Australian Government

Some Reflections on Living with Residual Stress

Lyndon Edwards

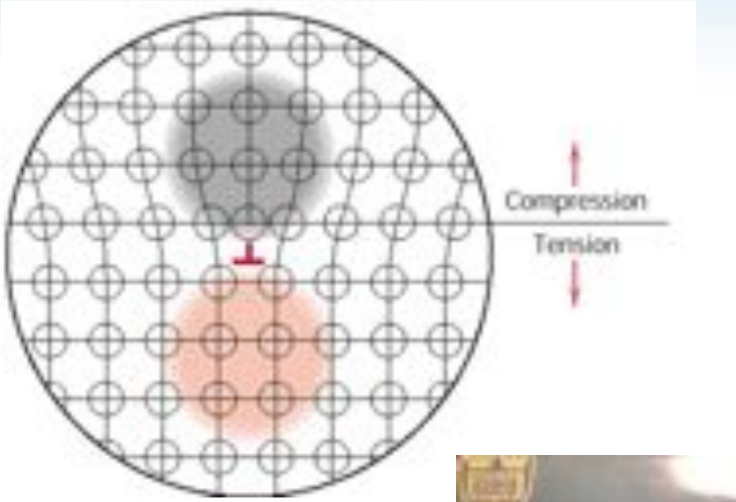
National Director
Australian Generation IV International Forum Research

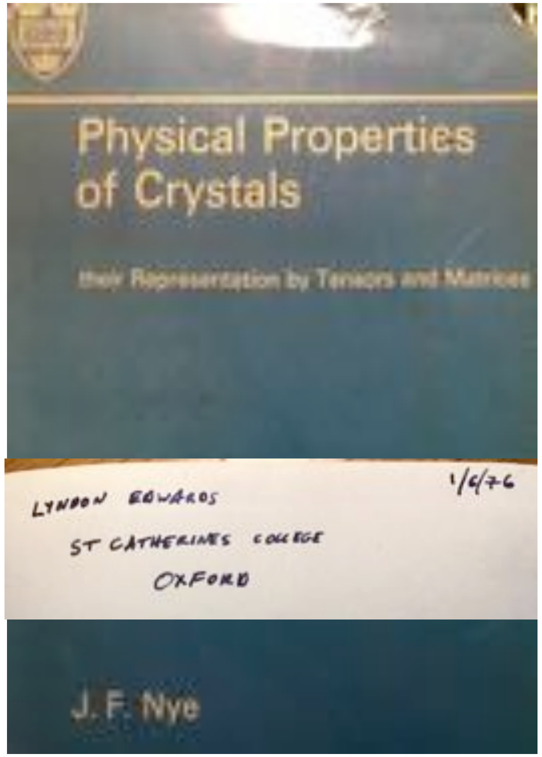
Structure

- A Bookshelf History of Residual Stress
- CXH: the start: Applied Mechanics: Sachs Boring, Start Neutron Diffraction at ILL
- NATO conference: A Transformational influence….
- ENGIN: First Dedicated Instrumentation
- ENGIN-X: Simply the Best ;-)
- VAMAS TWA 20: Setting the Standard
- Contour: A new Method is Invented.
- Industrial utility: RS in Welds - Aerospace and Nuclear
- Modelling comes of age: Validated Weld RS Simulations

First awareness of Residual Stress

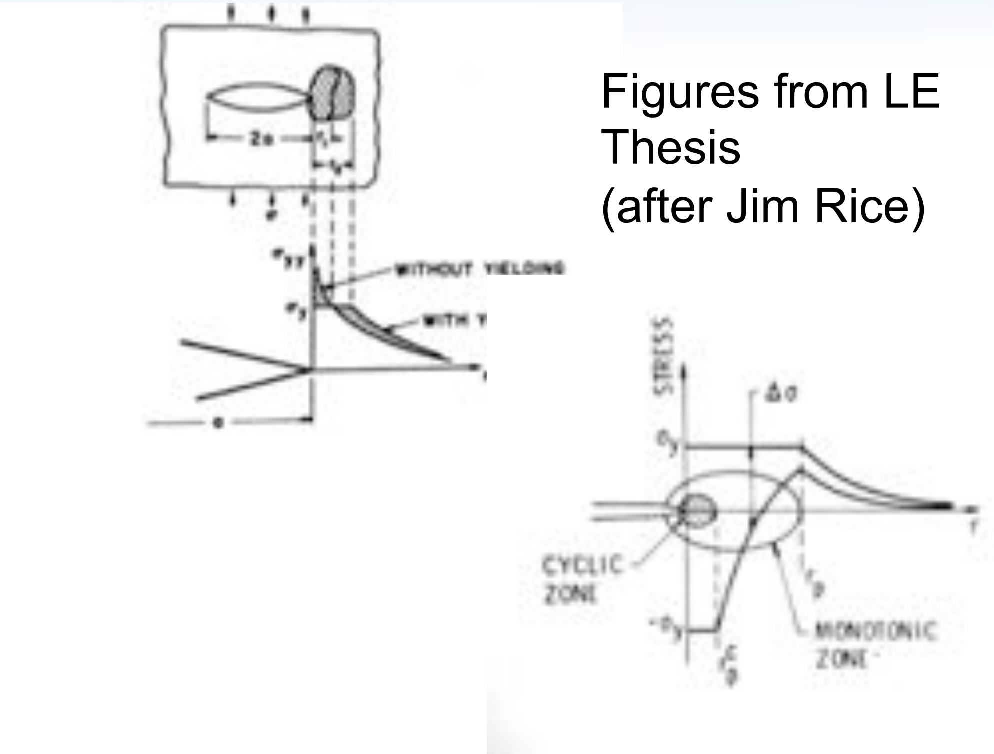
- Metallurgy U/G: 1974-1978 Stress as a tensor.
- Bought Nye on 1/6/76
- Suspect I did not understand it but recognised that it was important.
- Liked ‘simplicity’ of Tensors
- Internal stresses, Solute atoms, Dislocations
- Residual Stress: Tempered glass



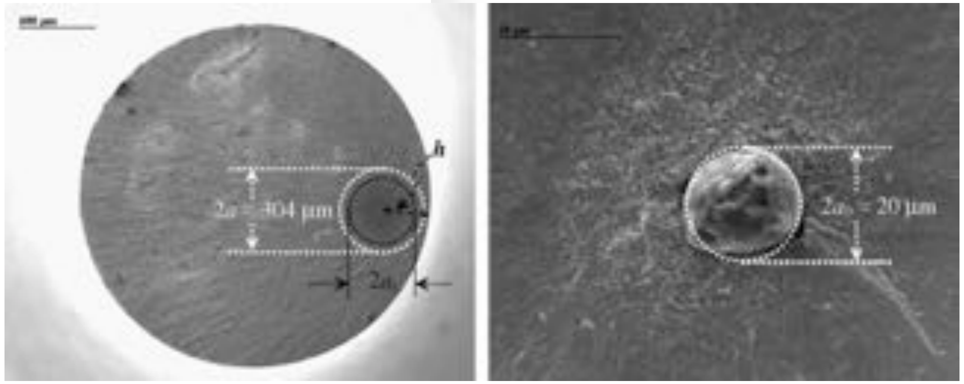


First awareness of Residual Stress

- LEFM P/G: 1978-1981 Fatigue crack growth mechanisms invoke reverse plasticity
- Mike Cowan, fellow PhD student was studying fatigue of nitrided steels.
- Used Sachs Boring to measure residual stress.
- Failure from internal cracks nucleating on alumina inclusions *(Tesselation?)*

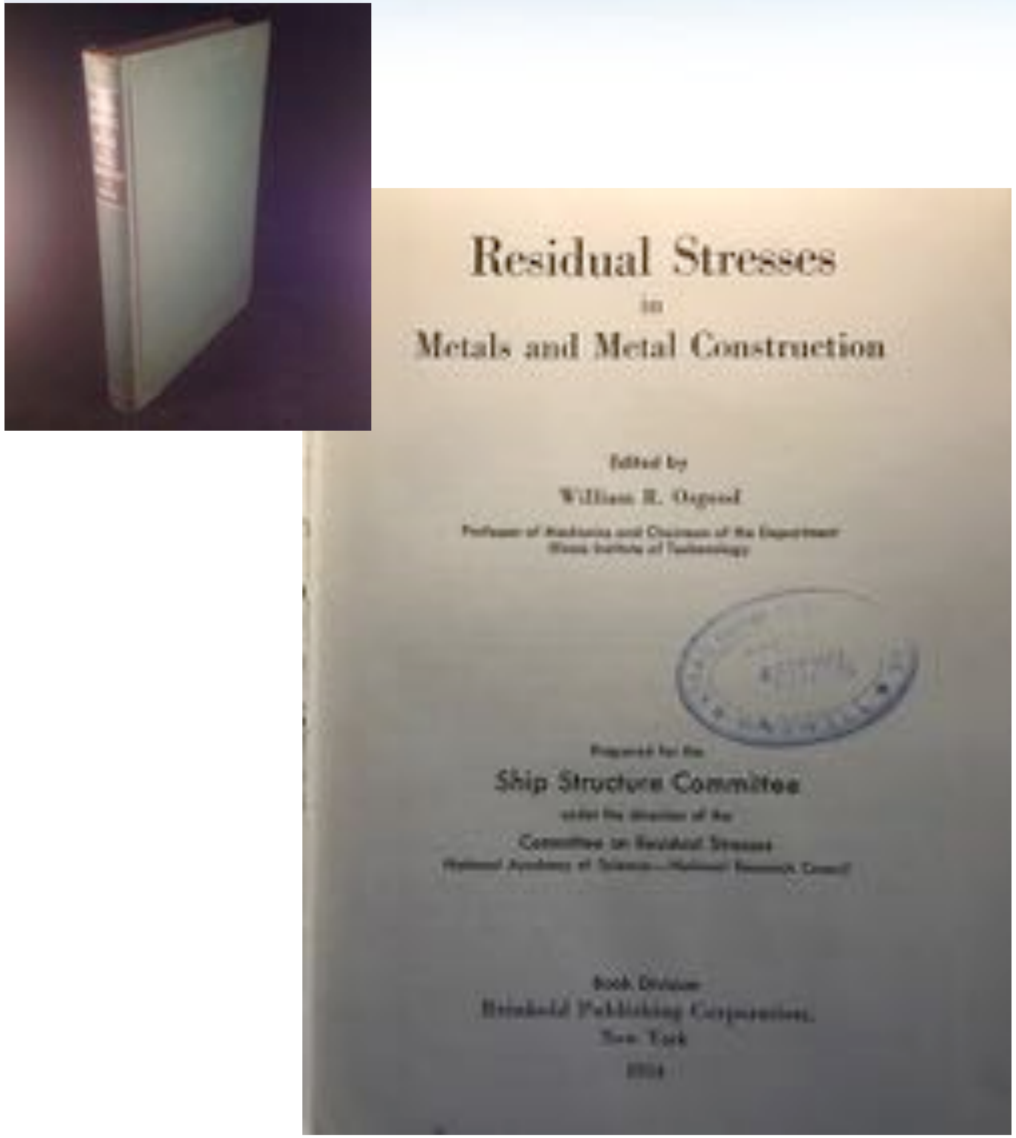


Figures from LE Thesis
(after Jim Rice)



From: http://ars.els-cdn.com/content/image/1-s2.0-S0013794407002731-gr4.jpg

Books: Residual Stress in Metals: Osgood, 1954



Residual Stresses
in
Metals and Metal Construction

Edited by
William R. Osgood

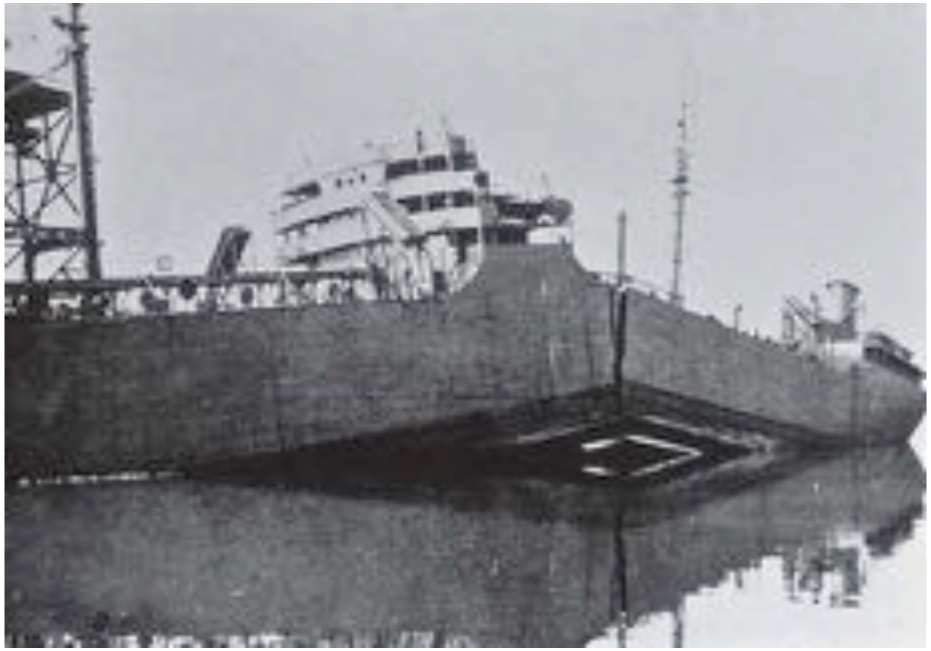
Prepared for the
Ship Structure Committee
under the direction of the
Committee on Residual Stresses

Book Division
Reinhold Publishing Corporation,
New York
1954

- ‘According to Lord Kelvin’s principle the best evidence of RS may be obtained by their measurement’
- ‘These various techniques of measurement call for some reservations with regard to their conformity to the principles of Applied Mechanics’
- ‘The measurement of residual stresses often has more the qualitative significance of a proof of the existence of residual stress rather than the quantitative significance of a precise determination’

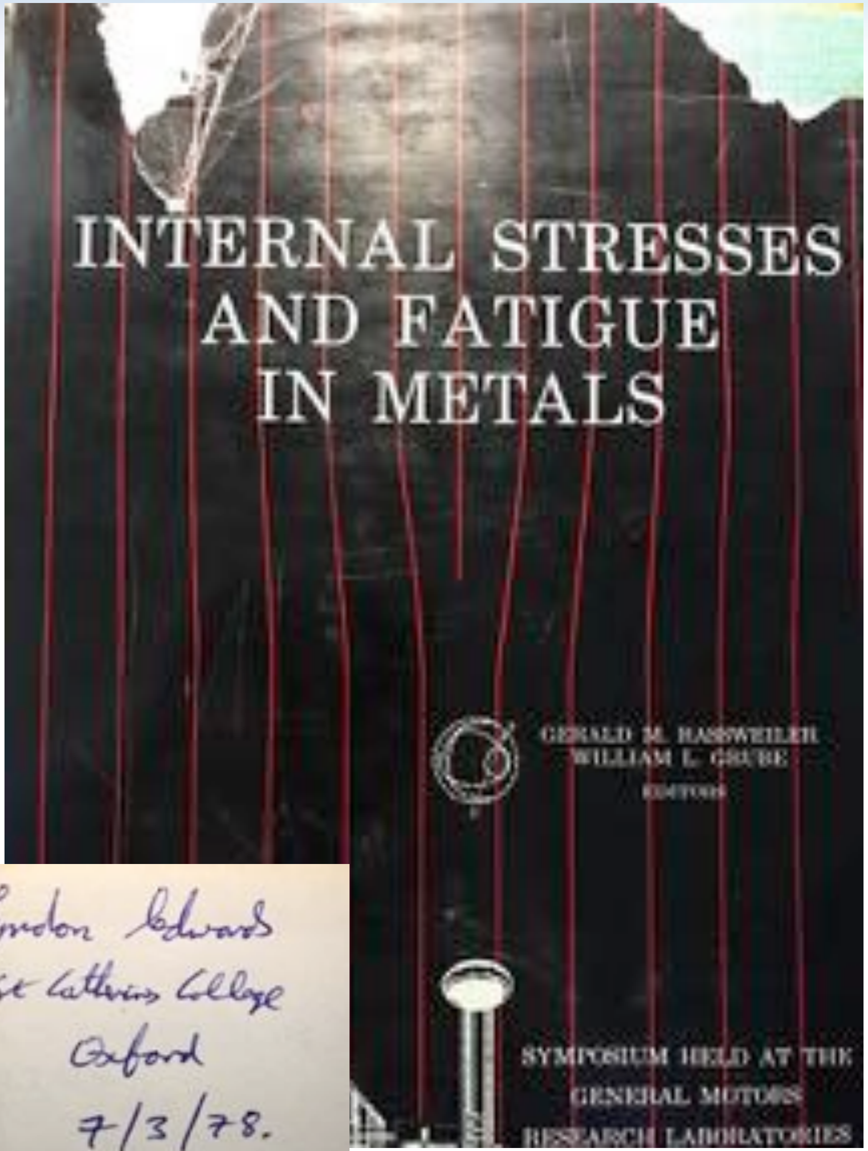
Books: Residual Stress in Metals: Osgood, 1954

Fig. 3



- Liberty Ship Failures
- Welded construction
- Fracture Mechanics was born

Books: Internal Stress & Fatigue in Metals - 1958

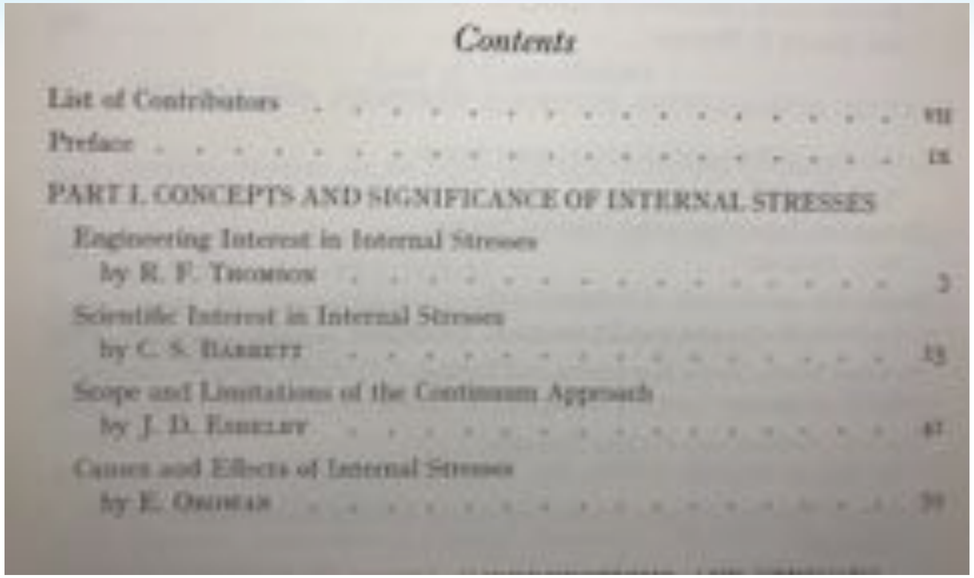


INTERNAL STRESSES
AND FATIGUE
IN METALS

GERALD M. RASSWEILER
WILLIAM L. GRUBE
EDITORS

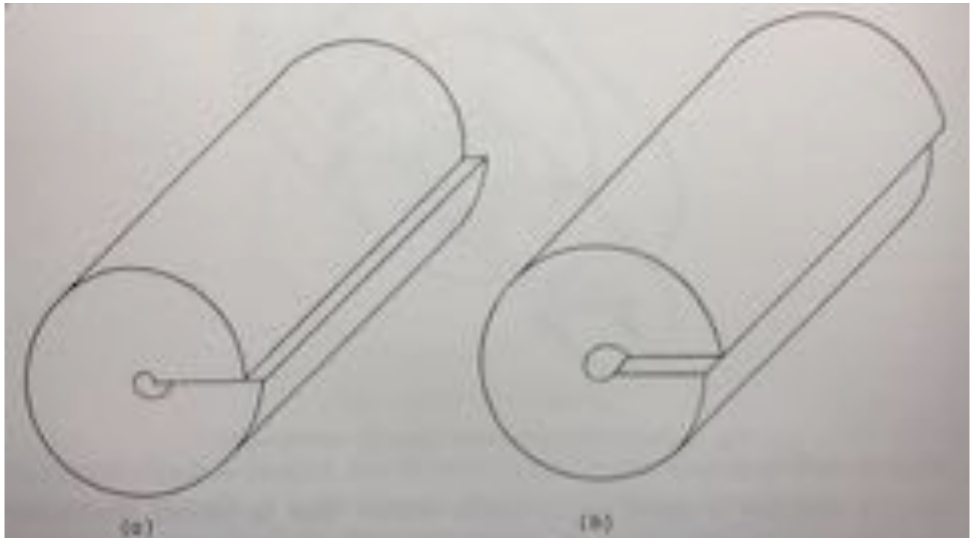
SYMPOSIUM HELD AT THE
GENERAL MOTORS
RESEARCH LABORATORIES

Lyndon Edwards
St Catherines College
Oxford
7/3/78.



Contents

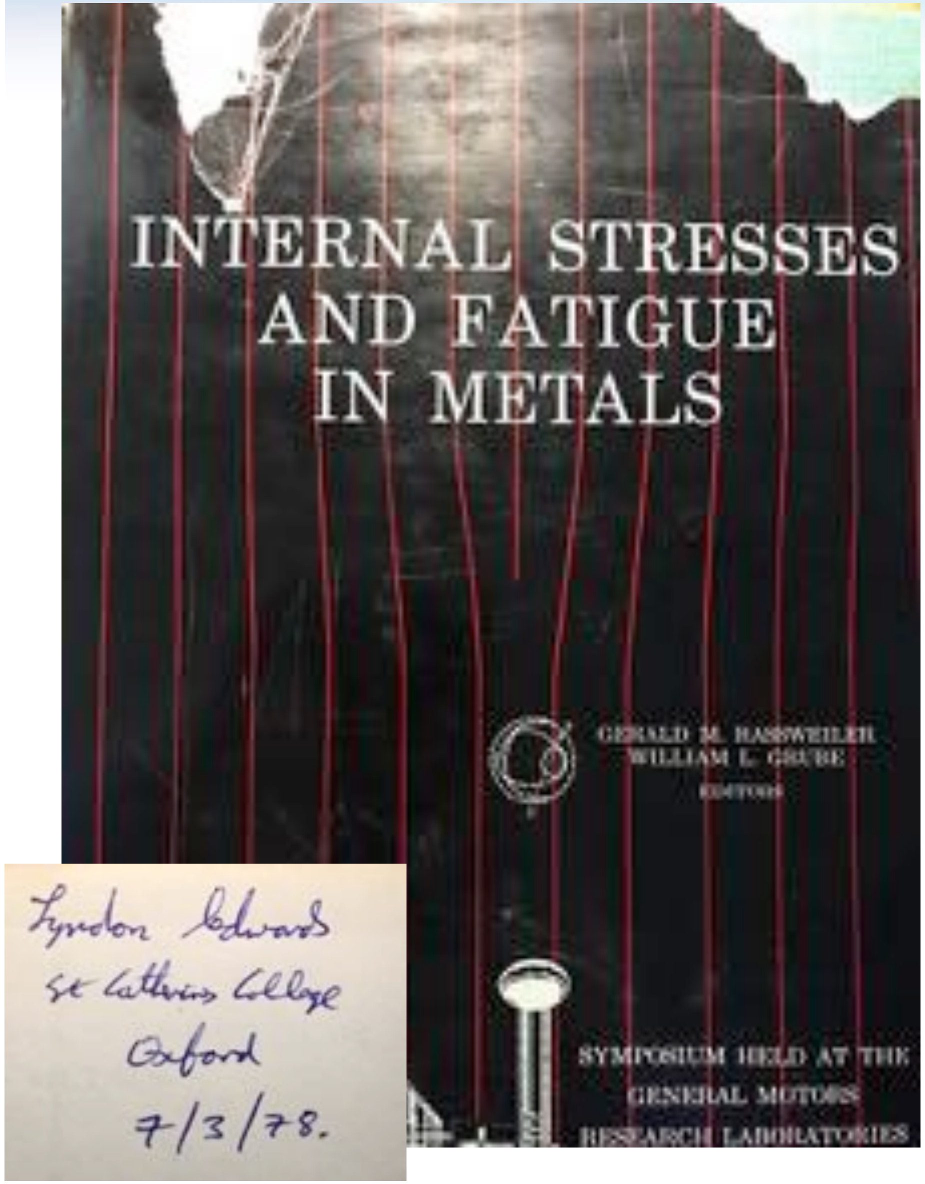
PART I. CONCEPTS AND SIGNIFICANCE OF INTERNAL STRESSES



(a) (b)

Fig. 3. Dislocations: (a) edge dislocation; (b) screw dislocation.

Books: Internal Stress & Fatigue in Metals - 1958



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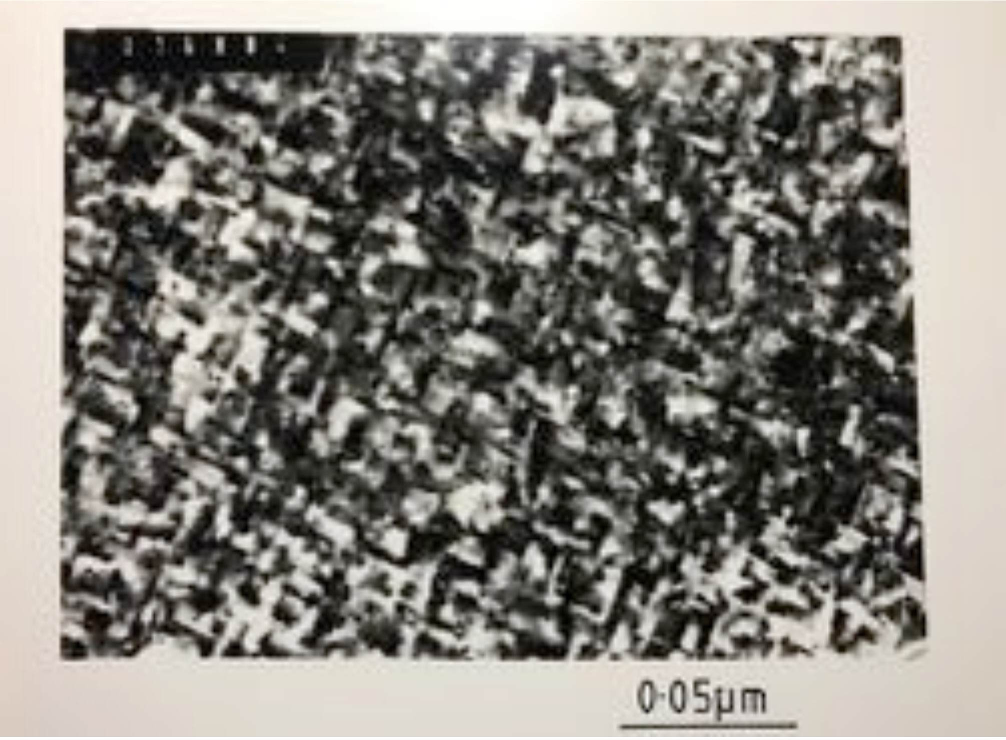
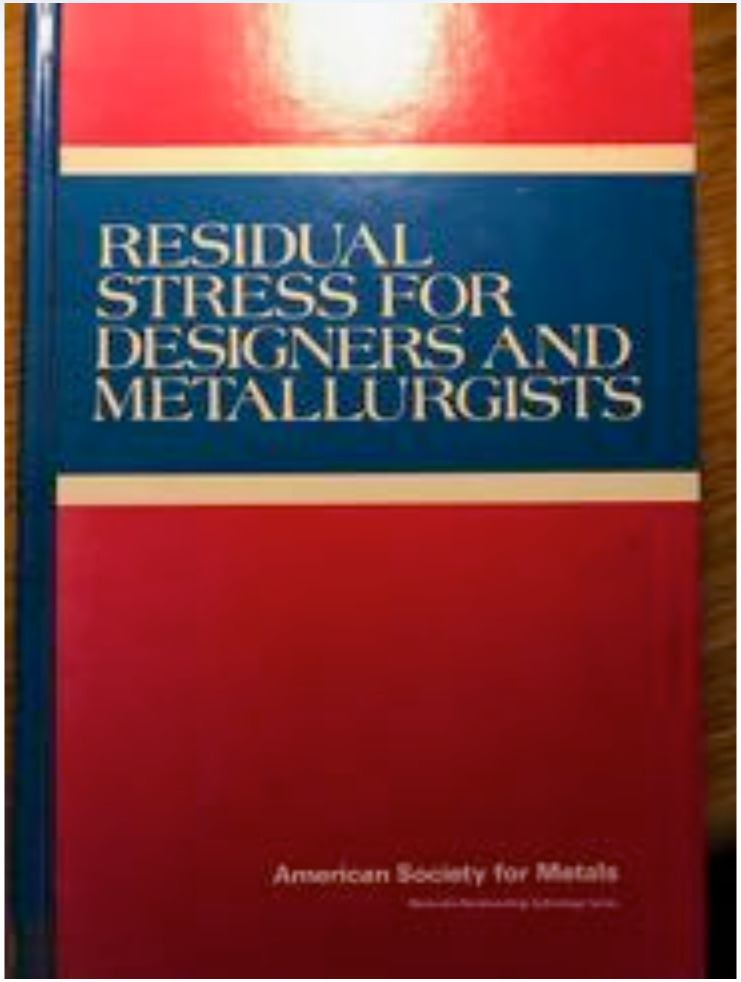


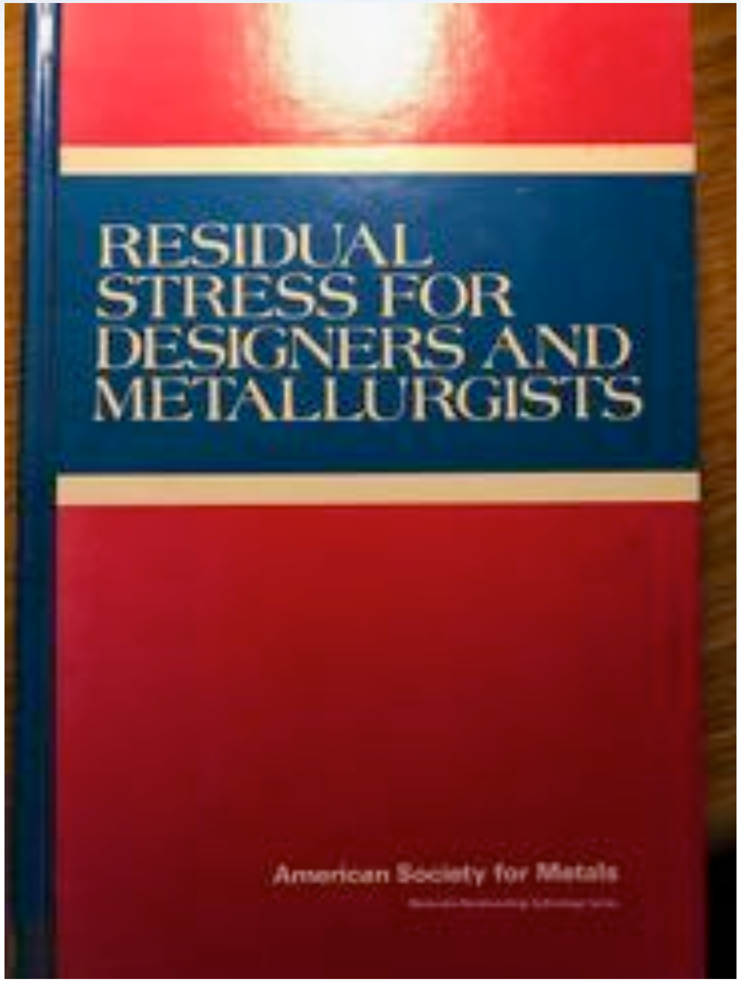
Figure from LE Thesis
Strain contrast around coherent precipitates

Books: Residual Stress for who? -1980



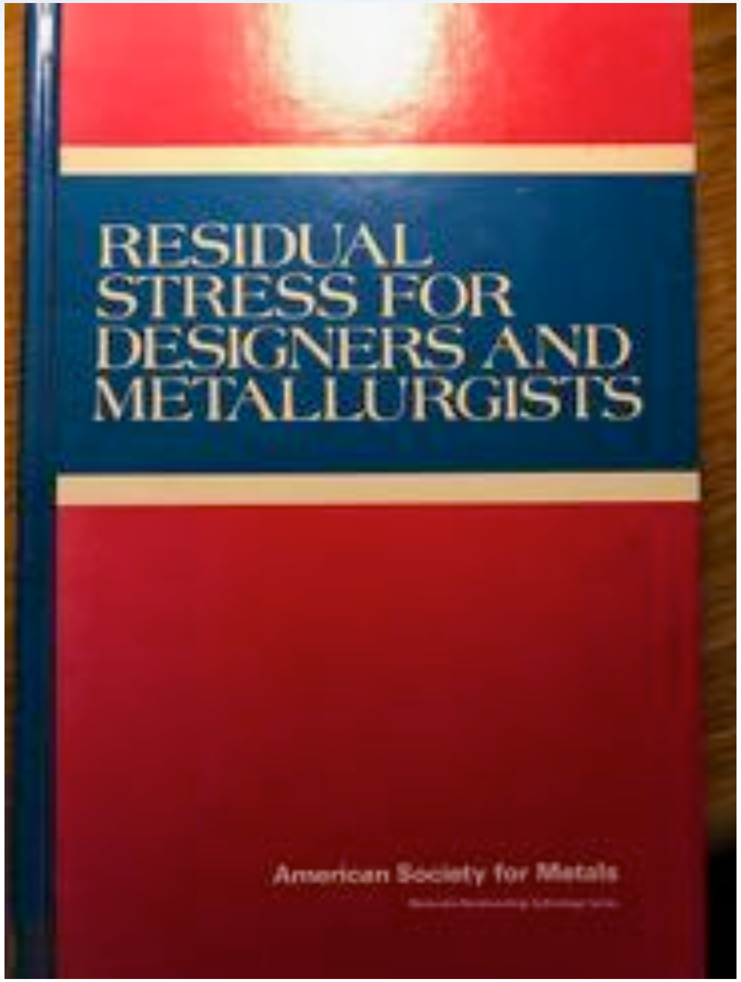
- ‘Existing methods for measuring stresses are limited in their capabilities and uncertain in their result’
- ‘Problems exist in the interpretation of measured data and in the detection of steep stress gradients inside bodies’
- ‘Research is needed to clarify the confusing effects of microstructural features on non-destructive residual stress measurements – and on the need of dependable approaches to selecting appropriate materials constants and conversion factors’
- ‘There is also an absence of adequate reference standards for calibrating or verifying measurement techniques’

Books: Residual Stress for who? -1980



- ‘There are two novel methods, both based on diffraction, which offer the potential for major advances in measuring residual stresses’
- ‘Neutron diffraction: which is essentially similar to x-ray diffraction except that the penetrating power of neutrons is up to several orders of magnitude greater’
- ‘The second is High Energy Photons which enable materials to be examined in a transmission mode’
- ‘This method may not be as conceptually straight forward as neutron diffraction it has the important advantage that it could result in a portable system”

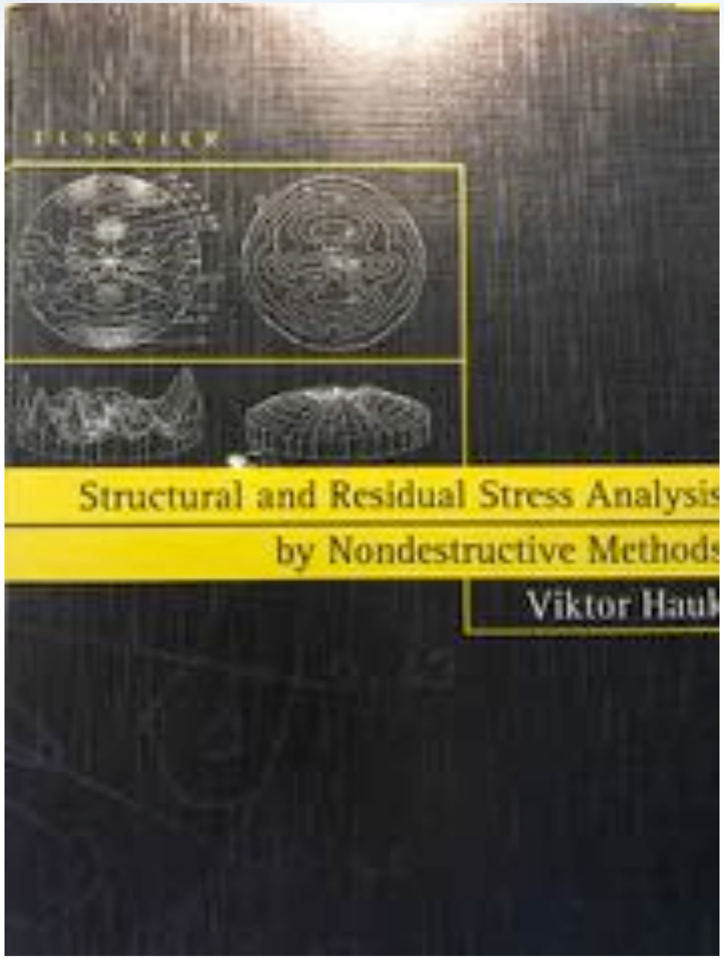
Books: Residual Stress for who? -1980



Aaron Krawitz in *The Early History of Neutron Stress Measurements also notes:*

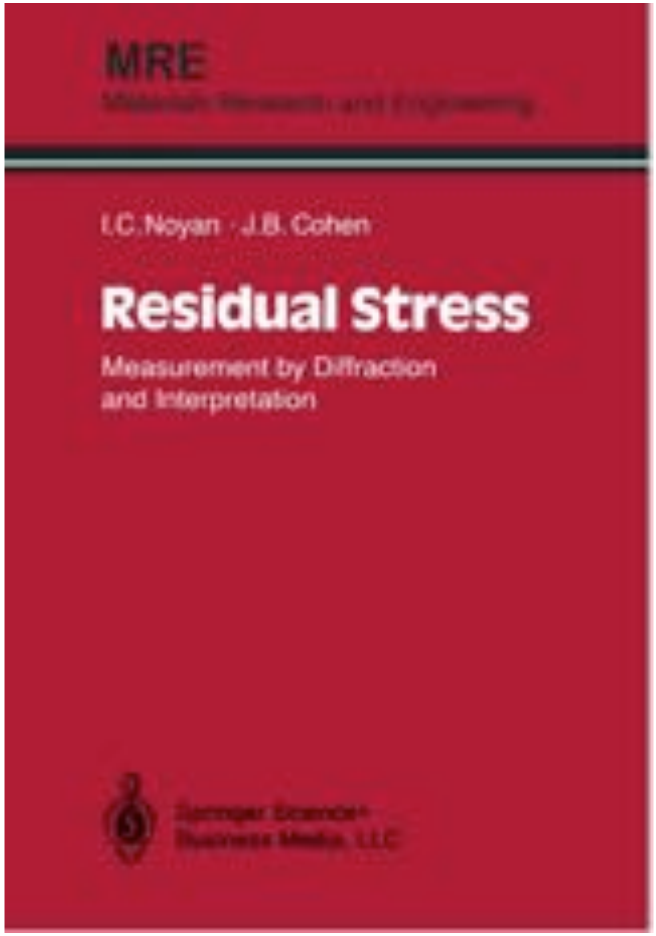
- ‘L.M Mordfin makes the case for diffraction as a nondestructive, subsurface, small volume probe to study residual stress in engineering materials’
- ‘He cites use of multi-peak time-of-flight backscatter measurements using a white beam as a means of enhancing accuracy of strain determination’
- ‘With further refinement the combination of these two developments promises to provide the resolution needed to measure three-dimensional stress profiles accurately’
- ‘So anticipating the use of pulsed sources’

More recent books: Hauk - 1997



- ‘No materials, components or structures are completely free from residual stress’
- ‘Despite this, the assessment of residual stress states is still often controversial
- Residual stress effects on materials properties have been discussed long before first quantitative proof of existing residual stress states has been made’
- ‘And even then, in most cases considerable time elapsed before the first successful attempts were made for a quantitative assessment of residual stress’

Other good books on my shelf…...

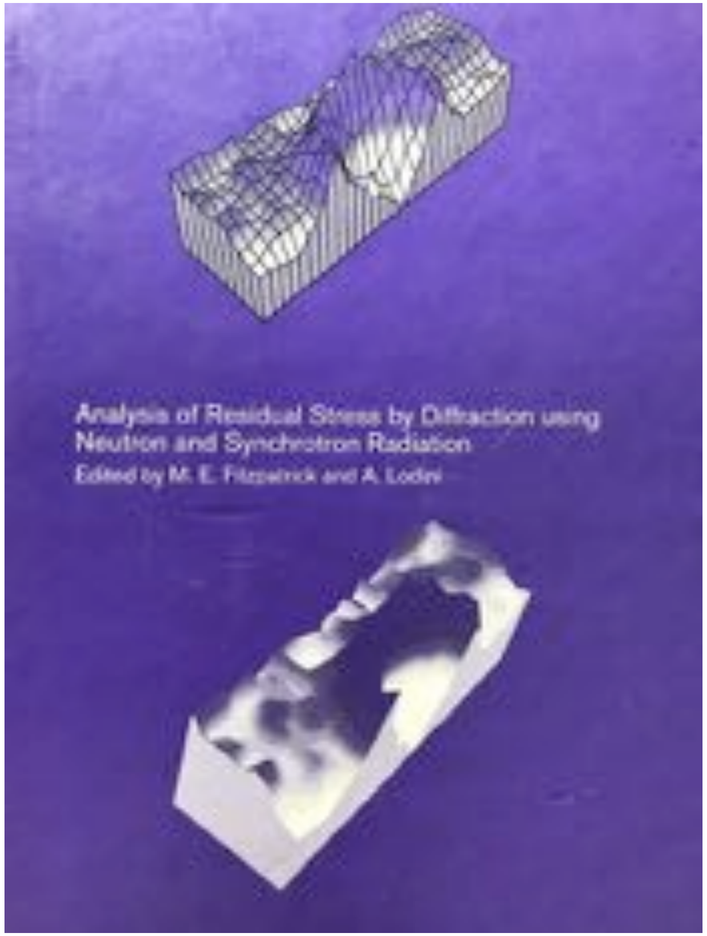


MRE
Materials Research and Engineering

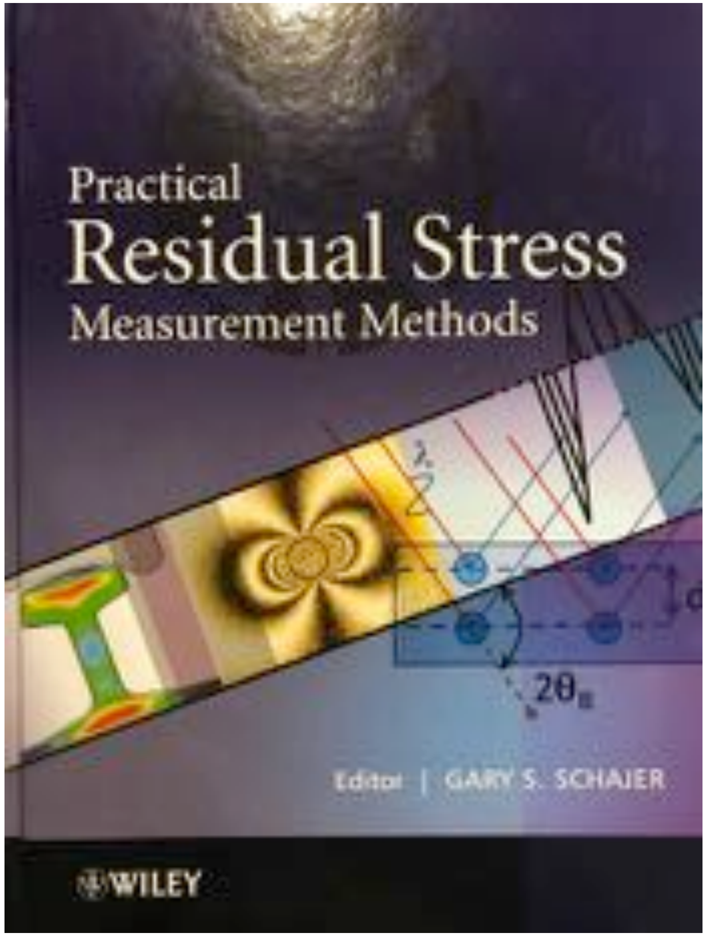
I.C. Noyan · J.B. Cohen

Residual Stress
Measurement by Diffraction
and Interpretation

Springer Science+
Business Media, LLC



Analysis of Residual Stress by Diffraction using
Neutron and Synchrotron Radiation
Edited by M. E. Fitzpatrick and A. Lodini



Practical
Residual Stress
Measurement Methods

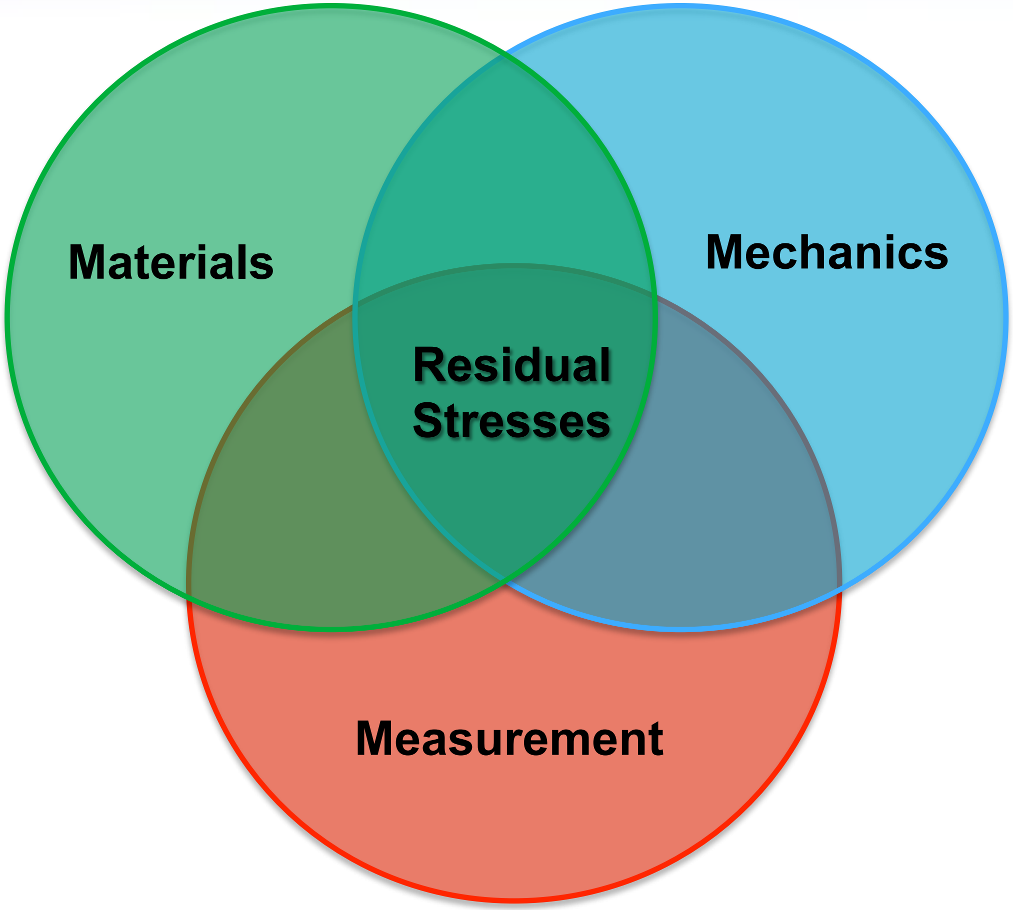
Editor | GARY S. SCHAJER

WILEY

So what are Residual Stresses?

