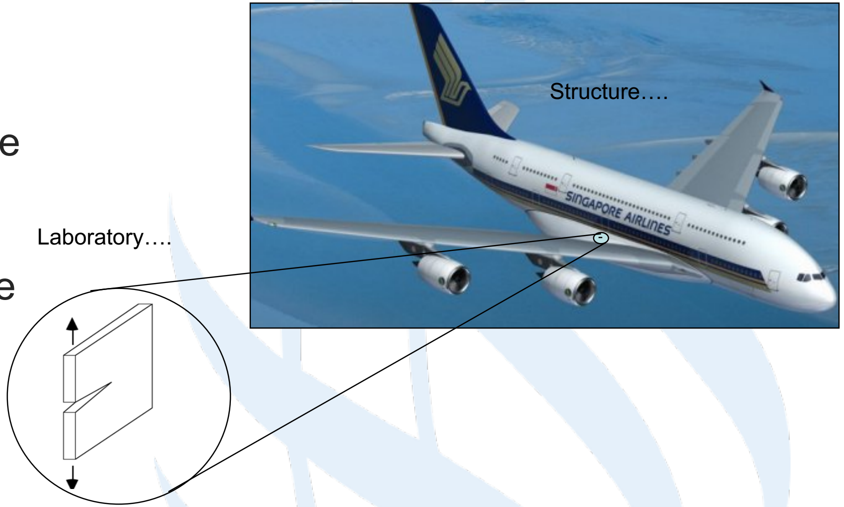
Residual Stress Analysis: Hole Drilling and the Contour Method

Professor Michael Fitzpatrick

Why do we want to know about stress?

- Stress doesn't exist!
- *Strain* can be determined
- ***Stress is a mechanics concept. It relates the materials response to an applied force as a consequence of the interaction of the strain field with the stiffness matrix.***
- So why do we want to know what the "Stress" is?
    - Similitude: direct extrapolation from the lab to the component in-service
    - Stress, not strain, correlates with all major failure mechanisms:
        - Tensile strength; Fatigue; Fracture; Creep

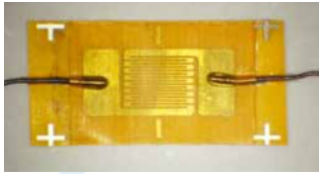


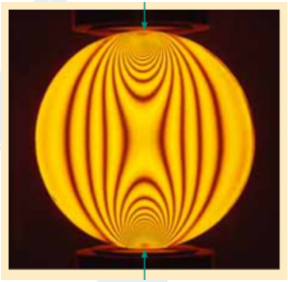
How do we measure strain?

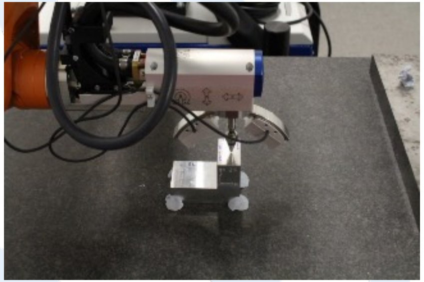
- Relative measurements: “before and after”
  - Strain gauges
  - Photoelastic techniques
- Direct measurements
  - Diffraction techniques: lattice strains
  - Mechanical techniques by strain relief
- Indirect measurements
  - Ultrasonic methods, magnetic methods etc
- ***But we are not measuring stress***

Strain measurement techniques

- Non-destructive methods
  - Strain gauges
    - Measuring changes in electrical resistivity
  - Photoelastic techniques
    - Measuring changes in optical transmission
  - Diffraction methods
    - Measuring changes in lattice spacing

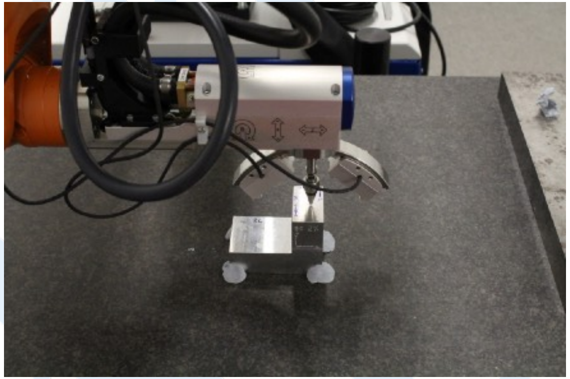






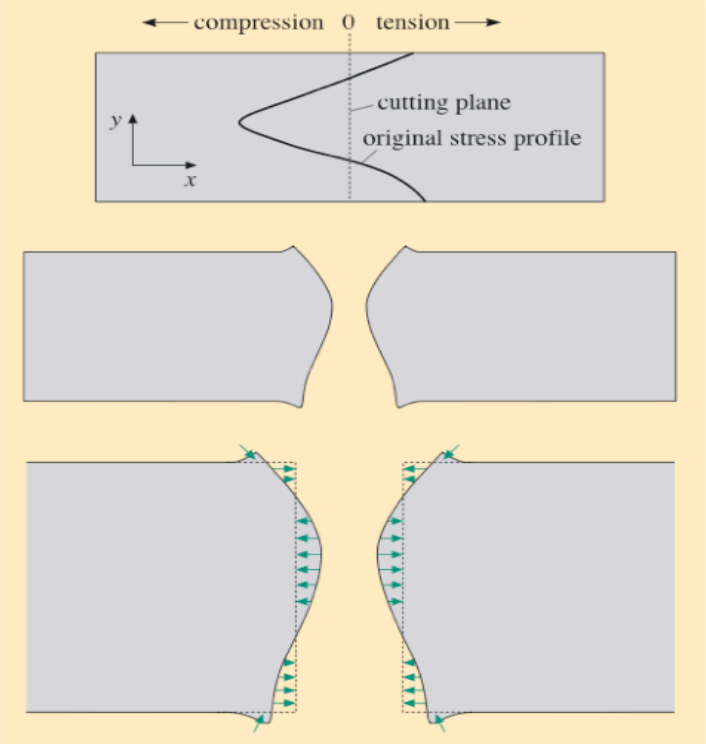
Strain measurement techniques

- “Semi”-destructive methods: *i.e.,* small amount of material removal. “Strain relief” methods
    - Incremental hole drilling
    - Diffraction with layer removal



