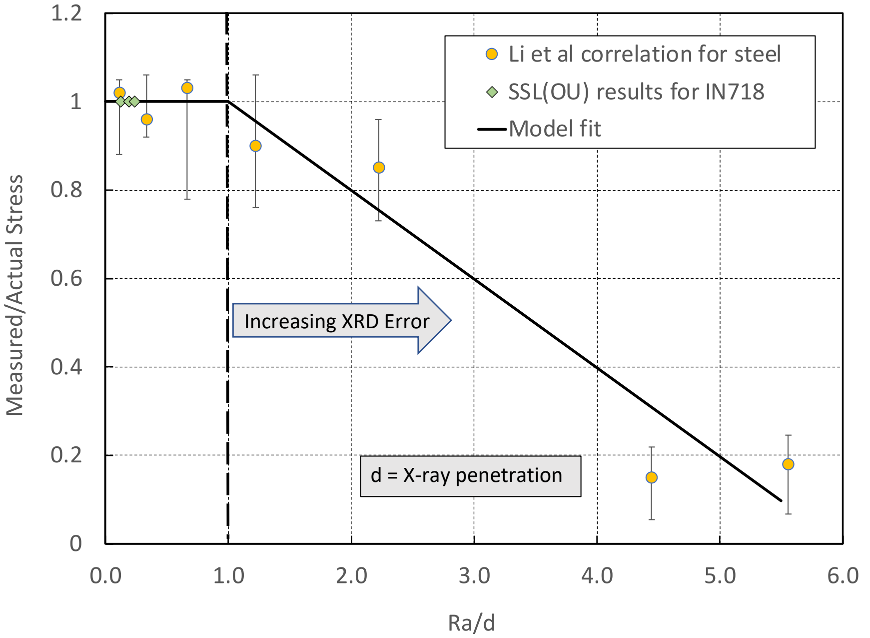
Used 25 ψ tilts

Significant Surface Roughness (Ra)

When Ra < d (penetration depth) XRD gives accurate stress results



When Ra > d (penetration depth) XRD gives increasingly erroneous results



Mitigation: If $R_a/d > 1.0$, then gently smooth with SiC papers followed by an electrolytic polish.

Acknowledgements: Dr Richard Moat (Open University); research funded by Stress-Space (SSL) & SPRINT
A. Li, V. Ji, J. Lebrun, and G. Ingelbert, Exp. Tech., vol. 19, pp. 9–11, 1995

Grain Size – SPRINT Project Outcome

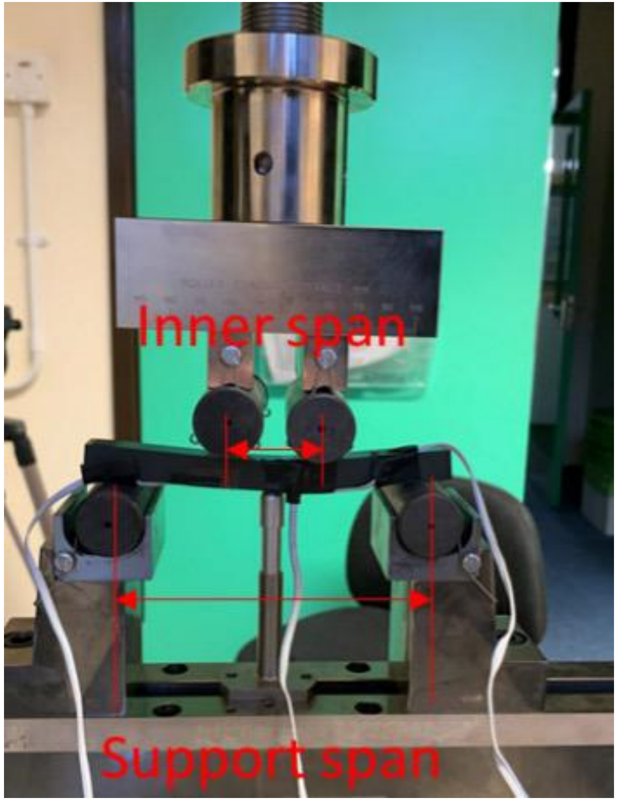
Materials having a large grain size challenge the validity of determining accurate measured stresses using laboratory XRD.

Inconel 718 beams (13.5 x 12.0 x 142) mm were solution heat treated at 955, 1050 and 1150 °C in an inert gas atmosphere and quickly cooled for 1h to obtain microstructures with the following grain sizes:

Small= 24 ± 3 µm   Medium = 56 ± 16 µm   Large= 117 ± 33 µm

The beams were then bent under 4-point loading and released to introduce tensile top and compressive bottom surface residual stresses.