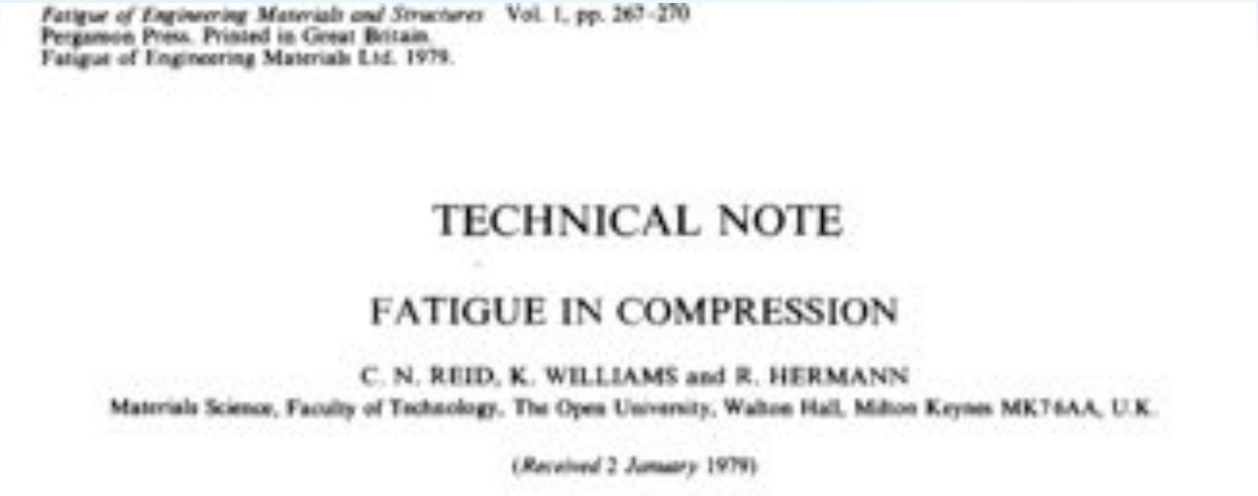
- Residual stresses exist in equilibrium within a body and are independent of any external loads or tractions.
- They are called residual stresses because they remain from a previous operation….
- Residual stresses exist in most manufactured components and structures
- Their potential to improve or ruin components and structures should not be underestimated
- They were postulated before they were experimentally confirmed
- They can take a lifetime to understand……

Understanding Residual Stress



- Can be calculated by continuum mechanics in some circumstances.
- e.g. Cylindrical symmetry as in Sachs Boring and gun barrels..
- But they exist within complex materials and so measurement is of paramount importance
- This has dominated last 50 years of Residual Stress research

Residual Stress at the Open University: 1983



Fatigue of Engineering Materials and Structures Vol. 1, pp. 267-270
Pergamon Press. Printed in Great Britain.
Fatigue of Engineering Materials Ltd. 1979.

TECHNICAL NOTE

FATIGUE IN COMPRESSION

C. N. REID, K. WILLIAMS and R. HERMANN
Materials Science, Faculty of Technology, The Open University, Walton Hall, Milton Keynes MK7 6AA, U.K.

(*Received 2 January 1979*)

- "The purpose of this note is to draw attention to the apparently little-known fact that stage II type fatigue cracks can initiate and grow under compressive applied loads."
- "It is *tentatively* suggested that during the initial compressive overload, a plastic zone is formed near the tip of the notch with a shape that depends on the depth below the surface of the specimen"
- "When the sample is unloaded, residual *tensile* stresses are developed in the vicinity of this plastic zone"
- "When subsequently a cyclic compressive load of a smaller amplitude than the preload is applied then the net tensile stresses in the overload plastic zone vary cyclically causing initiation and growth of a fatigue crack."

Revolution in racquet design in 1980’s

Attempted market entry by small UK firm

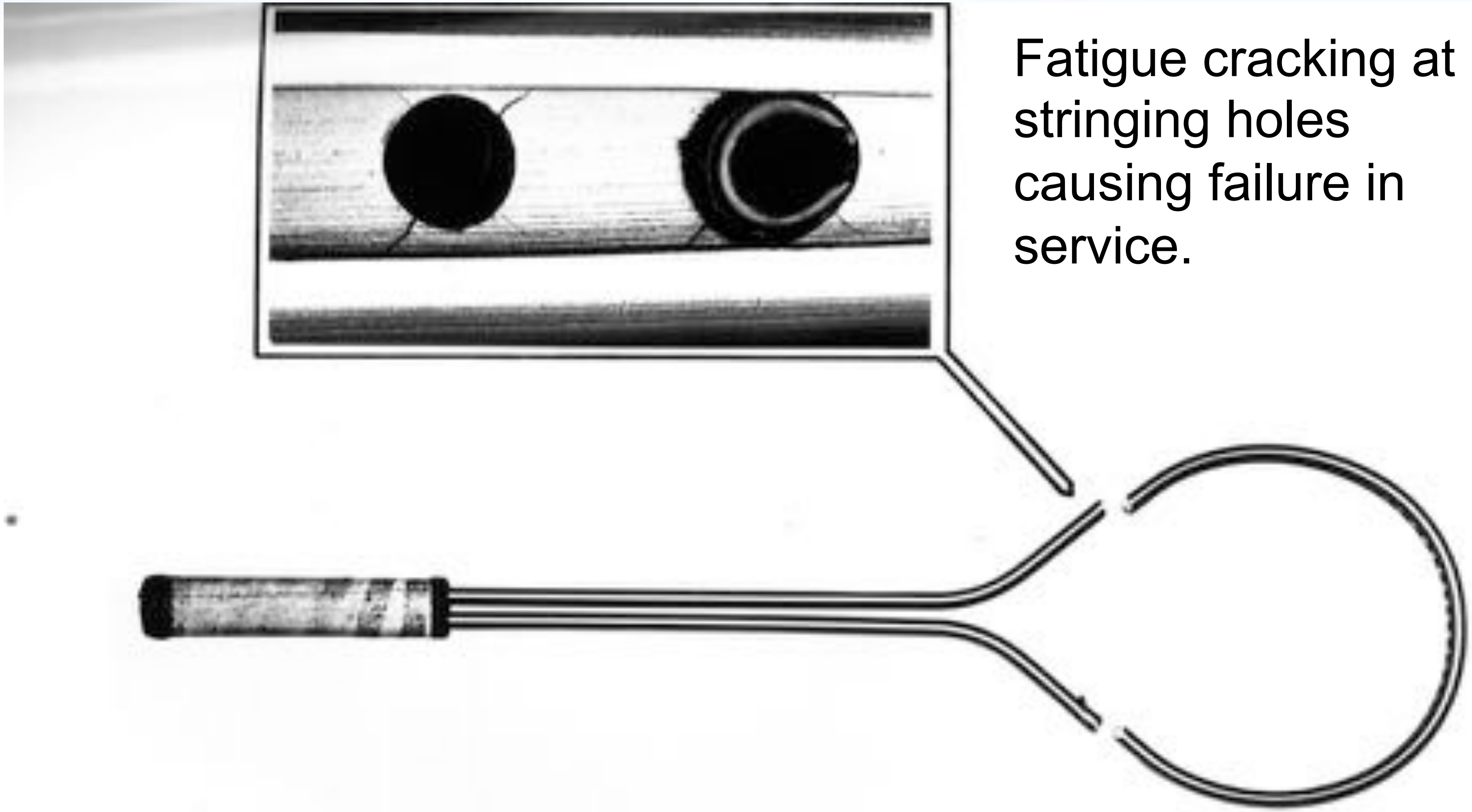
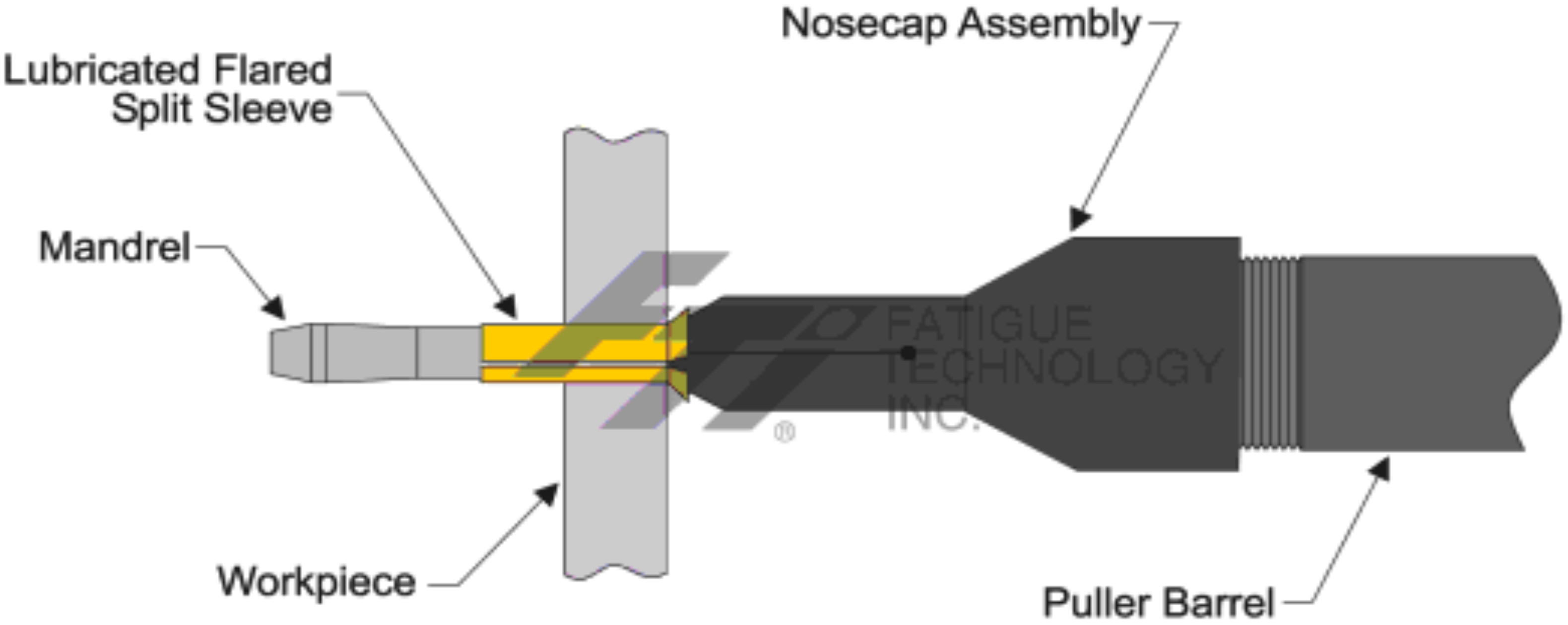


Plate 4.6 Control racquet after eight hours of play

Fatigue cracking at stringing holes causing failure in service.

Solution: Cold expand the holes….

- The cold expansion process (CXH) improves the fatigue life for both new and in-service aircraft.
- The split-sleeve cold expansion process is the most successful method. (in 1980s and now!)
- Costs $10 per hole - so not useful for tennis racquets.



Picture:http://www.fatiguetech.com/products/splitsleeve.html

Nick Reid invented novel taper roller expansion

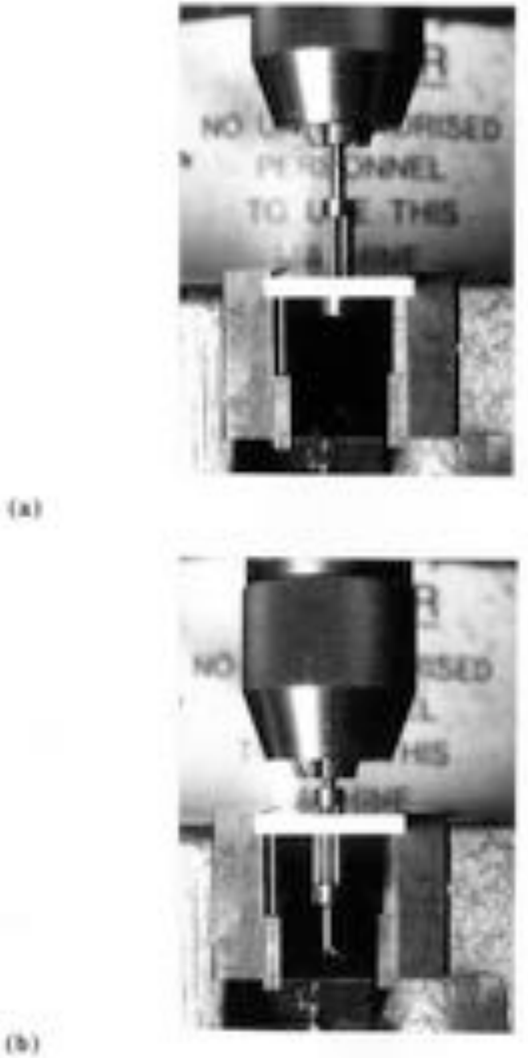


Figure 3.3 The Open University cold-expansion process. (a) Before expansion; (b) After expansion.

LE offered to undertake fatigue design

BUT

- How does residual stress affect fatigue?
- How much residual stress do we have?

Need data so undertook measurements:

- Sachs Boring method
- Neutron Diffraction

LE starts to think about Residual Stress and Structural Integrity in earnest…

Residual Stress Crack Interaction at CXH

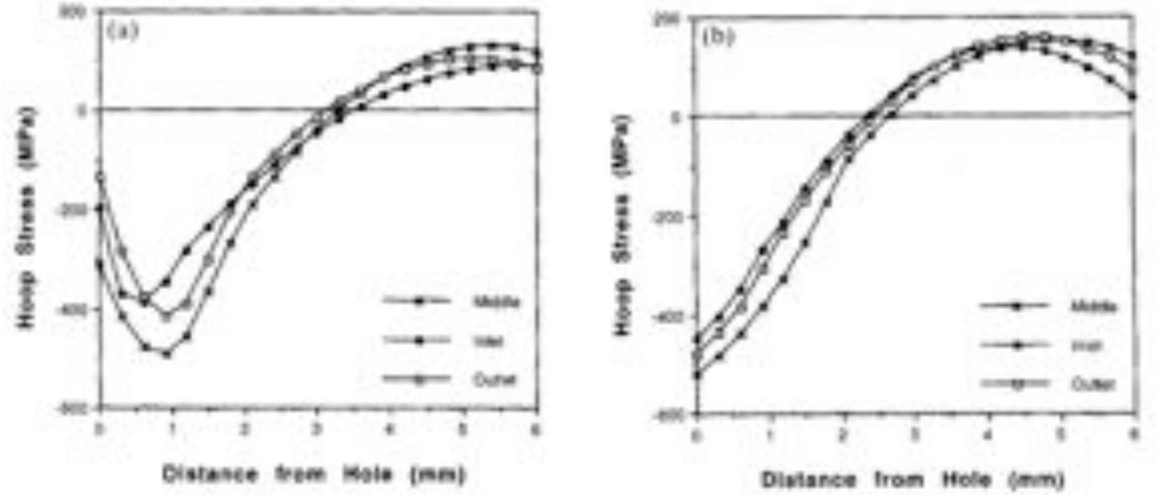


Fig. 2. Residual hoop stress distribution at (a) an unreamed 4% FTI expanded hole, and (b) at a reamed 4% FTI expanded hole.

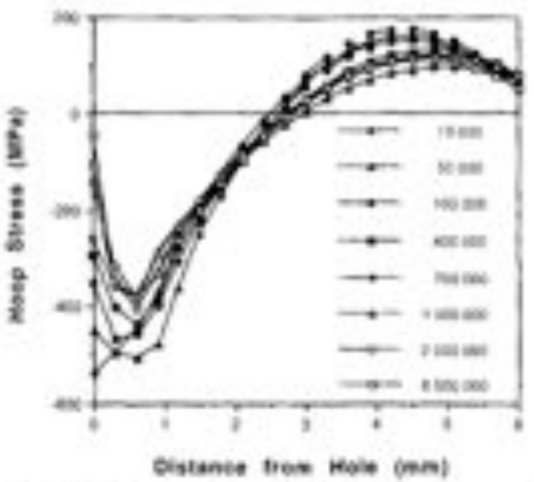


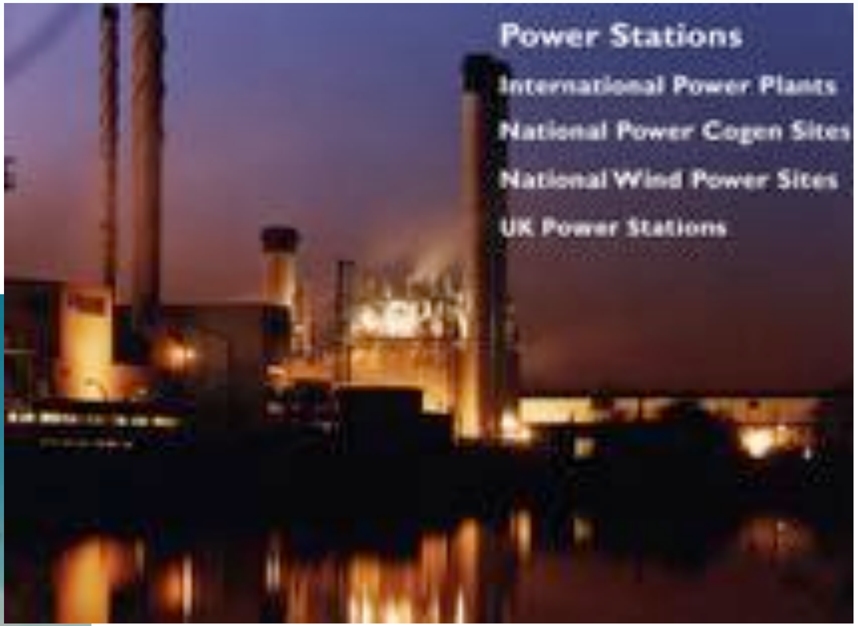
Fig. 5. Residual hoop stress distributions at reamed 4% FTI expanded holes cycled at the fatigue limit.

- How does residual stress affect crack growth.
- How does crack growth affect residual stress.
- Work funded by Royal Aircraft Establishment, Farnborough.
- Showed that substantial stress relaxation only occurred when cracks grew at or from the hole

Residual Stress and Structural Integrity

Residual stresses exist in almost all engineering components due to:

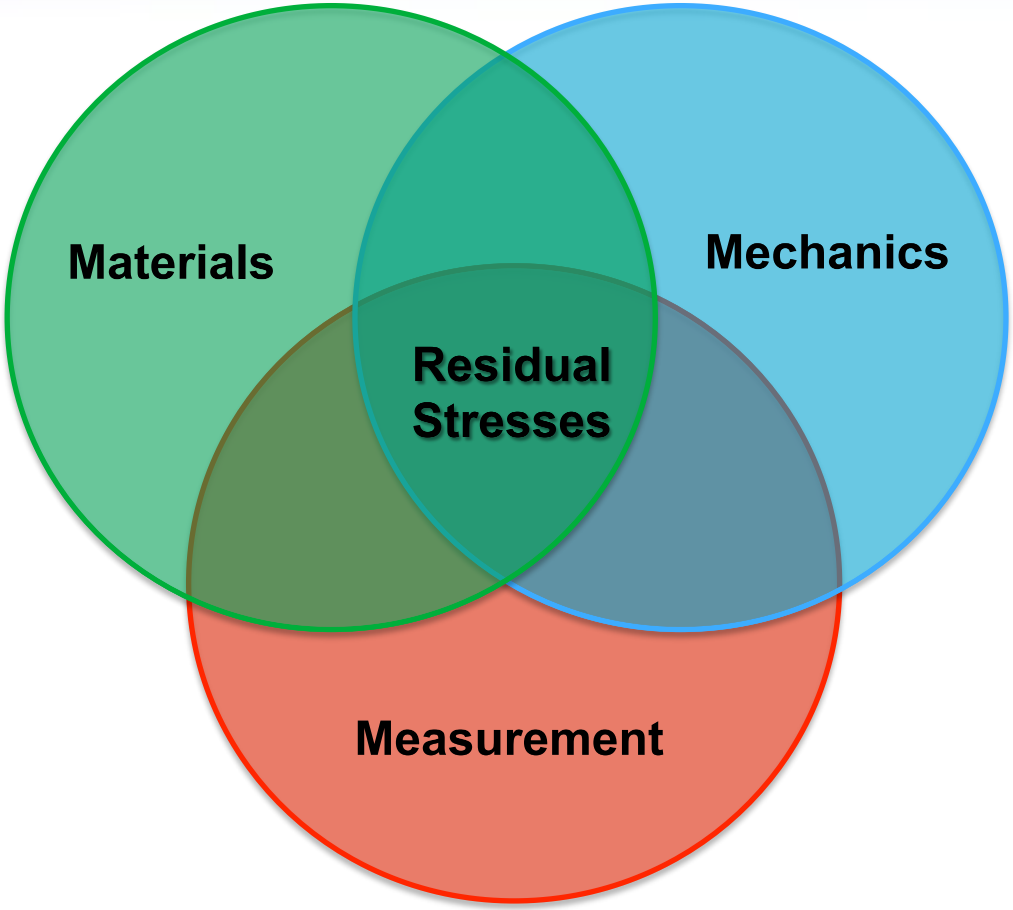
- **manufacturing processes**
- **loads experienced during use**



They affect:

- **fatigue resistance**
- **fracture toughness**
- **strength**
- **safety**
- **component lifetime**

Understanding Residual Stress: Why



- What do need the Residual Stress……
- To find out why something works or happens?.
- To improve a material or process
- To calculate likelihood of Failure
- Your answer actually defines what is the form and accuracy of what you want
- Manufacturing vs Structural Integrity

Structural Integrity

- Structural Integrity is the safe design and assessment of components and structures under load.
- It is increasingly important in engineering design.
- It requires both scientific understanding and relevant data to enable life prediction and hence safe design of components and structures that contain cracks.
- It’s ultimate aim is to integrate knowledge of stress analysis, materials behaviour and the mechanics of failure into the engineering design process.
- This includes Residual Stress when relevant

Nuclear Power Generation Plant Design and Safety

Power generation plant is designed to ‘traditional’ Construction Codes (*design by rule*) and owner specification regulated by Independent Authority:

- Plant is assumed to be ‘defect-free’ at start of life
- ‘Safe life’ is based on time to crack initiation
- No explicit knowledge of residual stresses is required
- Design codes are extremely conservative

BUT

- Effect of cracks found in service must be assessed
- Specific knowledge or residual stress needed to avoid over conservative code-based assessments

Aircraft Design and Safety

Aircraft also largely designed to ‘traditional’ ‘safe life’ rules BUT also need to ‘prove’ design is *Damage Tolerant* to regulatory authority:

- Structures normally fatigue limited
- Notional initial crack (1.5mm) assumed
- Crack growth life must allow for multiple inspections
- Fatigue improvements not propagated to design stress
- Nascent technology e.g. welds, treated conservatively
- Knowledge of residual stresses needed to perform damage tolerant analysis

Road Transport Design and Safety

Virtually all design occurs via mixture of historical heuristic knowledge and component testing.

- No explicit regulating authority
- Design must be ‘fit for purpose’
- Damage tolerant approach very rarely used
- Fatigue failure often considered endemic.
- Detailed analysis often ‘forensic’ in nature

Physical size scales: Science …

Types of Residual Stress

- Type 1: Macro-stresses

  Long range stresses that are only equilibrated within the whole body or with an externally applied load.

- Type 2: Micro-stresses

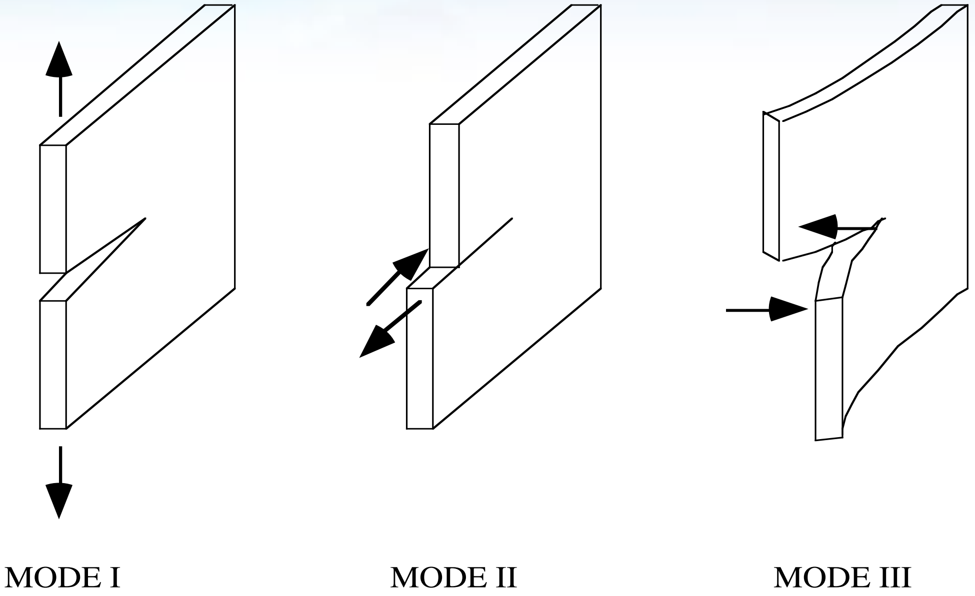
  Are nearly homogeneous across microscopic areas i.e. a grain or part of a grain of a material and are equilibrated across a small number of grains.

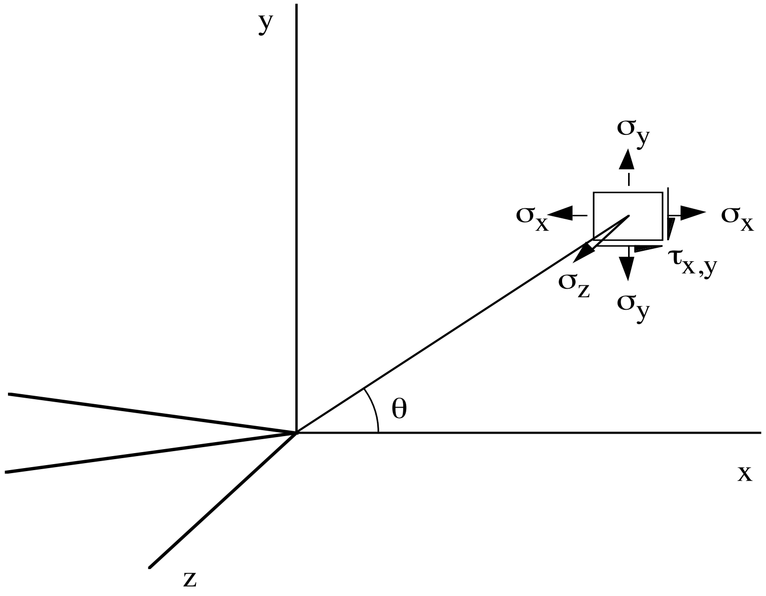
- Type-3: Sub-microscopic stresses

  Vary on an atomic scale (such as might arise from one or more dislocations) and are equilibrated across fractions of a grain.

A quick Fracture Mechanics Summary

- K field as described by Stress Intensity Factor gives similitude.
- Small scale yielding is also required.

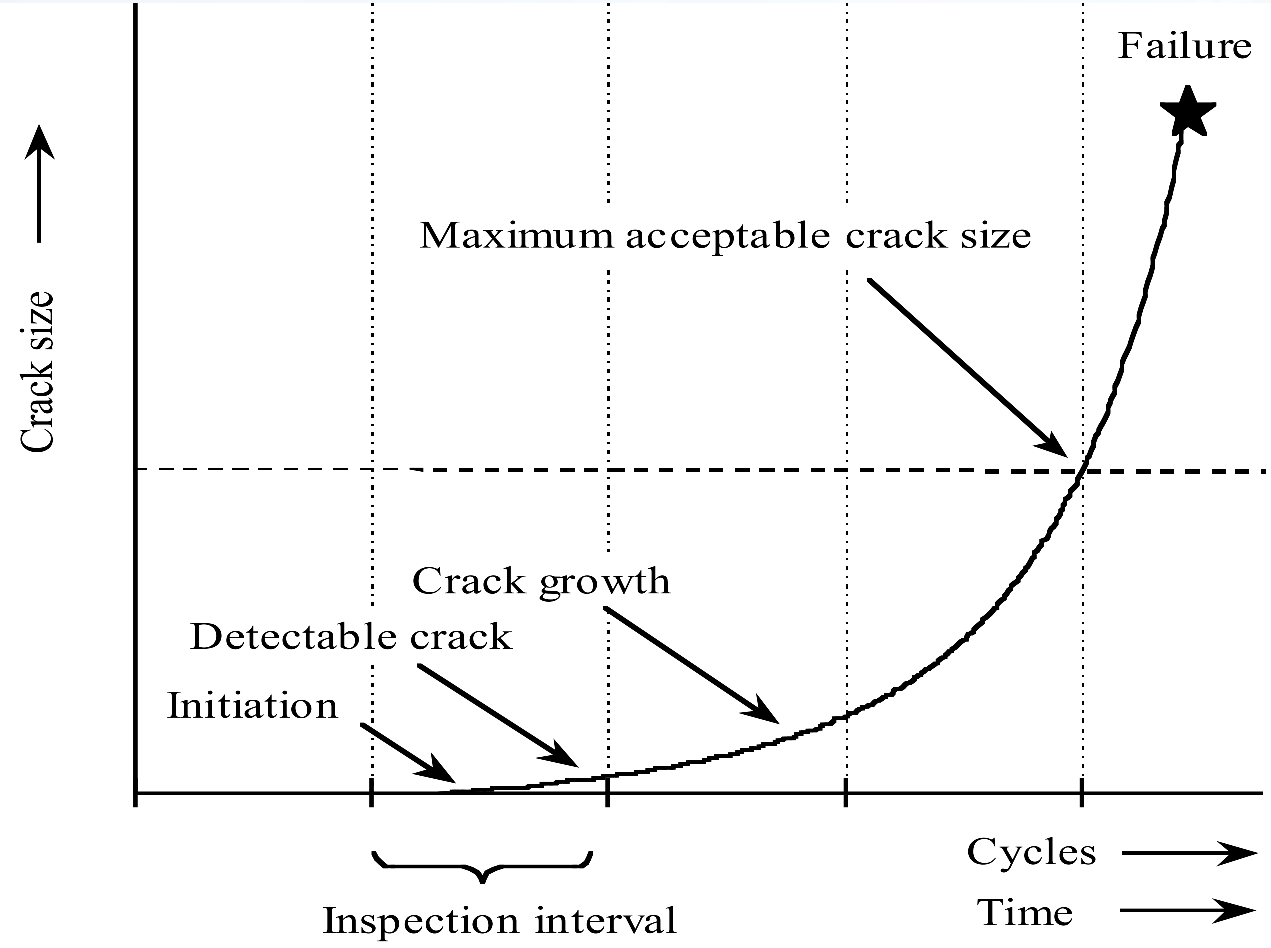




$$\sigma_{ij}(r,\theta) = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta)$$

$$K_I = Y\sigma\sqrt{\pi a}$$

Damage Tolerance based Life Assessment

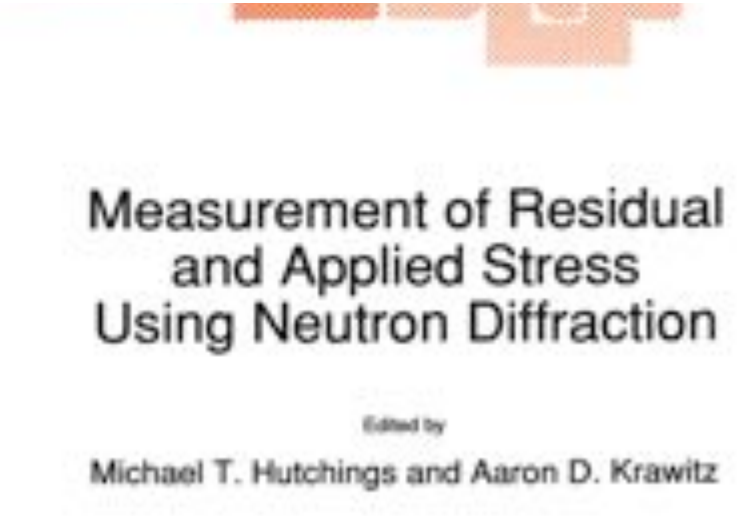


Is still usually a QA not a design process.

It requires:

- Critical crack sizes
- Crack growth kinetics
- Accurate, reliable knowledge of residual stress distributions

Books: NATO Conf. 1991 The formation of the Neutron Diffraction Community



Measurement of Residual
and Applied Stress
Using Neutron Diffraction

Edited by

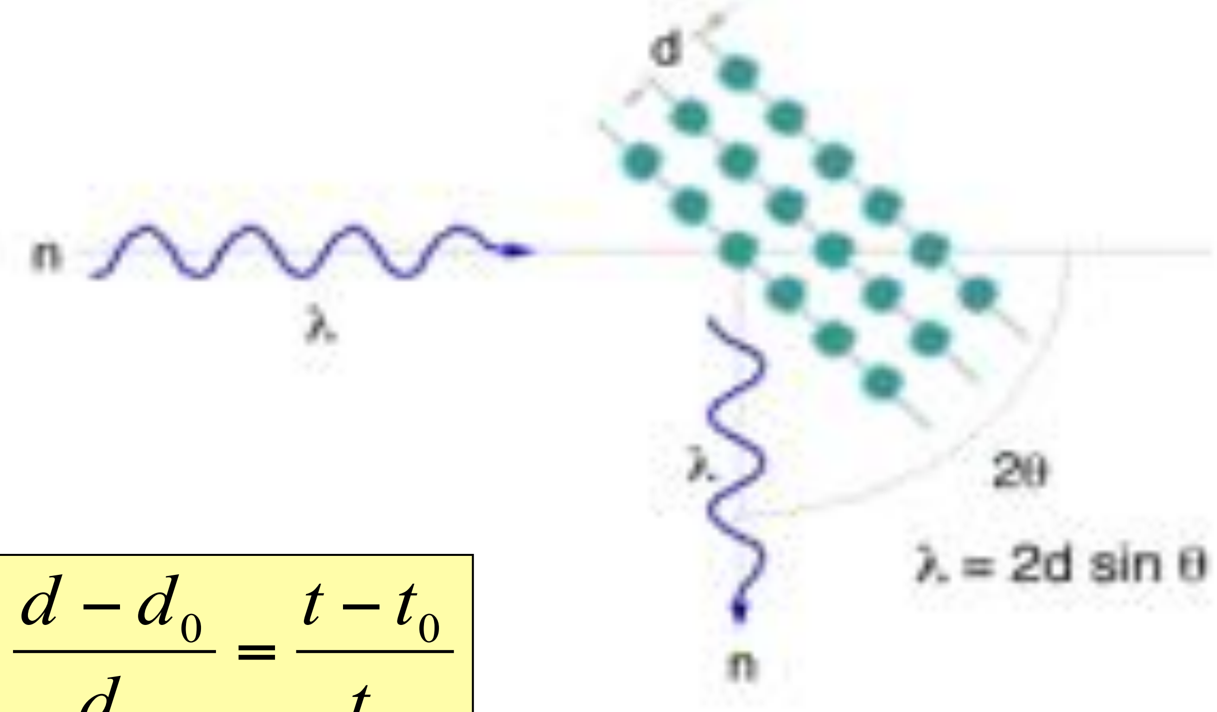
Michael T. Hutchings and Aaron D. Krawitz

NATO ASI Series

Series E: Applied Sciences - Vol. 216

NATO Neutron Residual Stress Conference Oxford, March 1991

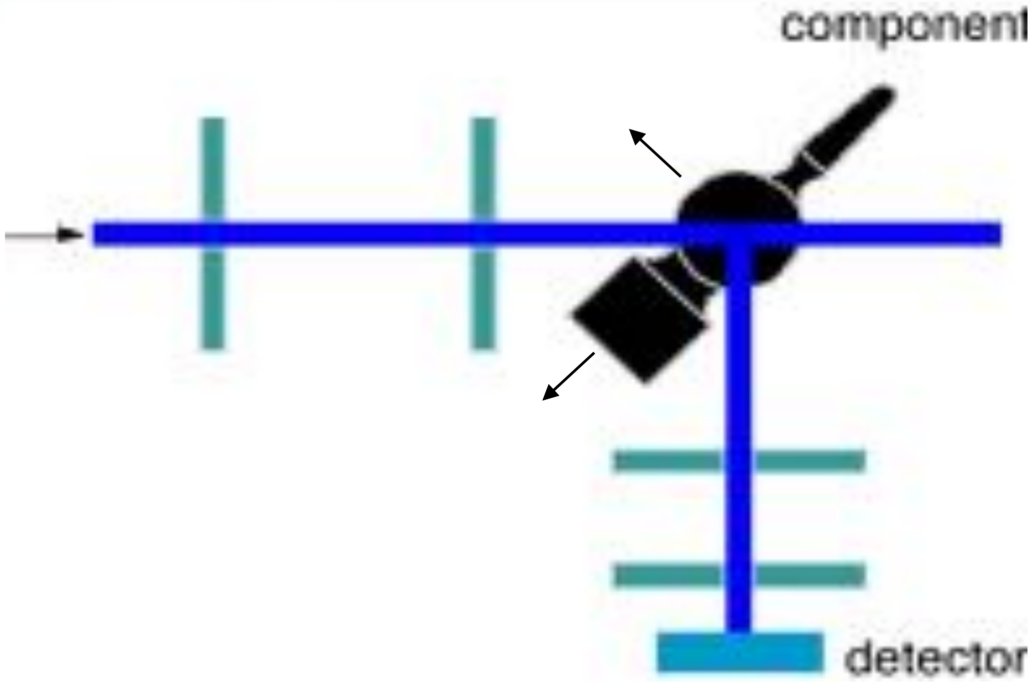
Diffraction-based Stress Measurement



$$\varepsilon = \frac{d - d_0}{d_0} = \frac{t - t_0}{t_0}$$

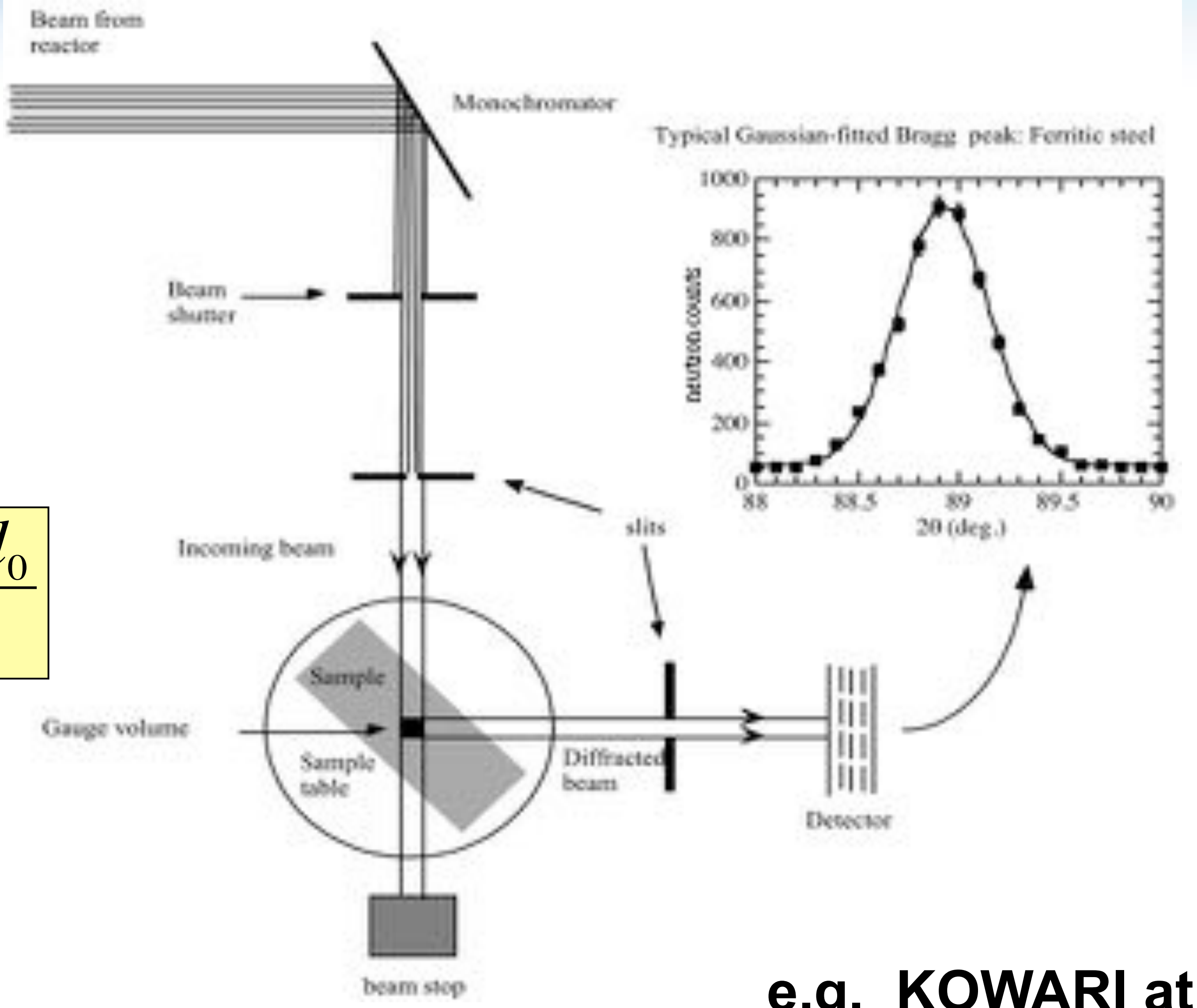
The Atomic Strain Gauge

Gauge Volume Definition



Can change size of gauge volume and sample

Reactor-based neutron stress measurement



$$\varepsilon = \frac{d - d_0}{d_0}$$

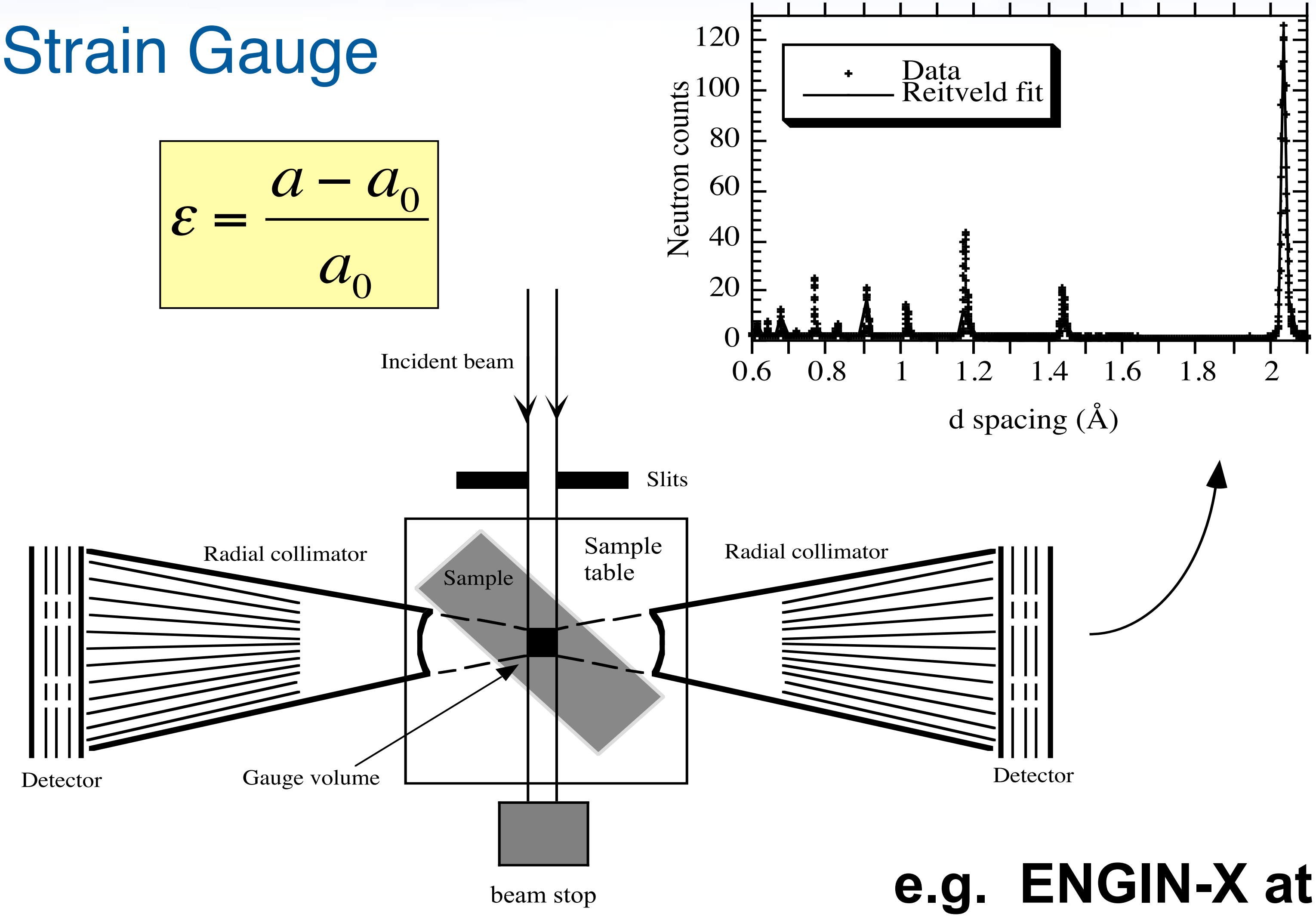
e.g. KOWARI at OPAL

Pulsed neutron stress measurement

The real Atomic Strain Gauge

$$\varepsilon = \frac{a - a_0}{a_0}$$

Typical spallation source diffraction pattern:
Ferritic Steel with Reitveld fit



e.g. ENGIN-X at ISIS

ENGIN Diffractometer: Student and Supervisor

ENGIN

- First dedicated stress instrument from ground up
- locates gauge volume to < 0.1mm

- takes sample weight up to 250 kg

- in a sample space >300 mm
- Note operators and camera!