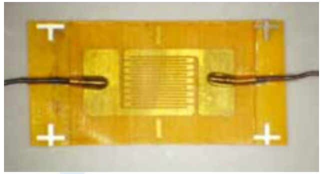
Strain measurement techniques

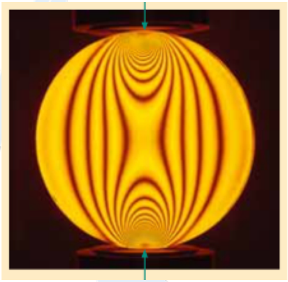
- Destructive methods
  - Deep hole drilling
  - Contour method
  - Slitting method

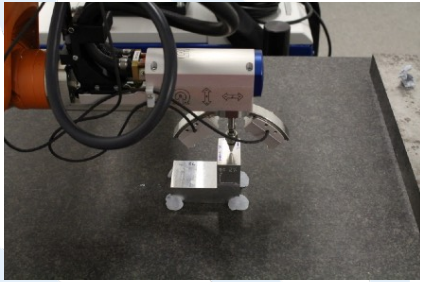


Strain measurement techniques

- Non-destructive methods
  - Strain gauges
    - Used to detect response to applied forces, and/or for long-term monitoring of a structure
  - Photoelastic techniques
    - Very few practical applications. Influenced by shear $(\sigma_1 - \sigma_2)$ so solution may be non-unique
  - Diffraction methods
    - Laboratory methods such as X-rays are near-surface
    - “Large-scale” facilities offer full-depth profiling

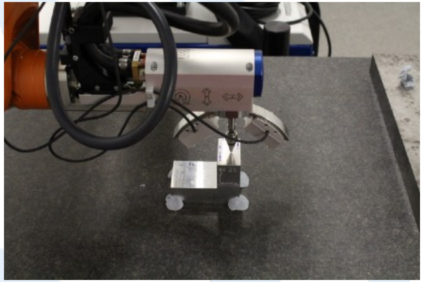






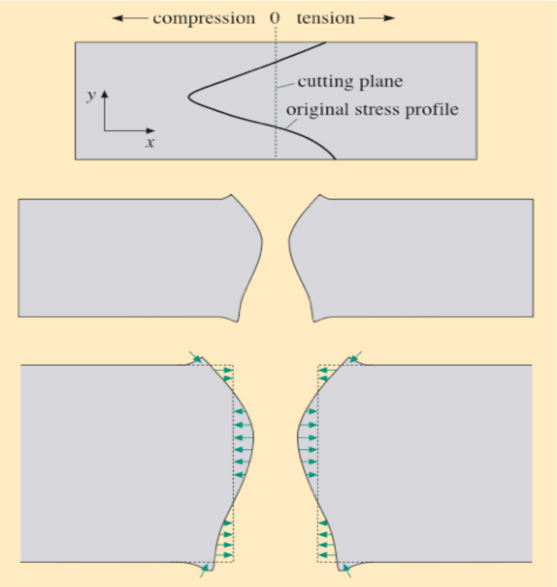
Strain measurement techniques

- “Semi”-destructive methods: *i.e.,* small amount of material removal
  - Incremental hole drilling
    - Near-surface, typically to 1.5 mm depth. Good method in the lab for validating X-ray measurements
  - Diffraction with layer removal
    - Very useful when applied alongside hole drilling. No robust and generalised method of correcting for relaxation or redistribution as layers are removed