The stresses were measured by XRD at 10 locations on each specimen using a range of test conditions: PSI and PHI oscillations, translations and multiple measurements.



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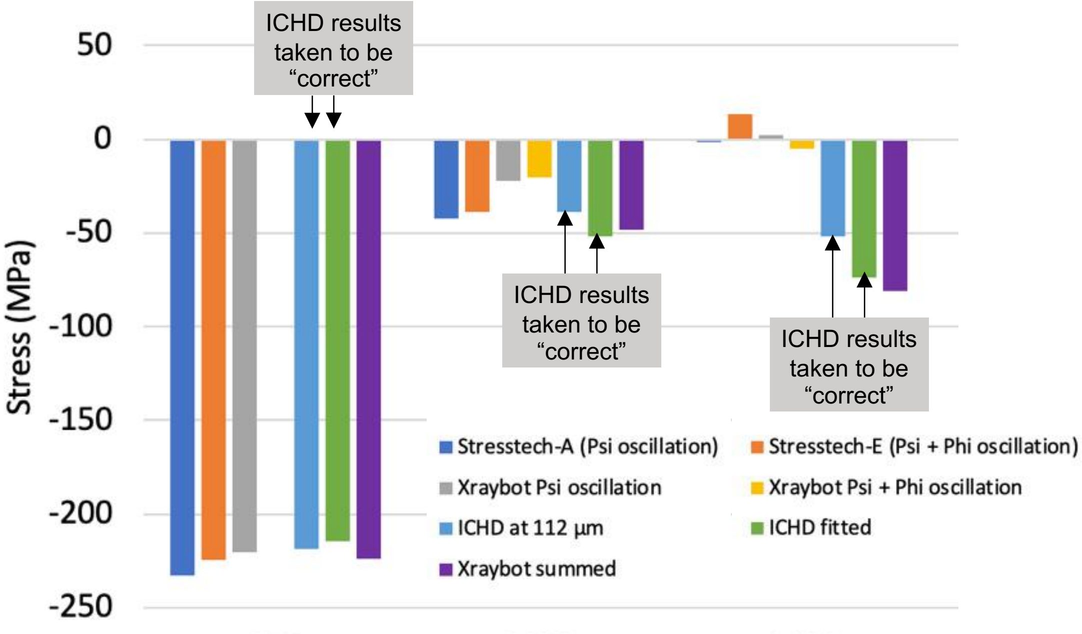

Grain size: Small = 24 ± 3 µm Medium 56 ± 16 µm Large = 117 ± 33 µm

Residual stresses in the bent IN718 beams with 3 different grain sizes were determined using two XRD instruments with different acquisition settings:

- **Stresstech**
- **X-Raybot**

Results were compared against ICHD measurements.

Note: max bending stress dependent IN718 yield properties associated with different grain sizes