A brief history of Strain Scanning

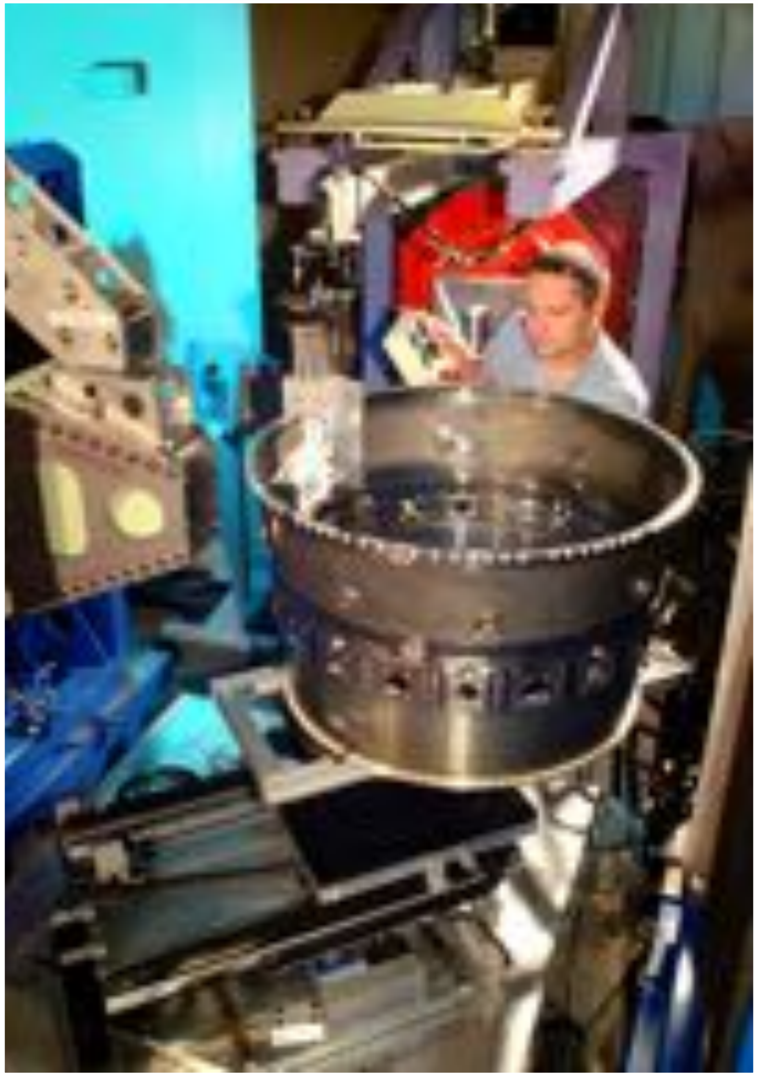
Gen I Pre-1990 temporarily modified powder diffractometers

Gen II 1990-2000 permanent installations designed for residual stress measurement e.g. ENGIN

Gen II Bespoke installations optimised for residual stress measurement e.g. ENGIN-X, SMARTS, SALSA STRESS-SPEC, VULCAN, KOWARI, TAKUMI, etc

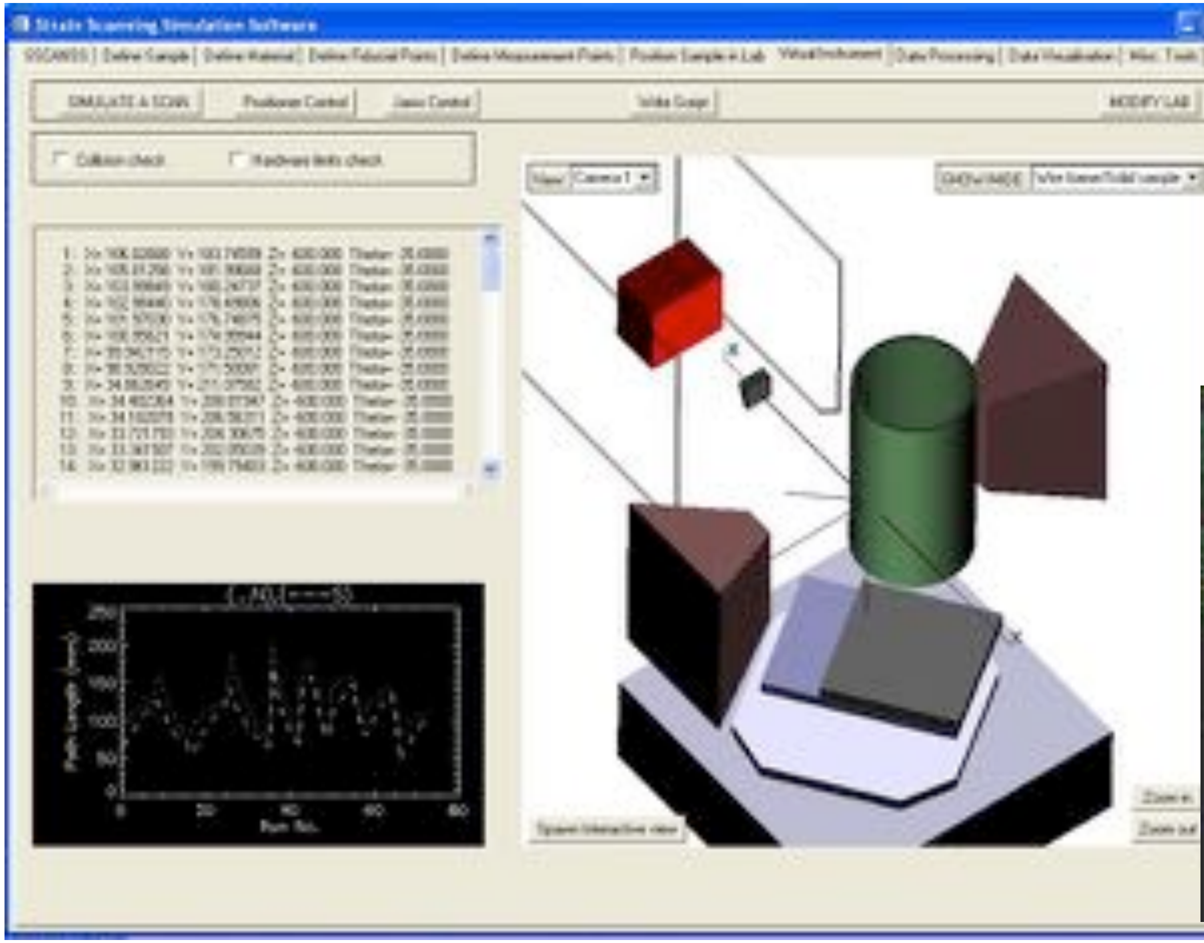
Gen IV ?

ENGIN-X: a 3rd Generation Instrument



SScanSS
simulation software for instrument control

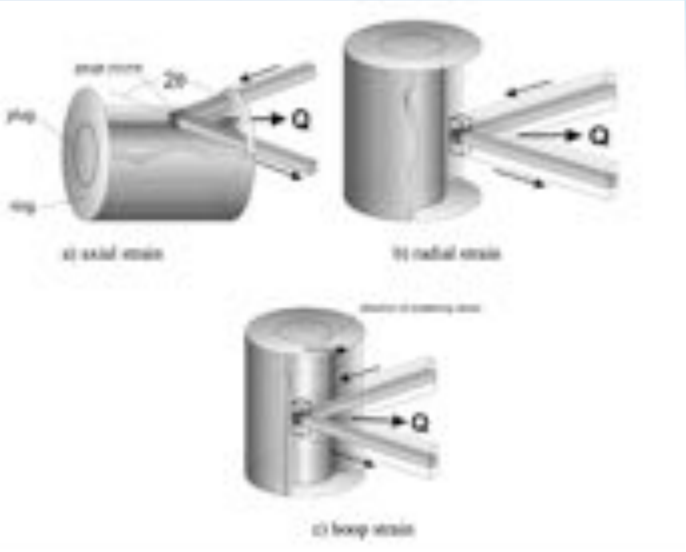
Automated conversion between laboratory, sample and positioner co-ordinate systems

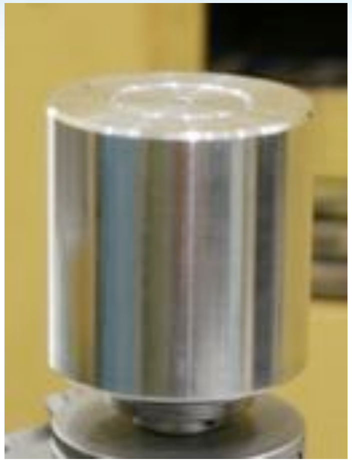


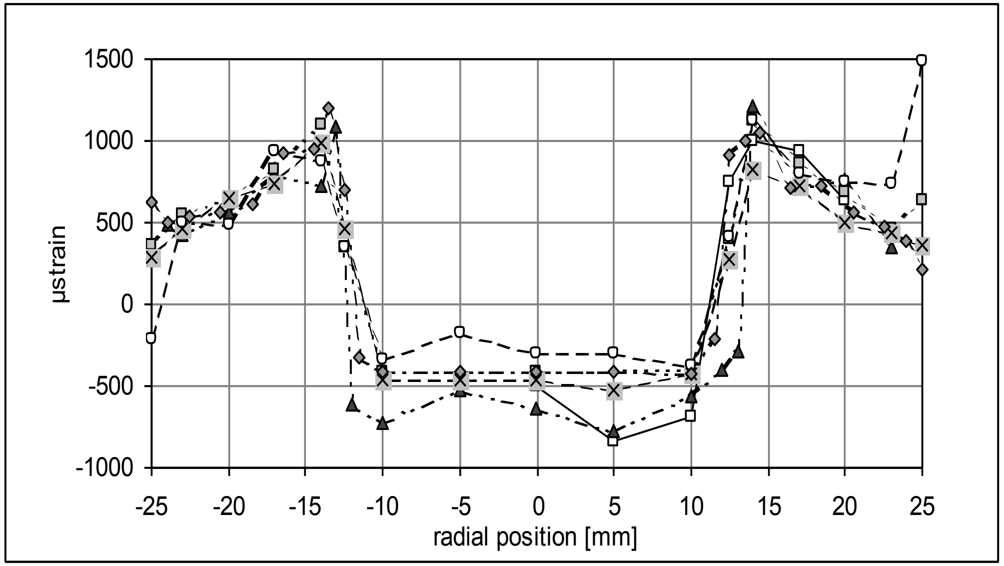
VAMAS TWA-20

- International standards working group containing representatives from across the community
- Set out with high ambitions and goals
- Used Round Robin ‘standard’ samples
  - shrink-fit aluminium alloy ring and plug assembly,
  - ceramic matrix composite
  - shot-peened nickel alloy plate
  - ferritic steel weld
- Only shrink-fit aluminium sample was a real success
- Samples became *de facto* standards e.g. like the Kg!

VAMAS TWA-20 Shrink Fit Aluminium sample







Strain measured at six sources

TECHNICAL SPECIFICATION

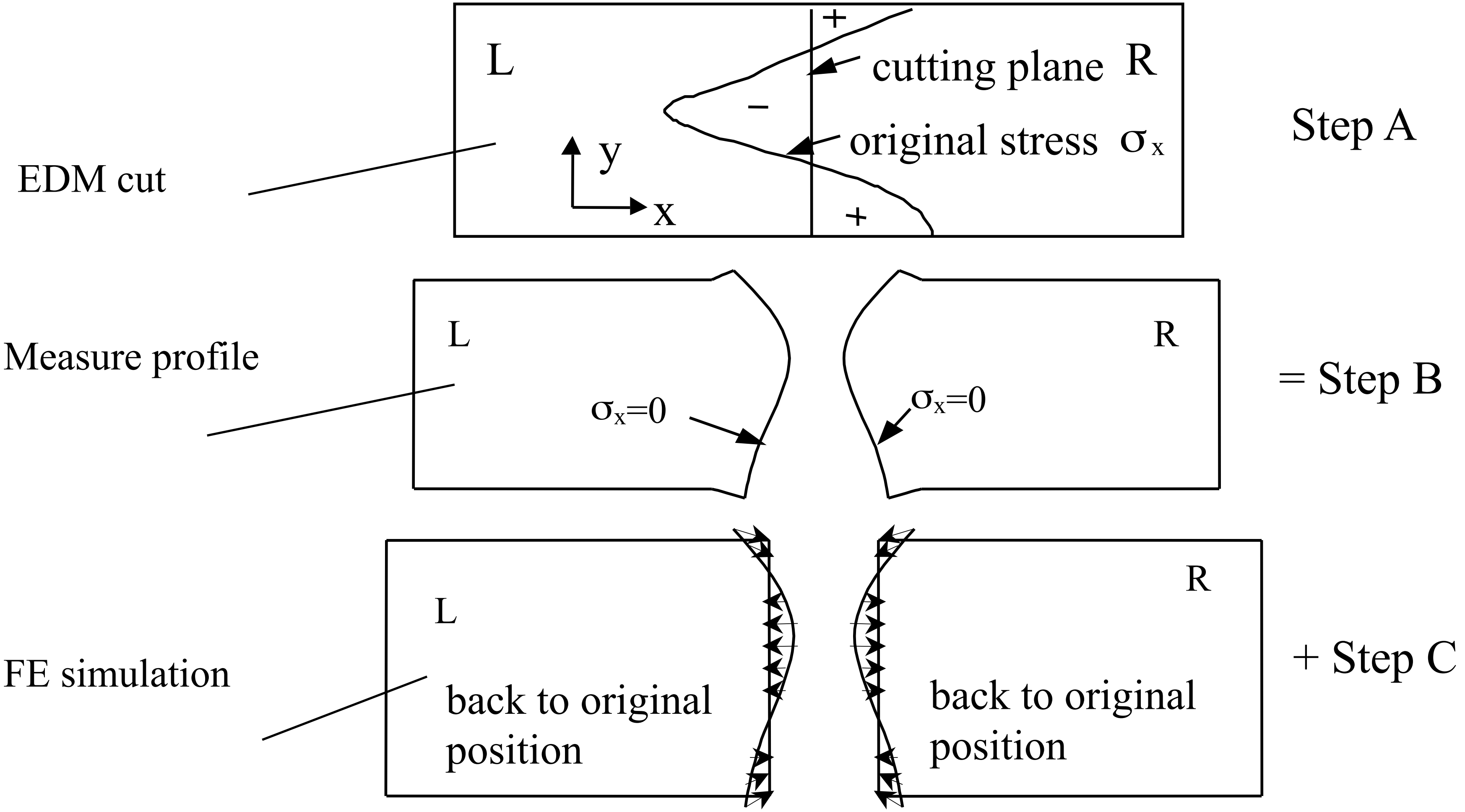
ISO/TS 21432

Non-destructive testing — Standard test method for determining residual stresses by neutron diffraction

Reference number
ISO/TS 21432:2005(E)

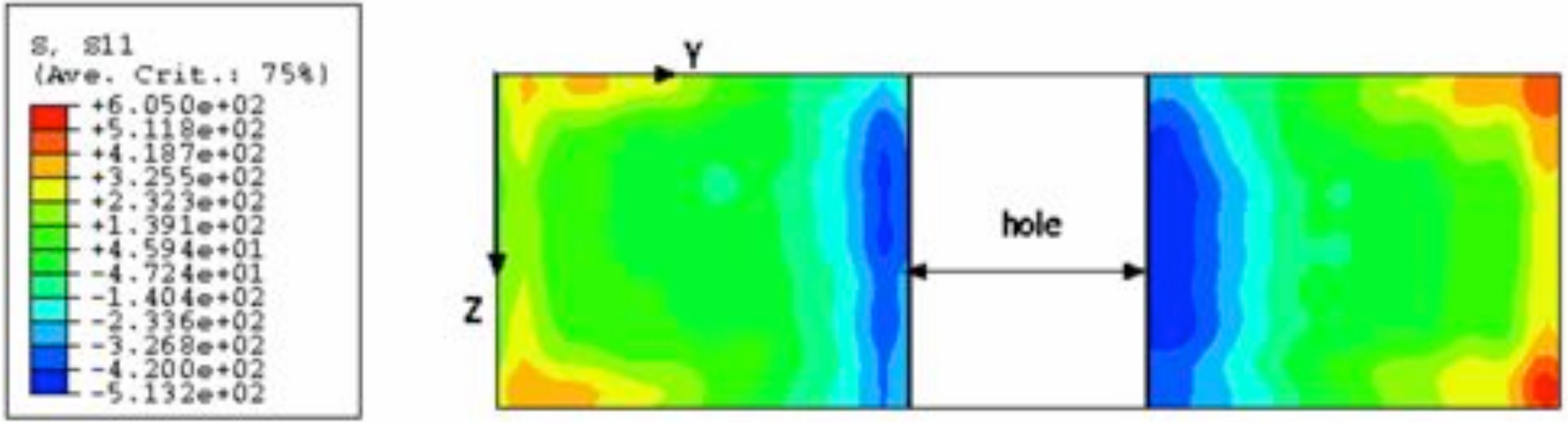
The Contour Method

Bueckner's principle of elastic superposition



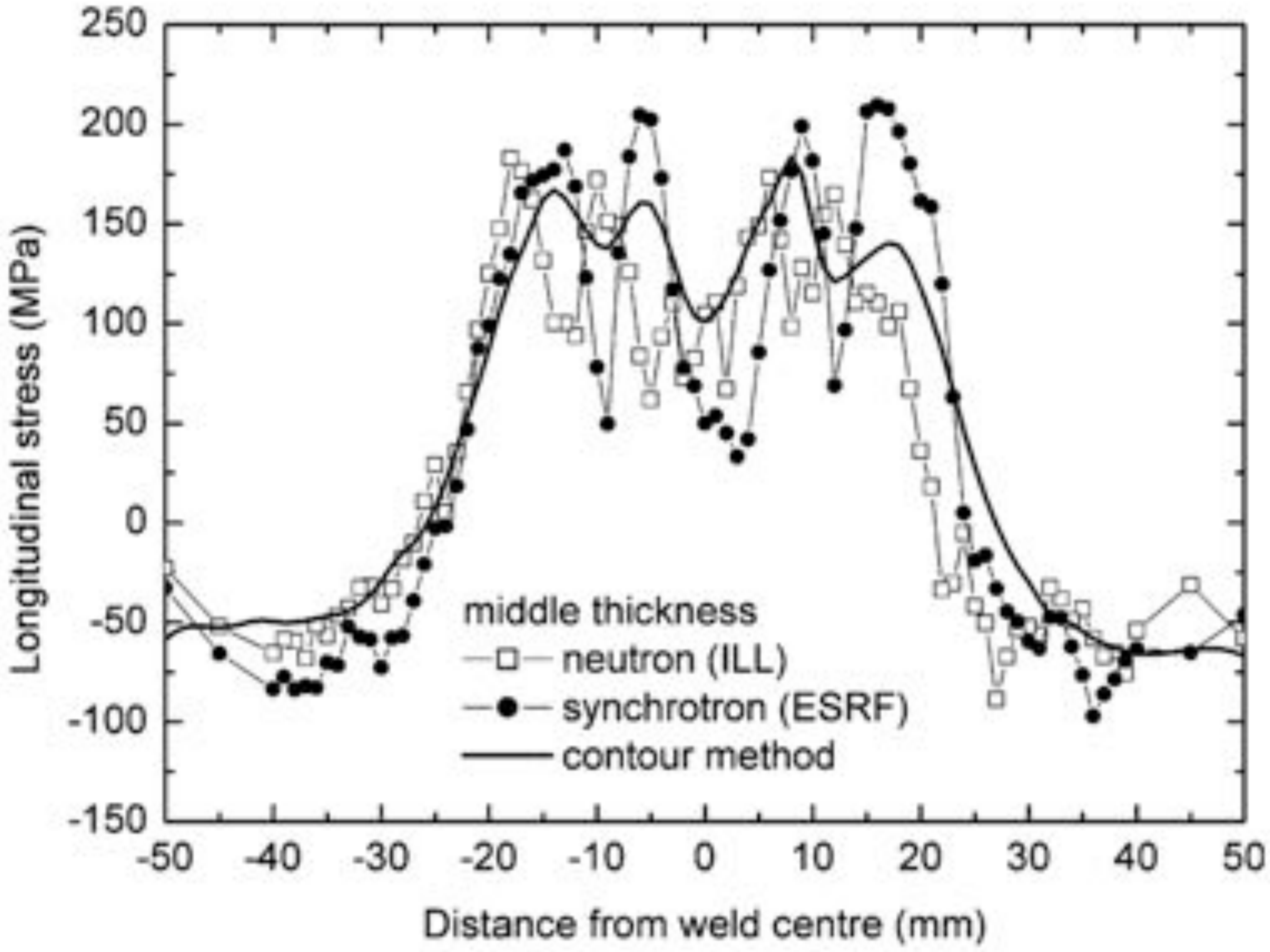
Contour at the Open University

- Mike Prime presented Contour Method in UK in July 2000
- Ying Zhang started her PhD in Sept 2000
- First results on Steel CXH (Chose steel to make strains high)
- Presented at ECRS-9 at Coimbra
- First *totally independent* use of technique (*no Prime numbers!*)

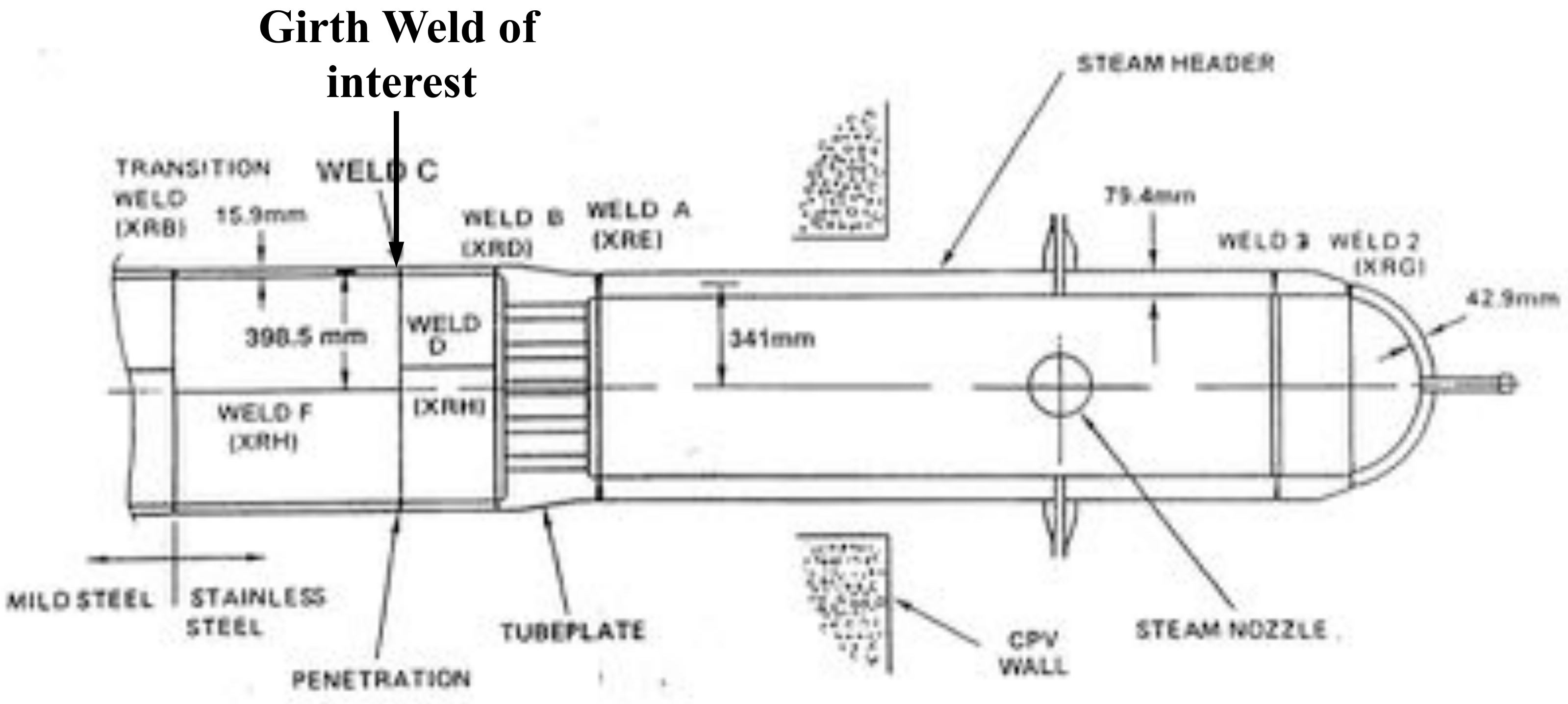


Hoop stresses at Steel CXH measure by the Contour method

A Comprehensive validation - Al VPPA weld

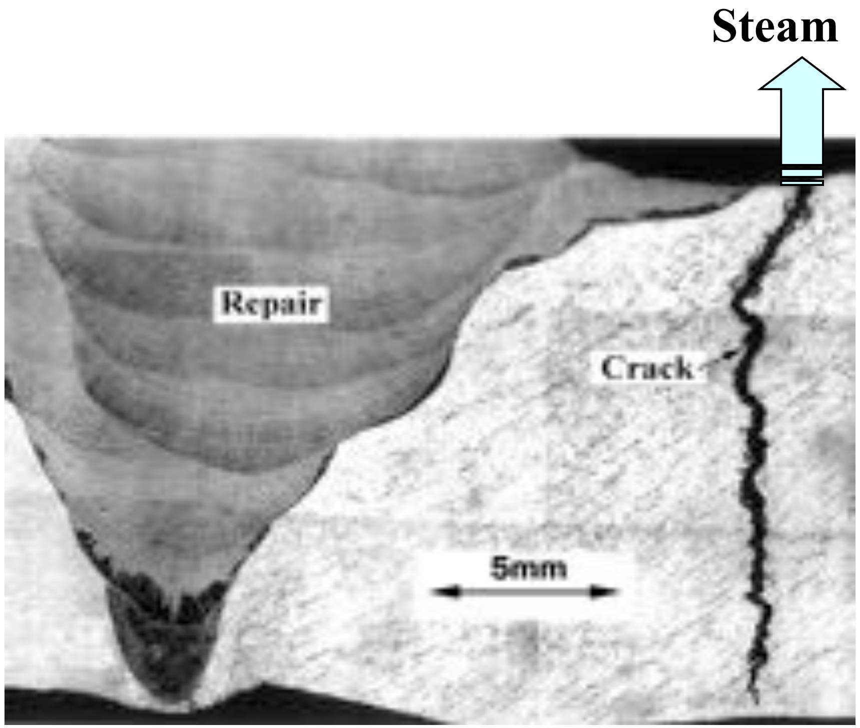


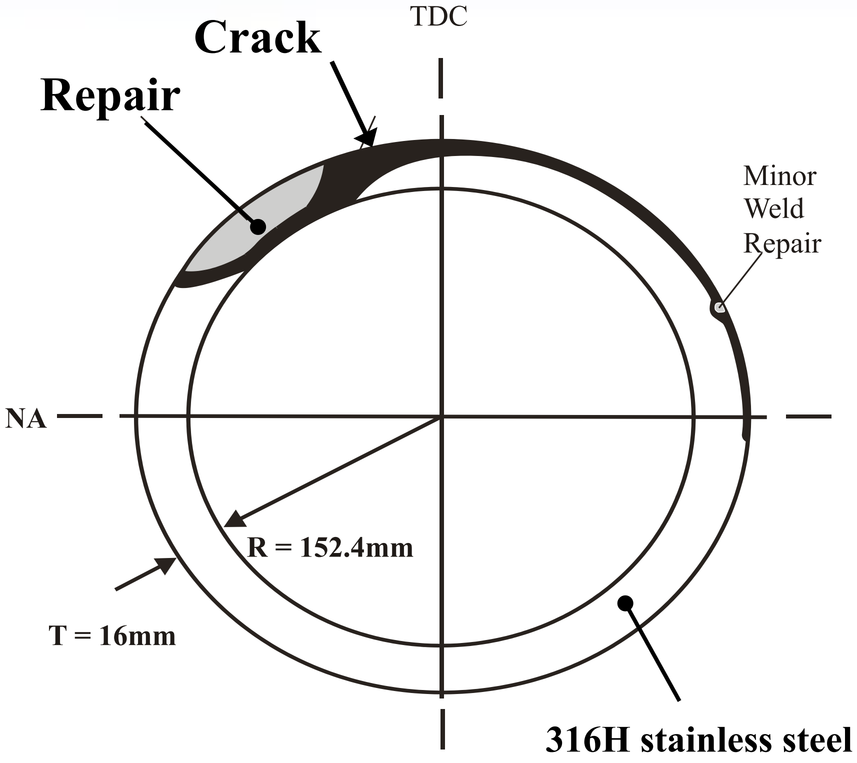
Residual Stress in Welds - Nuclear



An AGR superheater header, somewhere in the UK in the last century…

Reheat crack found near pipe repair weld





A UK Nuclear Power Plant: - developed steam leak in 199?

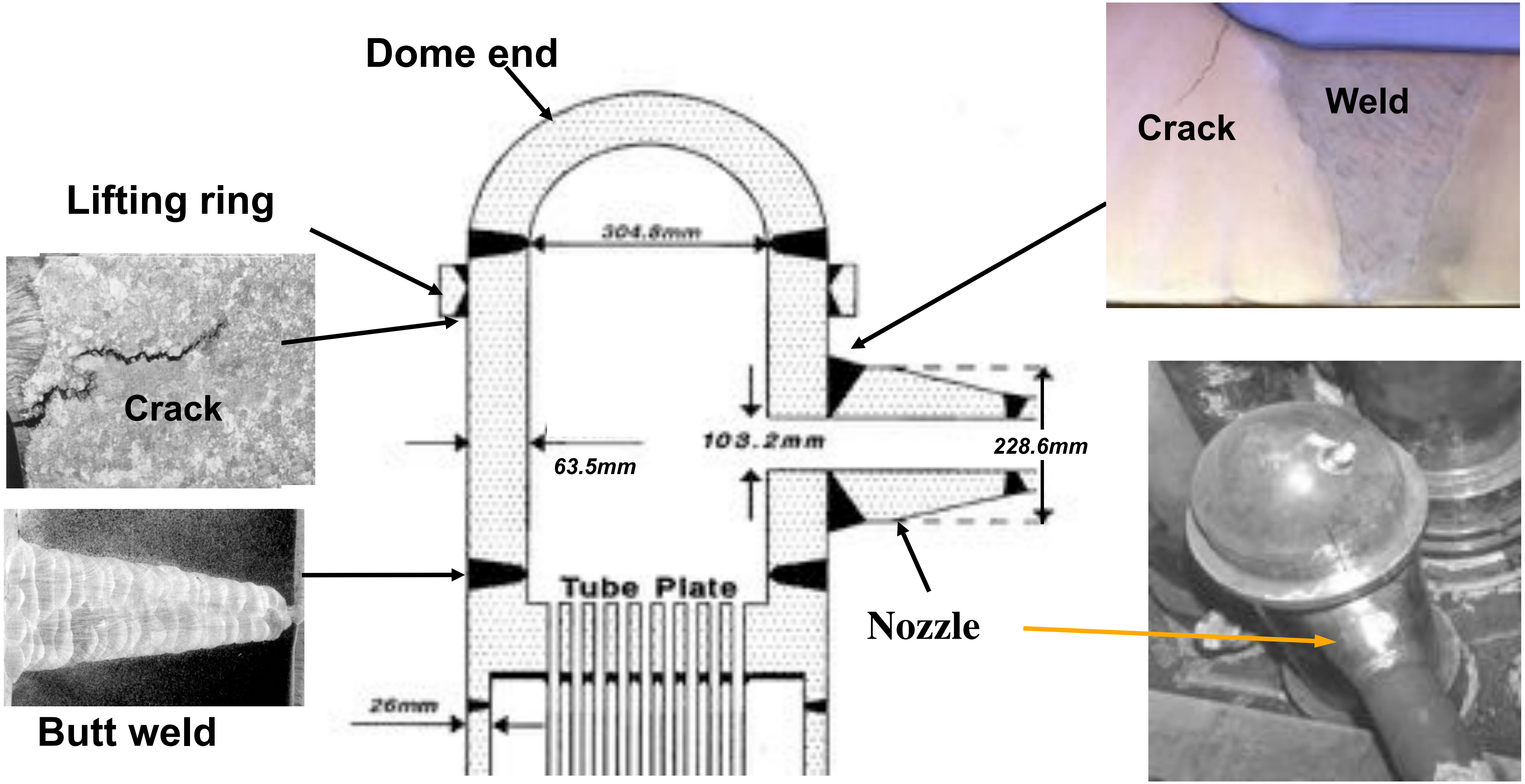
Repair weld residual stress + plant loads at high temperature (>500°C),

Creep cavitation » microcracking » crack growth » through-wall» leak

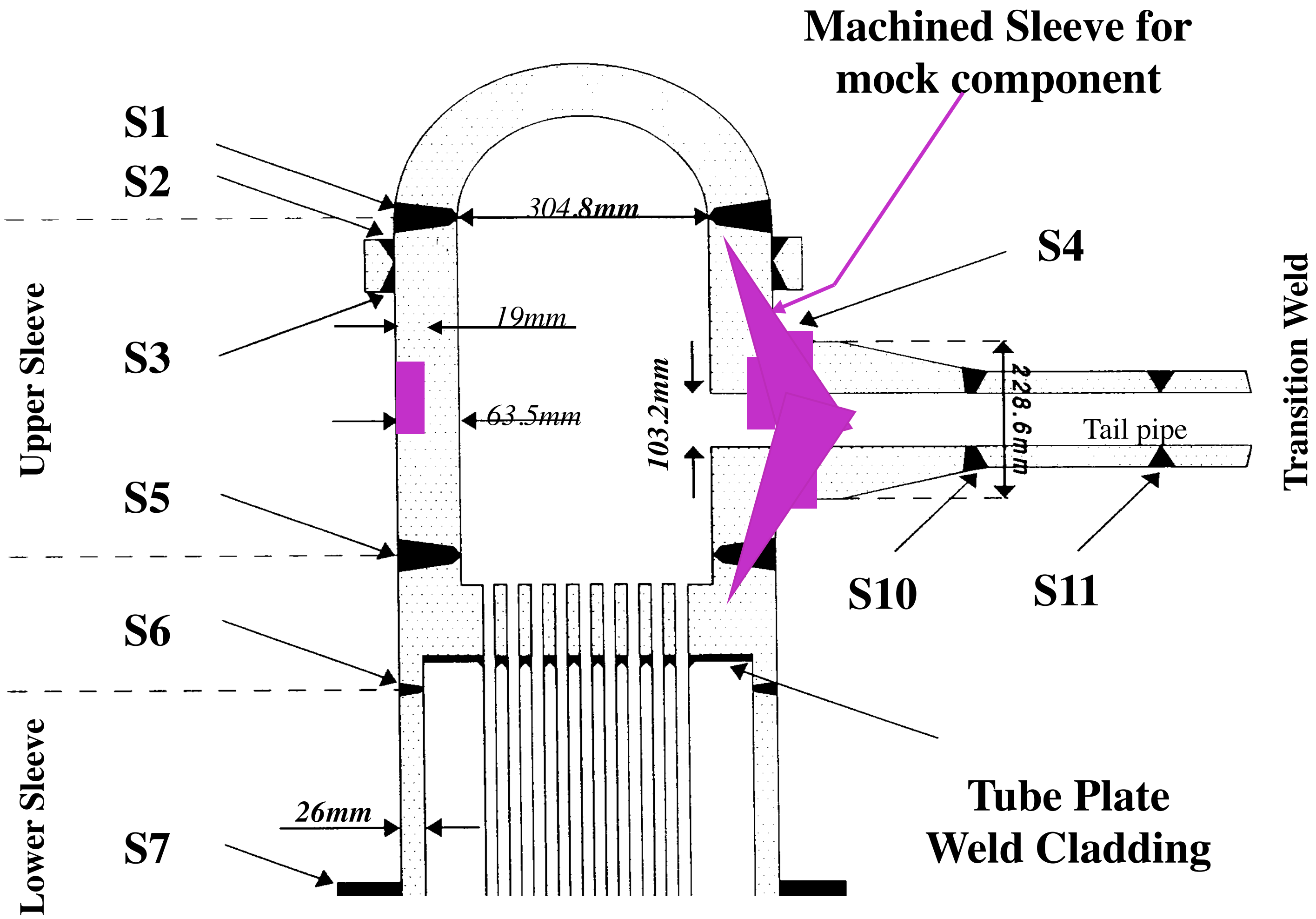
Detailed inspection for further cracking

- 261 observations of cracking at welds
- as-welded type 316H Austenitic Stainless Steel
- operating at 510 - 550^{o}C
- crack initiation after 10 - 50K hours (≈1-5yrs)
- located in HAZ a few mm from fusion boundary
- heavy section branch welds and repairs are most susceptible