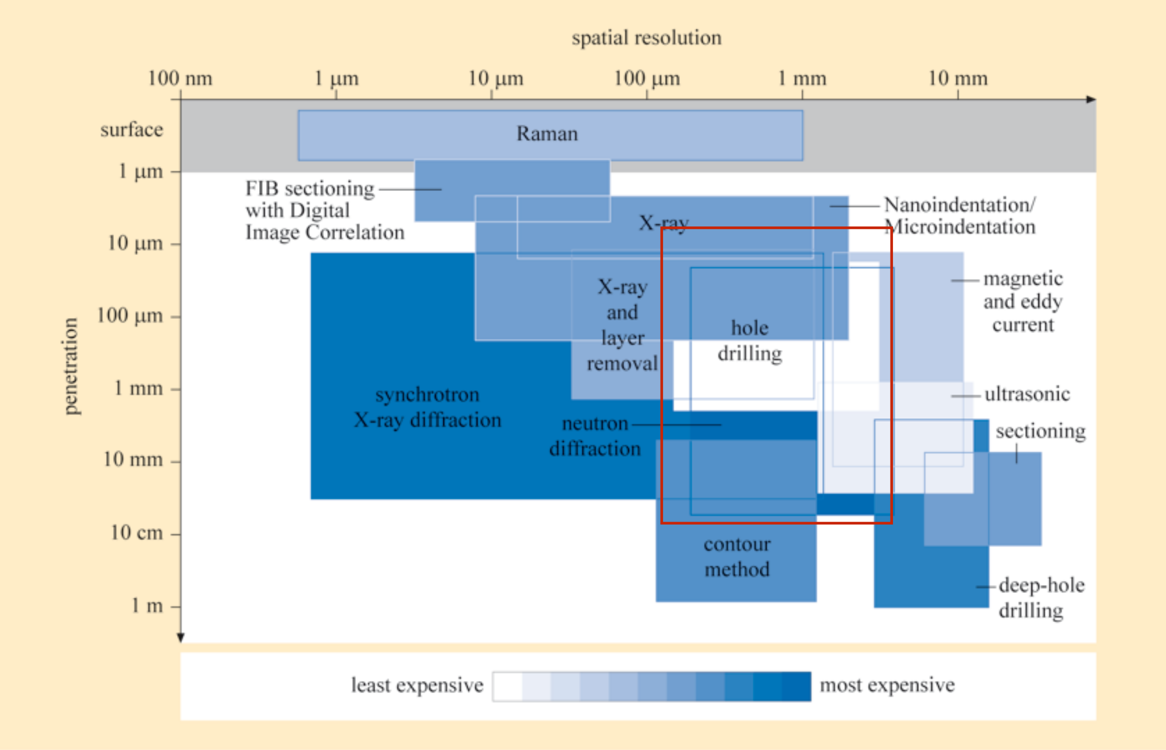


Strain measurement techniques

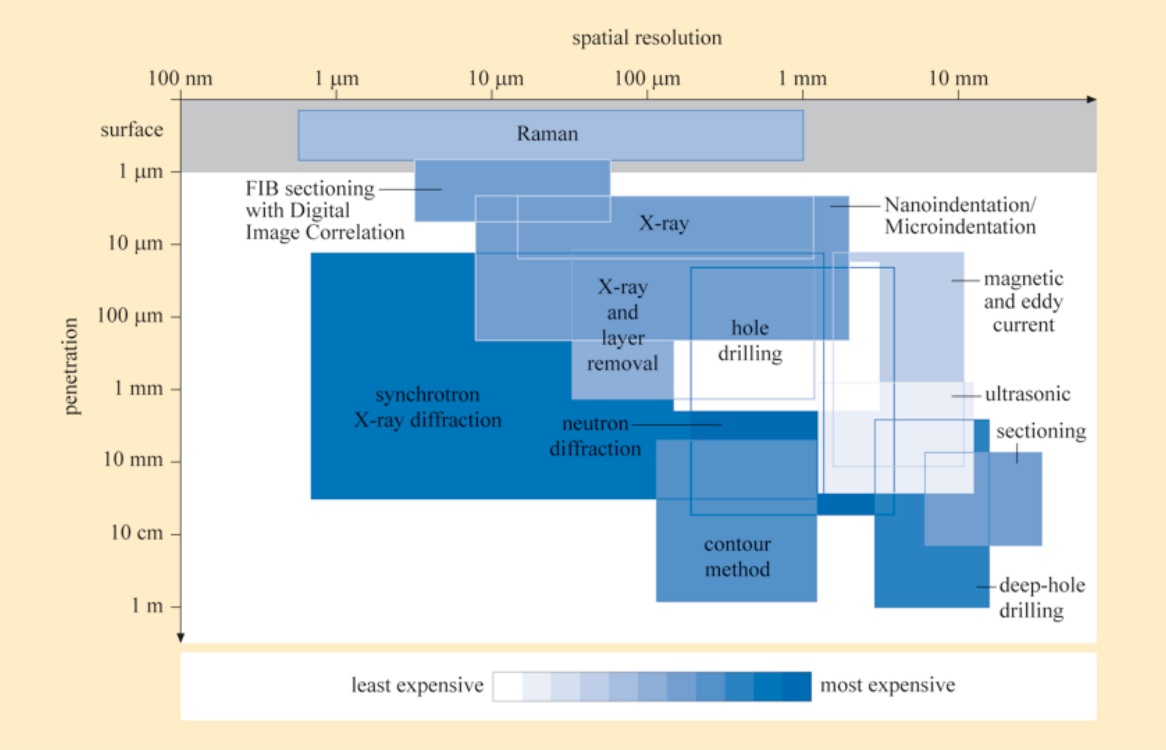
- Destructive methods
  - Deep hole drilling
    - Useful particularly for measurements on large components. Veqter have a virtual global monopoly on using the technique
  - Contour method
    - Full cross-sectional profile in a single measurement
  - Slitting method
    - Not used perhaps as often as it should be!



Stress Analysis Techniques



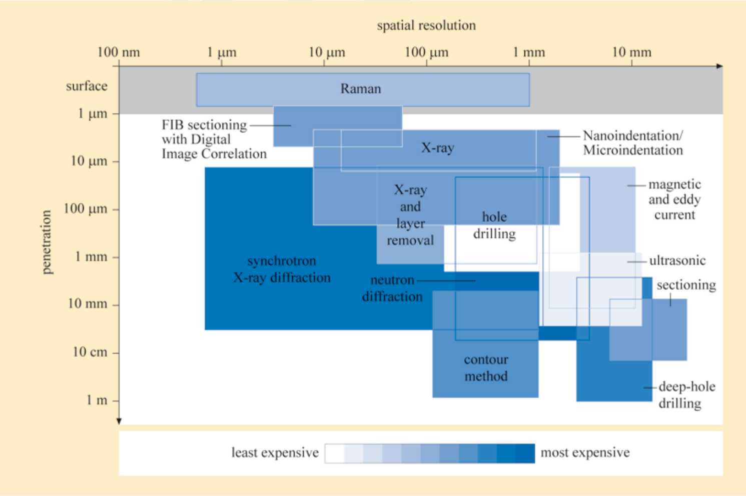
Analysis Techniques for Strain/Stress



- If a technique is not based on diffraction or strain relief, it can be *correlated* to strain/stress, **but has no direct relationship to it**
- It is also unclear which component of strain/stress drives changes in the measured property

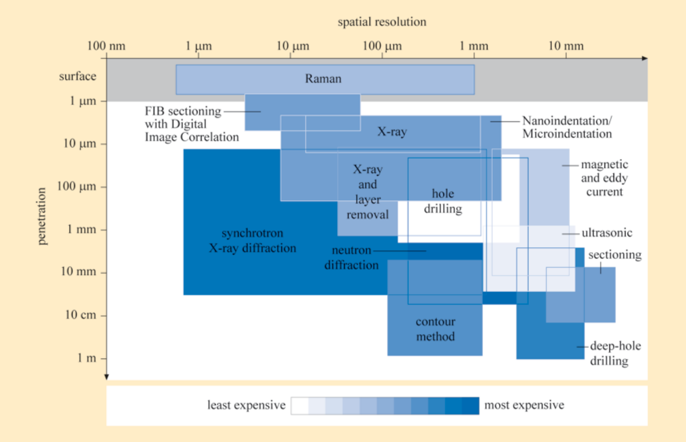
What about non-standard methods?

- Ultrasonic and magnetic measurements etc claim to be able to “measure residual stress”. Also Raman, X-ray fluorescence, nano-indentation etc.
- They do not even measure strain!
- The property being measured is *influenced* by strain/ stress
  - Calibration is required
  - Different calibrations may be required for **different microstructures of the same material**!
  - Is the property affected by one or more stress components? Shear stress? Etc etc…