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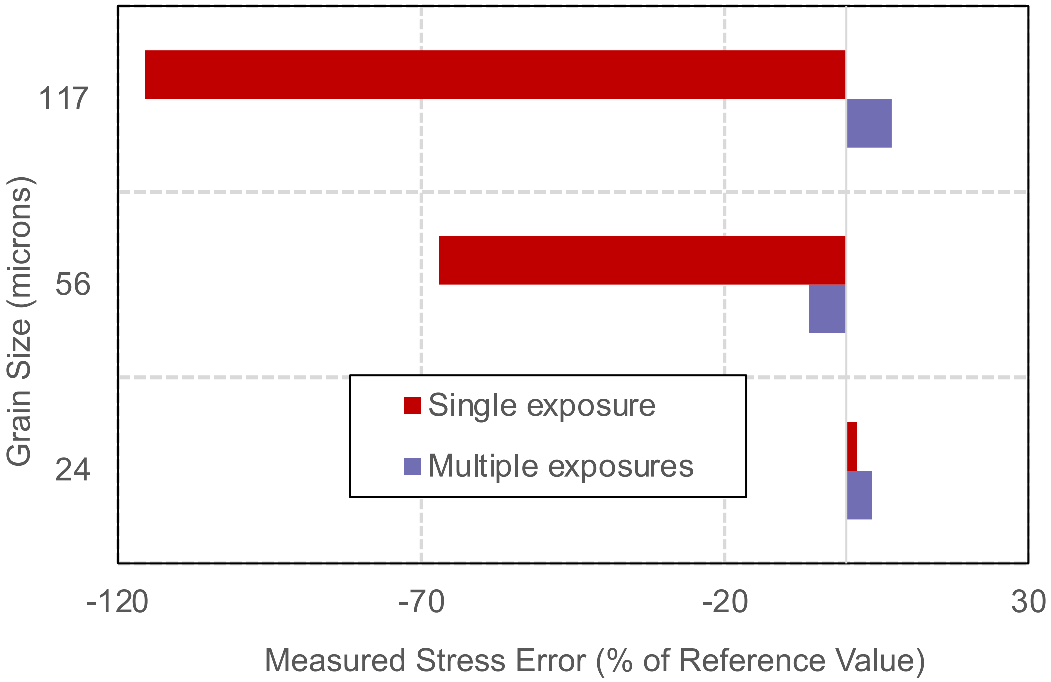
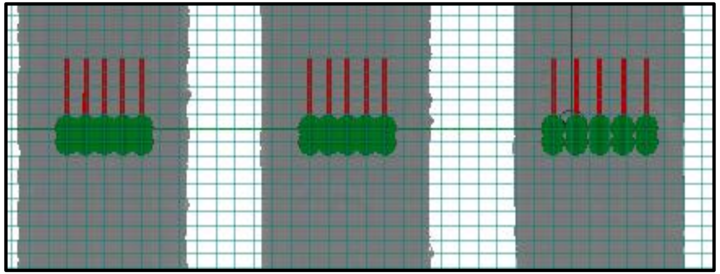
Grain Size - SPRINT Project Outcome





Conclusion:

X-Raybot multiple exposure method eliminated grain size measurement errors for the medium and large grain size IN718 beams

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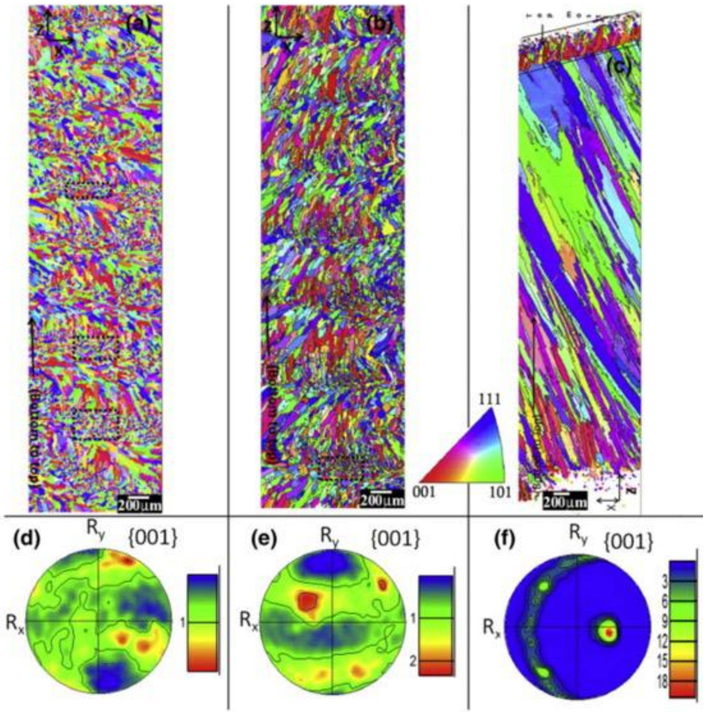
Texture

Microstructures with strong crystallographic texture are found in additive manufactured parts (worse than welding). e.g. in FCC austenitic steels, Al and Ni alloys.

Strong texture creates **anisotropic bulk elastic** properties.

At the **grain scale** the deformation response of crystallographic planes used for XRD (**diffraction constant**) is affected by both elastic and plastic anisotropic effects.

Thus E_{xxx} varies strongly with direction and a single value cannot be used for $\sin^2\psi$ fitting in laboratory XRD.