A common reheat cracking location

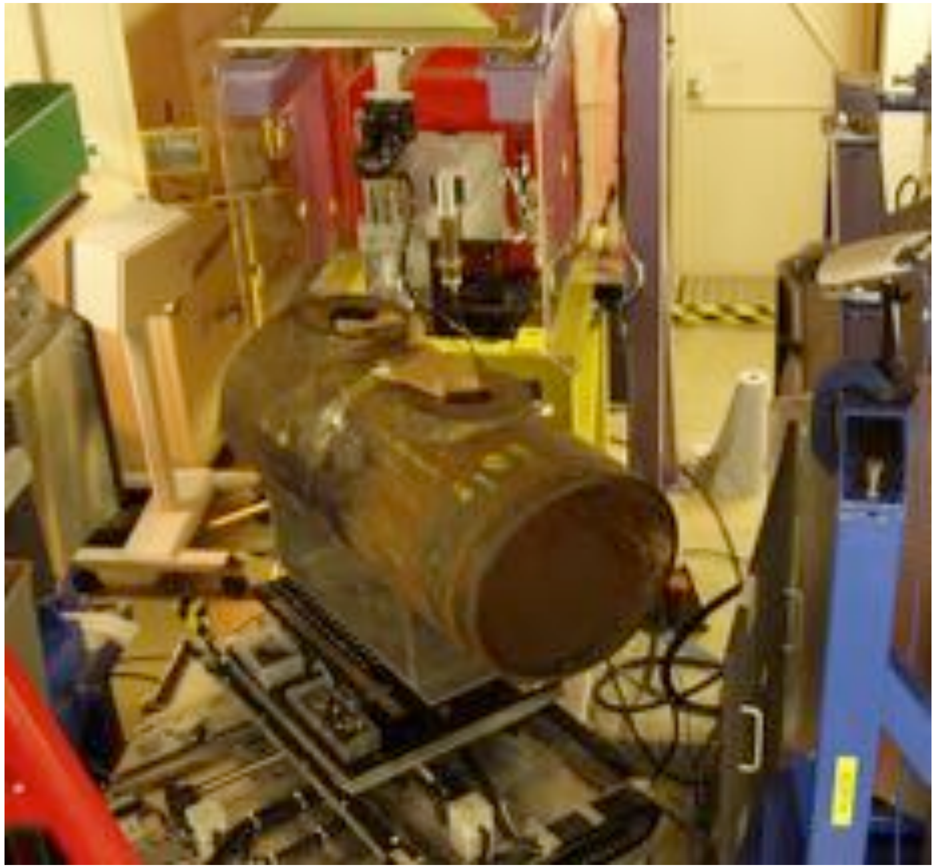


Ex-service mock-up component

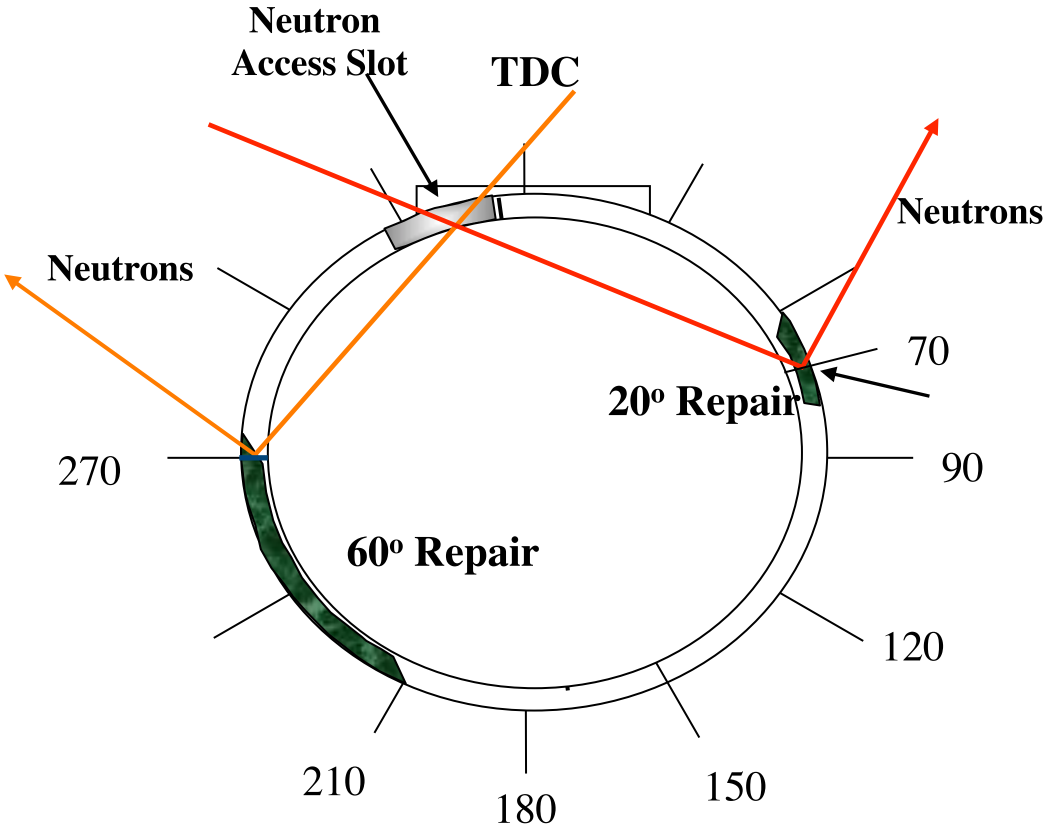


Original ex- service steam header

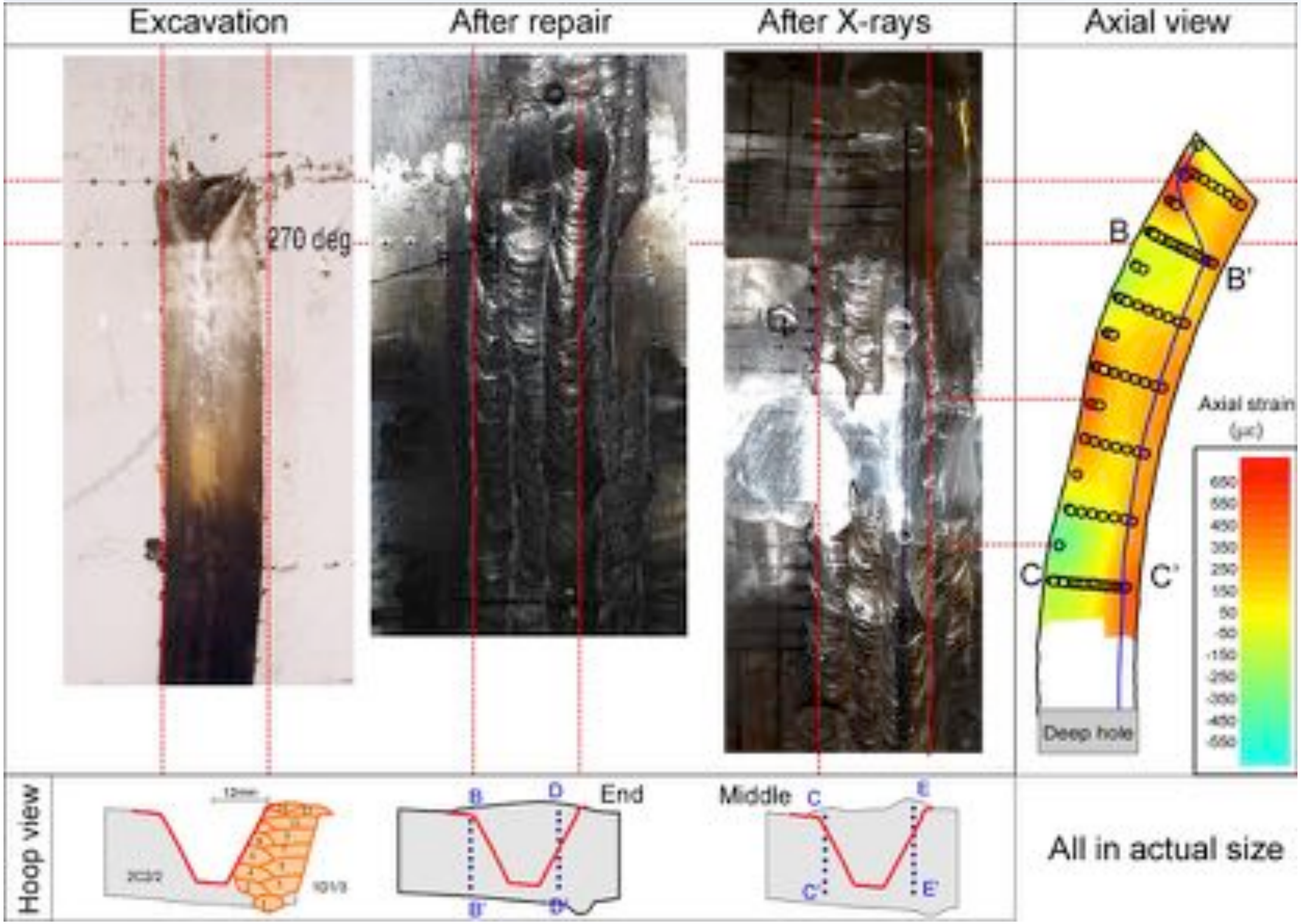
Header repair weld geometry

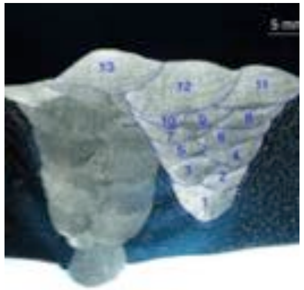


Welded pipe on Engin-X

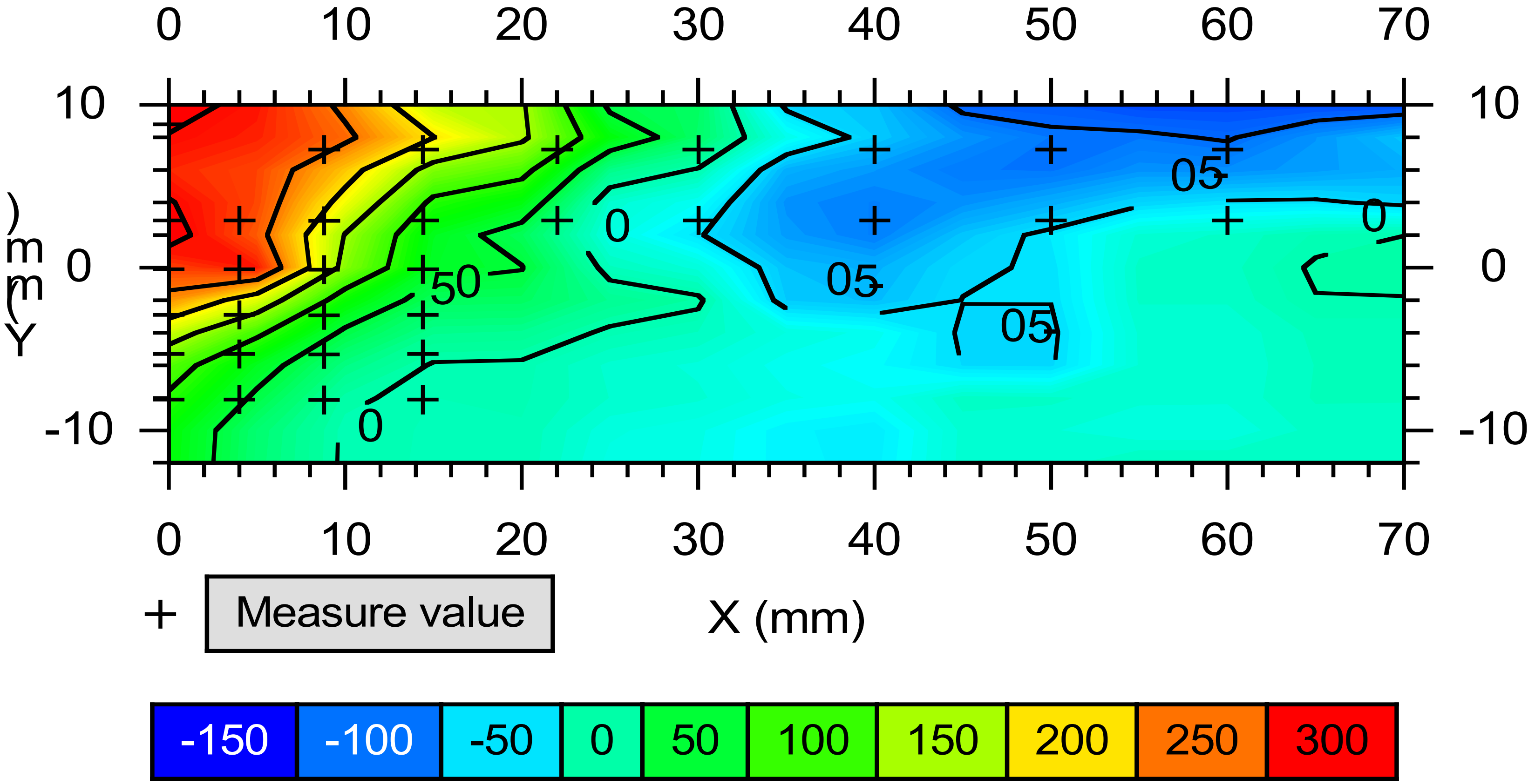


Location, location, location..

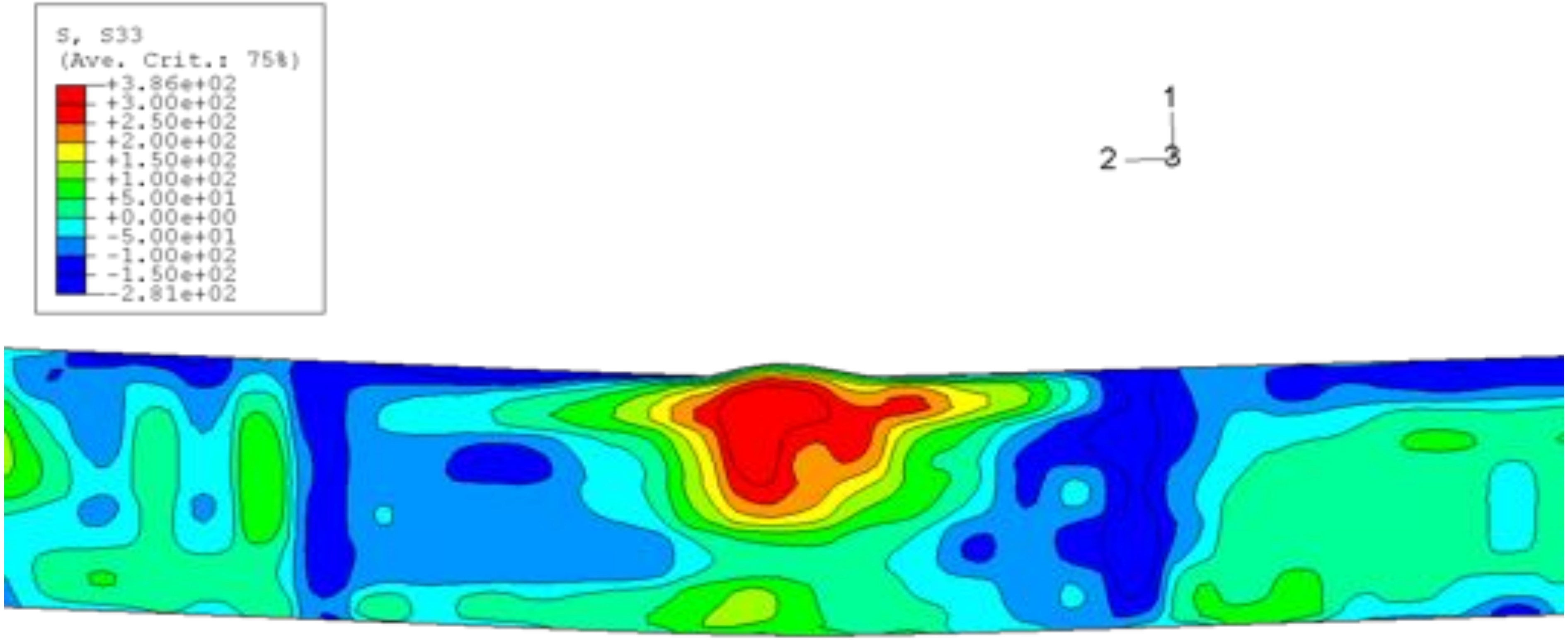




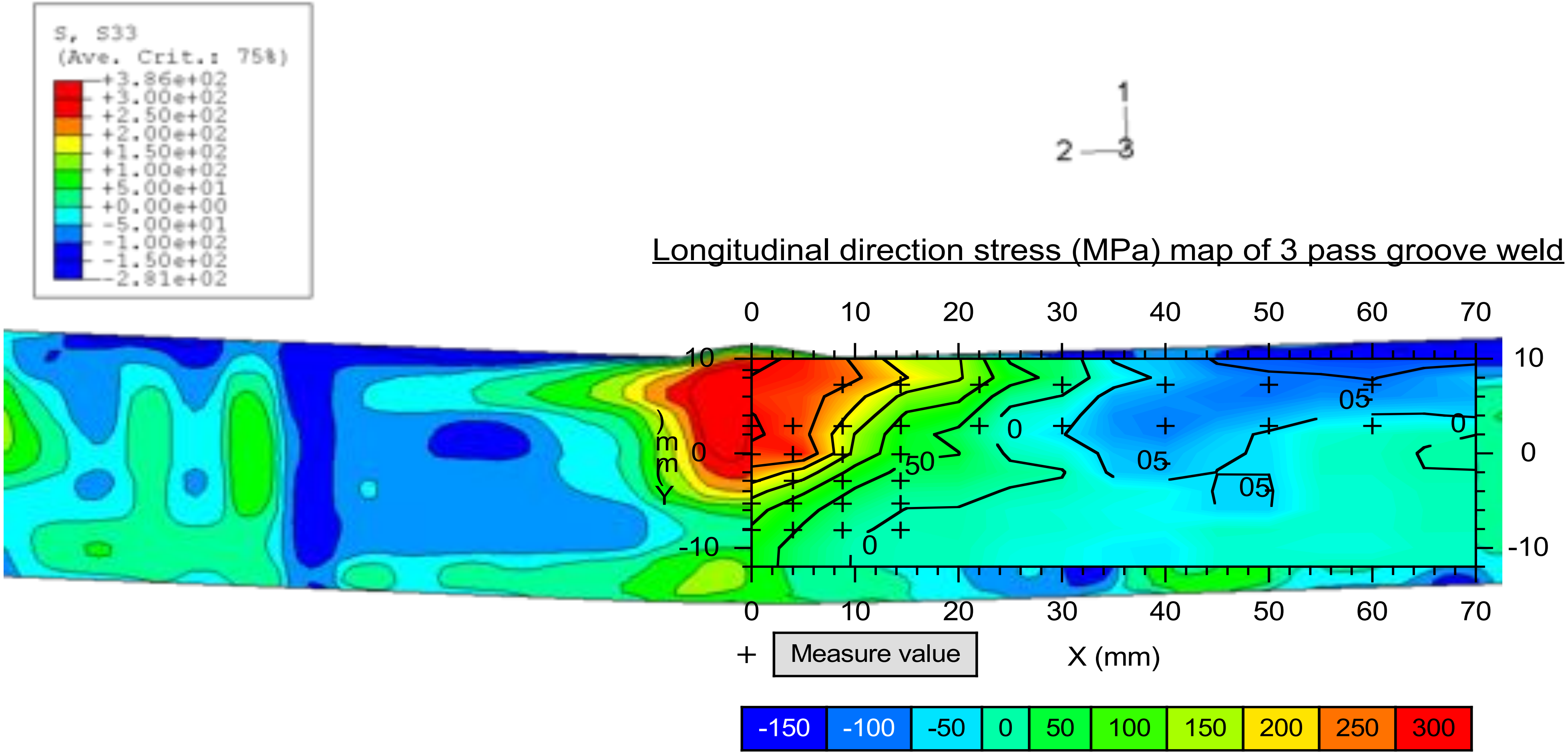
3 Pass groove weld longitudinal stress : Contour map



3 Pass groove weld longitudinal stress : Neutron Diffraction map



3 Pass groove weld longitudinal stress: Comparison



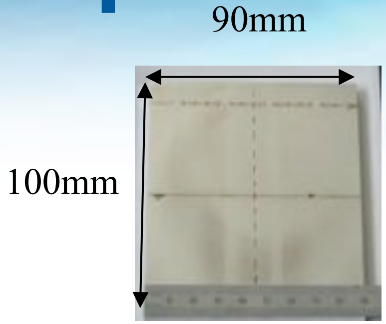
Longitudinal direction stress (MPa) map of 3 pass groove weld

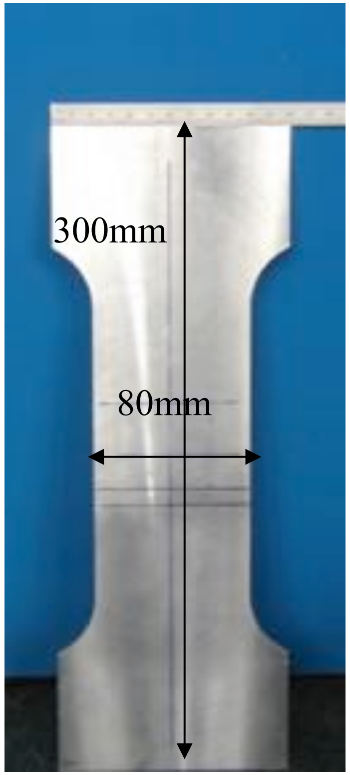
Residual Stress in Welds - Aerospace

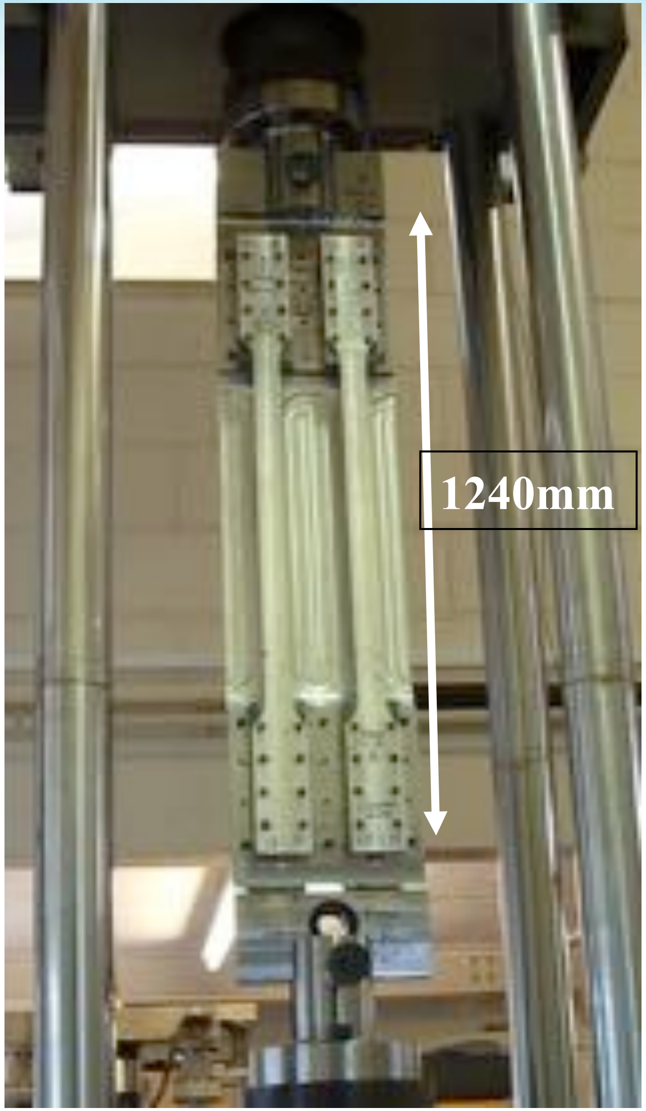
- Welding was a potential cost effective alternative to mechanical fastening for Very Large Aircraft (VLA)
- Rôle of weld microstructure and residual stress on fatigue life must be understood for *Failsafe, Damage Tolerant* design of safety critical aerospace structures
- How do we ensure similitude stills exist?

Scaling Requirements

- Wing structures to be machined after welding
- Typically welded at 12.5mm and skimmed to ≈7mm
- The short crack growth samples are 100×90×7mm
- The long crack growth M(T) samples 300×80×7mm
- Prototype skin stringer panel was 1240x350×80 mm
- Size and measurement density define the appropriate residual stress measurement method
- Then we can *hopefully* retain similitude!



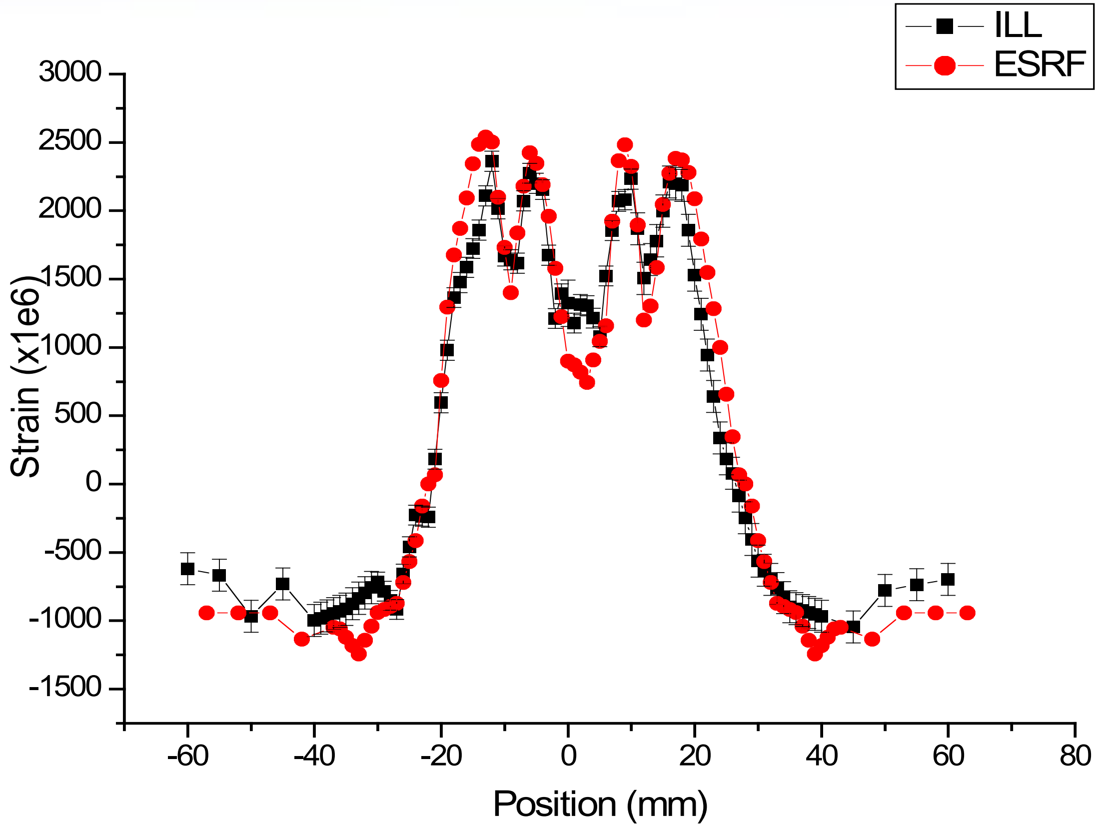




Example Test Matrix

Sample	Dimension	Source	Comments
As-Welded	240x280×12mm	Reactor neutron & synchrotron X-rays	Complementarity between the two sources established, also repeatability of weld process verified
Skimmed	240x280×7mm	Pulsed neutron & synchrotron X-rays	
M(T) Sample	380x80×7mm	Pulsed neutron	
Short Crack Sample	100x90×7mm	Synchrotron X-rays	3D Surface stress determined. Synchrotron X-rays used as it is best suited for surface stress measurement
Skin Stringer Assembly	1240x350×80mm	Pulsed neutron	Large structure only possible in the ENGIN-X dedicated strain scanner

Comparability and reproduceability

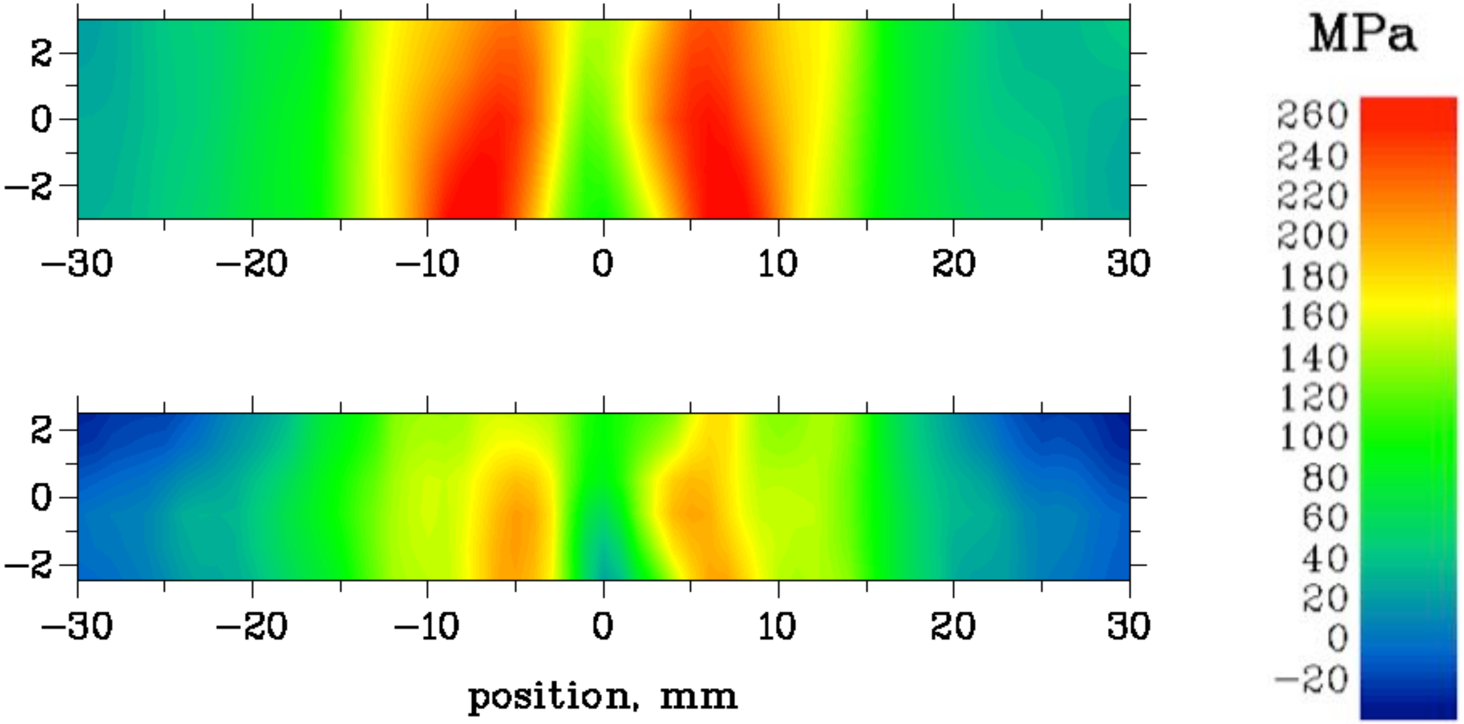


Measurements on ostensibly identical specimens

Validated weld reproducibility and stress measurement technique

Fast measurements give high density maps

Effect of machining on 7150 weld longitudinal stress distribution:

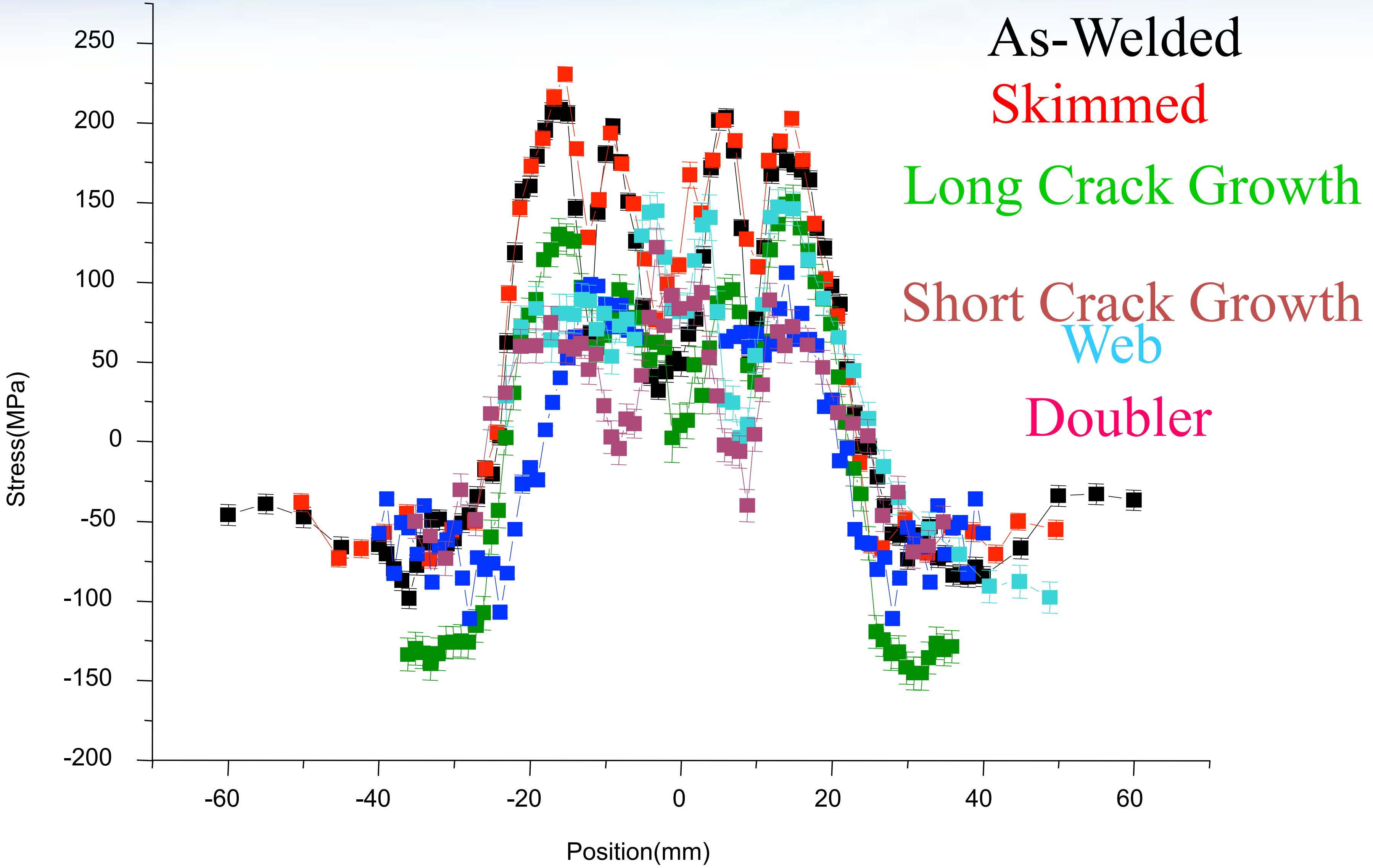


12.6 mm thick sample

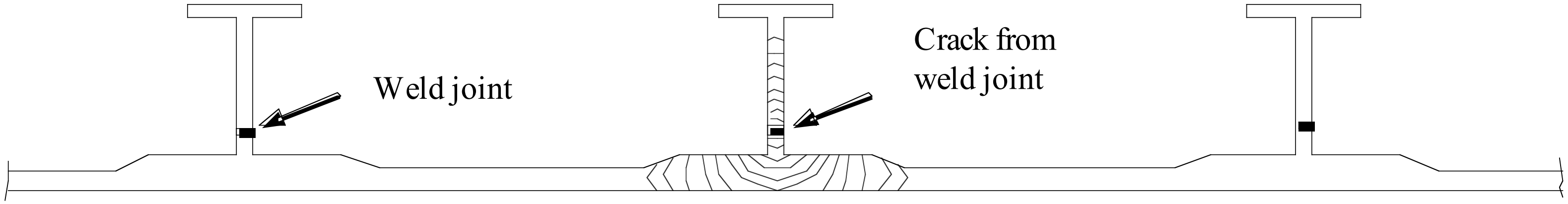
7 mm thick sample

Comparison visualisation made using centre-plane longitudinal stress

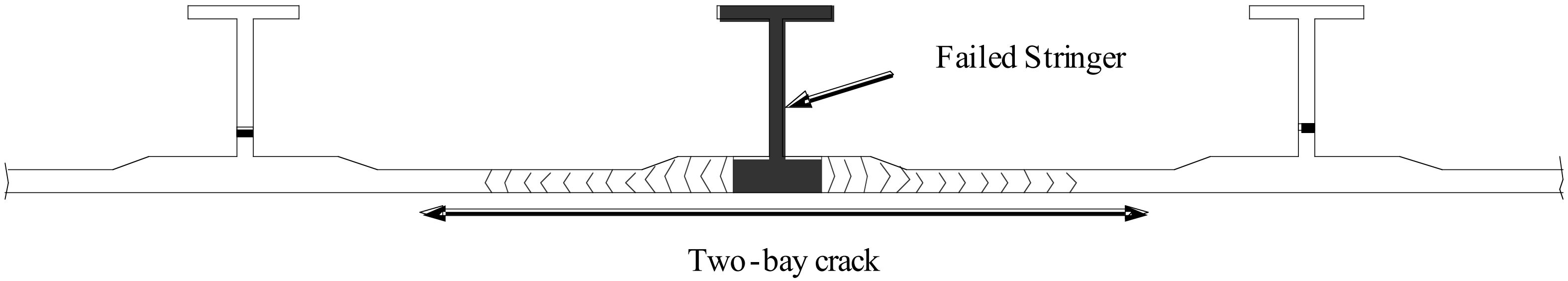
Longitudinal Residual Stress Evolution



Multi-Stringer Panel: Failure Scenarios

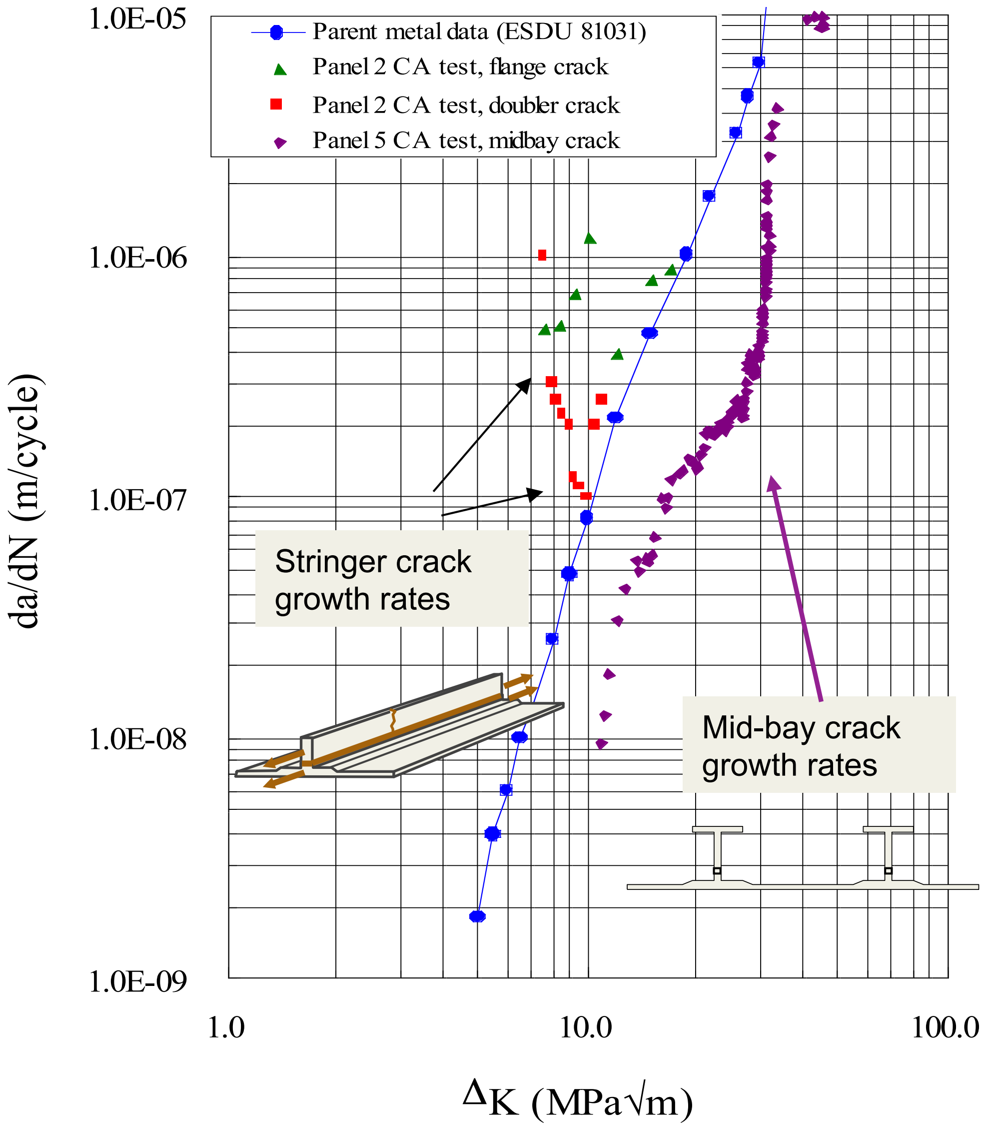


(a)



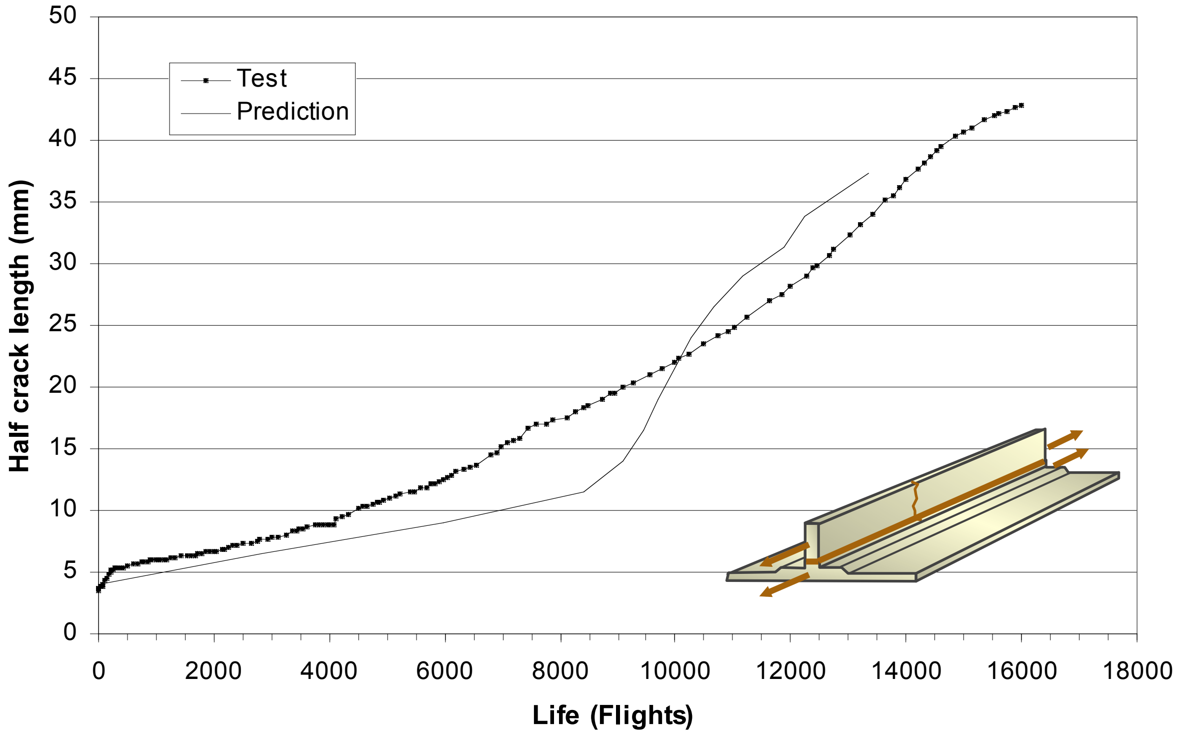
(b)

Panel crack growth rates



- VPPA welded 2024 panel
- Constant amplitude load: σ_{max} = 88 MPa
- Accelerated crack growth rates for stringer cracks
- Retarded crack growth rate for mid-bay cracks.
- Similitude is lost as result of welding residual stress
- No crack stoppers so less damage tolerant
- Solution: bonded crack retarders

Panel crack growth life



- VPPA welded 2024 panel
- Aircraft spectrum load, σ_{max} = 138 MPa
- Final crack growth life is quite well predicted…
- But the form of crack length versus cycle curve is different from the test

Fatigue crack growth is underestimated early in life and overestimated later in life……

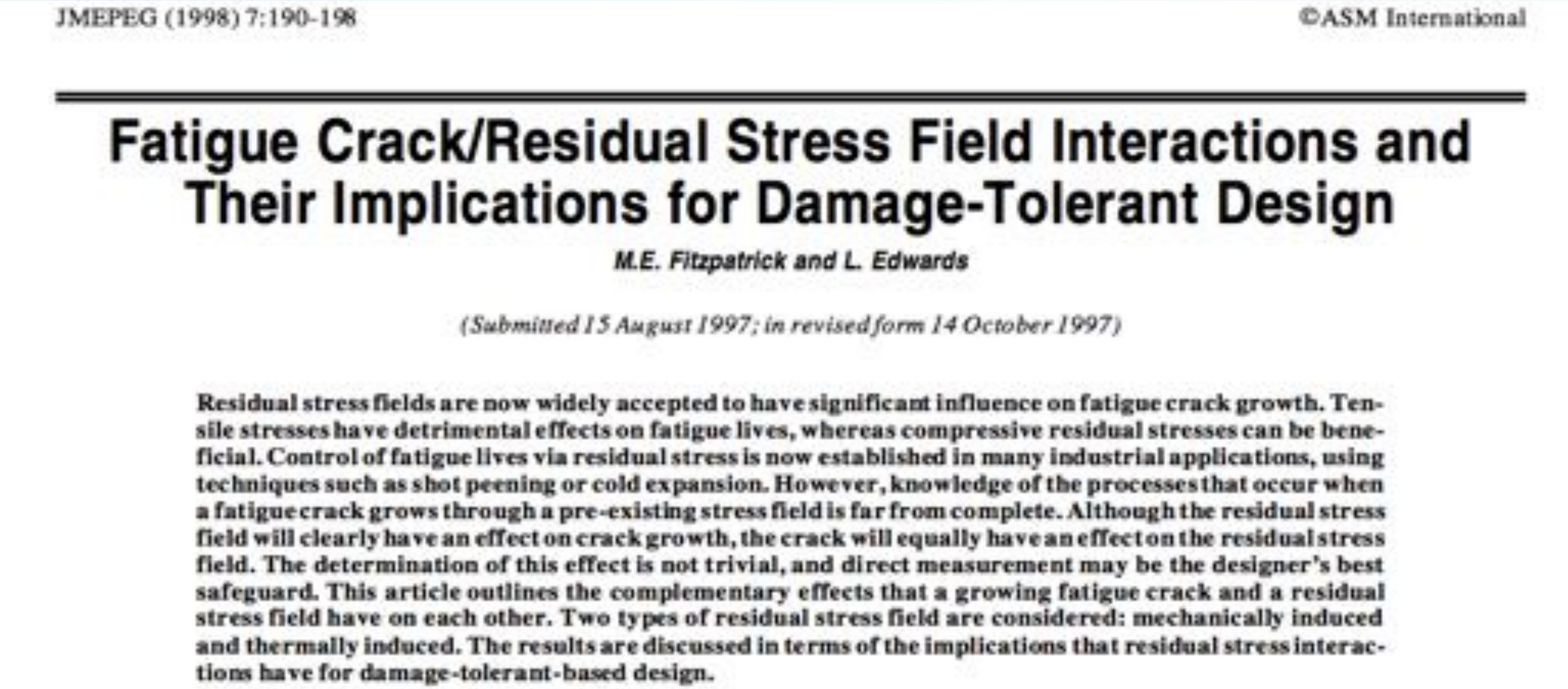
Conclusions: Welded Aerostructures

- Welded skin structures are superior to that of riveted joints and benefit to aircraft design in terms of fatigue durability.
- However, optimised structure has less damage tolerance
- Long fatigue crack growth behaviour is strongly affected by the presence of welding residual stress.
- Residual stress effect on life can be reasonably predicted by appropriate use of ΔK_{eff}.
- Fatigue crack growth is underestimated early in life and overestimated later in life
- Is this due to residual stress relaxation on redistribution?

The Question?

- Long fatigue crack growth behaviour is strongly affected by the presence of welding residual stress.
- Residual stress effect on life can be predicted by appropriate use of ΔK_{eff}.
- Residual stresses like applied stresses elastically re-distribute when cracks grow.
- Fatigue crack growth is typically underestimated early in life and overestimated later in life
- Is this due to residual stress relaxation?
- That is: Do fatigue cracks cause plastic relaxation?