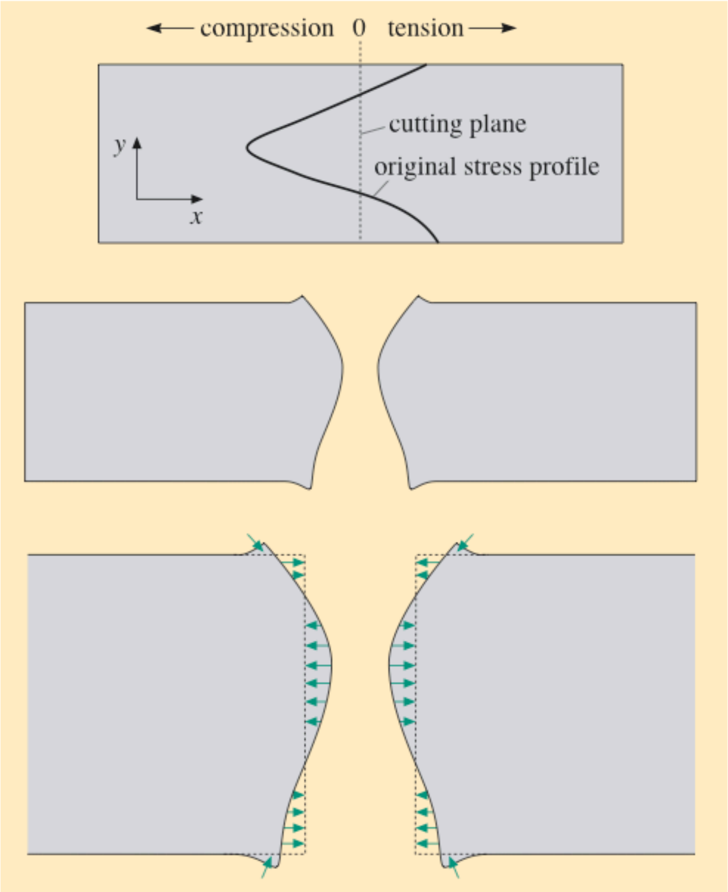


Which technique to choose?

- Why do you want to know the stress?
- What will you do with the results when you have them?
- Start with what is available locally / cheap / easy to access
- Using the large-scale facilities should not be seen as a “last resort
  - But know what your in-house expertise is and what the expertise is of the people that you work with



The contour method



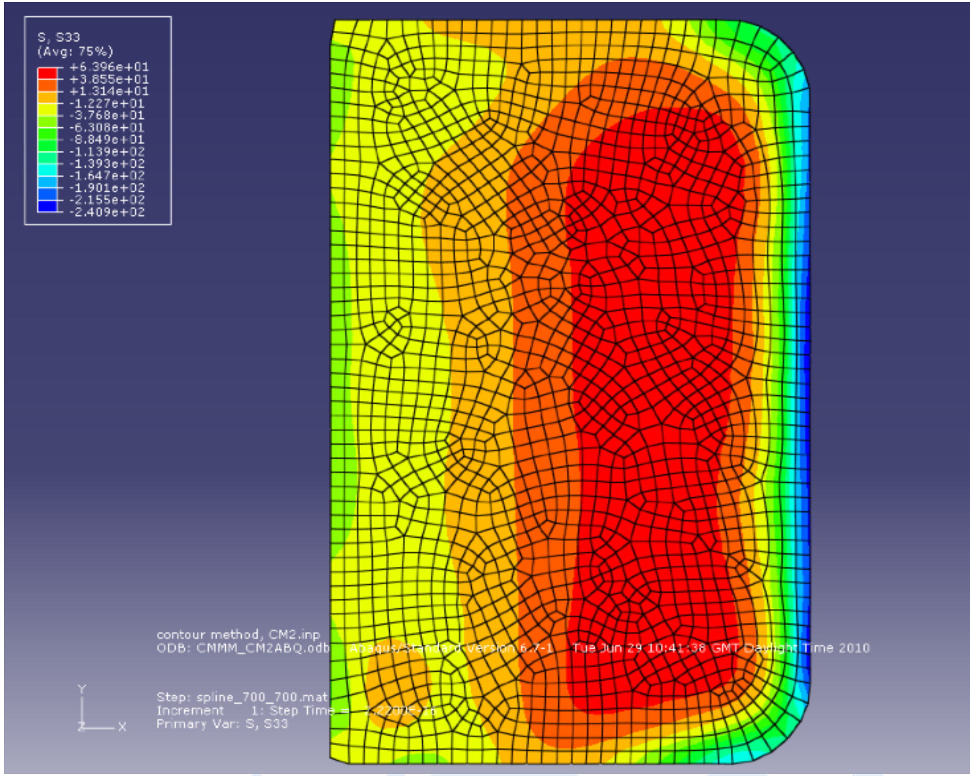
Original stress field

Cutting causes relaxation

Calculate stresses to recreate original surface

The contour method

- Line plots of residual stress/strain can be misleading
- The contour method allows determination of the full residual stress profile, in at least one direction
- Stress (force) must balance on a plane
    - *It does not have to balance along a line*
    - The contour method uses force balance as a key boundary condition in the calculation, so a contour plot of residual stress will always be in balance



Advantages

- Full cross-sectional map of the stress profile
- Insensitive to microstructure and crystallographic texture
- Reasonably time- and cost-efficient
- Can be extended to multi-axial stress components in certain geometries

- **Disadvantages**
  - Destructive
  - Sensitive to cutting, plasticity and data analysis

History

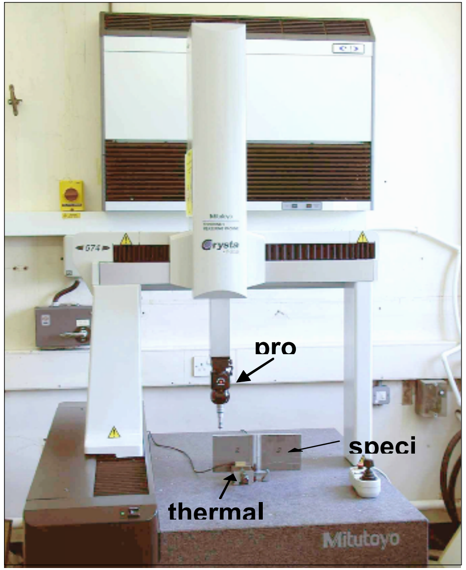
- Invented by Dr Mike Prime, Los Alamos
  - First presented at ICRS6 in Oxford, 2000
- First published in J. Engng Mater. Tech., 2001
- Worldwide patents
- Extended to multiaxial stress components by Hill and deWald
- Has been applied to a wide range of applications: welds, forgings, quenched plates, etc.