Typical microstructures and texture present in AM of FCC material taken from Lakshmi L. Parimi, Ravi G. A., Daniel Clark, Moataz M. Attallah, Materials Characterization, Volume 89, 2014, Pages 102-111

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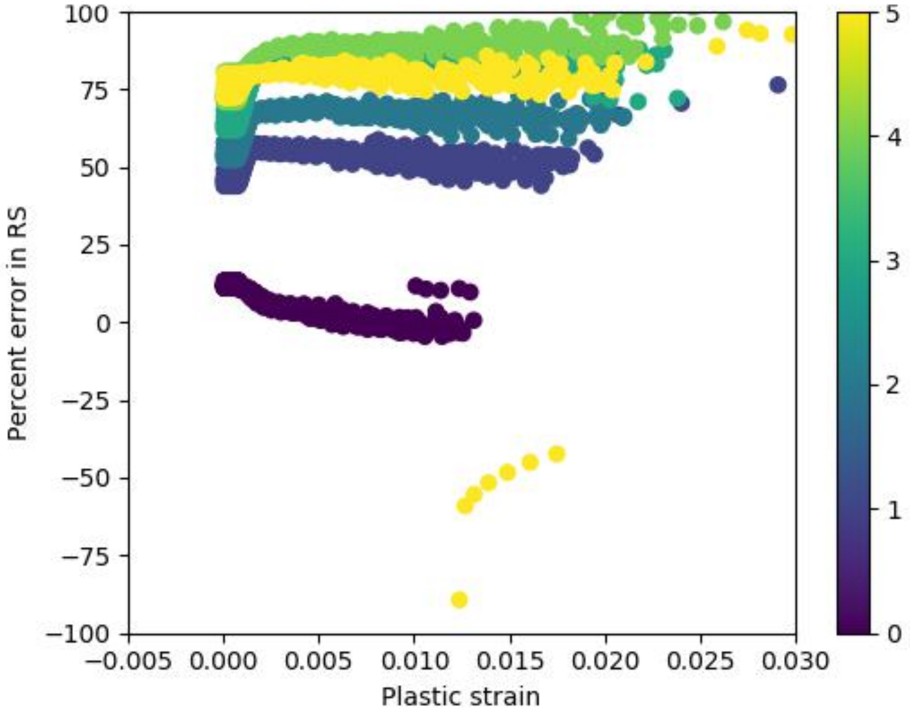
Texture - introduces error

Colour coded texture: 0 = random, 1=2, 2=3, 3=5, 4=11, 5=42 (unit of strain 10^{-3}%).



Texture anisotropy effects were examined using self-consistent modelling for materials with varying severity of texture. 1000s scenarios were simulated varying the applied stress & associated plasticity for 10 different levels of synthetic texture.

Simulation Results

- Large stress errors in $\sin^2$ psi method for stainless steel owing to texture along the (001) fibre direction assuming random texture bulk modulus.
- Errors in apparent XRD measured stress increase with degree of texture.

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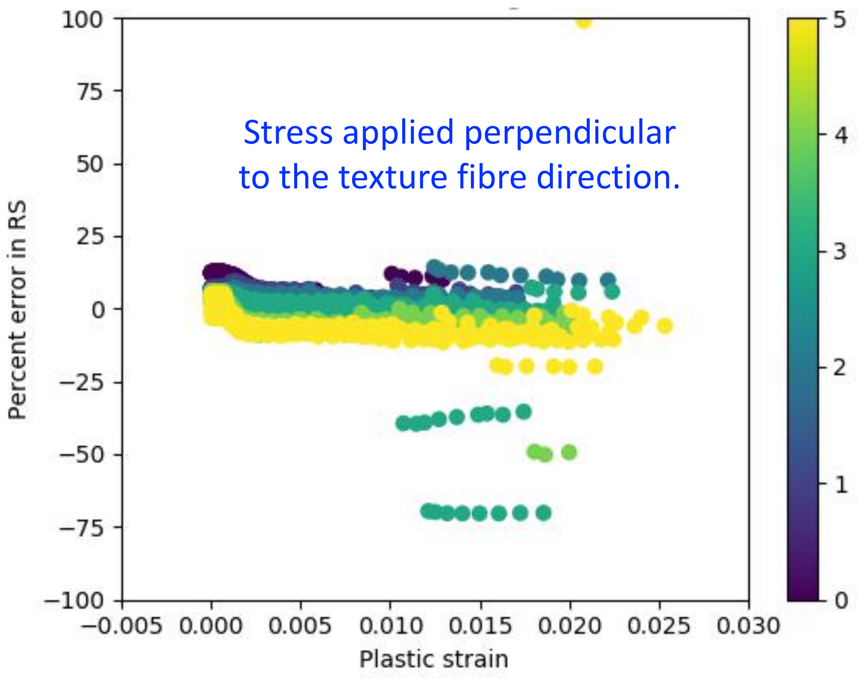
Dealing with Texture

Colour coded texture: 0 = random, 1=2, 2=3, 3=5, 4=11, 5=42 (unit of strain $10^{-3}\%$).