The Statements (20 years ago)



JMEPEG (1998) 7:190-198

Fatigue Crack/Residual Stress Field Interactions and Their Implications for Damage-Tolerant Design

M.E. Fitzpatrick and L. Edwards

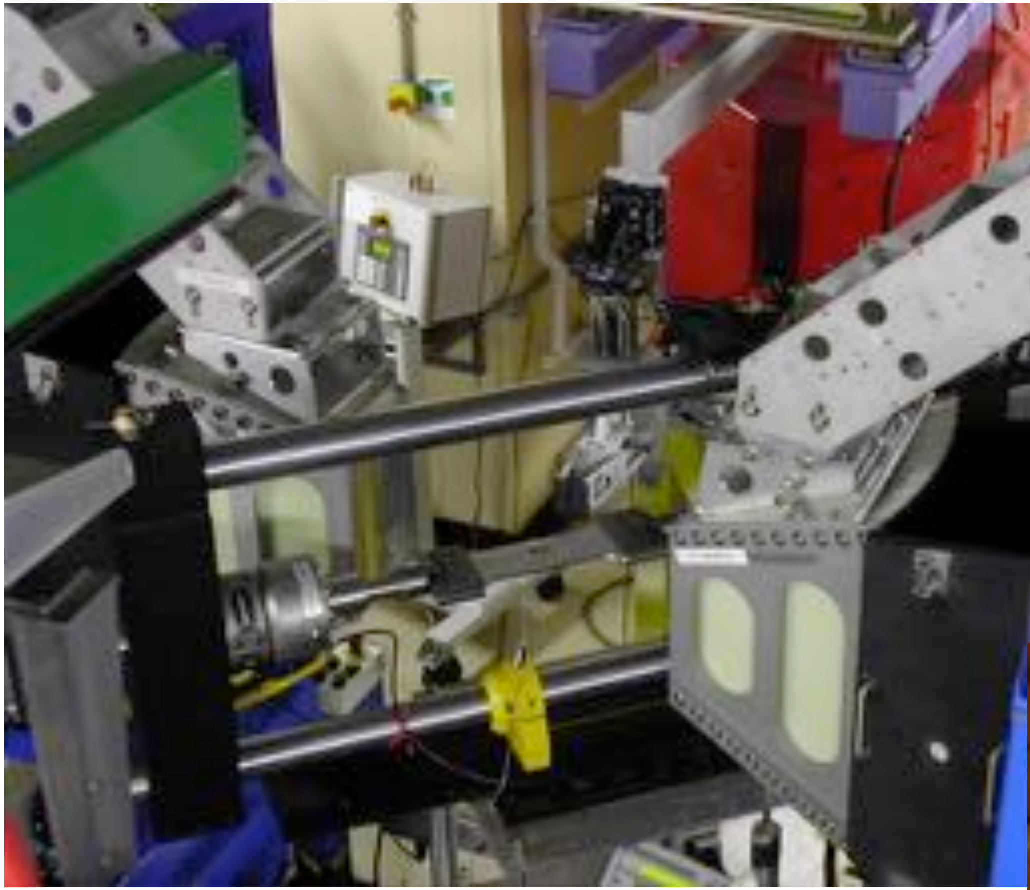
(Submitted 15 August 1997; in revised form 14 October 1997)

Residual stress fields are now widely accepted to have significant influence on fatigue crack growth. Tensile stresses have detrimental effects on fatigue lives, whereas compressive residual stresses can be beneficial. Control of fatigue lives via residual stress is now established in many industrial applications, using techniques such as shot peening or cold expansion. However, knowledge of the processes that occur when a fatigue crack grows through a pre-existing stress field is far from complete. Although the residual stress field will clearly have an effect on crack growth, the crack will equally have an effect on the residual stress field. The determination of this effect is not trivial, and direct measurement may be the designer's best safeguard. This article outlines the complementary effects that a growing fatigue crack and a residual stress field have on each other. Two types of residual stress field are considered: mechanically induced and thermally induced. The results are discussed in terms of the implications that residual stress interactions have for damage-tolerant-based design.

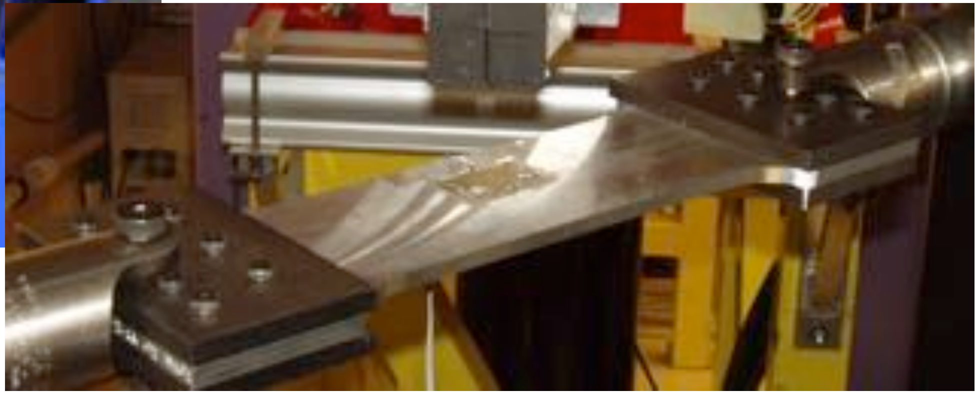
“Knowledge of the processes that occur when a fatigue crack grows through a pre-existing stress field is far from complete.

Although the residual stress field will clearly have an effect on crack growth, the crack will equally have an effect on the residual stress field.”

Measure how residual stress field is affected by fatigue crack growth.



- *In situ* testing feasible on 3rd Generation instruments
- VPPA welded 2024
- Residual stress measured after crack growth increments
- MT specimen fatigued *in situ*



Comparison of Different SIF Models

Mode-I SIF Expression for Arbitrary Stress Field

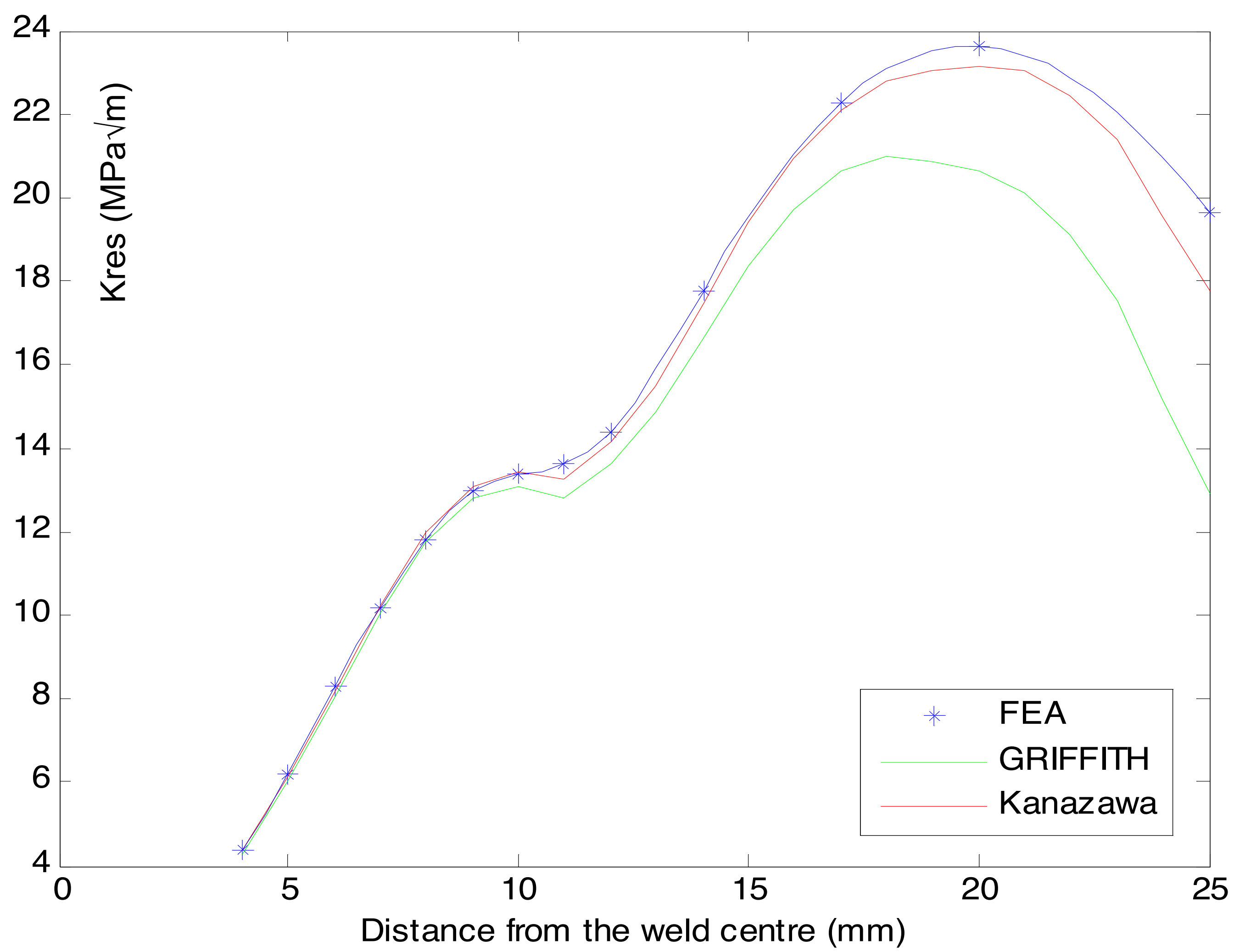
$$K_I = \int_{-C}^{C} \sigma_{ZZ}(x) \cdot \underbrace{G(x, C)}_{Green's\ or\ Weight\ Function} \cdot dx$$

SIF Models $G(x, C)$	Griffith-OU Green's Function	Kanazawa-Oba-Mahida Weight Function	Tada-Paris-Irwin Green's Function
	$\frac{1}{\sqrt{\pi C}} \sqrt{\frac{C \mp x_c}{C \pm x_c}}$	$\sqrt{\frac{2 \sin\left(\frac{\pi (C \mp x)}{W}\right)}{W \sin\left(\frac{2\pi C}{W}\right) \sin\left(\frac{\pi (C \pm x)}{W}\right)}}$	$\left\{ \begin{array}{l} \frac{1}{\sqrt{W}} \times \left[\frac{\pi}{\sqrt{\pi^2 - 4}} - 1\right] \times \sqrt{1 - \left(\frac{x}{C}\right)^2} \times \left[1 - \cos\left(\frac{\pi C}{W}\right)\right] \\ \times \sqrt{\tan\left(\frac{\pi C}{W}\right)} \cdot \frac{\left[1 + \sin\left(\frac{\pi x}{W}\right) \big/ \sin\left(\frac{\pi C}{W}\right)\right]}{\sqrt{1 - \left[\cos\left(\frac{\pi C}{W}\right) \big/ \cos\left(\frac{\pi x}{W}\right)\right]^2}} \end{array} \right\}$
Solution Approach	Exact Closed-Form or Numerical Integration	Numerical Integration only	Numerical Integration only

Increase in complexity & computational resources →

Calculation of K_{res} from residual stress field

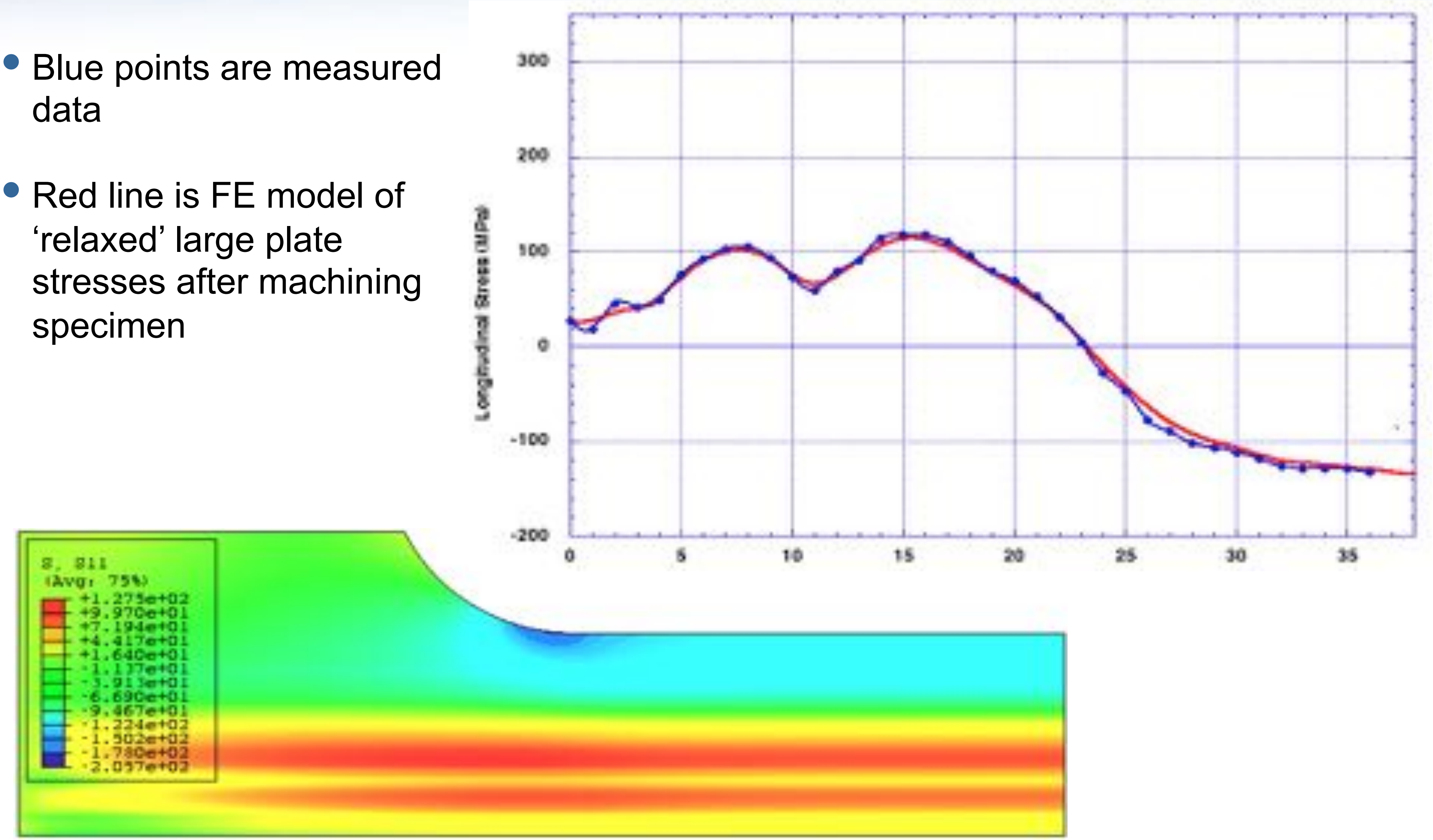
- Greens/weight function models and FE simulations give reasonable Kres predictions.



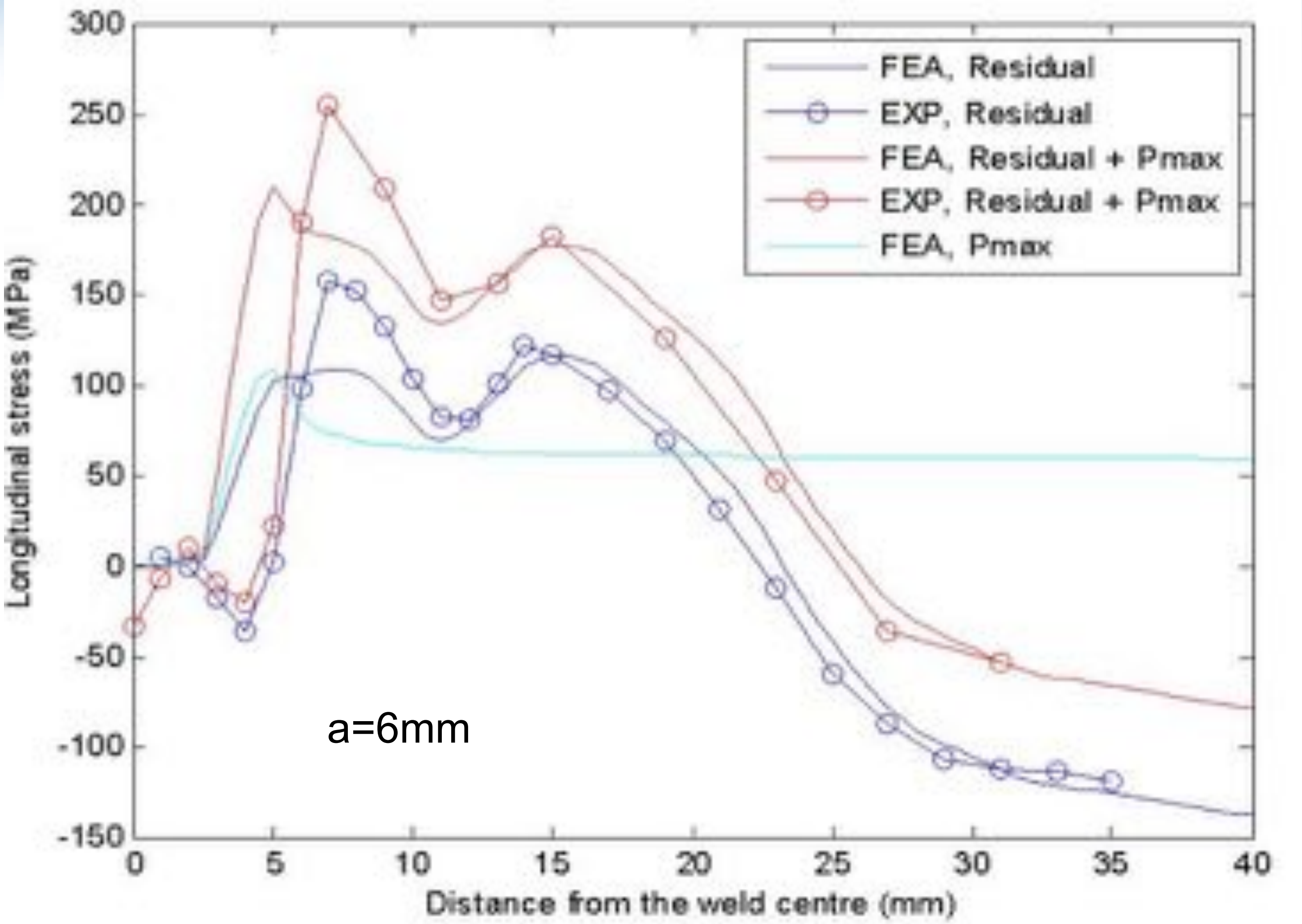
Starting longitudinal residual stress field

- Blue points are measured data

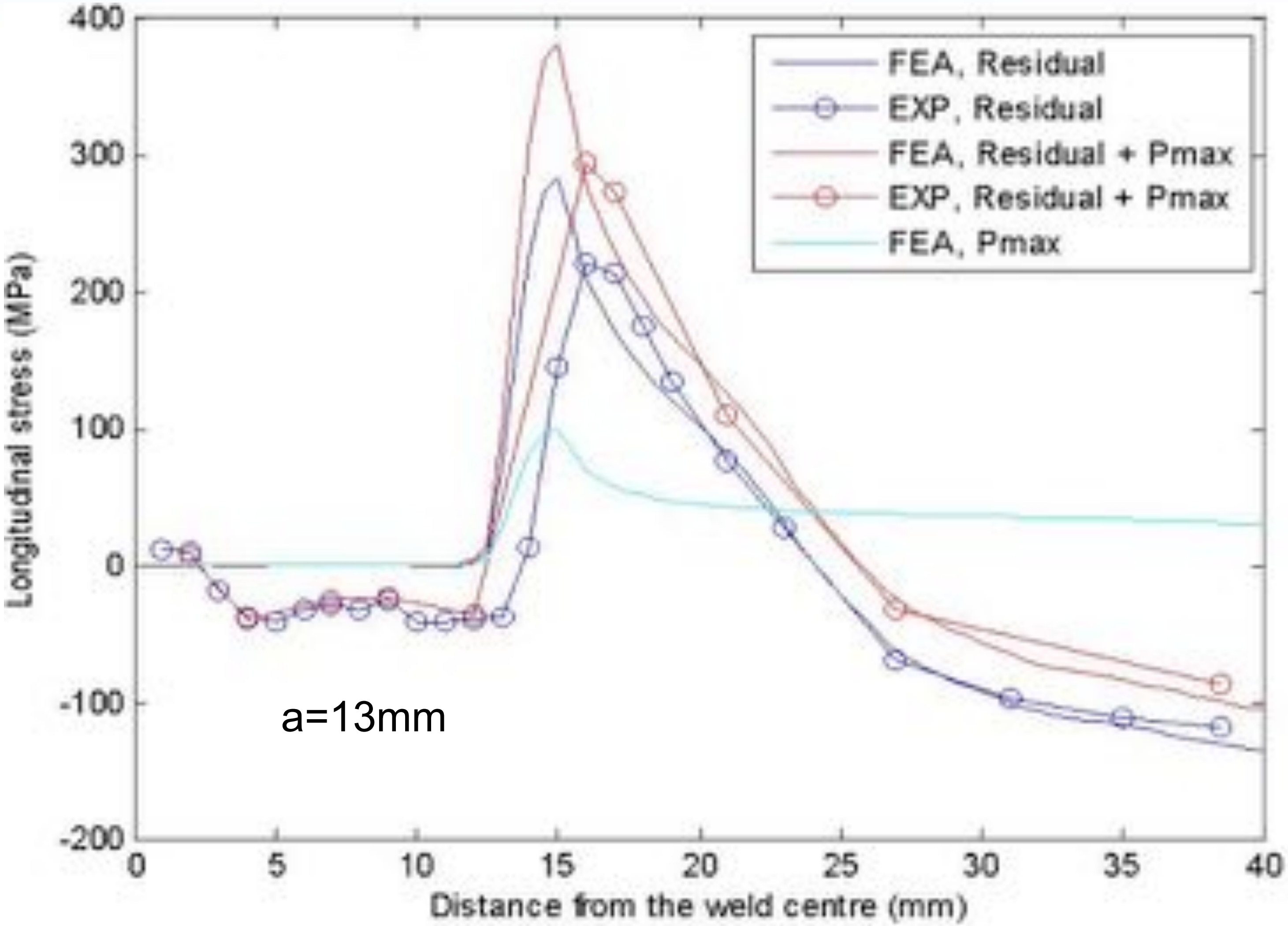
- Red line is FE model of ‘relaxed’ large plate stresses after machining specimen



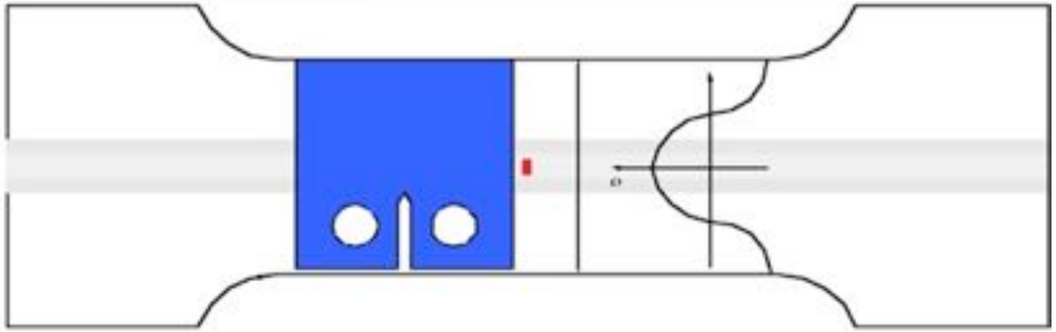
Longitudinal stresses satisfy superposition



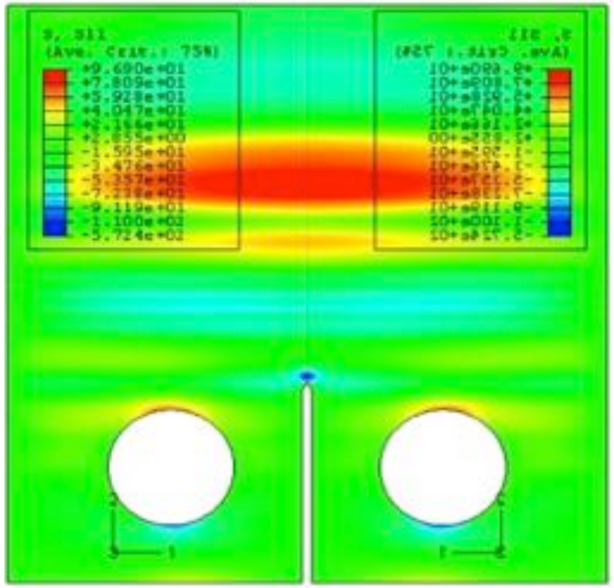
Stress relaxation at longer crack lengths

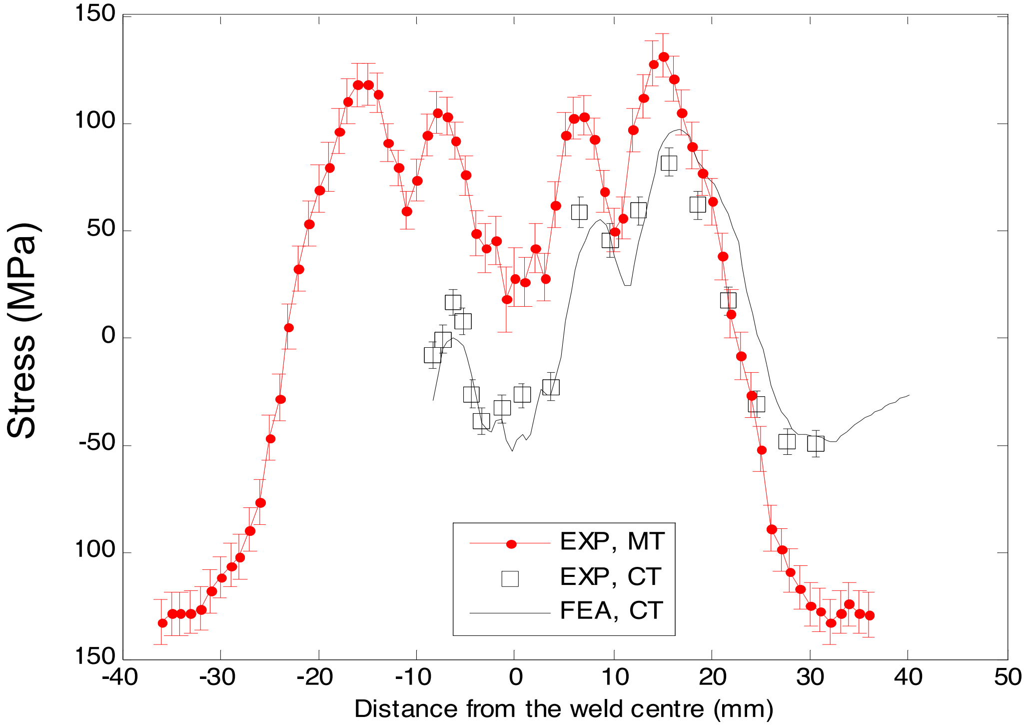


CT is a popular fatigue crack growth specimen

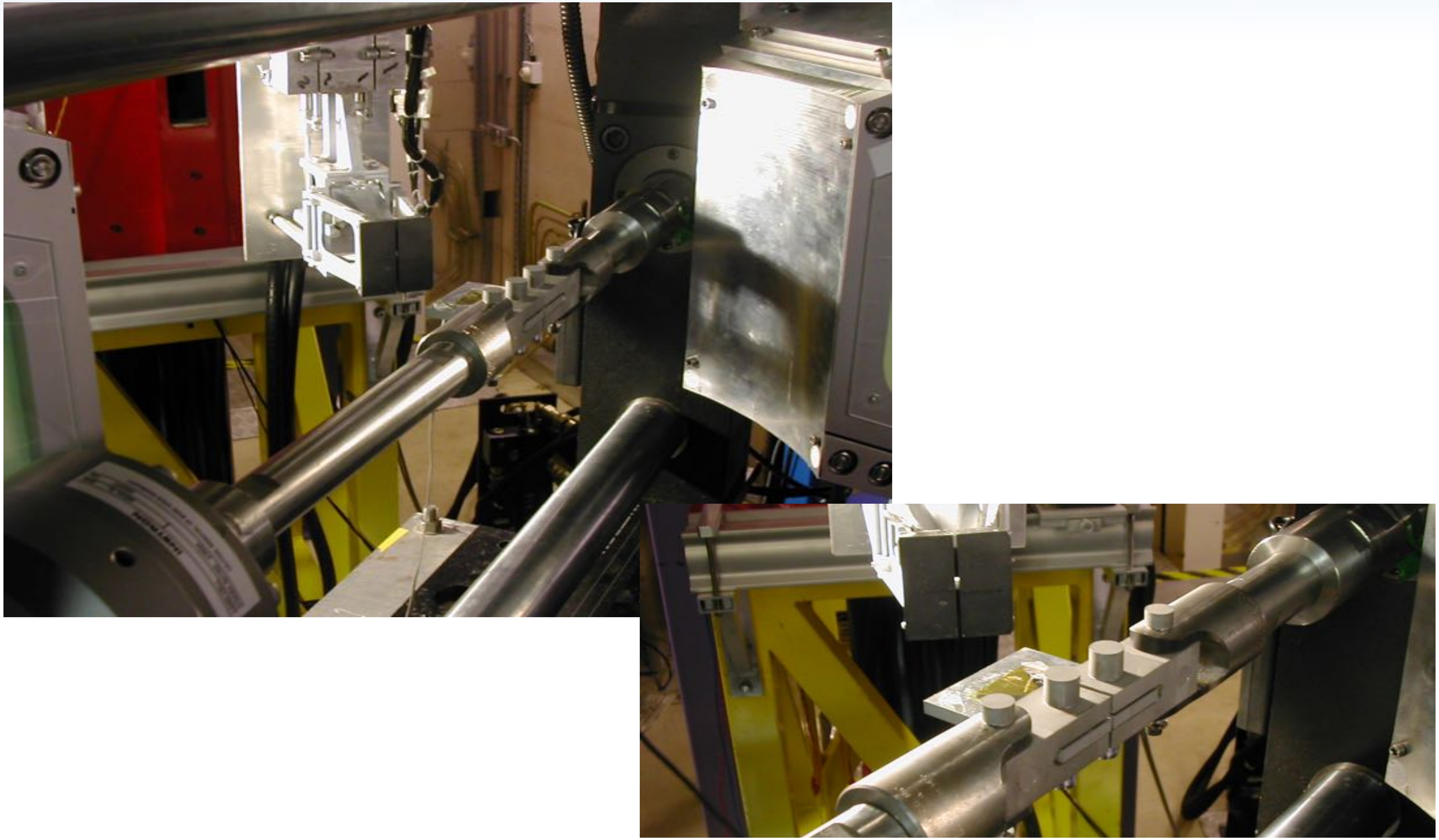


Machining CT specimen makes residual stress at notch compressive

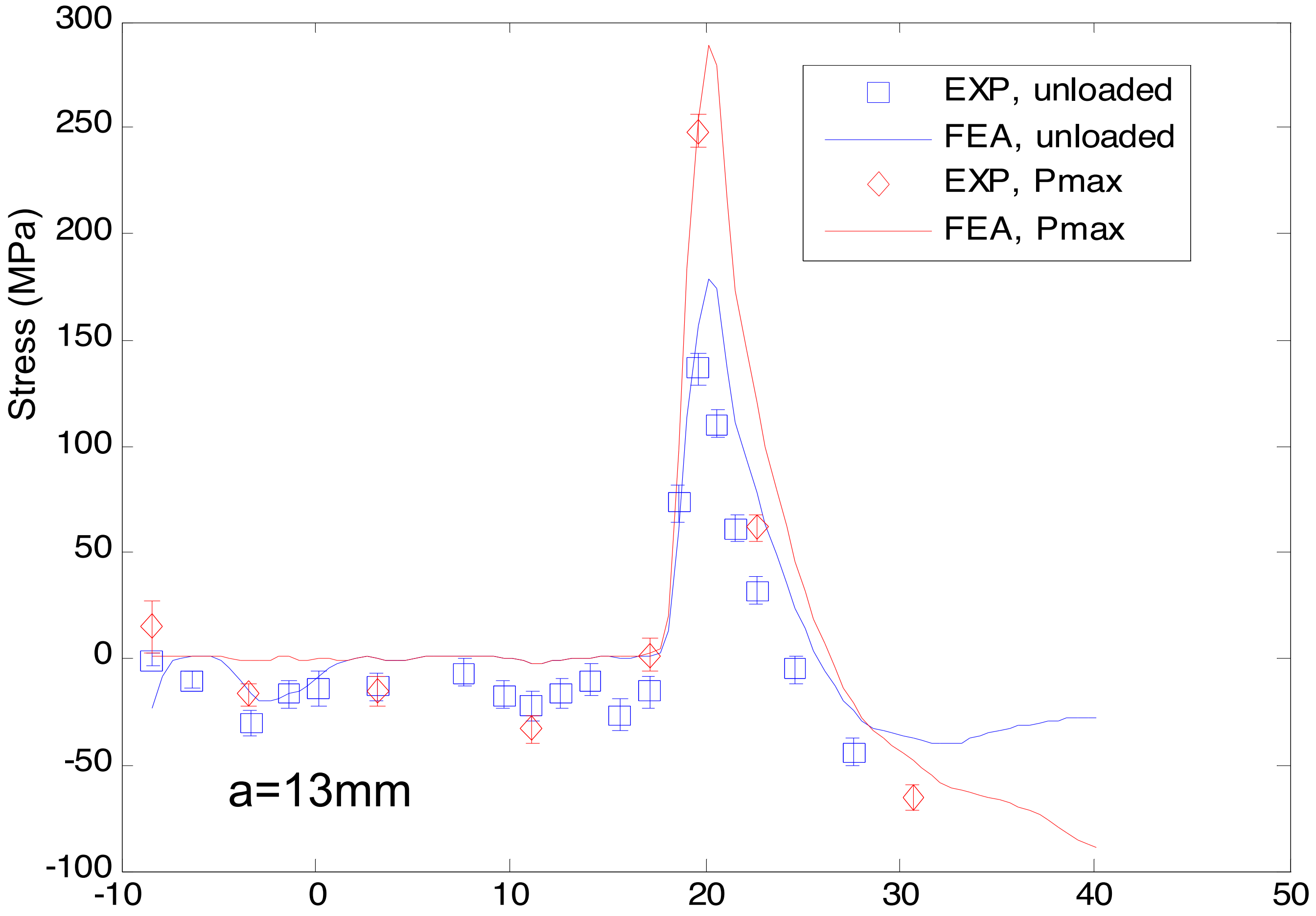




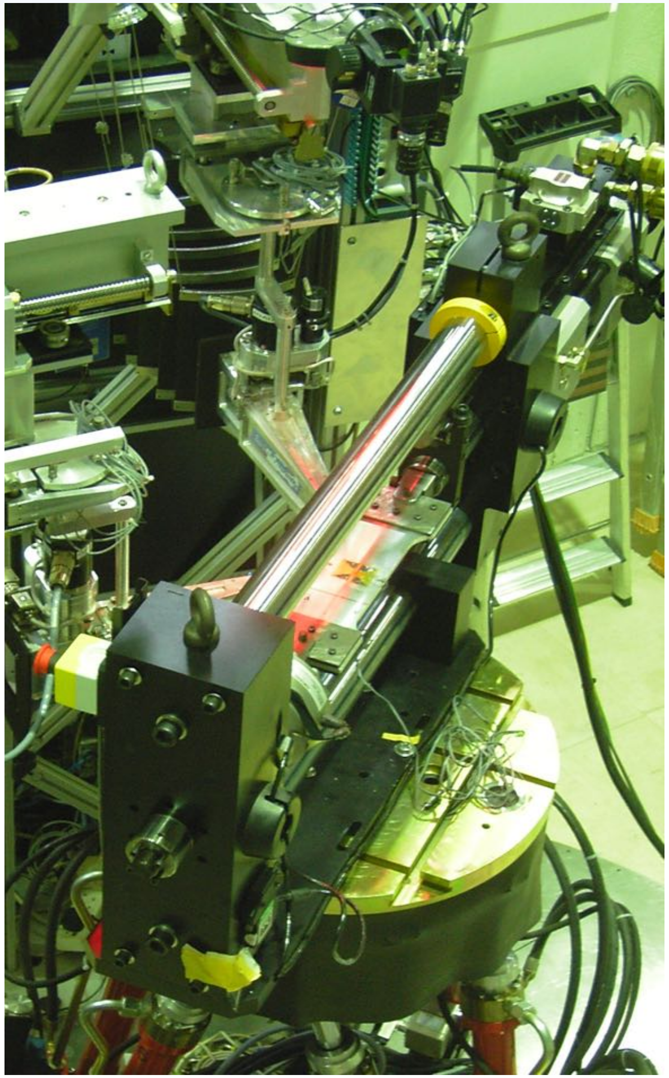
CT longitudinal residual stress evolution



Little stress relaxation in CT specimen

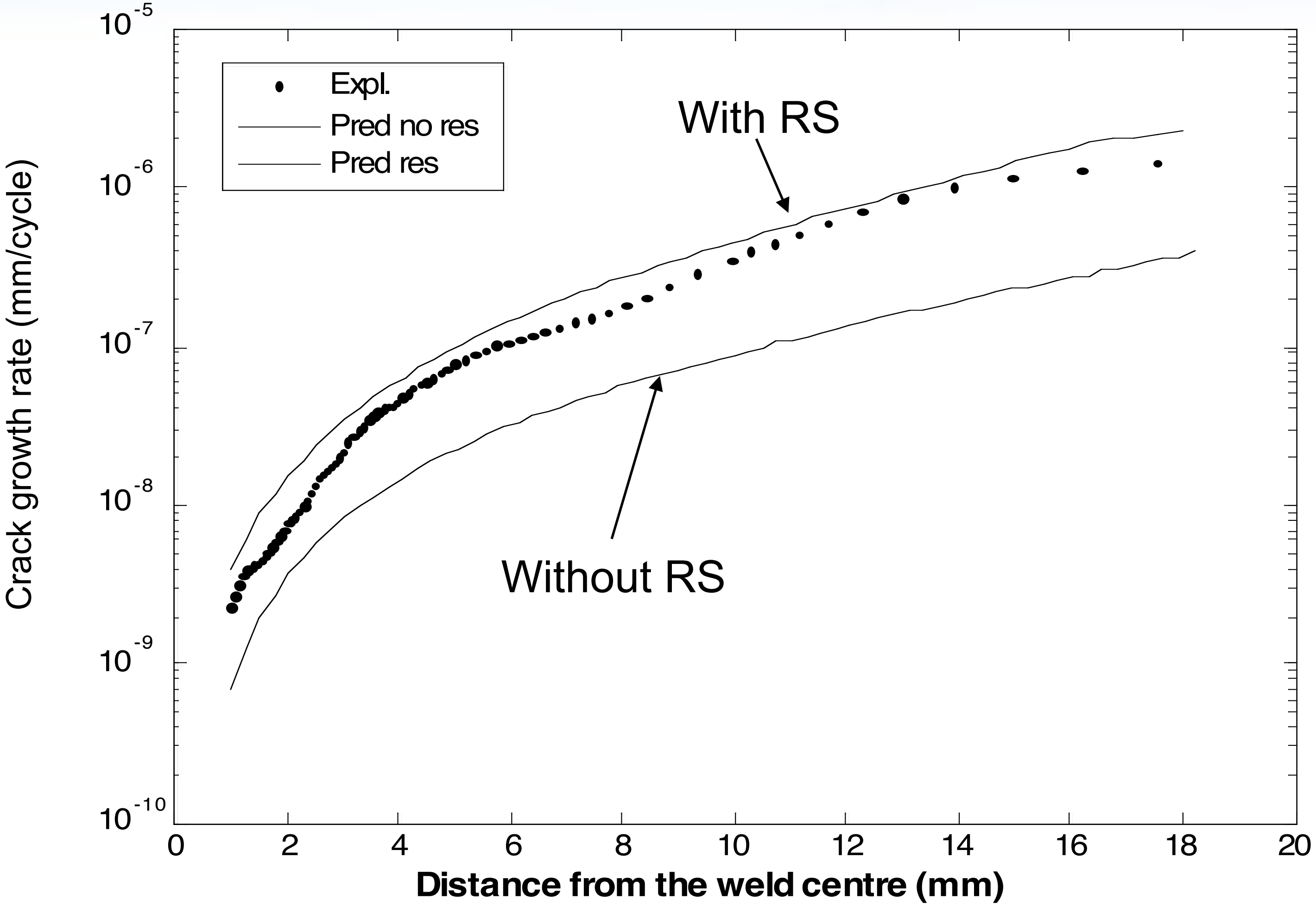


Is relaxation driven by peak stress?



- Most cracks in see constant peak loading *not* constant K
- Under these conditions K and da/dN increase with crack length
- Does this make cause more relaxation?
- Experiment undertaken on SALSA at ILL
- Load rig rotated to measure two strain directions.

Predicting crack growth: MT Const ΔP



Conclusions: RS/fatigue crack interaction

- In situ neutron diffraction can give powerful insight into the interaction between fatigue cracks and the residual stresses they are embedded in.
- Relaxation as well as re-distribution of the residual stress field *is* observed.
- However, it appears that the assumption of small scale yielding can still be maintained and elastic re-distribution models can be used to predict fatigue crack growth rates.
- However, detailed knowledge of the initial residual stress field is always required.

Conclusions: RS/fatigue crack interaction

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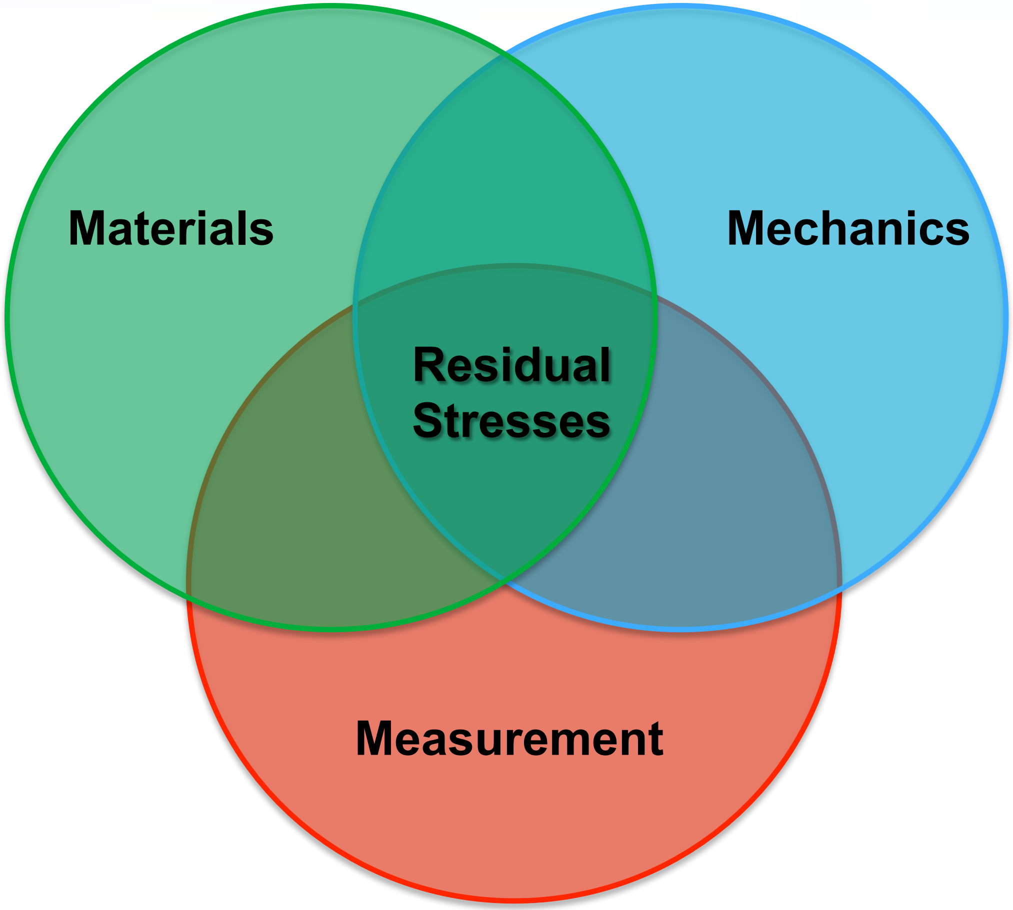
- However, detailed knowledge of the initial residual stress field is always required.

SO WE WERE WRONG!