Principles and assumptions

- A part containing a residual stress is sectioned in such as way that the initial stress is relaxed elastically and no new stress is introduced
  - Use EDM wire cutting
    - Non-‘standard’ cut parameters
    - Incorrect cutting can destroy relaxed profile
  - Part is clamped to prevent elastic distortion which could change the pre-existing stress field
- Assume that any shear stresses present are small
  - Shear stresses are accounted for by measuring both cut surfaces
- Assume that cutting occurs on a flat plane

Measuring the surface contour

- Need precise relative measurements
  - Typical relaxed profile has 10-100 µm peak-to-valley variation
- Two classes of technique currently used
  - Contact CMM
  - Optical profiling



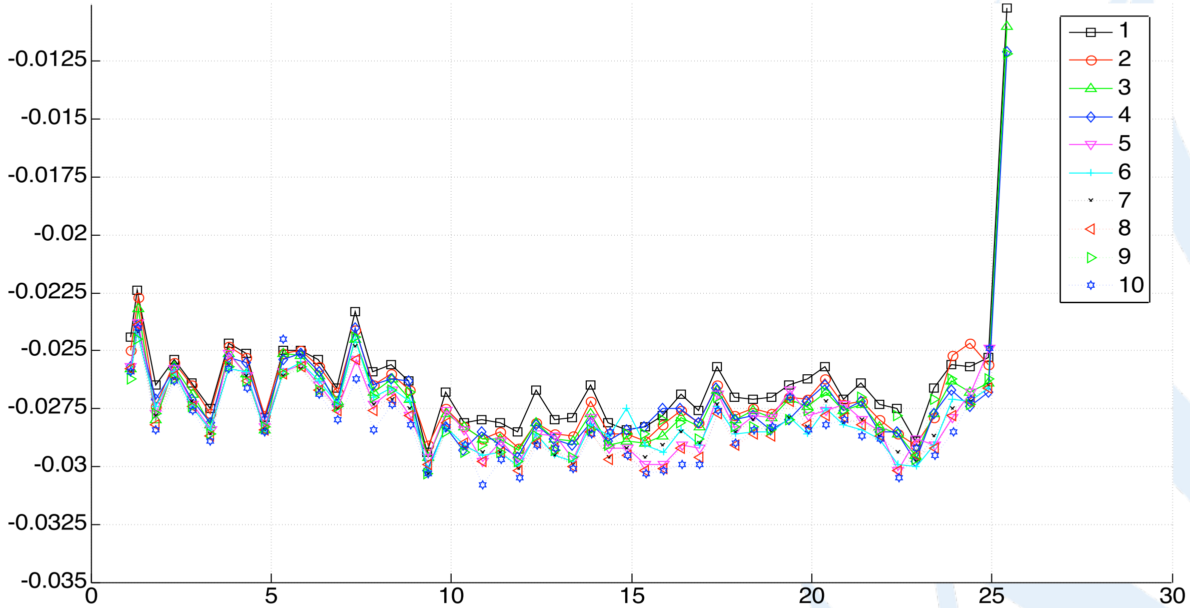
Accuracy of 5 µm over 500 mm

0.1µm resolution

Precision ±0.6 µm

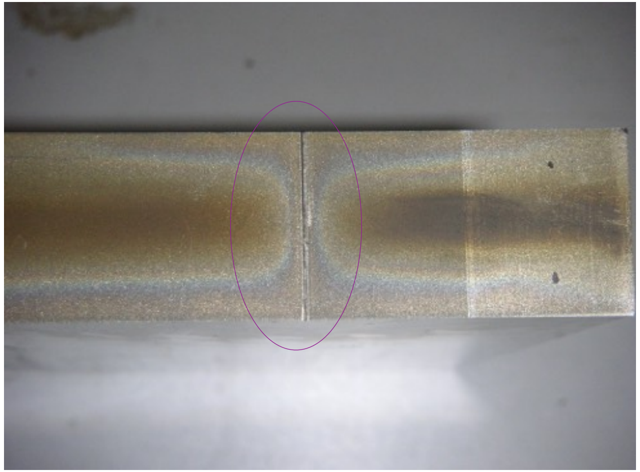
Contact CMM

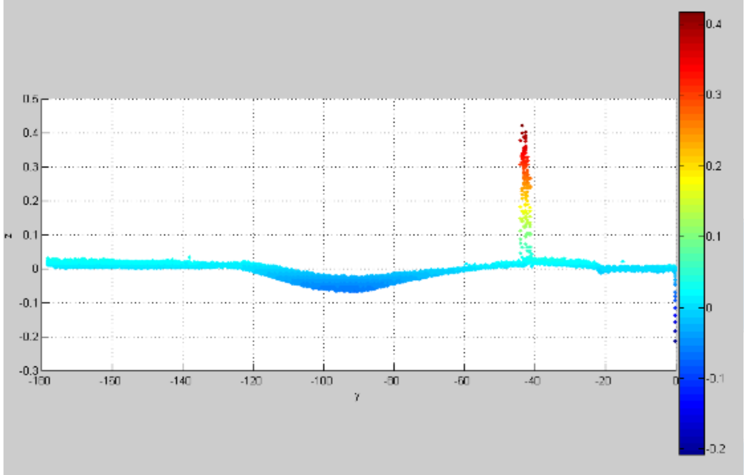
- Comparisons of independent repeat measurements suggest a stress accuracy of ±15 MPa, but there is no analytical method to derive the accuracy directly
- Measurements are highly reproducible



Data analysis

- Raw data needs to be smoothed for input to the FE model
  - Outliers removed
    - e.g., effects of wire breakage