1. Stress error much less using modulus calculated from slope of modelled stress-strain curve
2. XRD residual stress measurements are potentially feasible for stresses acting in the 2 directions orthogonal to the <001> fibre direction in FCC materials, if an appropriate elastic modulus is used and angular sweeps are made around this fibre direction.
3. The transverse isotropic modulus can be determined by EPSC modelling for given texture, or from a columnar grain aggregate model or by measurement (ASTM standard method).

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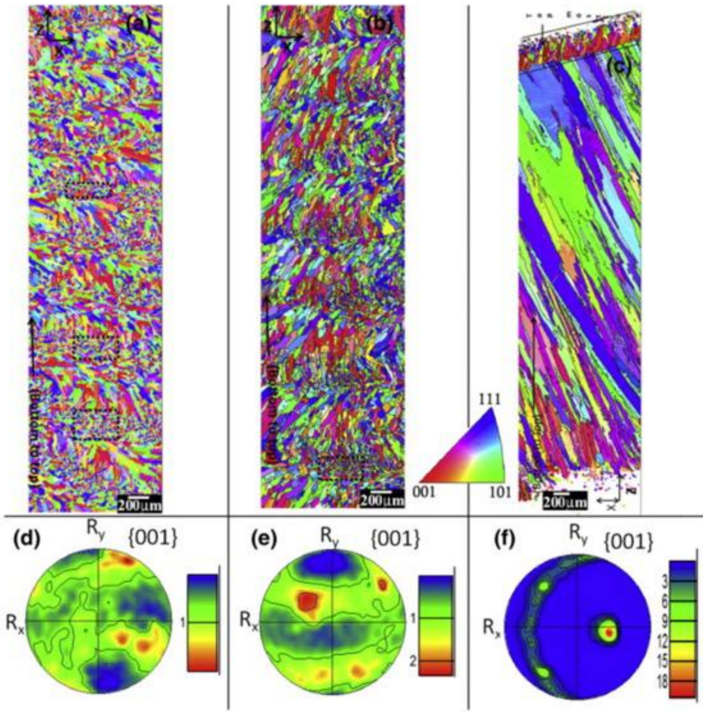

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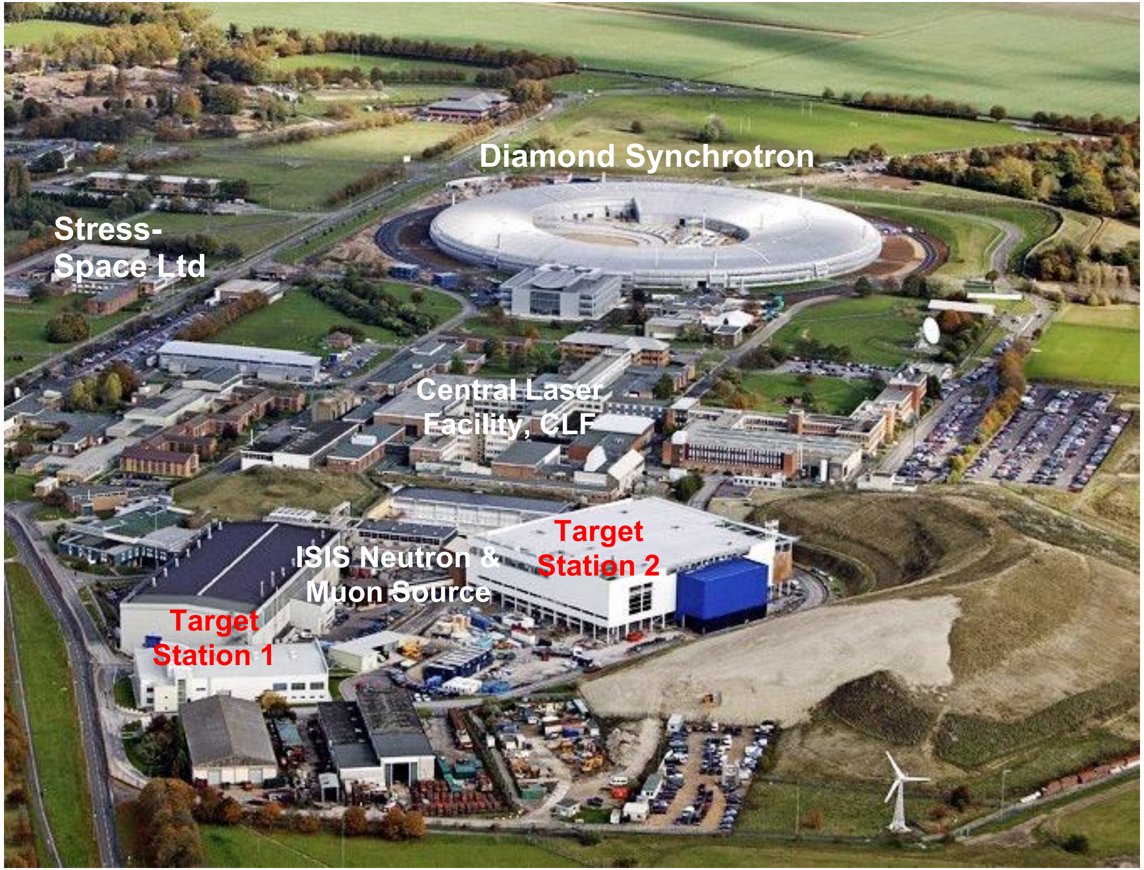
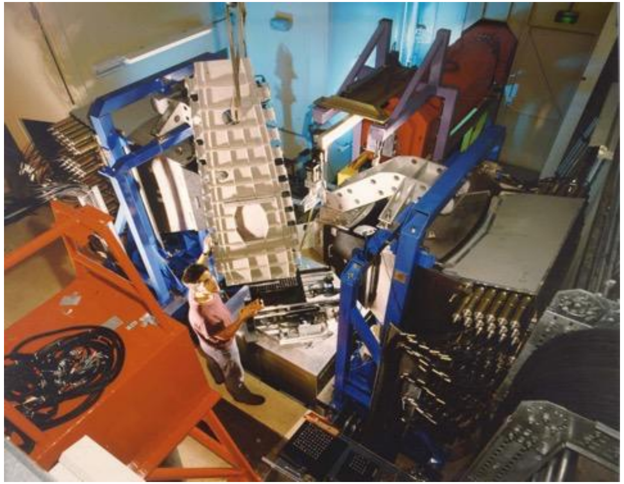
Awkward Location