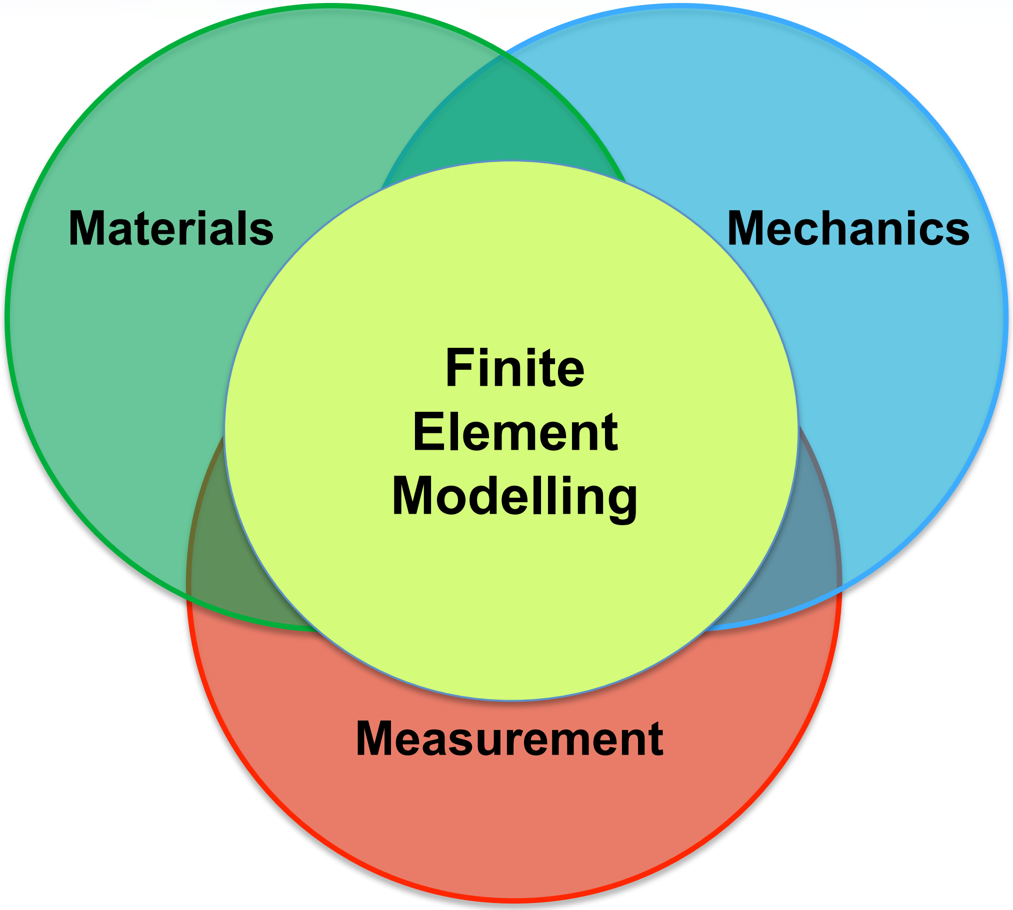
Buckner's Principle rules!

Has modelling come of age…



- Residual stresses Finite Element Modelling is NOT Mechanics.
- Requires knowledge of materials properties
- Must be validated by measurement (ideally not by fitting end results)

Has modelling come of age…



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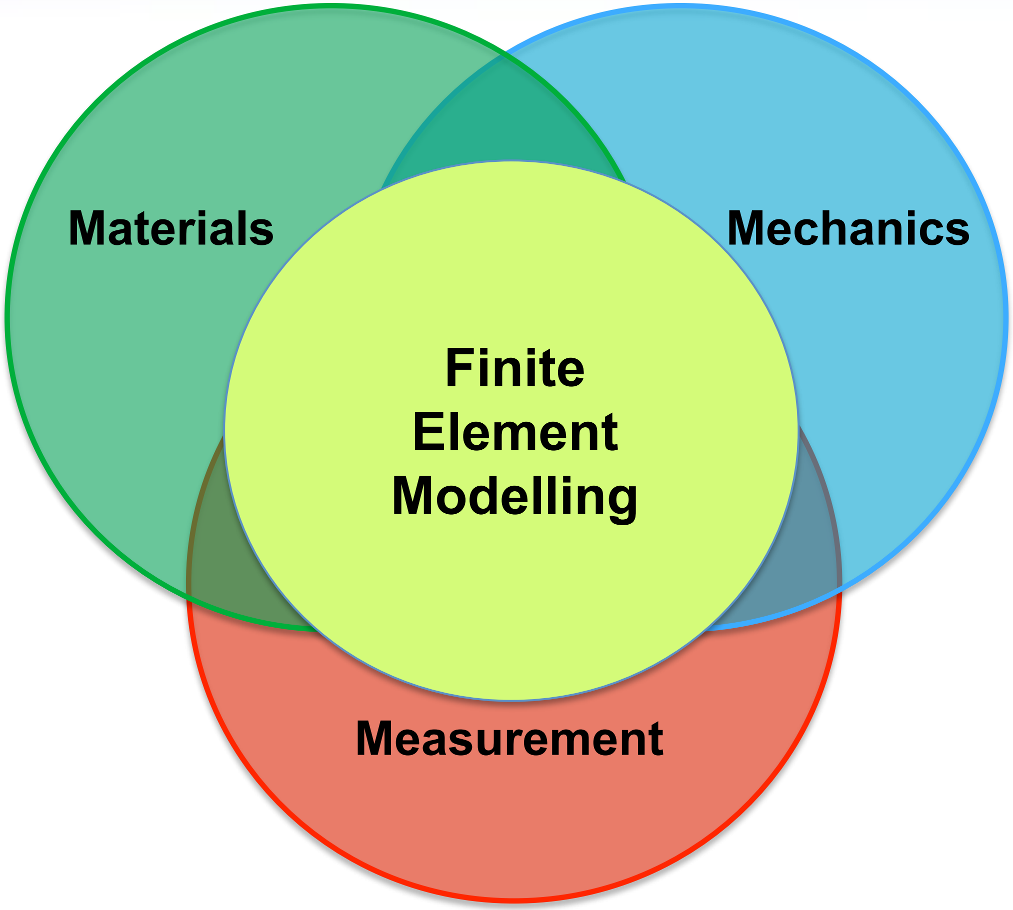


- Residual stresses Finite Element Modelling is NOT Mechanics.
- Requires knowledge of materials properties
- Must be validated by measurement (ideally not by fitting end results)

- Or does Modelling merely cover up and obfuscate the issue ;-)

ANSTO: Validated WRS Methodology

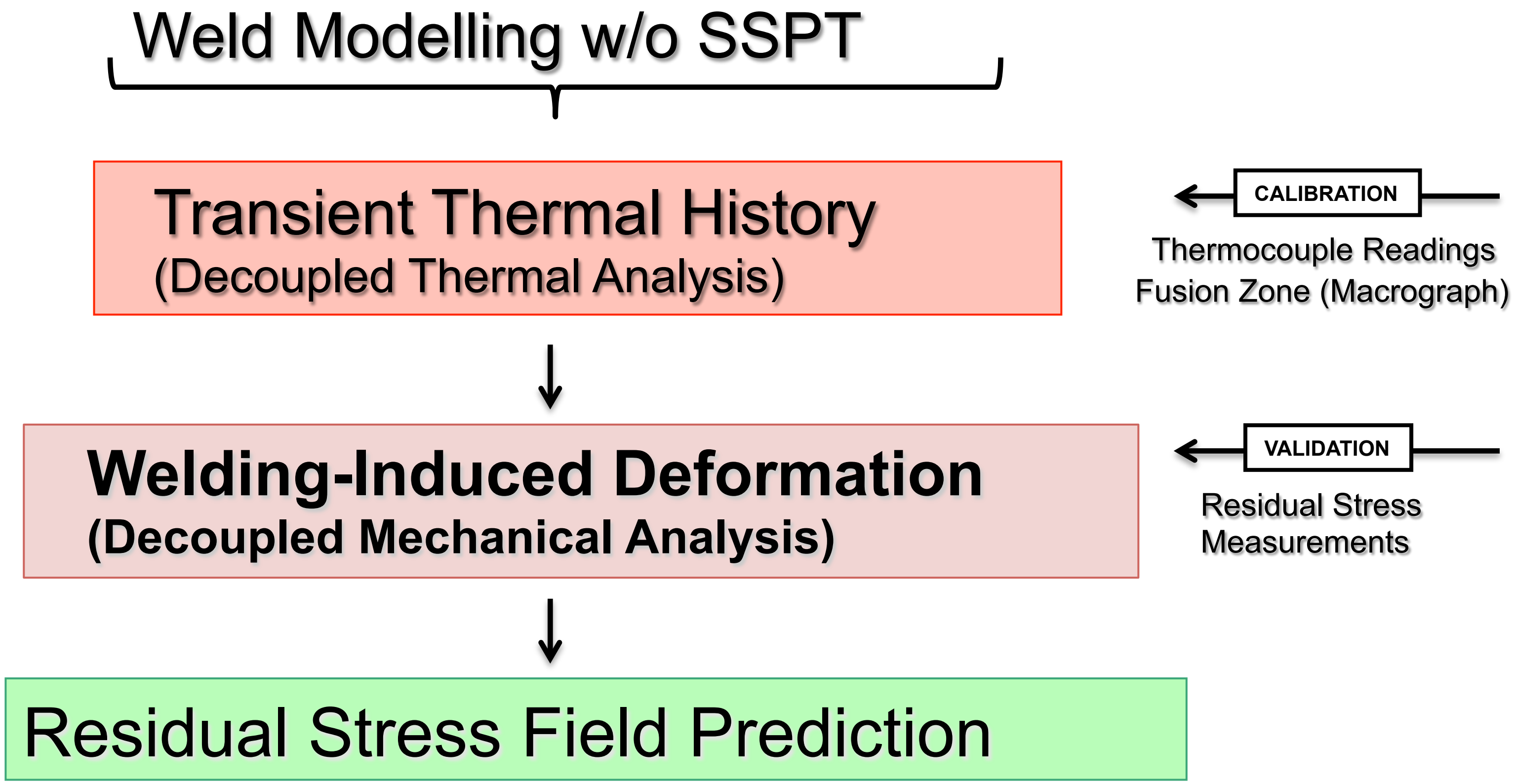
Benchmarking

- Multi-pass austenitic steel weld
- Single-pass ferritic steel weld

Application

- Multi-pass dissimilar metal weld

Weld Modelling:
without Solid State Phase Transformation



Weld Modelling w/o SSPT

Transient Thermal History
(Decoupled Thermal Analysis)

CALIBRATION

Thermocouple Readings
Fusion Zone (Macrograph)

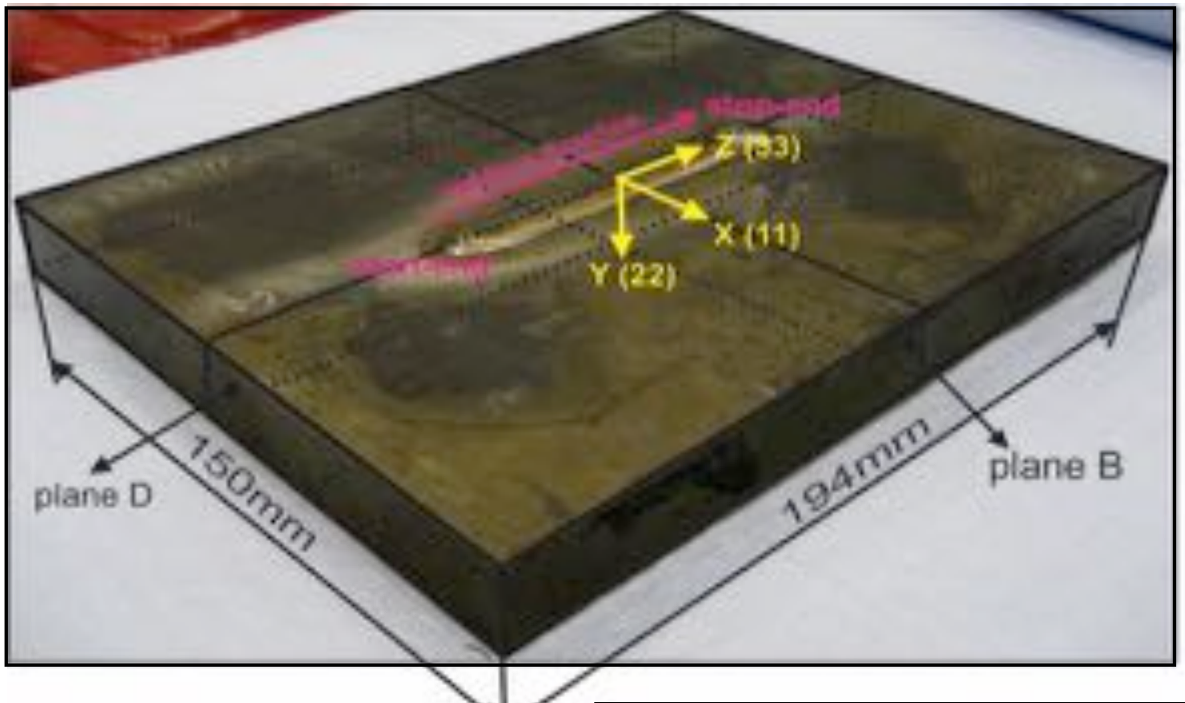
Welding-Induced Deformation
(Decoupled Mechanical Analysis)

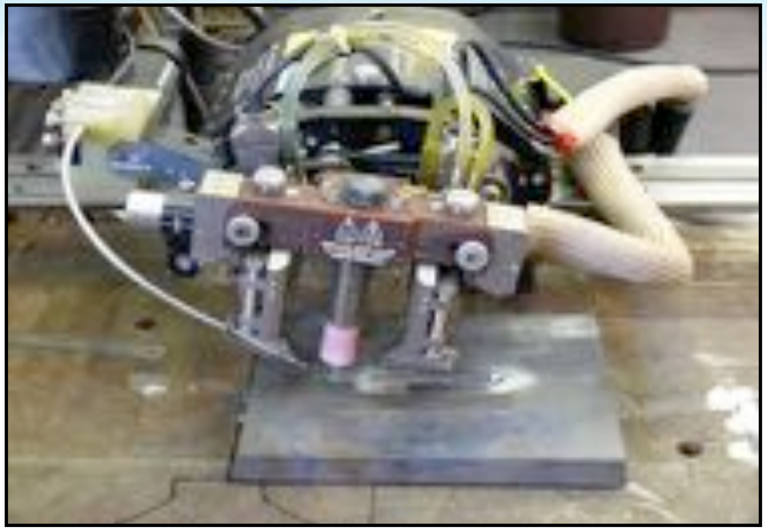
VALIDATION

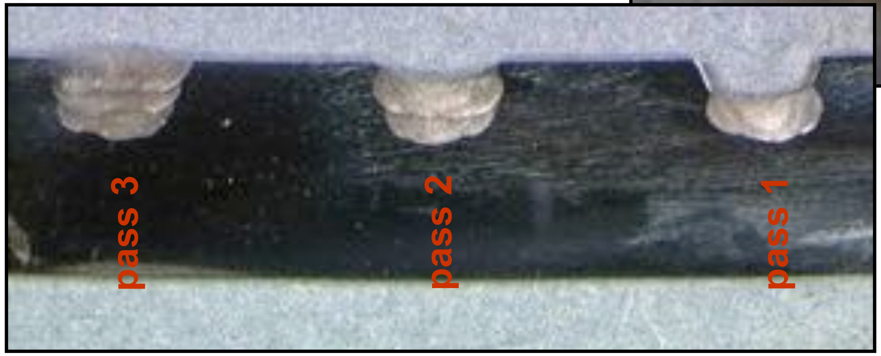
Residual Stress
Measurements

Residual Stress Field Prediction

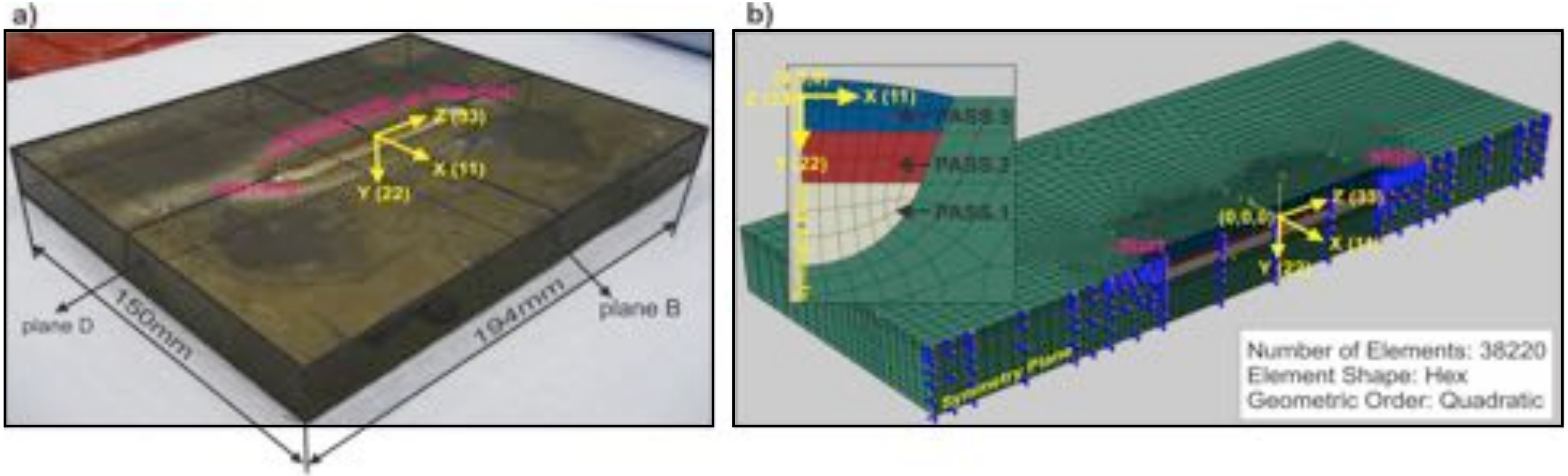
3-Pass Slot Weld





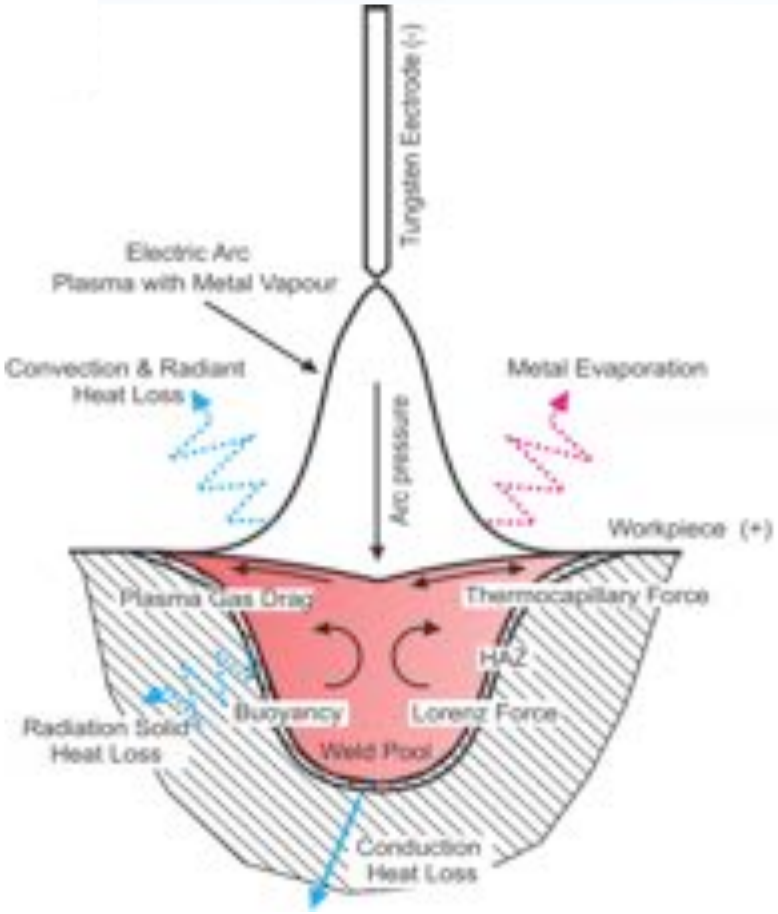


3-Pass Slot Weld



(a) NeT - TG4 three-pass slot weld in an AISI 316LN stainless steel (international benchmark specimen). **(b)** The Abaqus half model depicting the basic plate geometry and three consecutive passes filling the slot. The insert shows in detail elements associated with passes 1 to 3.

Welding Process: Reality



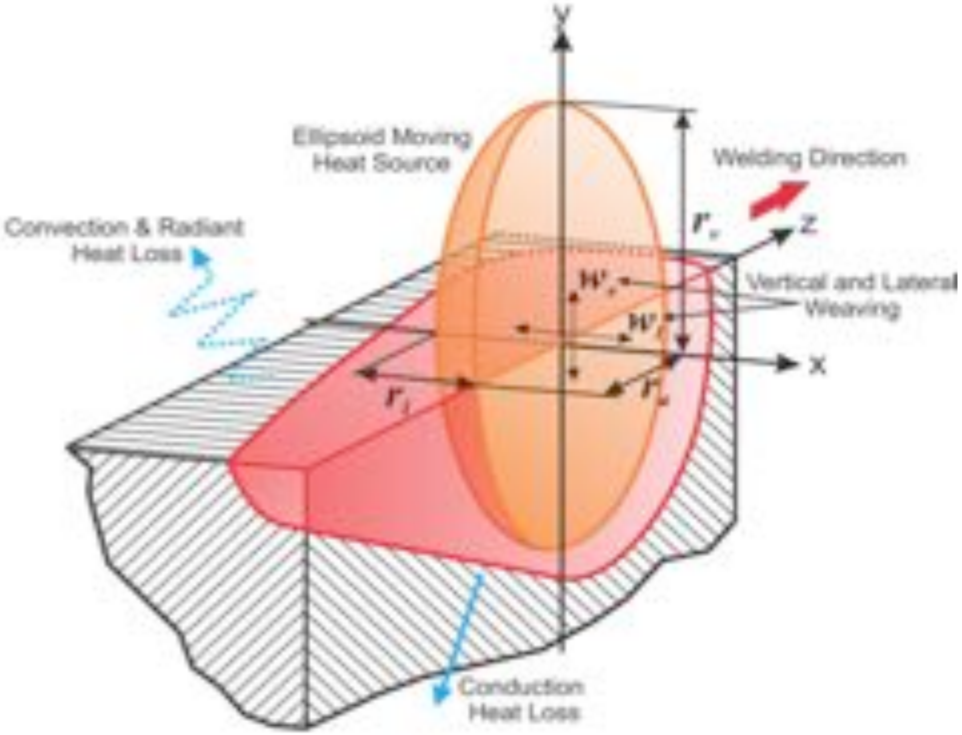
- Convection & Radiant Heat Loss
- Conduction Heat Loss

- Arc Pressure
- Thermocapillary Force
- Radiation Solid Heat Loss
- Plasma Gas Drag
- Buoyancy
- Lorenz Force

Welding Process: Model

ellipsoidal heat source

$$\left(\frac{x}{r_l}\right)^2+\left(\frac{y}{r_v}\right)^2+\left(\frac{z}{r_a}\right)^2$$



- Convection & Radiant Heat Loss
- Conduction Heat Loss

Global Heat Source Parameters

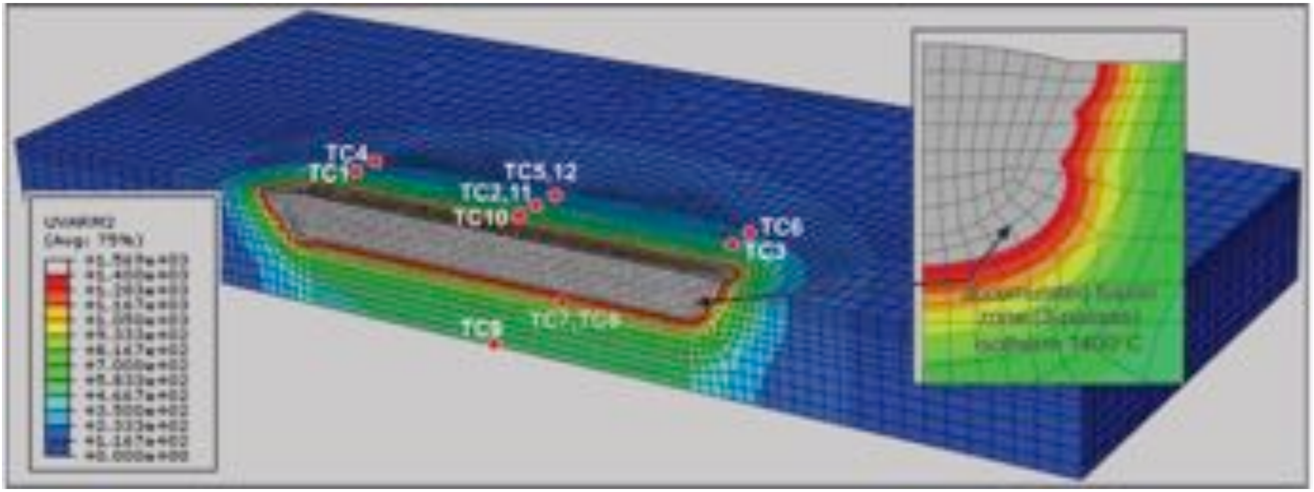
- I, welding current
- U, arc voltage
- v, travel speed
- E, efficiency

Local Heat Source Parameters

- r_L, r_A, r_V – radii of the ellipsoid distribution
- w_L, w_V - weaving

Thermal Model: Heat Source Optimization

Global Heat Source Parameter

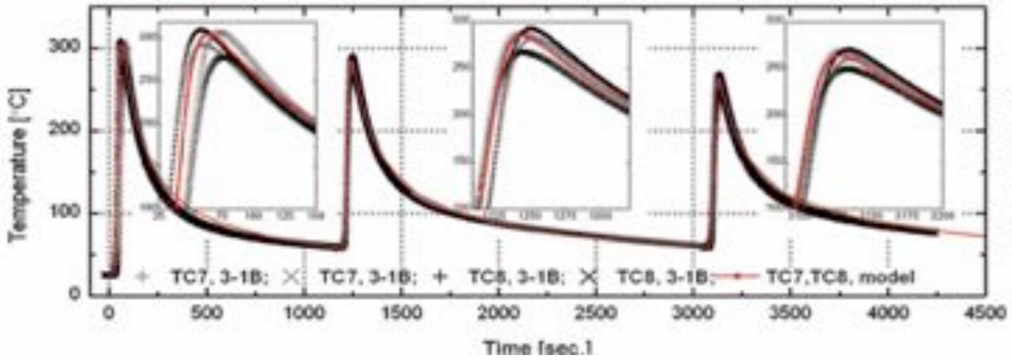


PASS.1
EFFICIENCY = 0.73

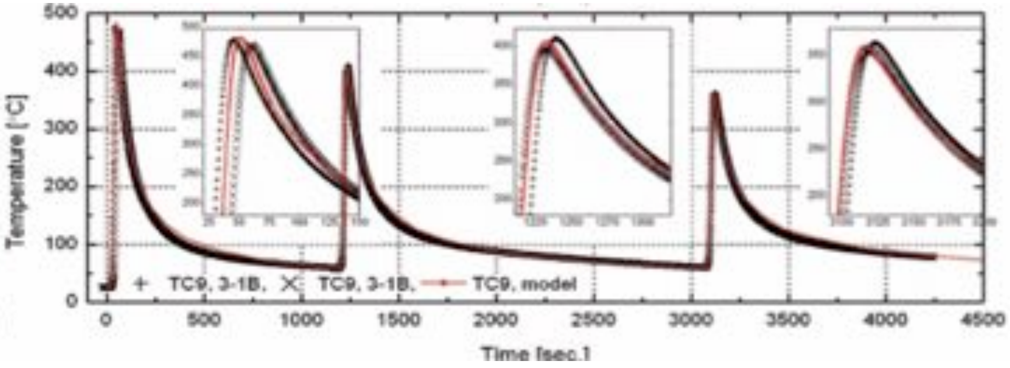
PASS.2
EFFICIENCY = 0.72

PASS.3
EFFICIENCY = 0.71

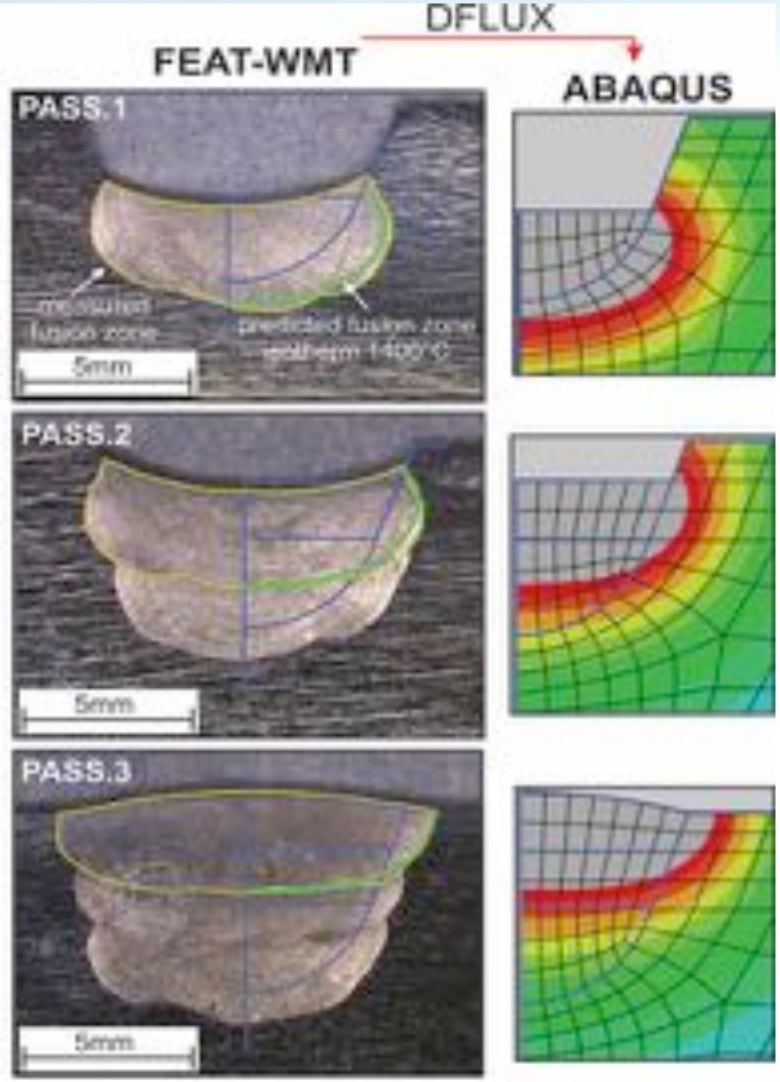
TC7, TC8



TC9



Thermal Model: Fusion Zone matching



fusion area
101% of measured
(28.81mm²)

---

fusion area
100% of measured
(29.16mm²)

---

fusion area
100% of measured
(30.22mm²)

Welding-Induced Deformation

total strain

Weld Modelling w/o SSPT

reversible **irreversible**

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{th} + \cancel{\varepsilon_{ij}^{tr}} + \cancel{\varepsilon_{ij}^{tp}}$$

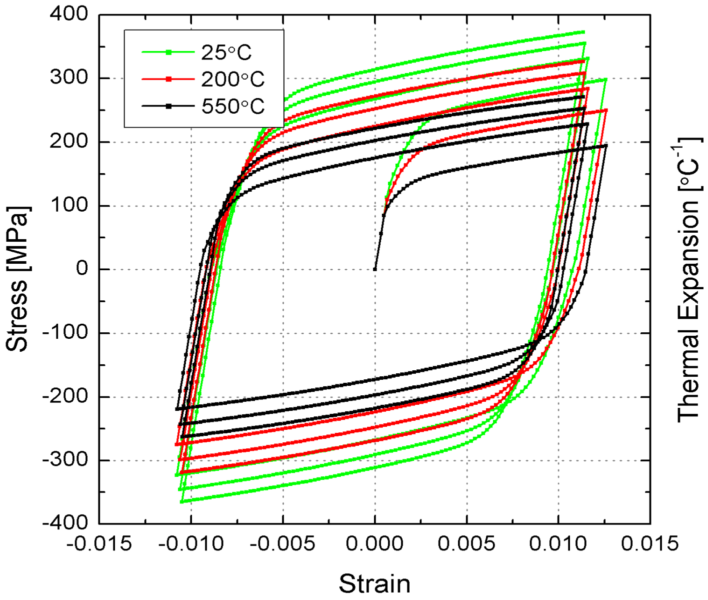
elastic strain

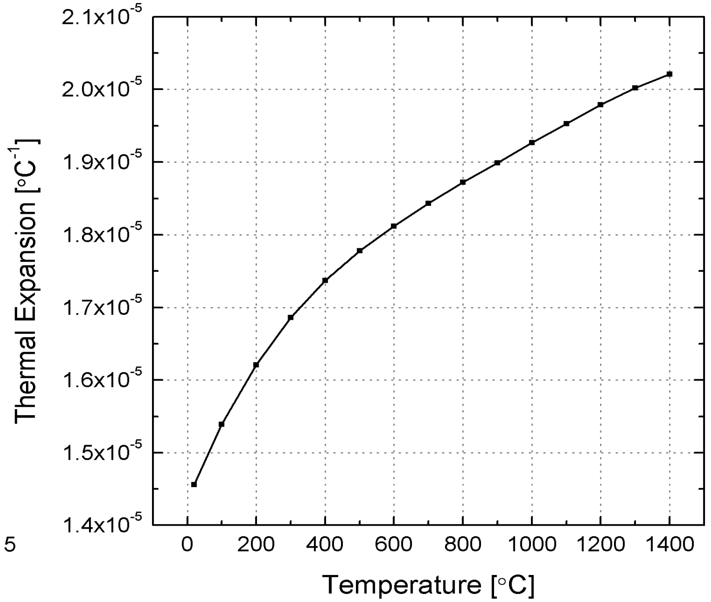
plastic strain

thermal strain

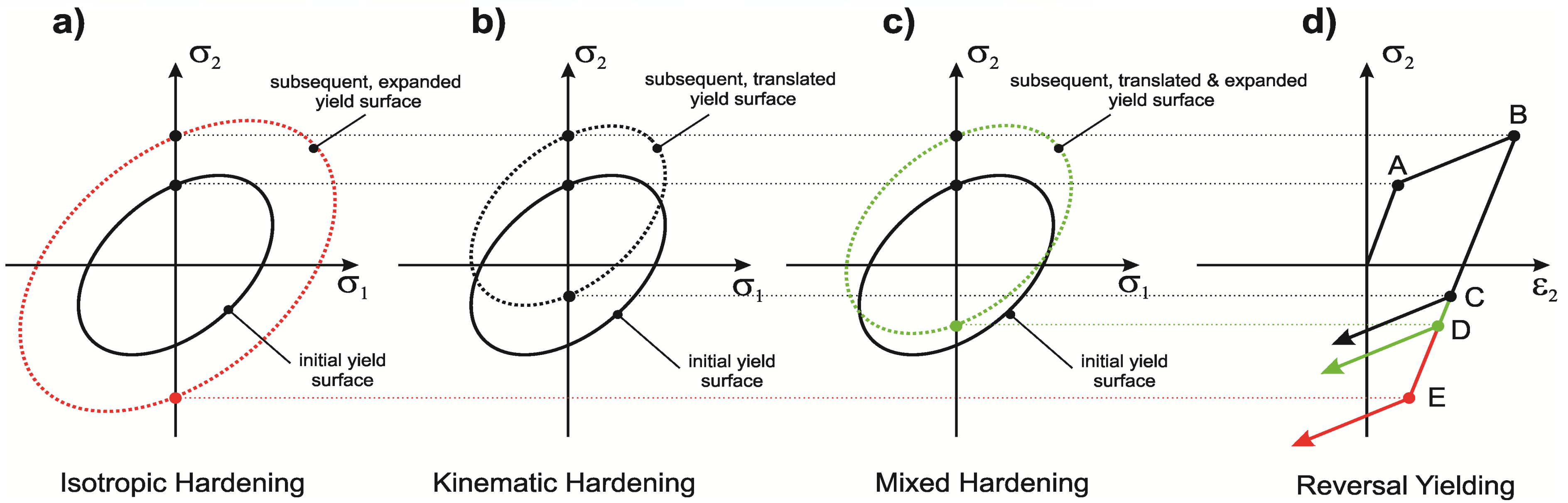
metallurgical transformation strain

transformation-induced plastic strain





Plasticity Models: Reversal Yielding

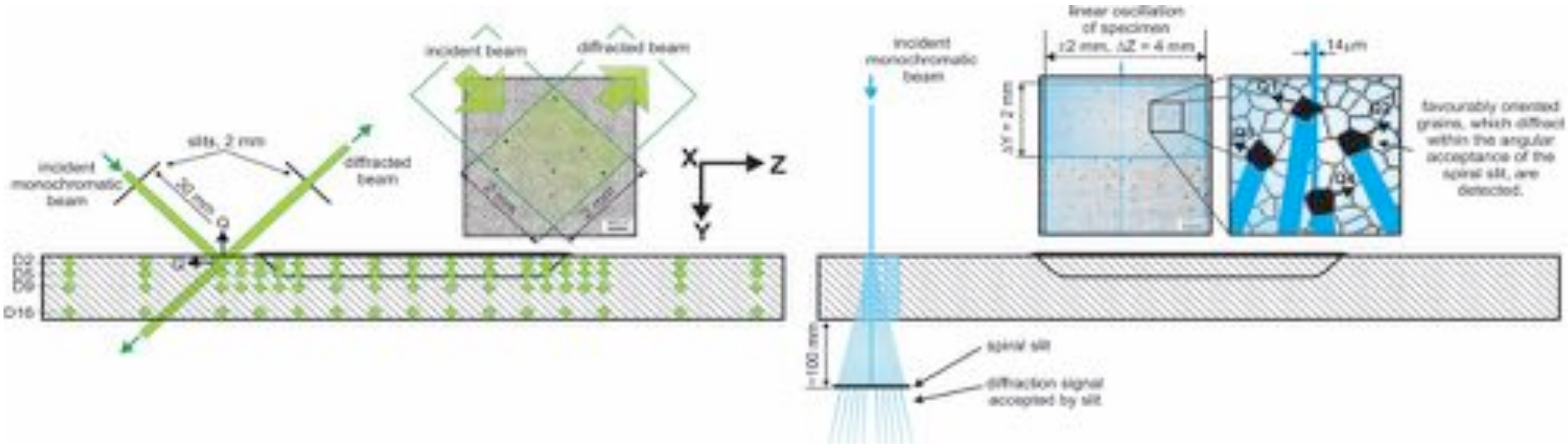


(a) Isotropic hardening model showing the expansion of the yield surface with plastic strain; **(b)** kinematic hardening model showing the translation of the yield surface with plastic strain; **(c)** mixed isotropic-kinematic hardening model showing the expansion and translation of the yield surface with plastic strain; and **(d)** resulting stress-strain curves showing different yield stress in compression as predicted by different plasticity models: **C** – kinematic hardening, **D** – mixed hardening, and **E** – isotropic hardening.

Model Validation

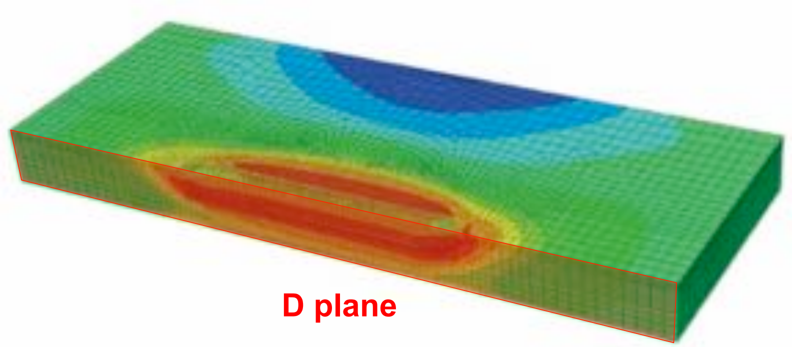
Neutron Diffraction

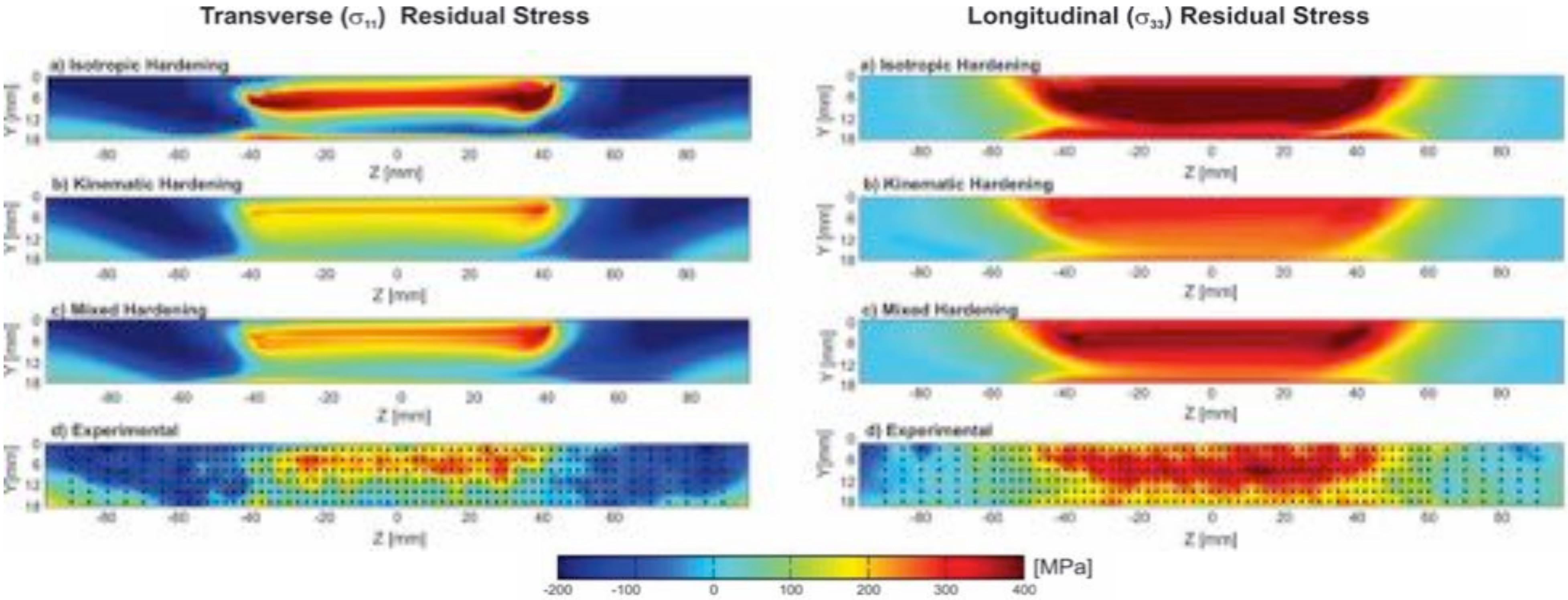
Synchrotron Diffraction



(**a**) The schematic drawing of the neutron diffraction geometry, the positions of measuring points on the D plane (along the weld centerline), and the gauge volume depicting a random number of grains satisfying the diffraction condition (black grains). (**b**) The schematic drawing of the synchrotron spiral-slit technique, and the gauge volume created by linear oscillation (Z direction) and diffraction data binning (Y direction). ΔY is set arbitrarily during the analysis of the data, not during the experiment, i.e. ΔY is "adjustable" and thus the Y-thickness of the light shaded box. All diffracting grains which are within the angular acceptance of the slit, are captured at once for each specimen X/Z position.

Residual Stress: D plane

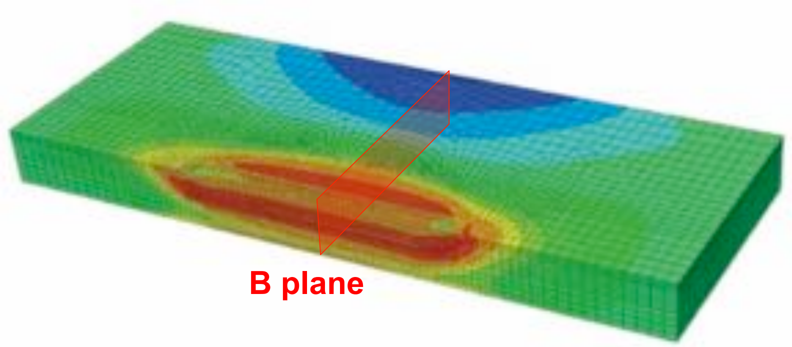


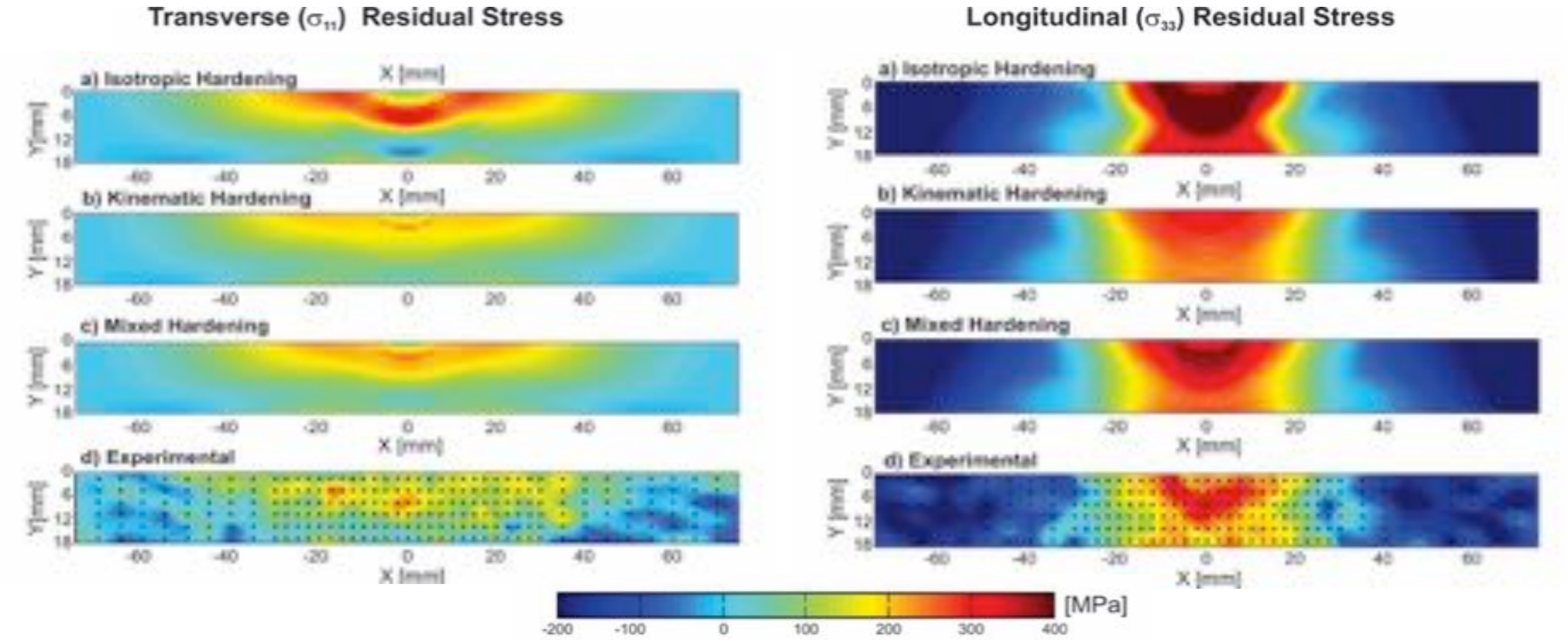


(**a**) 2D maps of the transverse (σ_{11}) and longitudinal (σ_{33}) residual stresses on the D plane as predicted by (**a**) isotropic, (**b**) kinematic, and (**c**) mixed hardening models, together with (**d**) synchrotron-measured residual stresses.