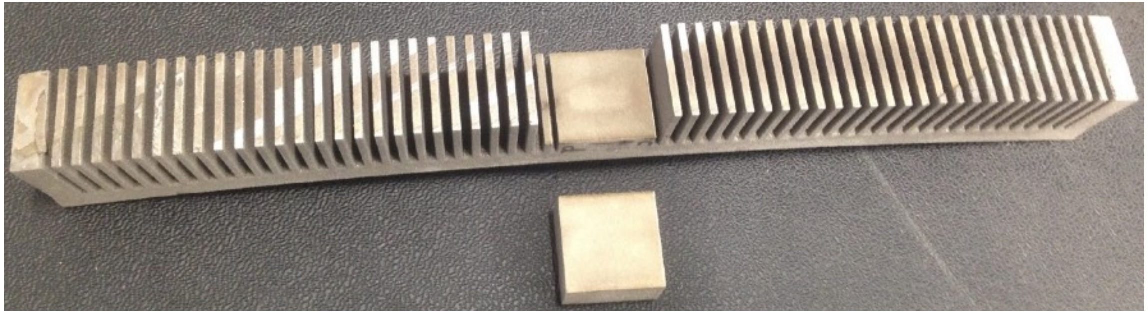


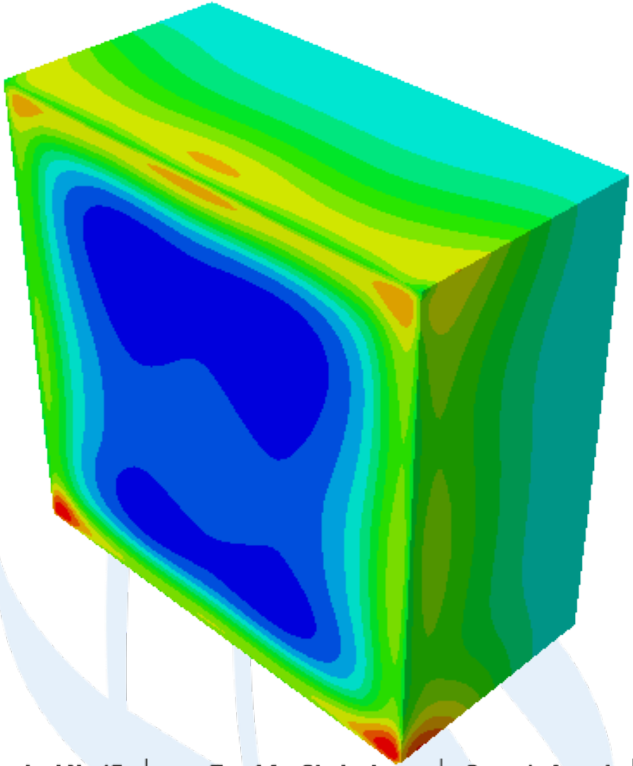


Data analysis

- Data from both surfaces is aligned and averaged
- Fitted and smoothed
    - Typically using cubic spline methods
- Exact values of results are dependent on the fitting parameters and FE coding
    - e.g., details of the spline fit, FE element density, etc.
- Significant user intervention and interpretation required in defining the final result

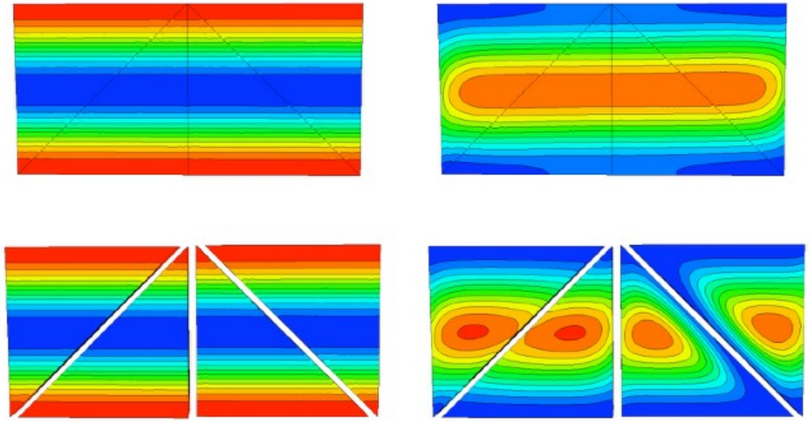
Example: additive manufacturing



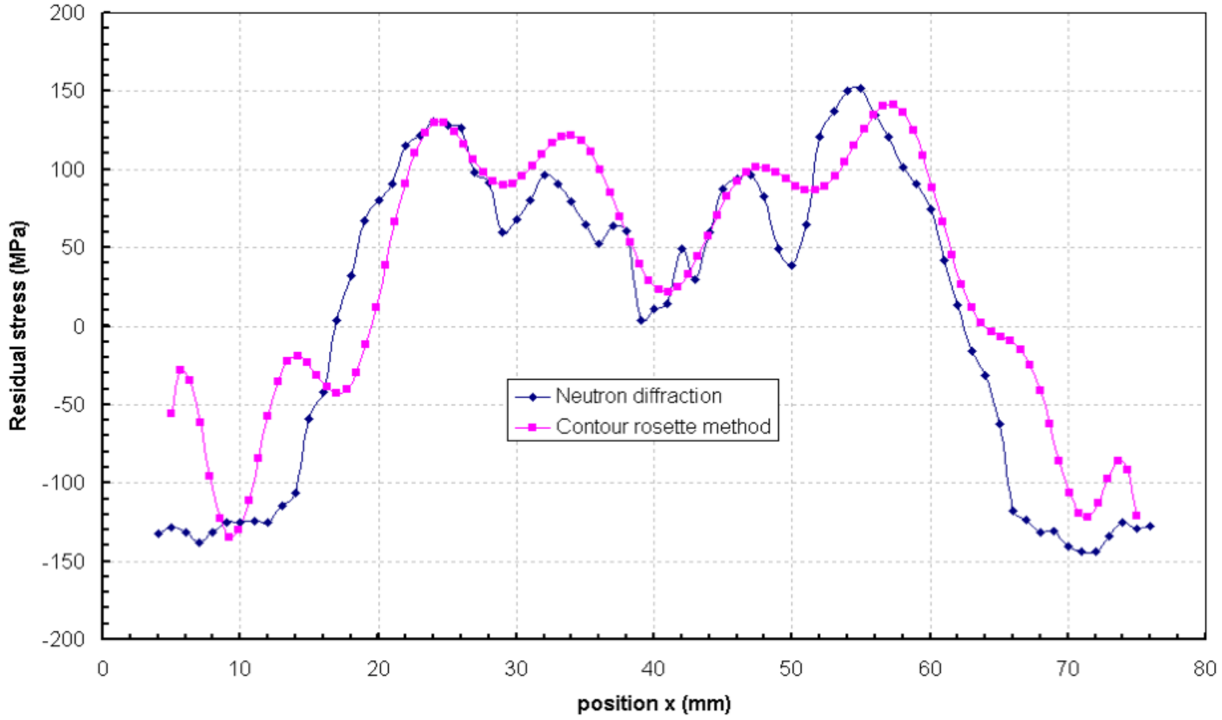


Full stress tensor analysis

- Uses eigenstrain concept
  - Eigenstrain not relaxed by sectioning
- Restricted to ‘continuously-processed’ parts
  - Require 2:1 length:width ratio
- After initial cut, remaining sections are cut at 45˚
- Allows calculation of full stress tensor