ENGIN-X Neutron Diffractometer

1. In-situ "field" measurements
2. Restricted access
3. Remote control essential

Can surface residual stresses be measured by XRD at the same time as bulk stresses by neutrons?

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STFC Proof of Concept Grant awarded (13 Jan 2023)

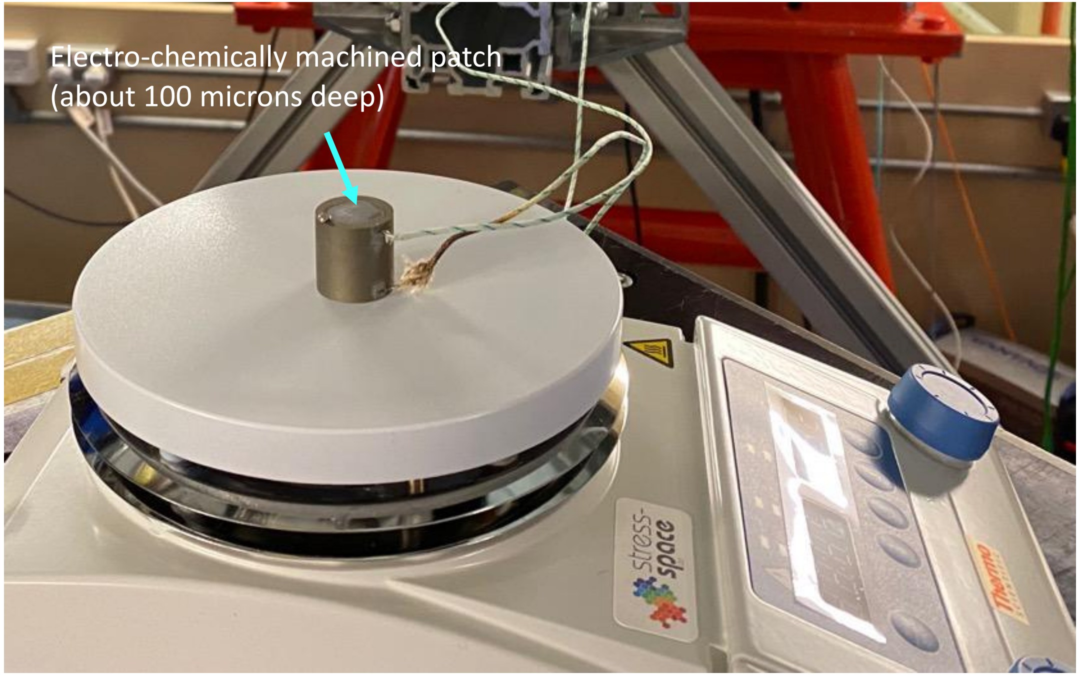
X-ray Diffraction		Neutron Diffraction
Vision Guided X-Raybot	+	ENGIN-X Central Facility
$Sin^2\psi$ method		Full stress tensor
Surface residual stress		Bulk residual stress