Experimental: Martins, R.V., Ohms, C., Decroos, K., 2010. Full 3D spatially resolved mapping of residual strain in a 316L austenitic stainless steel weld specimen. Materials Science and Engineering: A 527, 4779-4787

Residual Stress: B plane

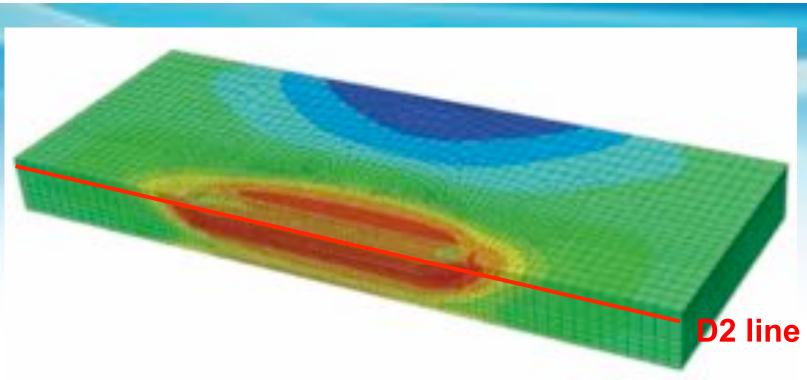


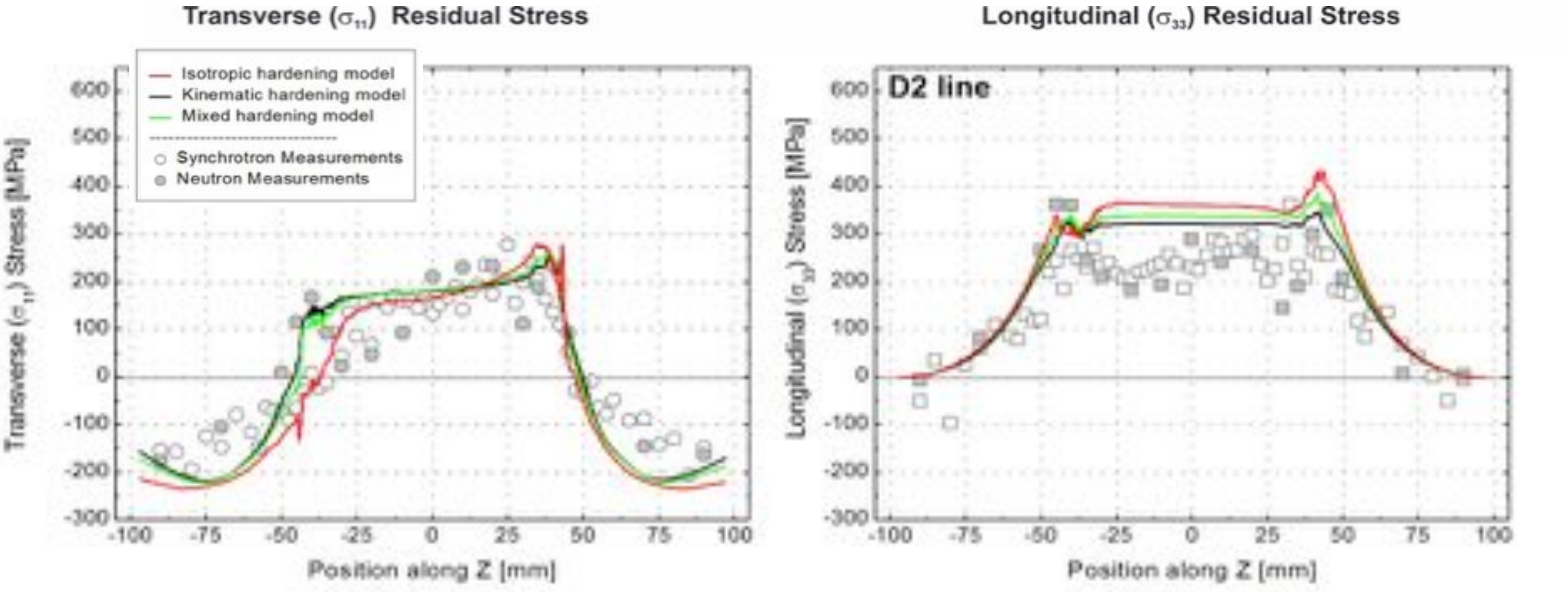


(**a**) 2D maps of the transverse (σ_{11}) and longitudinal (σ_{33}) residual stresses on the D plane as predicted by (**a**) isotropic, (**b**) kinematic, and (**c**) mixed hardening models, together with (**d**) synchrotron-measured residual stresses.

Experimental: Martins, R.V., Ohms, C., Decroos, K., 2010. Full 3D spatially resolved mapping of residual strain in a 316L austenitic stainless steel weld specimen. Materials Science and Engineering: A 527, 4779-4787

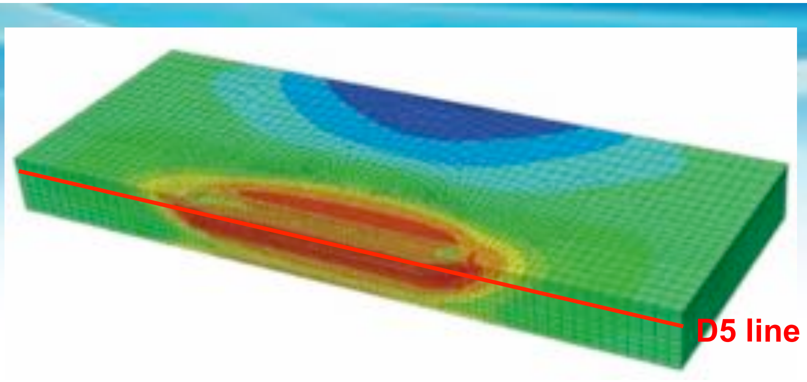
Residual Stress: D2 line

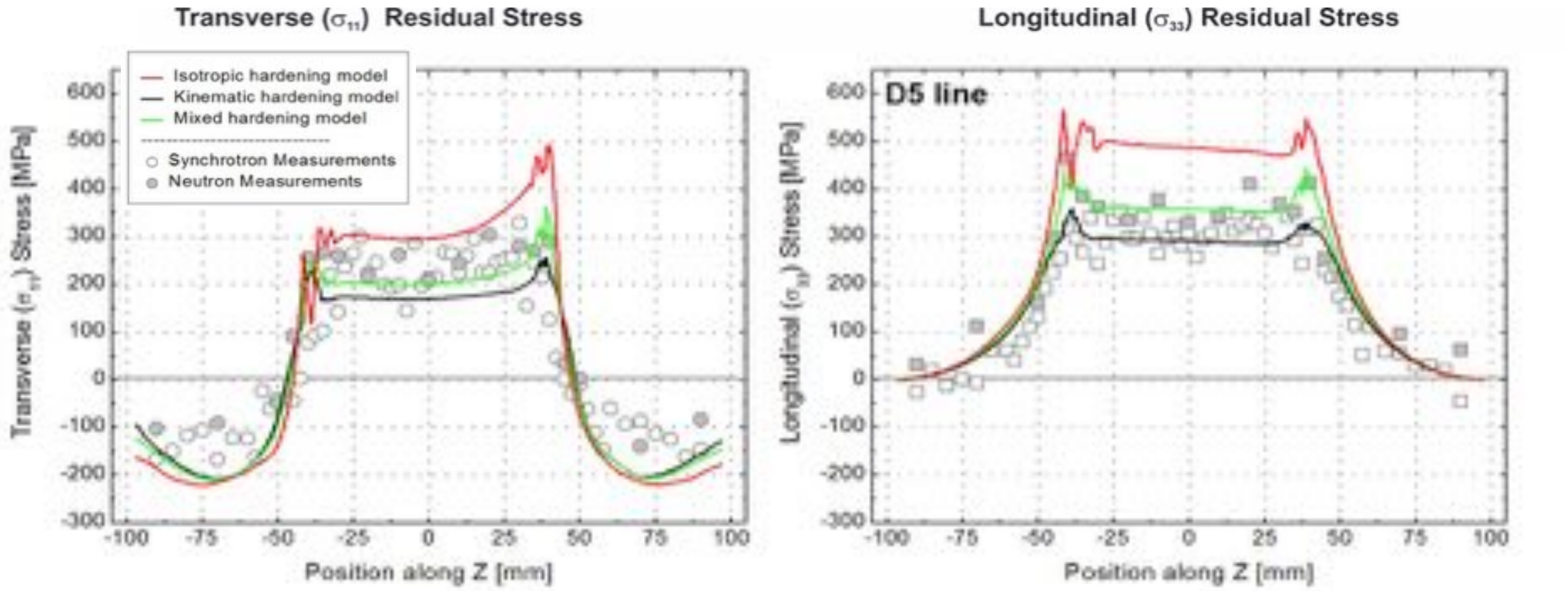




Comparison of the predicted residual stresses along **D2** line together with synchrotron (open symbol) and neutron (solid symbol) diffraction measurements. The margin of error associated with each measurement is approximately 40MPa.

Residual Stress:
D5 line

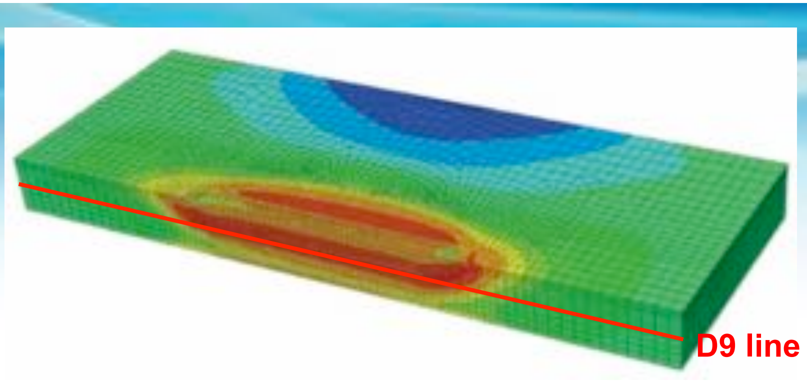


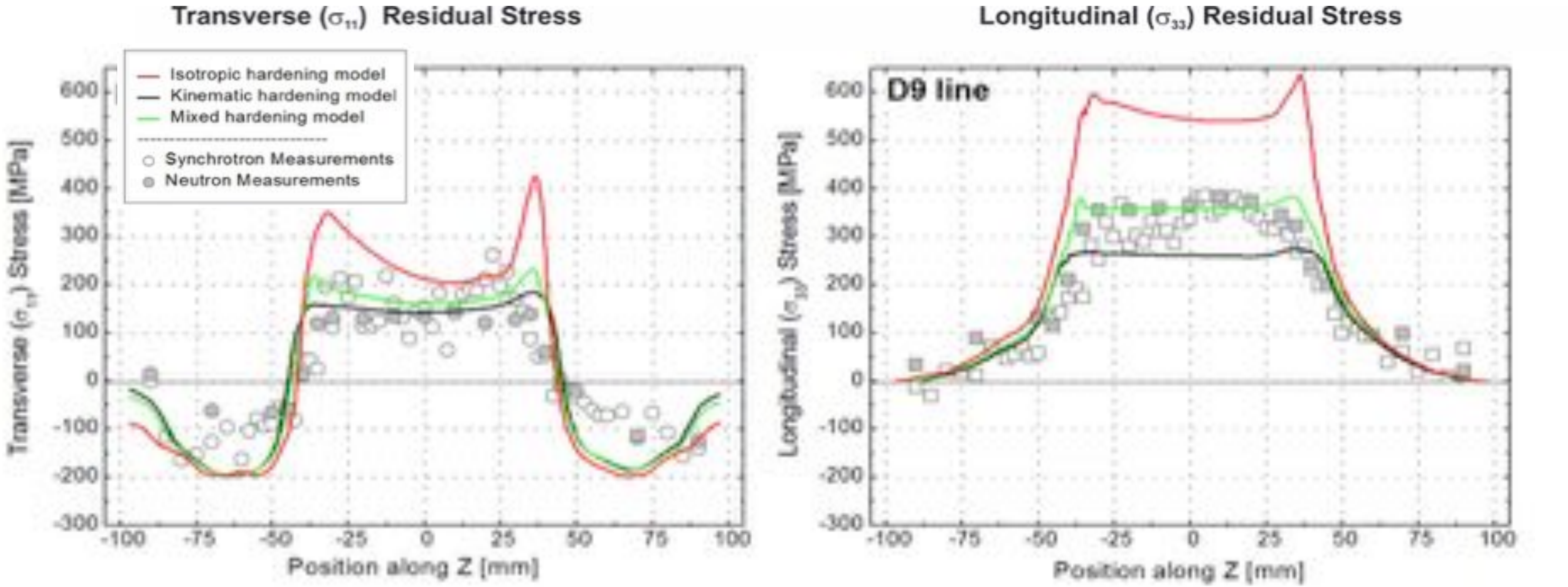

Transverse (σ_{11}) Residual Stress

Longitudinal (σ_{33}) Residual Stress

Comparison of the predicted residual stresses along **D5** line together with synchrotron (open symbol) and neutron (solid symbol) diffraction measurements. The margin of error associated with each measurement is approximately 40MPa.

Residual Stress:
D9 line

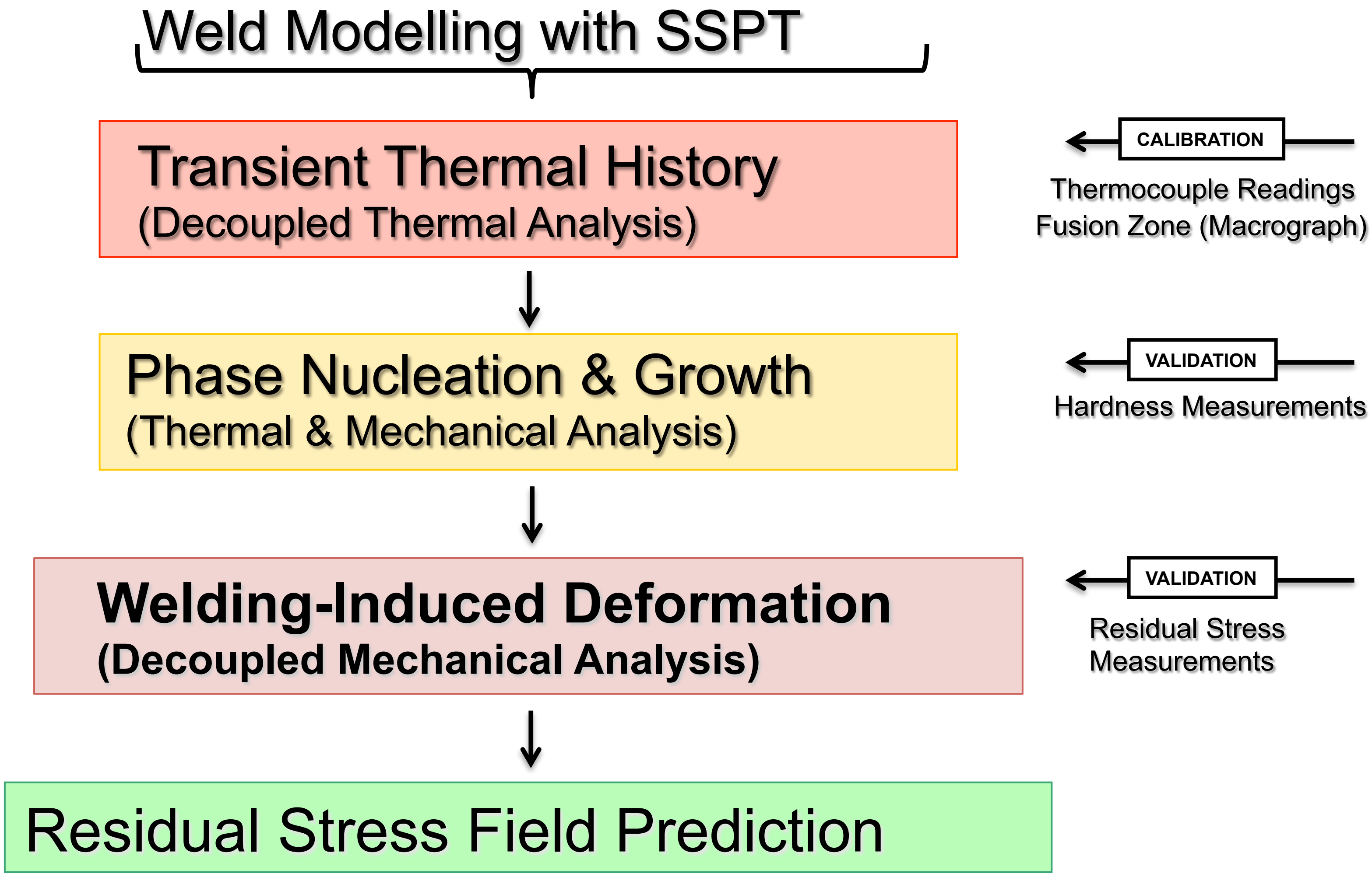



Transverse (σ_{11}) Residual Stress

Longitudinal (σ_{33}) Residual Stress

Comparison of the predicted residual stresses along **D9** line together with synchrotron (open symbol) and neutron (solid symbol) diffraction measurements. The margin of error associated with each measurement is approximately 40MPa.

Weld Modelling:
with Solid State Phase Transformation



Weld Modelling with SSPT

Transient Thermal History
(Decoupled Thermal Analysis)

CALIBRATION

Thermocouple Readings
Fusion Zone (Macrograph)

Phase Nucleation & Growth
(Thermal & Mechanical Analysis)

VALIDATION

Hardness Measurements

Welding-Induced Deformation
(Decoupled Mechanical Analysis)

VALIDATION

Residual Stress Measurements

Residual Stress Field Prediction

TG5 NeT Specimen

- SA508 Gr.3 Cl.1

- Autogenous TIG beam weld (no dilution effects)

- Two specimen sets tested with varying torch speeds:

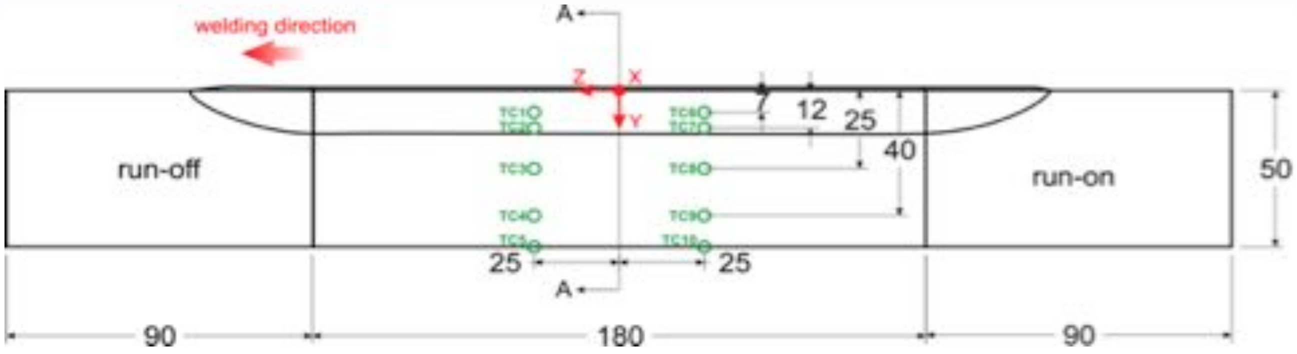
Fast weld => 300mm/min

Slow weld => 75mm/min

- Run-on and run-off plates only on fast weld

- Pre-heat (150°C) was applied to slow weld sample only

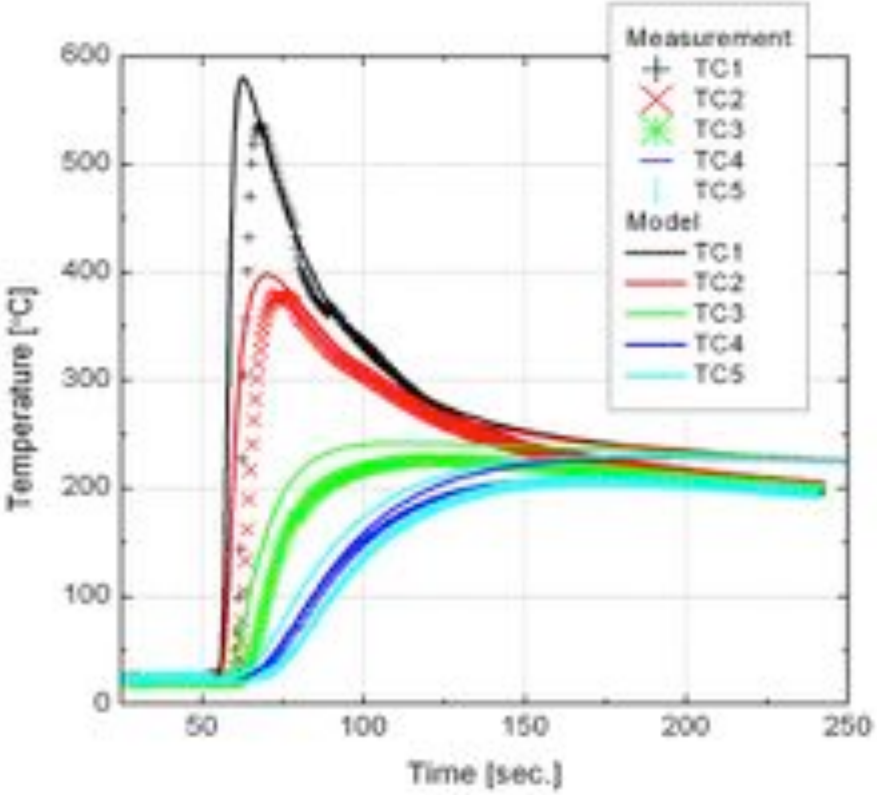
- Part of international round-robin investigation



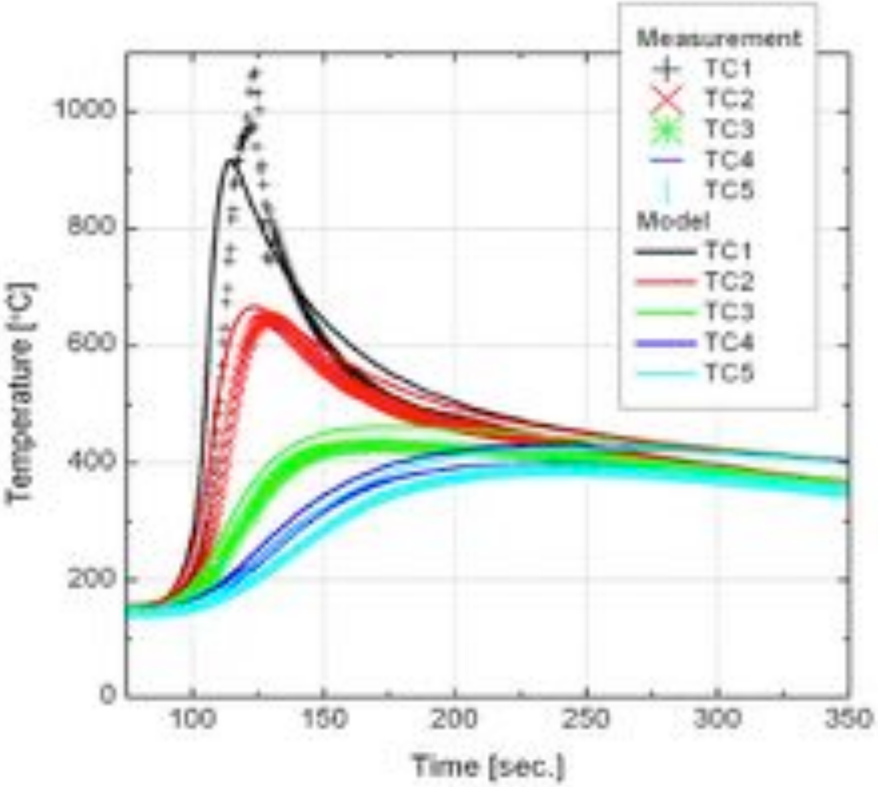

Fast Weld

Thermal Analysis - Thermocouples

Fast Weld

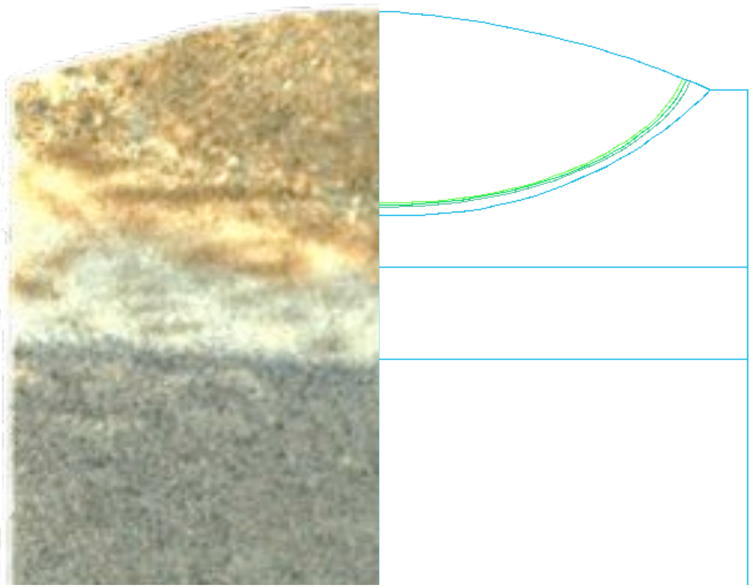


Slow Weld



Thermal Analysis – Fusion Zone

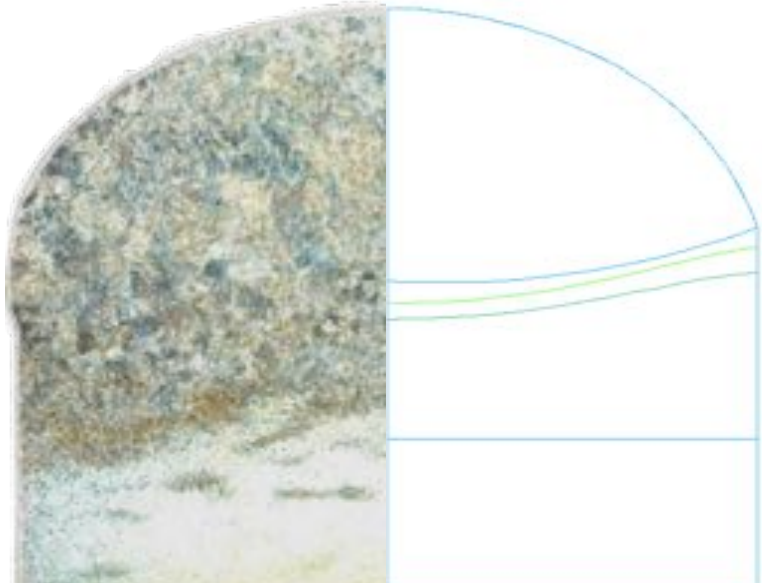
Fast Weld



observation

FEAT prediction

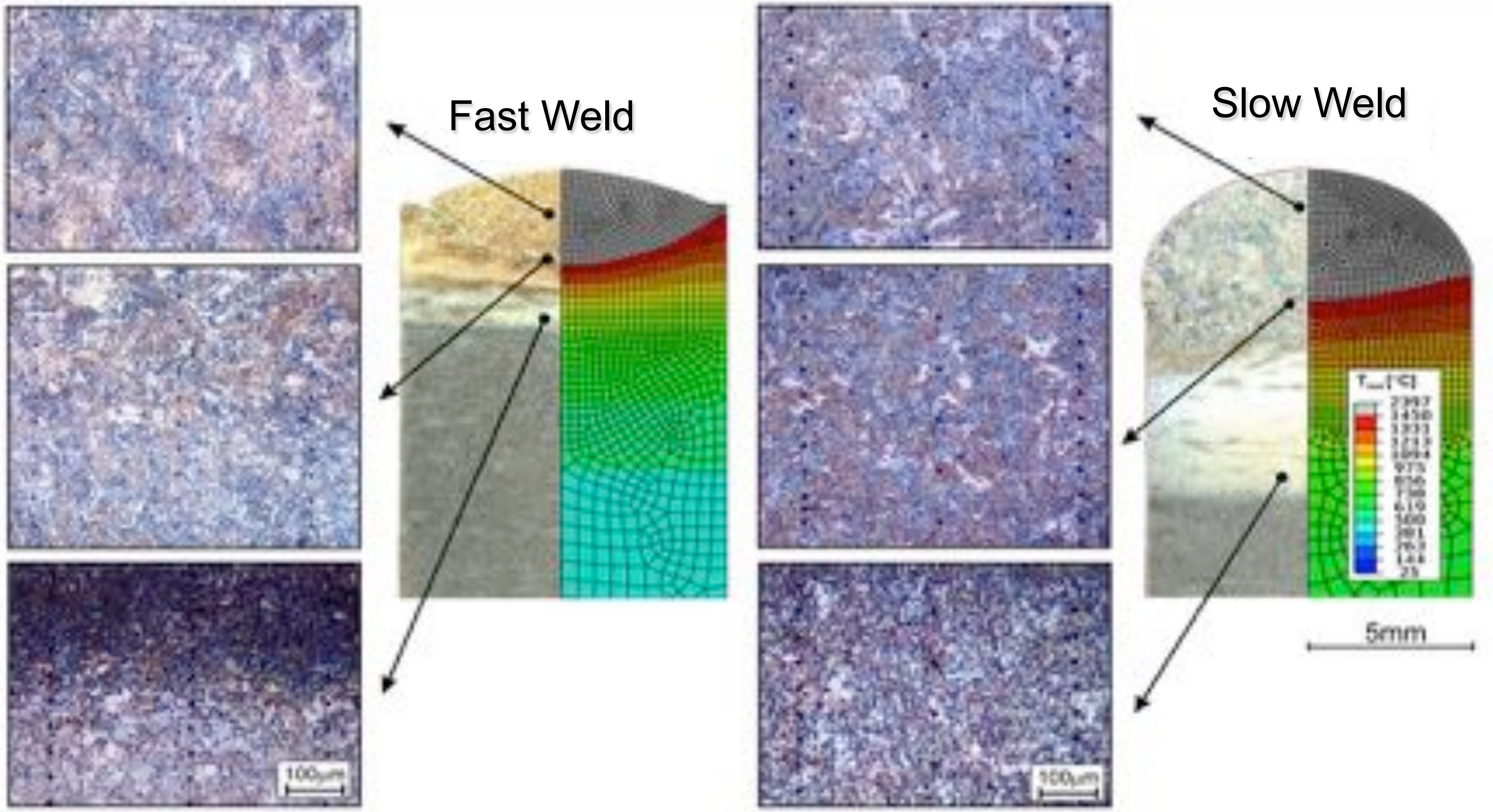
Slow Weld



observation

FEAT prediction

Microstructures



Isothermal Phase Nucleation

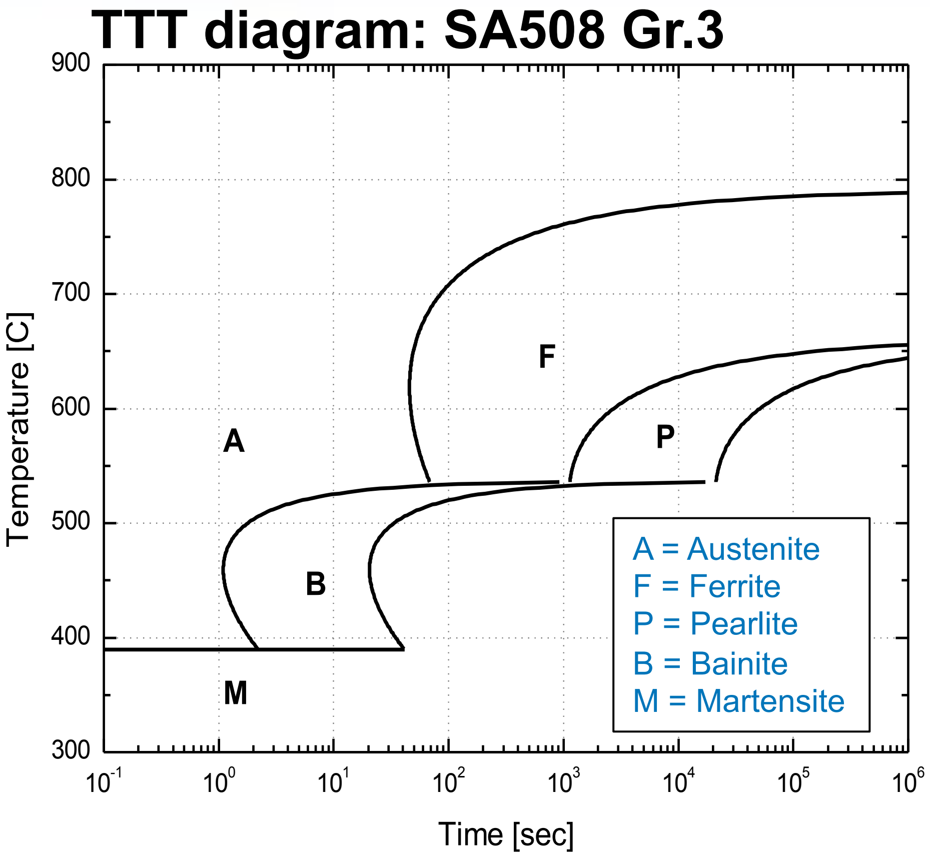
- Semi-empirical formulae developed by Li et al. (1998), modified from Kirkaldy and Venugopalan (1984).

$$\tau(X,T) = \frac{F(C,Mn,Si,Ni,Cr,Mo,G)}{\Delta T^{n} \exp(-Q/RT)} S(X)$$

The model describes the time (τ) required for a given transformation to reach a fraction of completion X at constant temperature T.

- Martensite start temperature based on Kung and Rayment (1982)

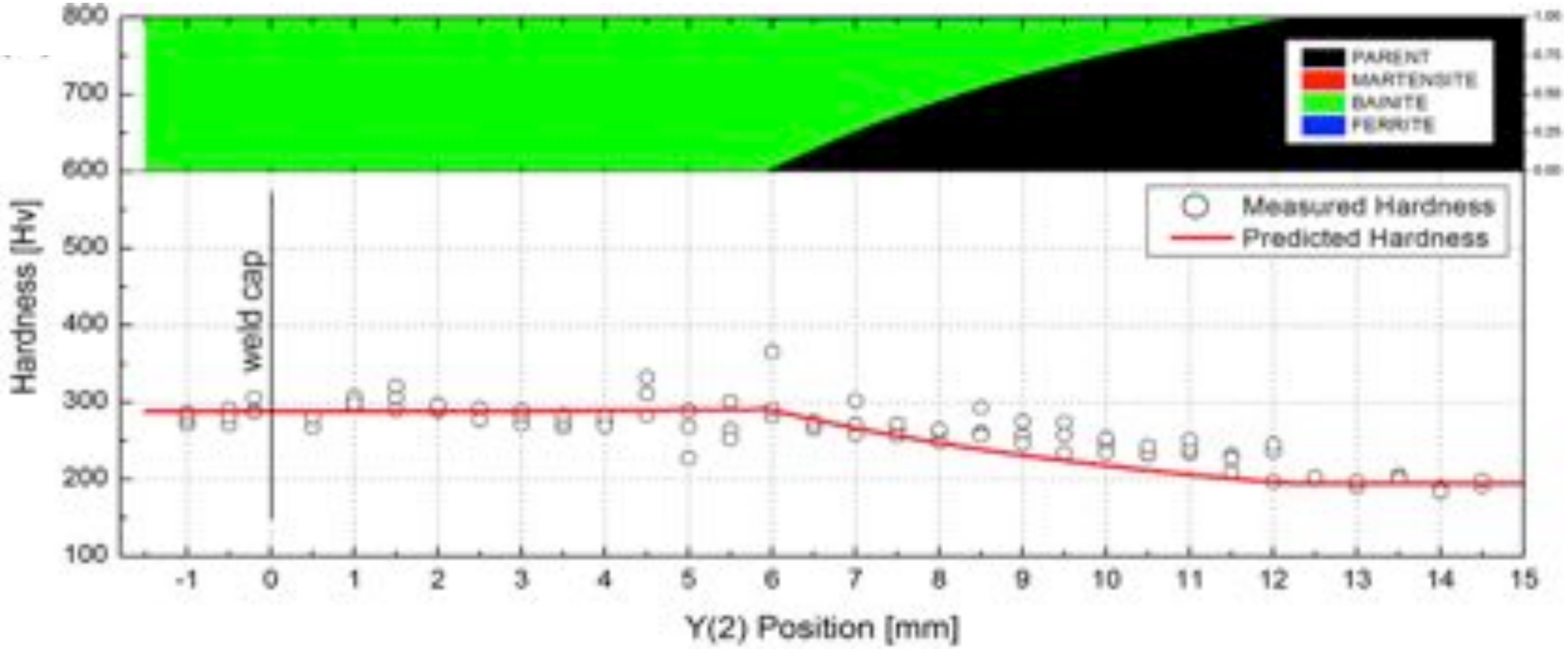
$$M_S = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 7.5Mo + 10Co - 7.5Si$$



TTT diagram: SA508 Gr.3

- F is a function to the steel composition and the ASTM grain size number G, ΔT is the amount of undercooling, Q is the activation energy for the diffusion reaction, R is the gas constant, n is an empirical constant based on the effective diffusion mechanism, and $S(X)$ is a sigmoidal function defining the reaction rate.

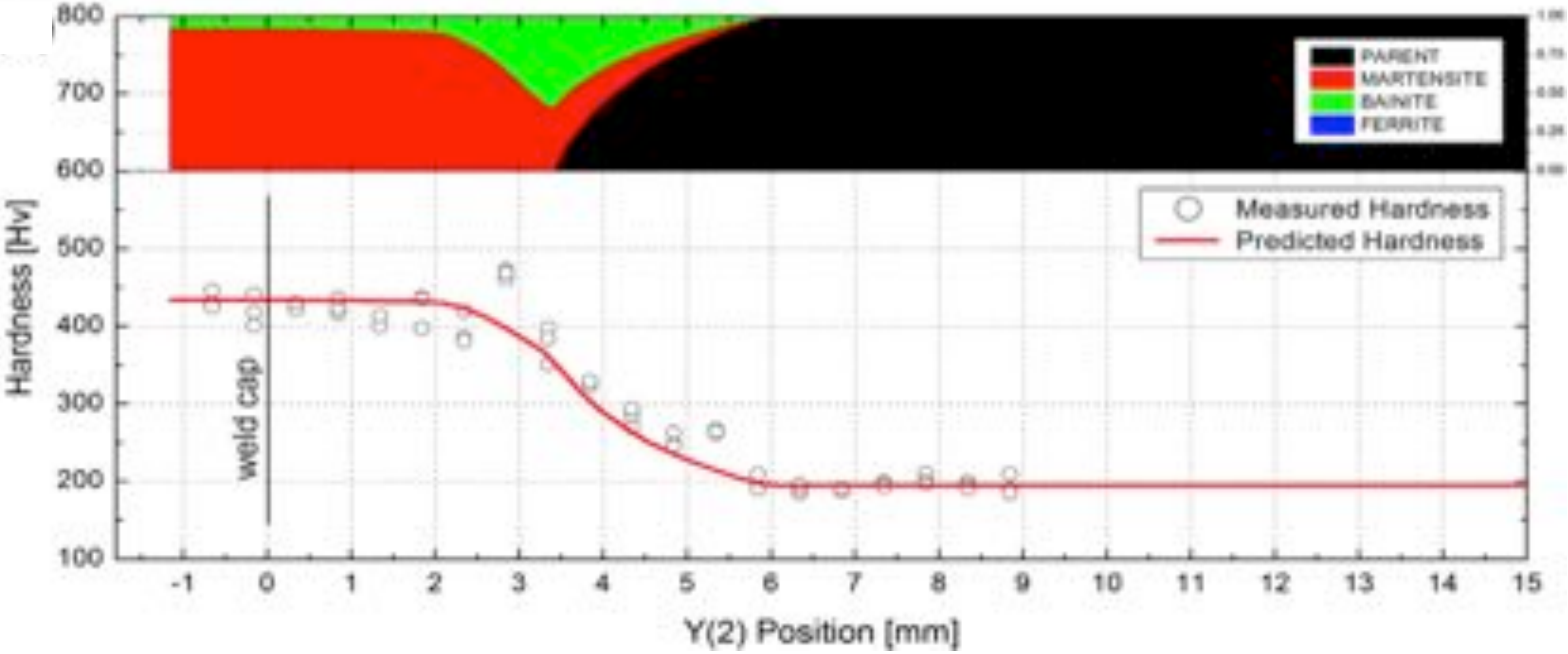
TG5 Slow Weld Phase Distribution Validation


Slow Weld: Microhardness

Comparison of measured and predicted hardness values for **TG5 Slow**, including the predicted phase distribution used for hardness calculations. Value are taken from the steady-state region of each weldment.

TG5 Fast Weld Phase Distribution Validation

Fast Weld: Microhardness



Comparison of measured and predicted hardness values for **TG5 Fast Weld**, including the predicted phase distribution used for hardness calculations. Value are taken from the steady-state region of each weldment.