Experimental verification



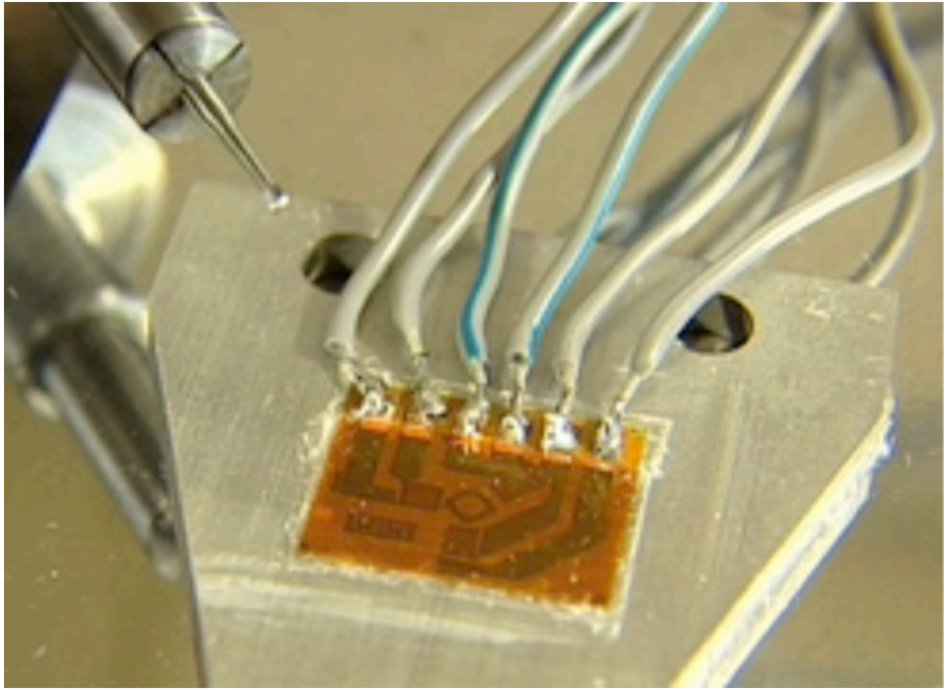
M. E. Kartal, C. D. M. Liljedahl, S. Gungor, L. Edwards, M. E. Fitzpatrick, 'Determination of the Profile of the Complete Residual Stress Tensor in a VPPA Weld Using the Multi-Axial Contour Method', *Acta Mater*., 2008:56:4417-4428

What needs to be considered

- How to choose EDM cutting parameters ?
- How to hold components during cutting ?
- How to measure the surface contour ?
- How to analyse the surface data ?
- How to cut specimens ?
- How to measure complex engineering components ?
- How to apply to micro-specimens and thin sections ?
- How to obtain more than 1 component of the stress tensor ?

Incremental hole drilling

- https://podcasts.apple.com/gb/podcast/drilling-holes/id380225232?i=1000411372321



Incremental hole drilling

Stresscraft Report No. 04-234 | *Mg peened untested* | Fig. No. 1

Gauge Type = 062UL | Hole diameter = 2 mm | ***Gauge No. 1***

depth	Relaxed Strains (με)					
	measured			smoothed		
μm	ε1	ε2	ε3	ε1	ε2	ε3
32	9	11	7	8	9	6
64	12	13	9	15	15	14
96	27	21	30	28	24	30
128	44	40	49	42	38	47
192	62	59	70	61	58	68
256	75	73	81	73	70	80
320	80	73	86	79	75	85
384	80	80	87	81	79	87
512	87	83	87	85	84	87
640	85	88	86	85	82	84
768	82	69	78	83	78	80
896	83	86	77	82	83	76
1024	79	90	72	81	89	74
1152	81	90	75	81	90	74
1280	81	91	73	81	90	73
1408	80	89	71			

depth	Residual Stresses (MPa)				
	principal		direct		shear
μm	σmax	σmin	σ1	σ3	τ13
16	-44	-70	-62	-52	12
48	-42	-67	-53	-56	-12
80	-67	-124	-87	-105	-27
112	-86	-109	-90	-105	-9
160	-37	-45	-39	-42	4
224	-11	-14	-14	-11	1
288	10	7	7	10	0
352	23	11	16	18	6
448	18	8	11	16	4
512	18	13	13	17	1
640	19	15	15	19	-1
768	19	10	13	15	4
896	20	6	12	14	7
1024	21	1	11	12	10