Proof of Concept Experiment on ENGIN-X (March 2023)

Supported by: *Graham Appleby, Saurahb Kabra, Tung Lik Lee and Joe Kelleher (STFC) and Adrien Sprauel (MRX-Rays)*

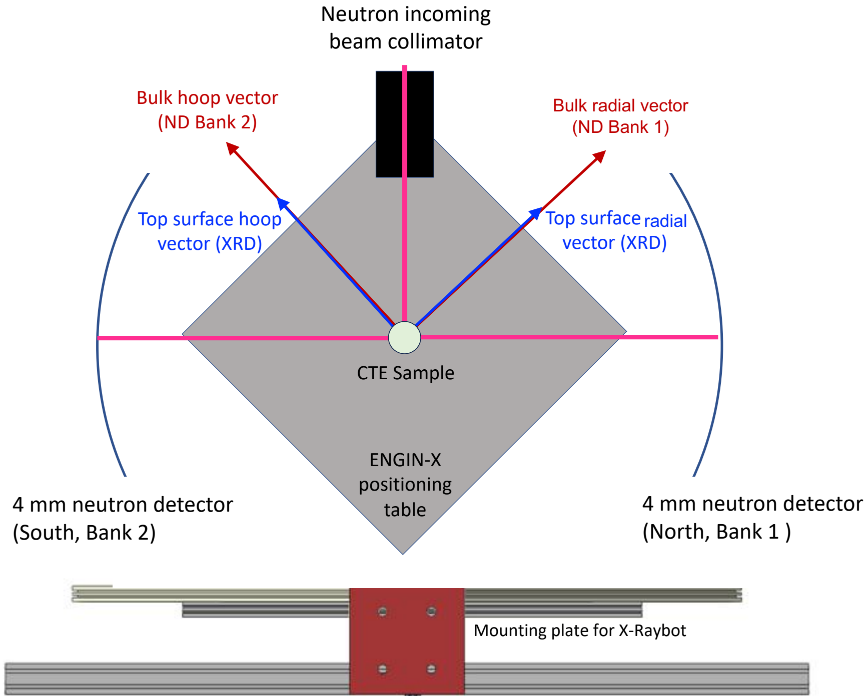
Experimental plan: Measure CTE of test sample

1. 20 mm dia cylindrical test coupon
2. Extracted from A508 Cl 3 steel ring-weld (after stress relief).
3. Top surface was electrochemically milled to a depth of 100 microns to remove any residual stresses introduced by EDM machining.
4. Cylinder was thermo-coupled at the top and bottom.
5. Temperature was raised in approx. 20 ^{o}C increments from room temperature to 240 ^{o}C using a hot plate.