Welding-Induced Deformation

total strain

Weld Modelling w/ SSPT

reversible **irreversible**

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{th} + \boxed{\varepsilon_{ij}^{tr}} + \boxed{\varepsilon_{ij}^{tp}}$$

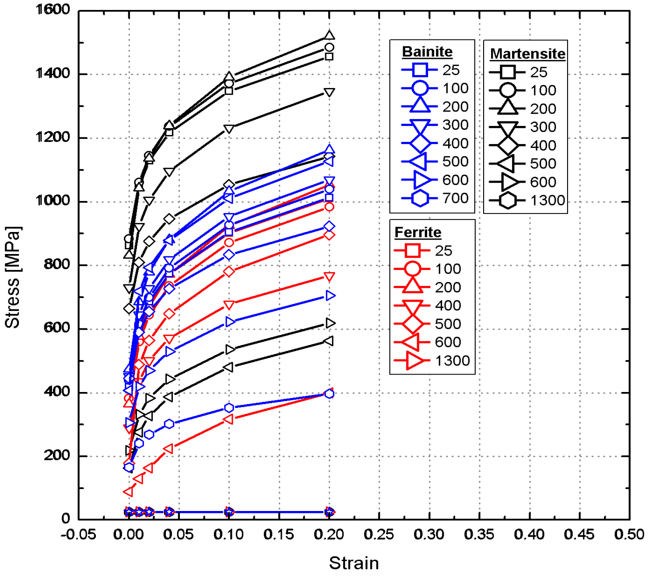
elastic strain

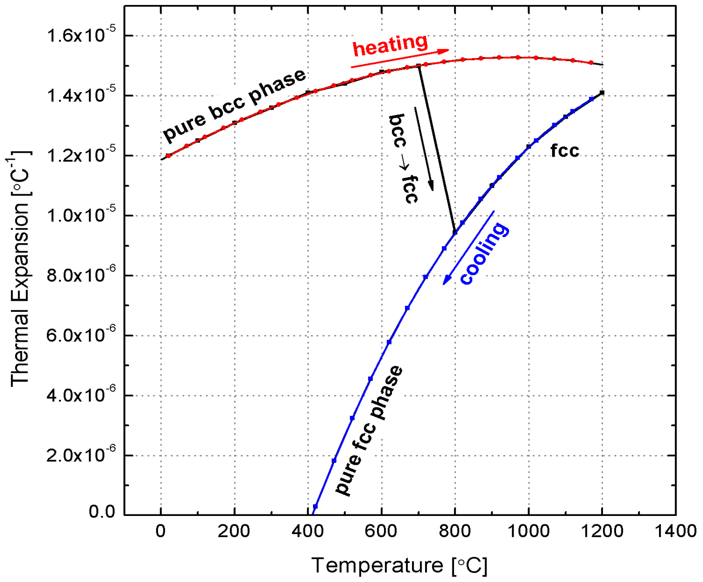
plastic strain

thermal strain

metallurgical transformation strain

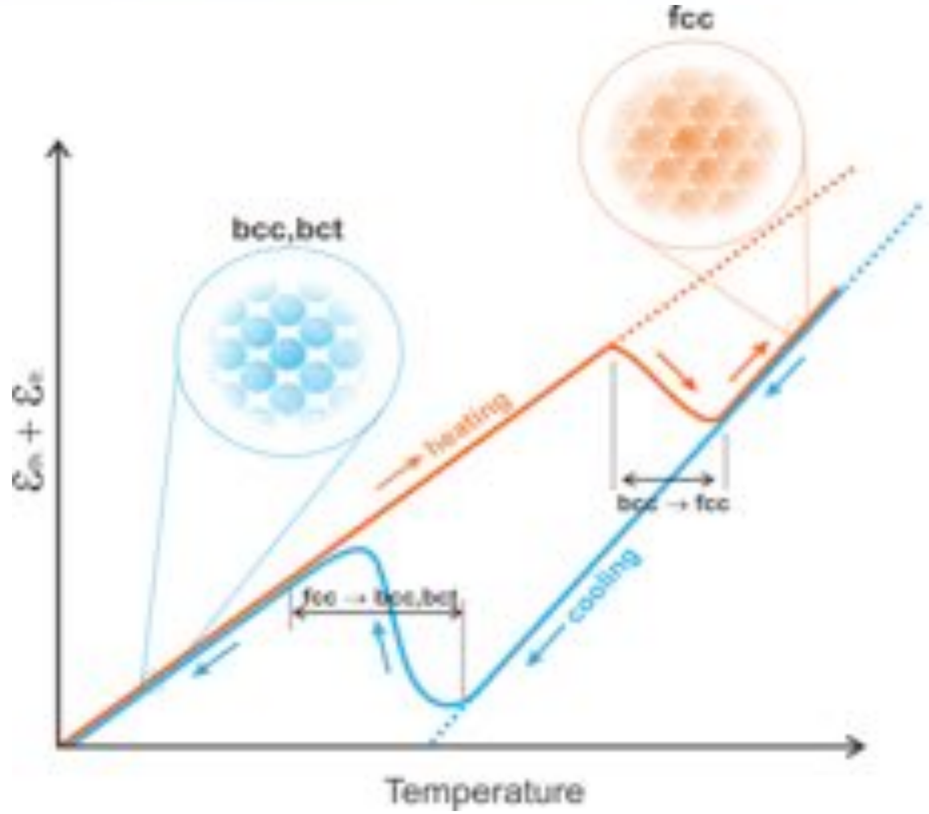
transformation-induced plastic strain

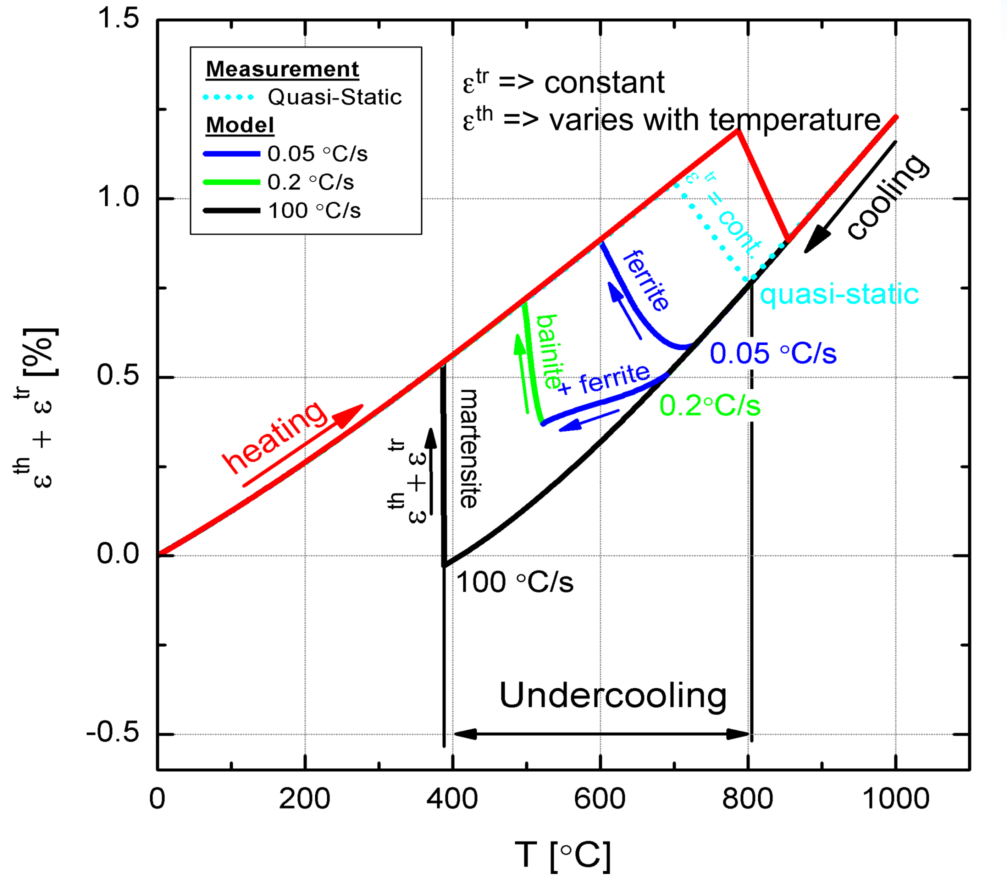




Thermo-Metallurgical Strain (Reversible)

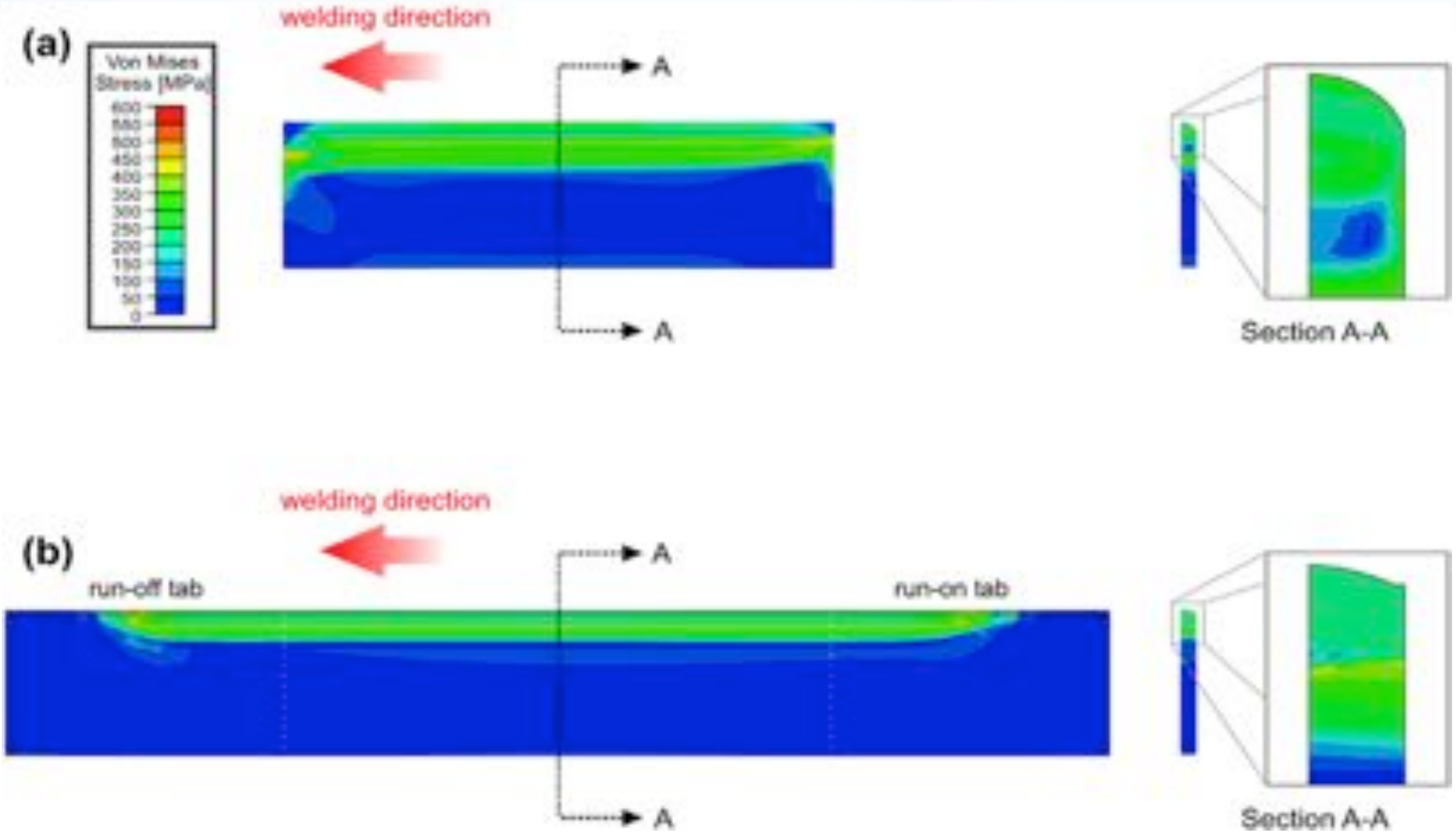
Volume Change





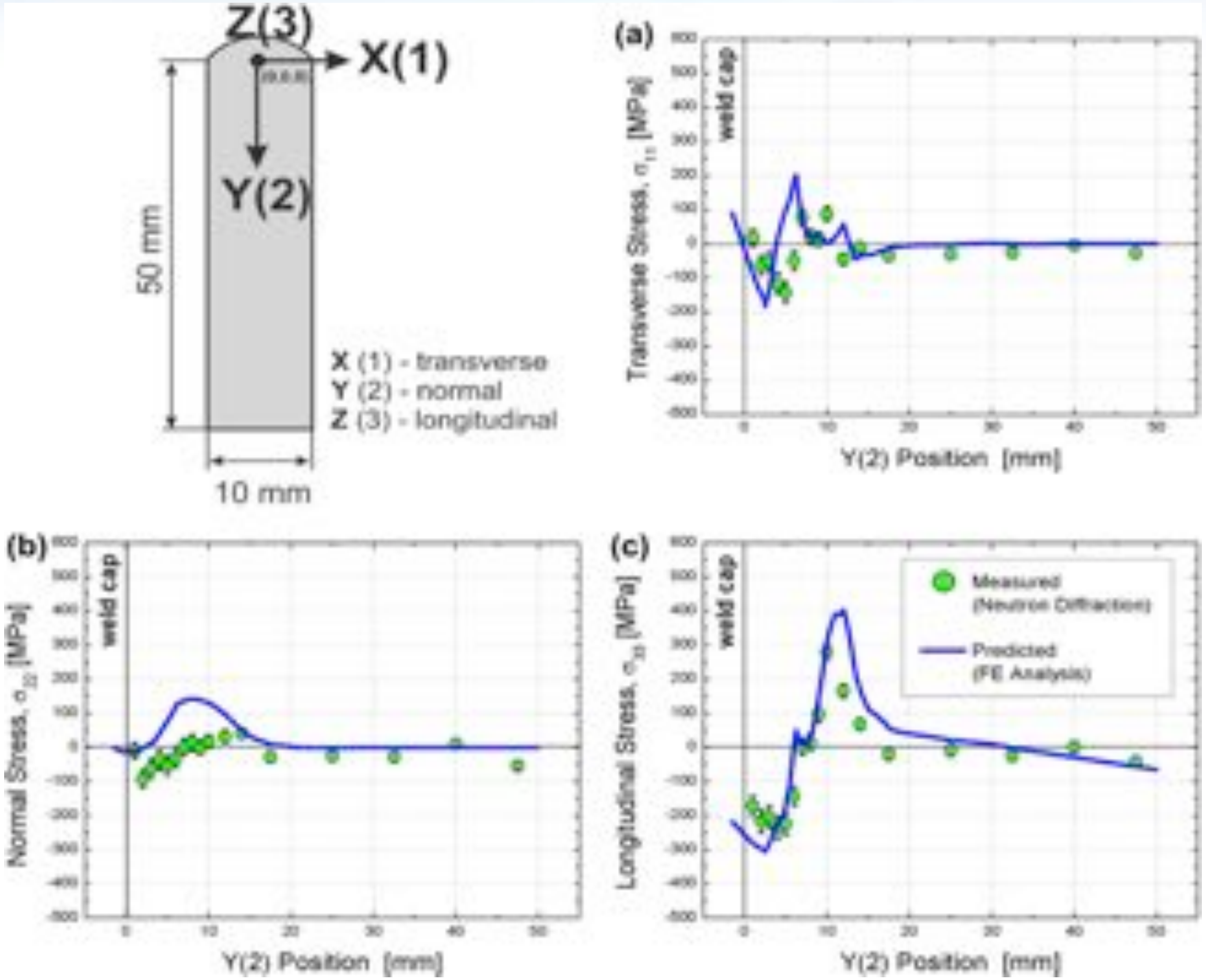
- Metallurgical transformation strain results from a volumetric change during the SSPT
- In steels, the austenitic decomposition is accompanied by a volumetric expansion of between 1-4%, depending on the chemical composition and the transformation temperature

Post-Weld Residual Stresses

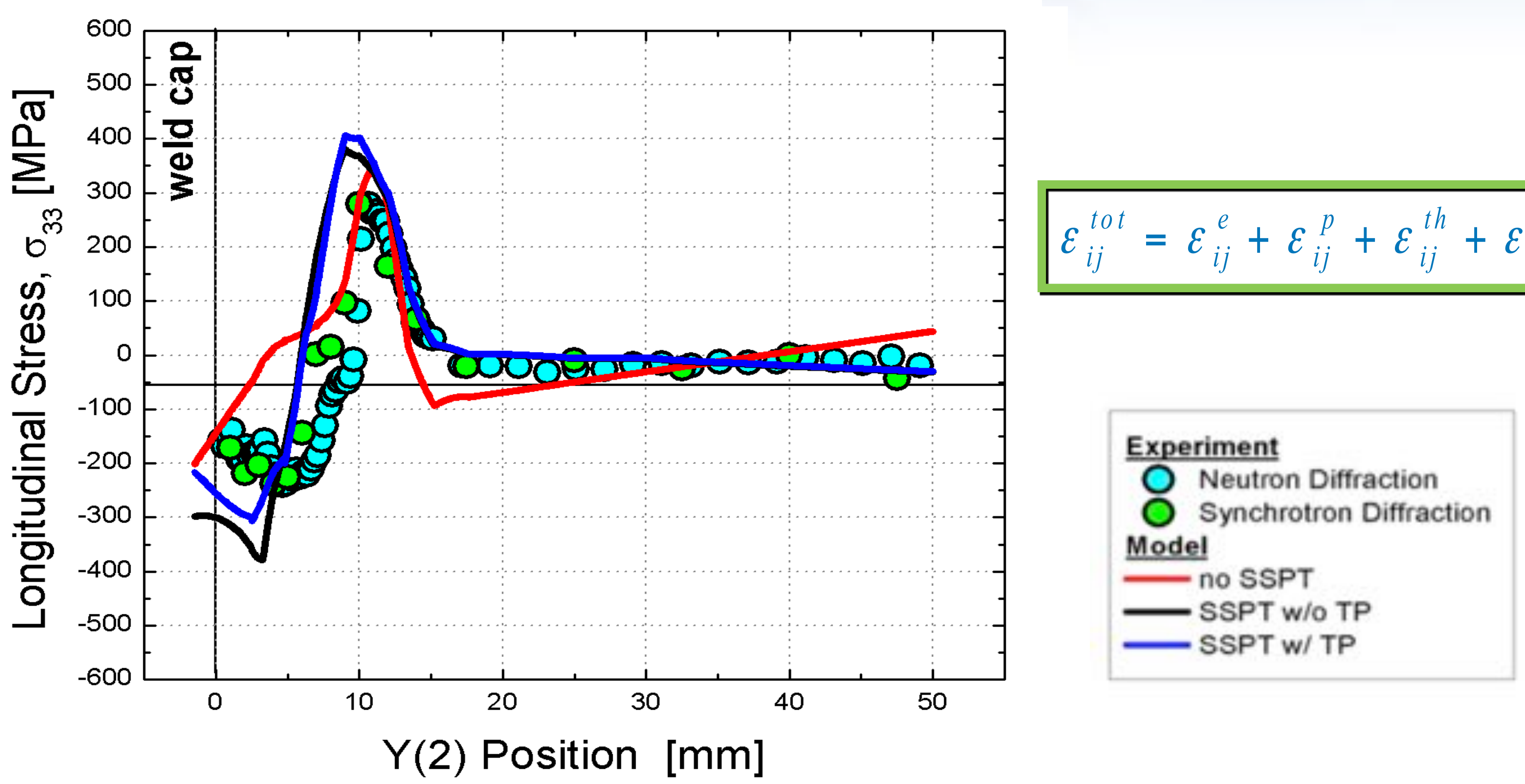


Post-Weld Residual Stresses

Slow Weld:



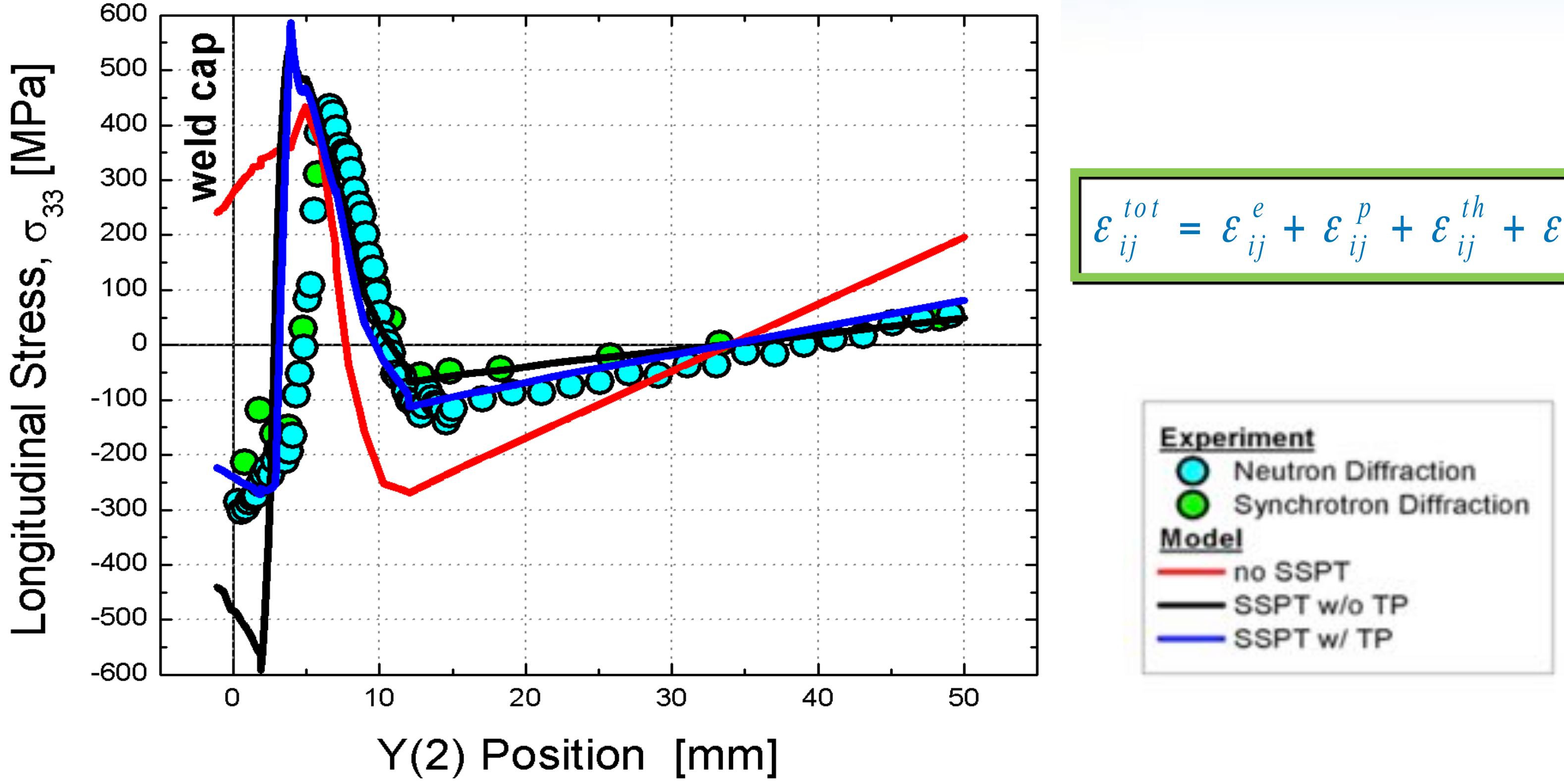
Post-Weld Residual Stresses



$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{th} + \varepsilon_{ij}^{tr} + \varepsilon_{ij}^{tp}$$

Variation in model accuracy for TG5 Slow Weld, when predicting longitudinal WRS using three different models. Model 1 (red) does not explicitly consider anisothermal SSPT kinetics. Model 2 (black) predicts the thermo-metallurgical strain related to SSPT kinetics, but does not consider transformation plasticity. Model 3 (blue) considers both thermo-metallurgical strain and transformation plasticity.

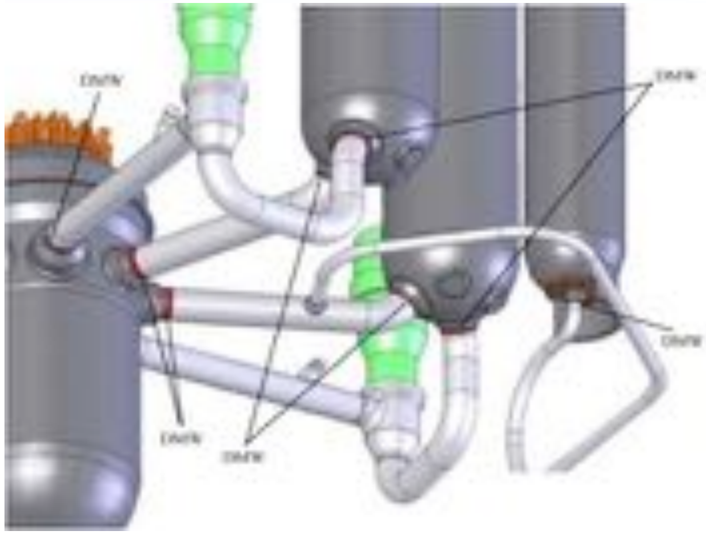
Post-Weld Residual Stresses

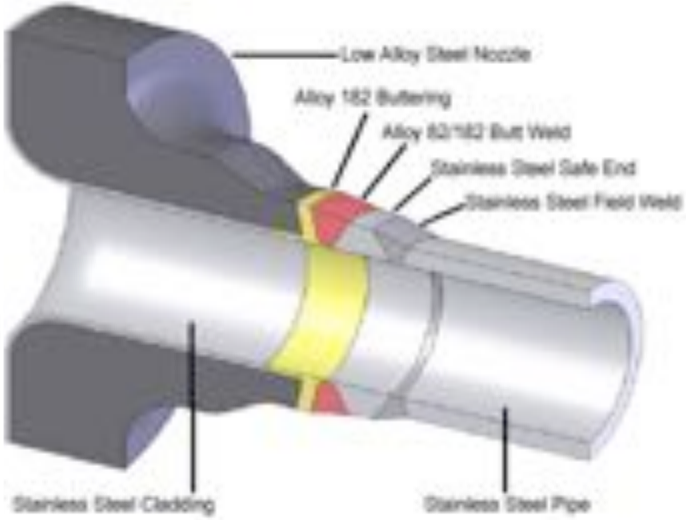


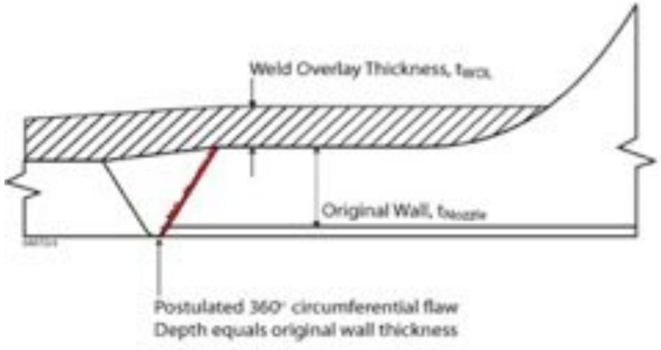
$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{th} + \varepsilon_{ij}^{tr} + \varepsilon_{ij}^{tp}$$

Variation in model accuracy for TG5 Fast Weld, when predicting longitudinal WRS using three different models. Model 1 (red) does not explicitly consider anisothermal SSPT kinetics. Model 2 (black) predicts the thermo-metallurgical strain related to SSPT kinetics, but does not consider transformation plasticity. Model 3 (blue) considers both thermo-metallurgical strain and transformation plasticity.

Weld Modelling: Stress Corrosion Cracking in Pressurised Water Reactor Welds

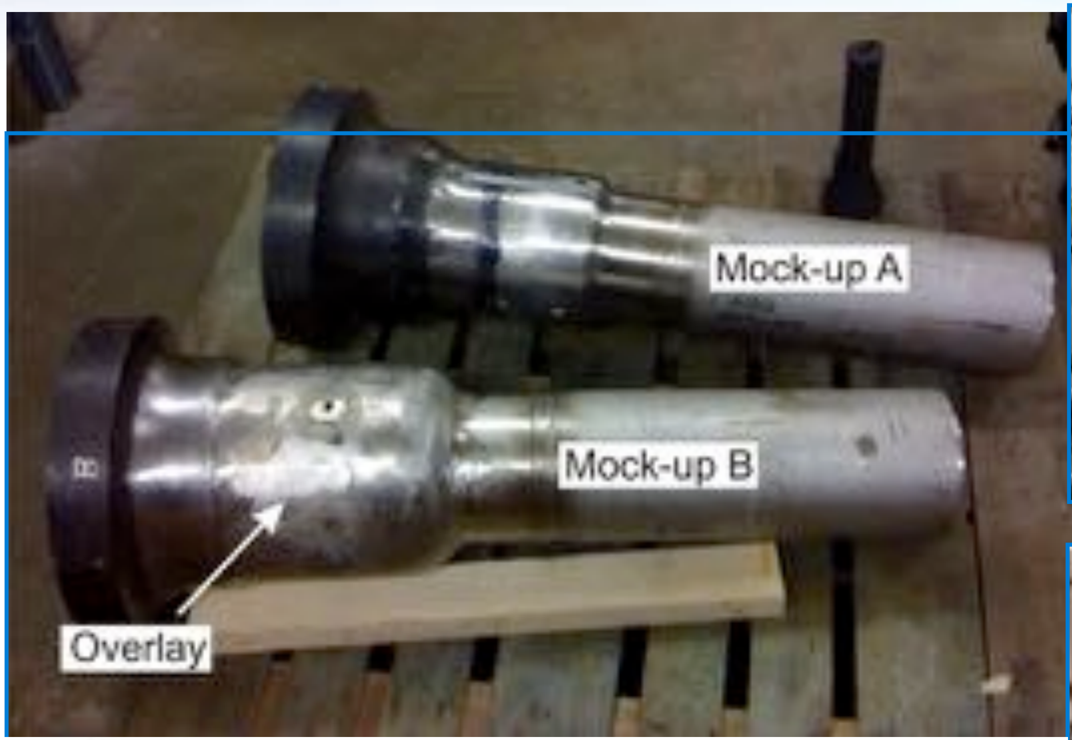


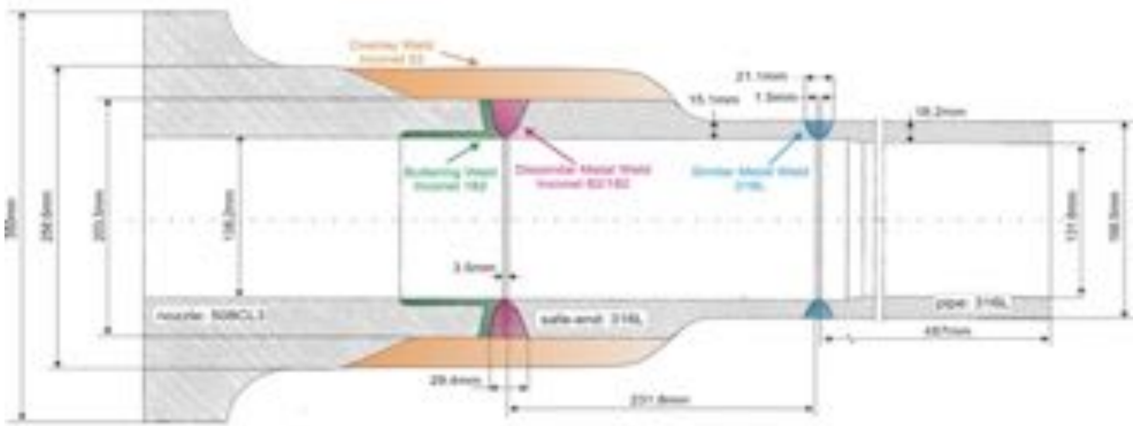




- Since 2000, 19 cracks found at dissimilar metal welds
- Engineering solution is full structural weld overlays
- Structural Integrity assessment needs weld stresses
- ANSTO/UoMan working with Nuclear Regulatory Commission (US) and British Energy (UK) to develop validated weld modelling of dissimilar metal welds

Dissimilar Metal Weld Mock-Ups

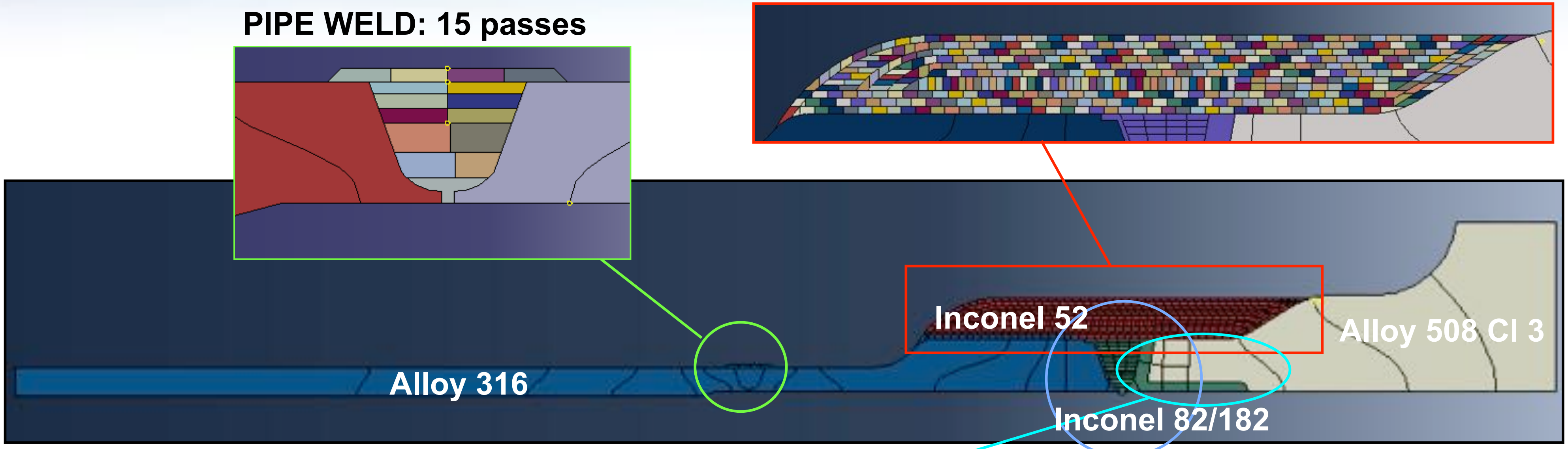




Modelling the Dissimilar Weld Overlays

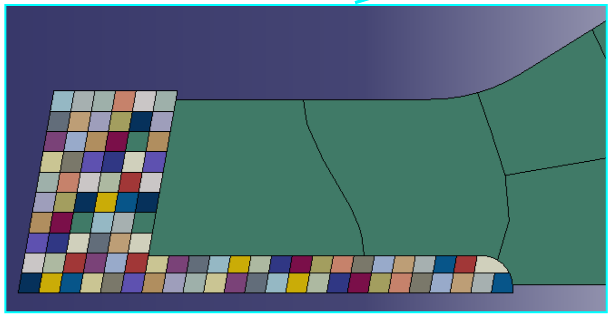
OVERLAY: 543 passes

PIPE WELD: 15 passes

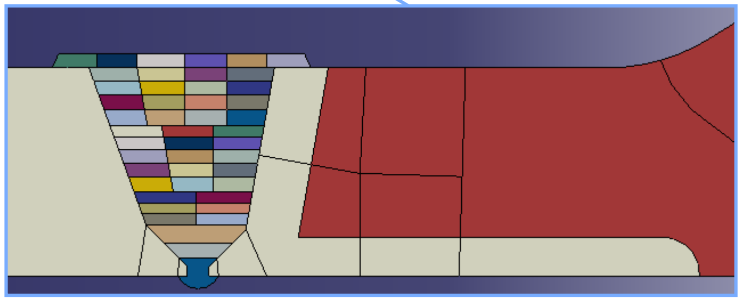


INSTRUMENTED MOCK UP

BUTTERING: 94 passes

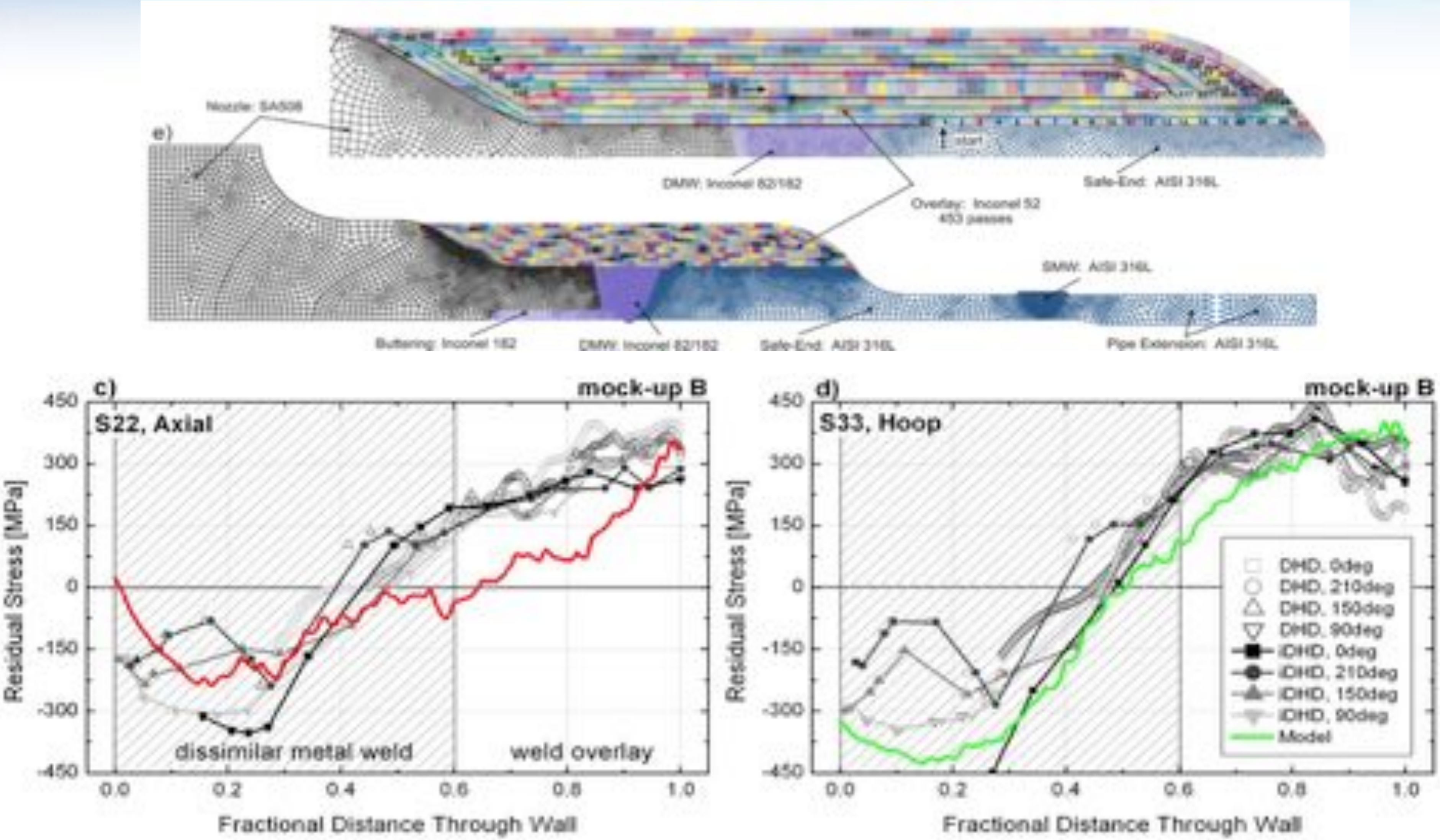


DISSIMILAR WELD: 46 passes

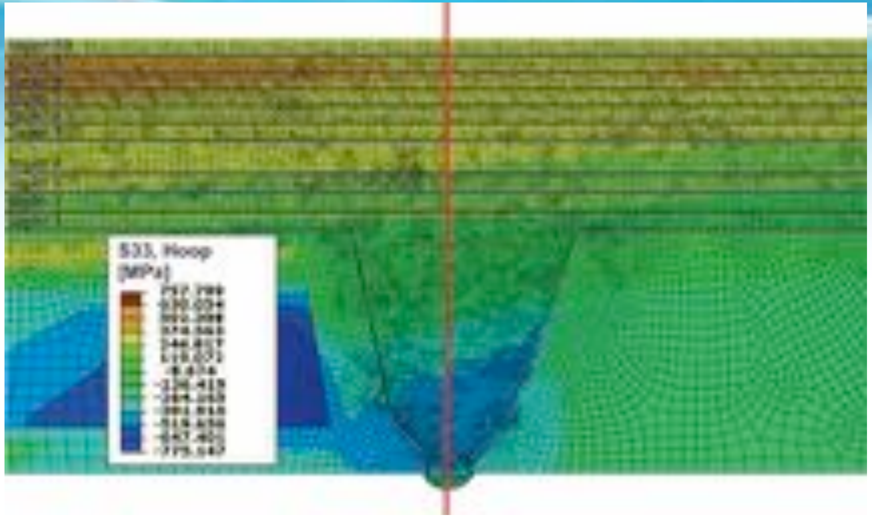


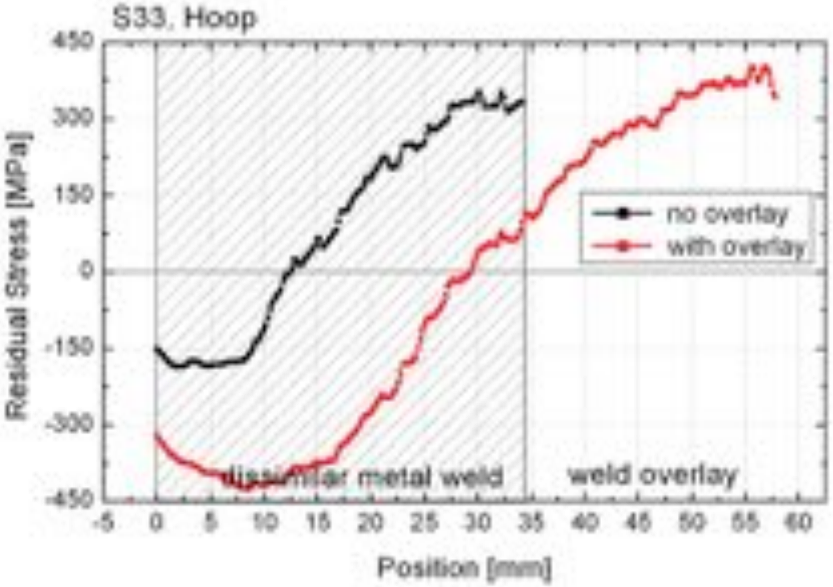
Full axi-symmetric model of instrumented mock up contains 598 weld passes in four different alloys

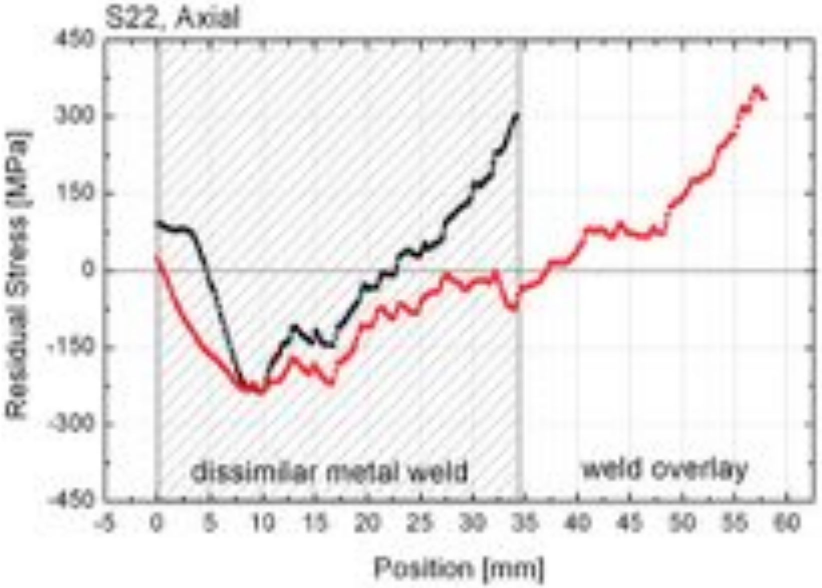
Model Validation, with Overlay



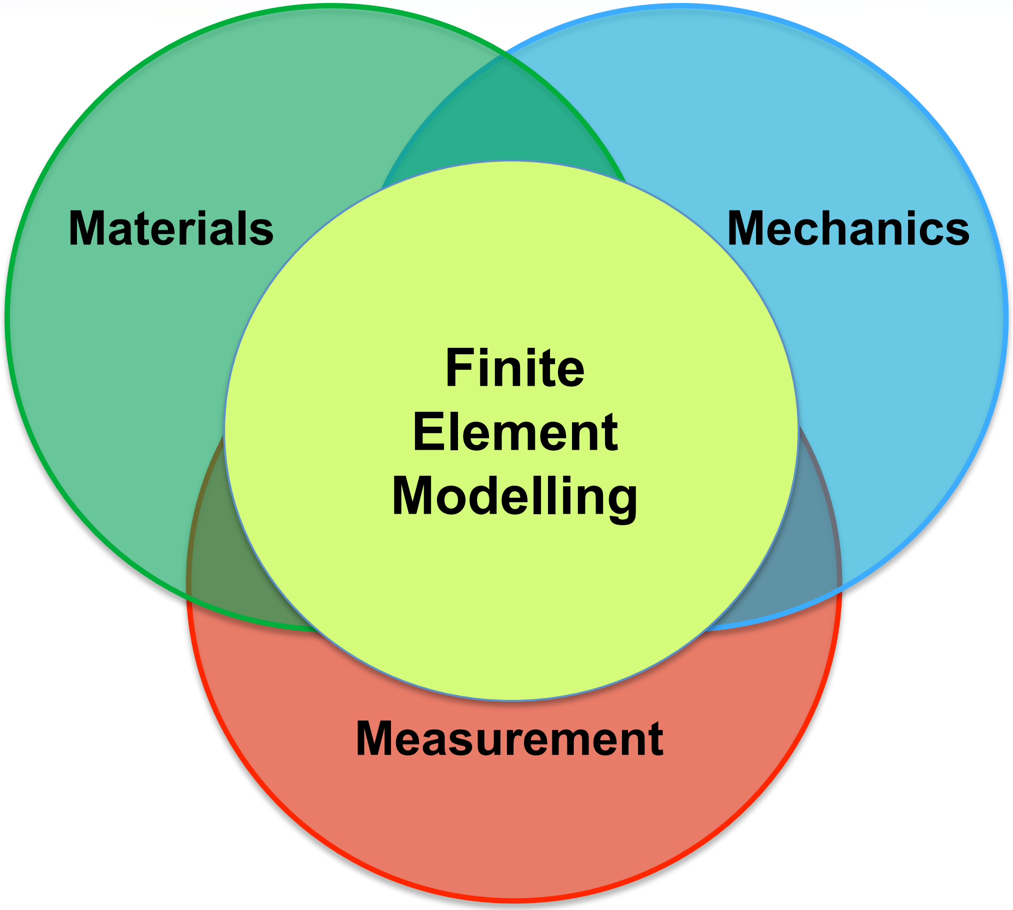
Effect of Overlay weld







The End… at last…



- Where are we today…..
- Do we apply what we know already (are we like corrosion?)
- Many techniques have (in a good way) become “fast food”
- But we are not McDonalds or Toyota yet – quality varies
- Need SQUEPed people when it matters
- So how do we produce them?

Acknowledgements!

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Tracy at ICRS10, July 2016

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Questions and Comments?