transverse

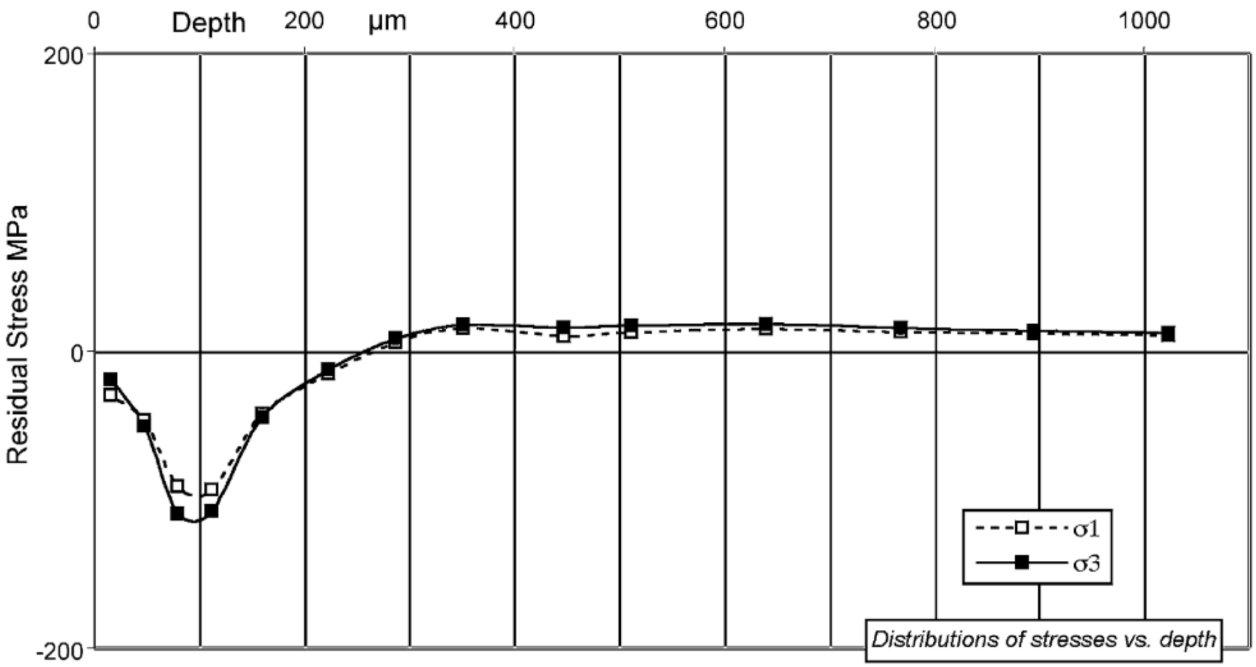
longitudinal

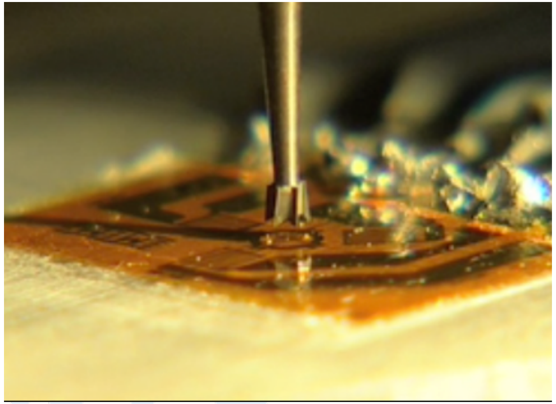
[Stresscraft RS INT v5.1.2] MAY05

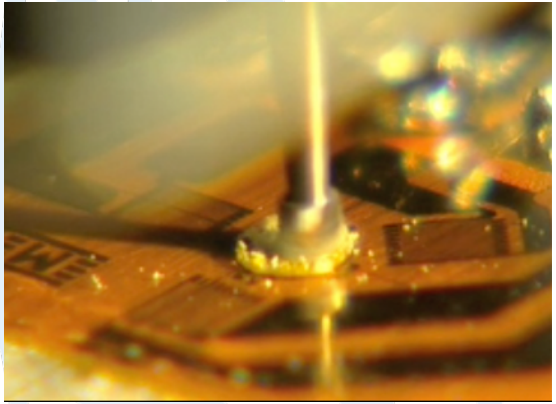
- Three strain gauges around a central hole
- Careful drilling (ideally *milling*) of the hole, and measuring of the relaxed strains
- Increasing increments with depth as the material removed becomes further from the measurement location on the surface

- ASTM E837
- Schajer & Whitehead, ‘Hole-Drilling Method for Measuring Residual Stresses’, Morgan Claypool, 2020.

Incremental hole drilling example: Mg alloy shot peened

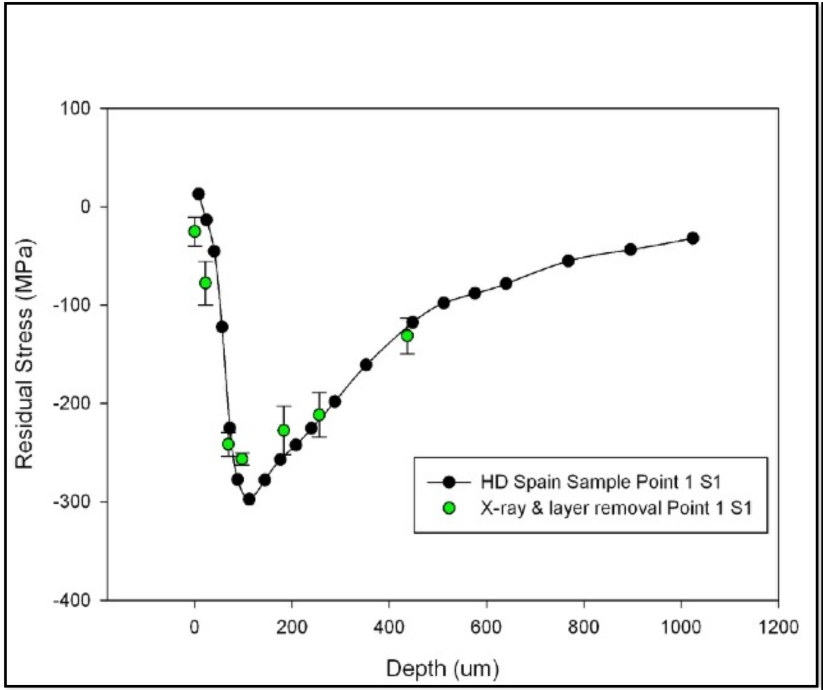


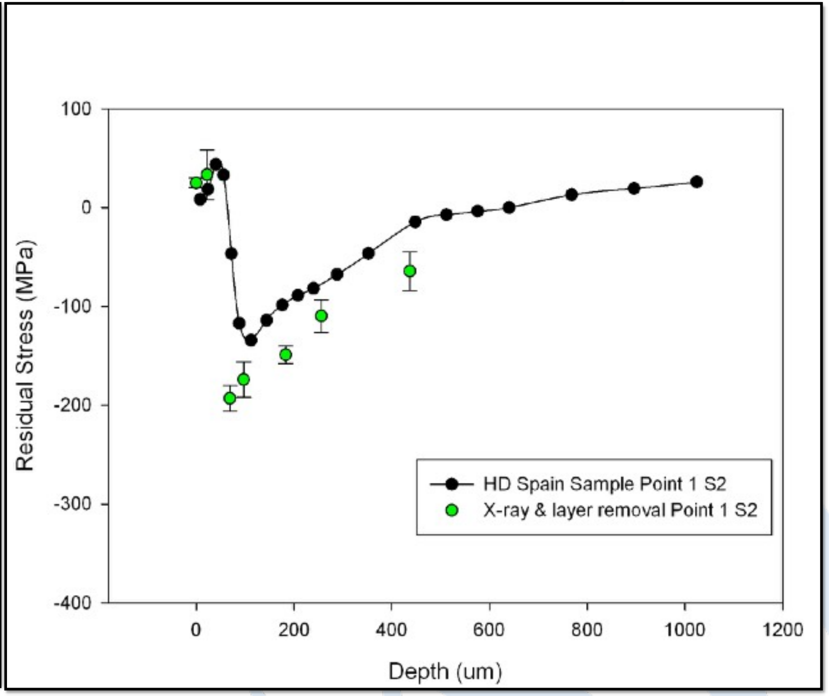




Validation is an important part of experimental stress analysis

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





Summary

- Stress is a core concept in engineering design. It drives failure processes, among other things. But is must be remembered that it is a useful **concept**, reflecting the interaction of forces with the elastic response of the material.
- There are many experimental stress analysis techniques
- None of them “measures” stress
- There is no “ideal” measurement technique
- An experimenter needs to determine:
    - **Why** the determination of stress is required
    - **What** measurements are required, and whether strain, rather than stress, will suffice
    - **How** to conduct the measurements
    - **Whether** the results are sensible, or even physically possible!


Coventry
University
Questions?