CTE is the mean coefficient of thermal expansion

Remote In-situ Measurements



Laser scan

Reference XRD measurements

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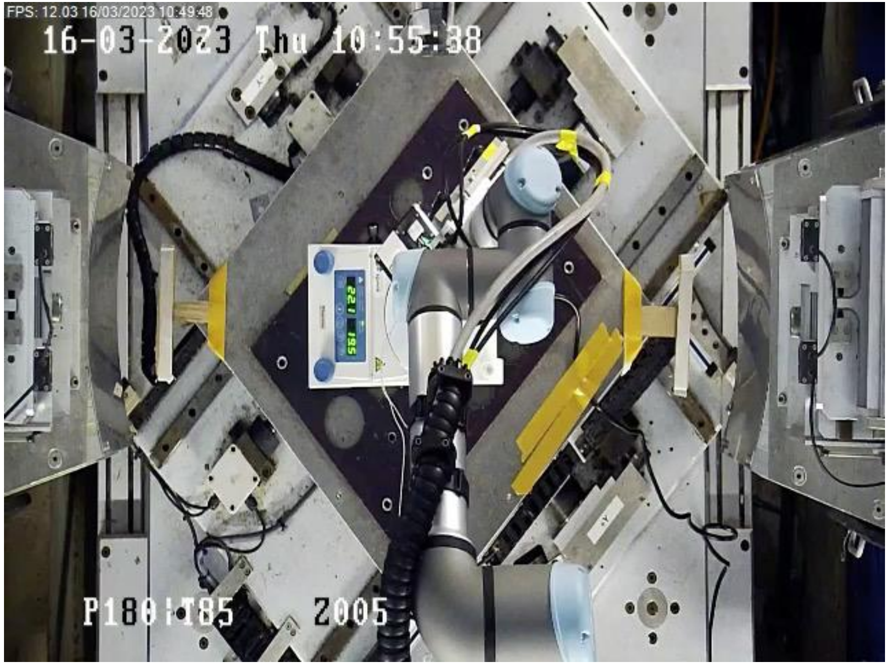
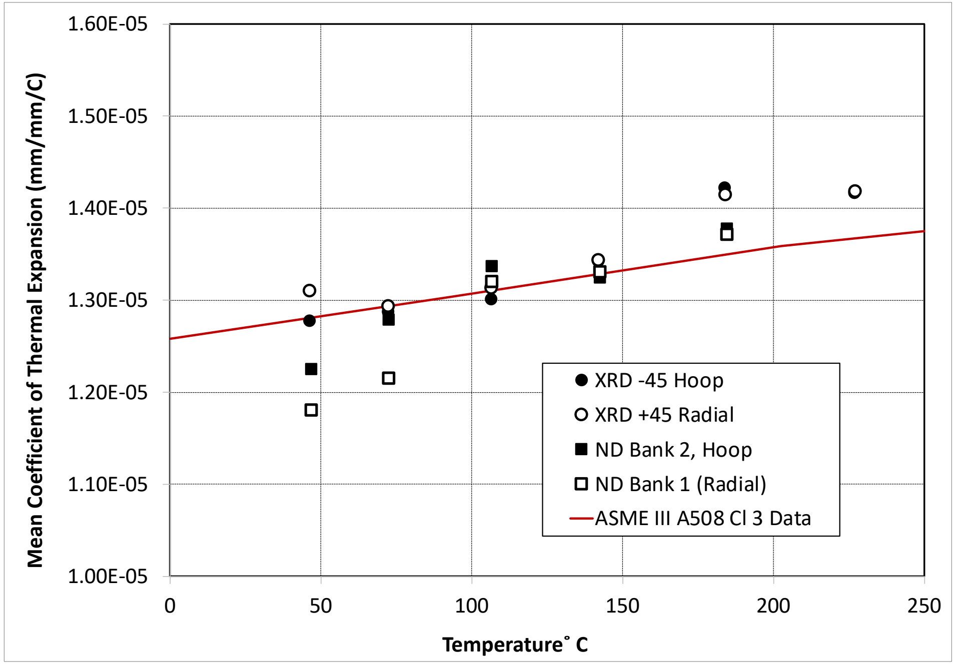
	Stress-free powder		Stressed reference (-509 ± 35) MPa	
Alignment	Direct stress (MPa)	Shear stress (MPa)	Direct stress (MPa)	Shear stress (MPa)
+ 45^{o}	-6 (17)	-7 (3)	-533 (19)	1 (3)
-45^{o}	-12 (10)	7 (2)	-537 (17)	-1 (3)

Birds eye view of adaptive laser scan of surface for defining measurement points and vectors

CTE measurement results



Bird's eye video clip showing X-Raybot {211} lattice parameter measurements using $Sin^2\ \psi$ method



Mean CTE measured by XRD and neutron diffraction compared with ASME A508 Class 3 code data

Summary of Solutions

Awkwardness	Some Solutions
Location: structure/plant/production line cannot be moved (or hazardous environment)	Measure in-situ using portable XRD equipment (use remote controlled robotic XRD system for hazardous cases)
Material: surface roughness (Ra/d > 1)	Smooth surface (light abrasive) then electro-polish
Material: large grain size	Use larger gauge area, oscillation and/or sum multiple exposures
Material: texture	Measure normal to the <001> fibre direction in FCC alloys using transverse isotropic diffraction elastic constants.
Geometry: Complex 3D curved surfaces	Define measurement position, surface normal and measurement vectors using a laser guided adaptive XRD system (e.g. X-Raybot)
Geometry: Restricted XRD goniometer access	Try different mounting, other diffraction planes, or restrict angular range of tilts (compensate for by maximizing number of tilts).
Geometry: High stress gradients	Use smaller gauge size & high resolution global/local positioning system (e.g. laser guided adaptive X-Raybot)