Australian Government
Department of Defence
Science and Technology

Computational model development for Additive Manufacturing (AM) based laser cladding structural repairs of high strength metallic aerospace components

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Acknowledgements

Thanks to

- Dr Scott Walker and Mr Dan Galea from IR Signatures Group at DST
- Prof Milan Brandt and Dr Cameron Barr from RMIT Centre for Advanced Manufacturing
- Dr Qianchu Liu DST Group for support to Laser Cladding research and development

Presentation Outline

- Aim
- Why Laser Cladding (LC)?
- Previous work with AerMet®100 Steel
- Modelling residual stress – 4340 steel
- Accounting for phase change effects
- Comprehensive investigation into 316L and 300M steels
- Conclusion and ongoing/future work
- Questions

Aim: Develop certified, structurally significant repairs for high strength steel components such as landing gear

https://www.nwfdailynews.com/news/20180822/nose-down-f-35-grounded-during-investigation-second-f-35-suffers-bird-strike

Example case: F-35 NLG Piston, 300M Steel

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Why Laser Cladding as a repair technology?

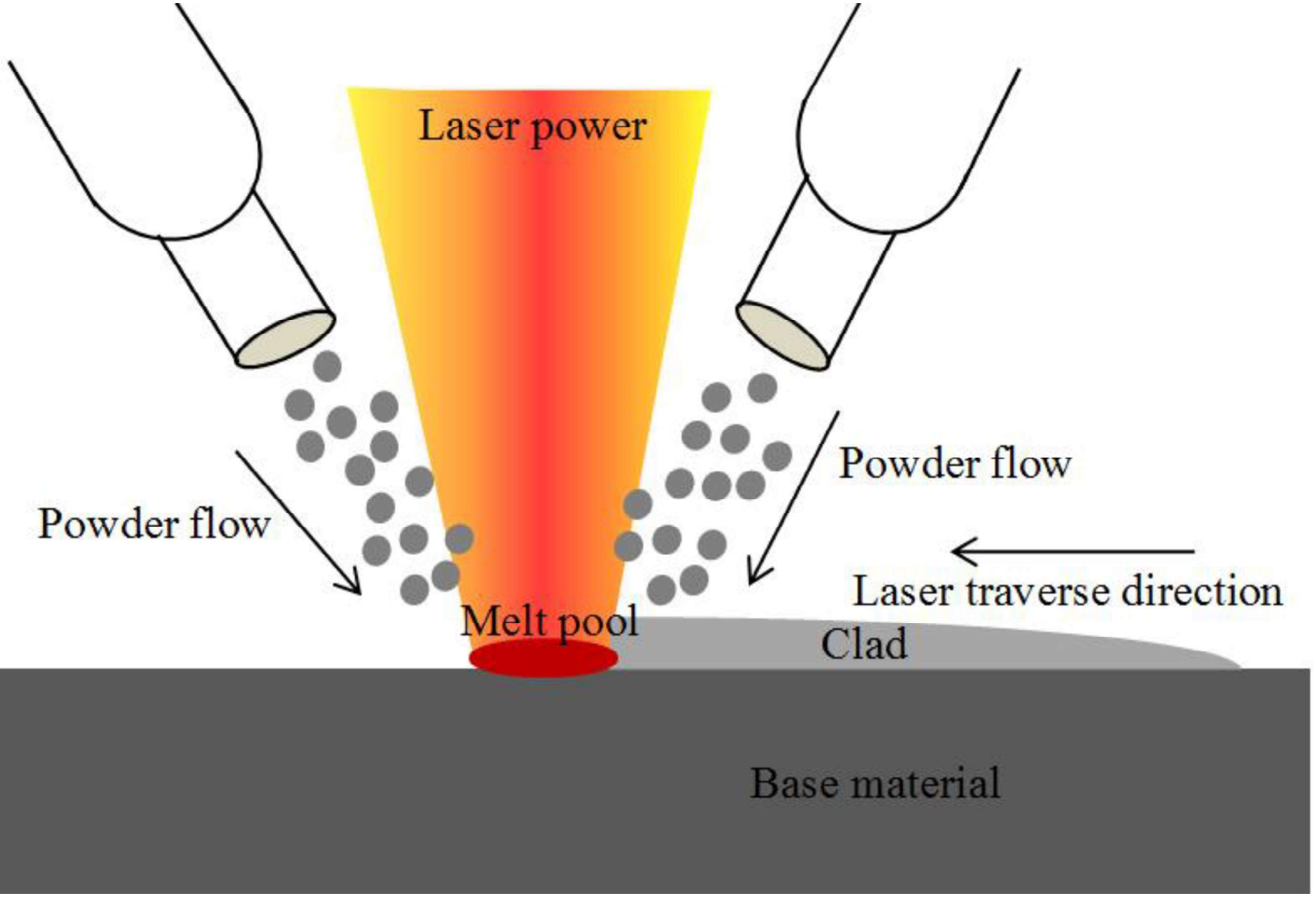
- Makes repair of expensive components possible
- Can repair components when lead-time may be excessive
- Can improve performance of the part

Liu, Q., Janardhana, M., Hinton, B., Brandt, M., and Sharp, P., *Laser cladding as a potential repair technology for damaged aircraft components.* International Journal of Structural Integrity, 2011. 2(3): pp. 314-331.
Liu, Q., Walker, K.F., Djugum, R., and Sharp, P.K., *Repair of Australian military aircraft components by additive manufacturing technology*, in *NATO Specialists Meeting on Additive manufacturing for Military Hardware*. 2016: Tallinn, Estonia.
Liu, Q., Djugum, R, Sun, S., Walker, K., Choi, J., and Brandt, M., *Repair and Manufacturing of Military Aircraft Components by Additive Manufacturing Technology*, in *17th Australian Aerospace Congress*. 2017: Melbourne, Australia.

Advantages of Laser Cladding

- Low dilution and heat input
- Low material distortion
- Low porosity, no micro-cracking, minimal heat affected zone, no or minimal damage to the substrate
- Good metallurgical bond
- Good mechanical properties
- Powder blend and process can be managed to achieve desired mechanical properties

Laser Cladding Process



Two categories of repair

Geometry restoration

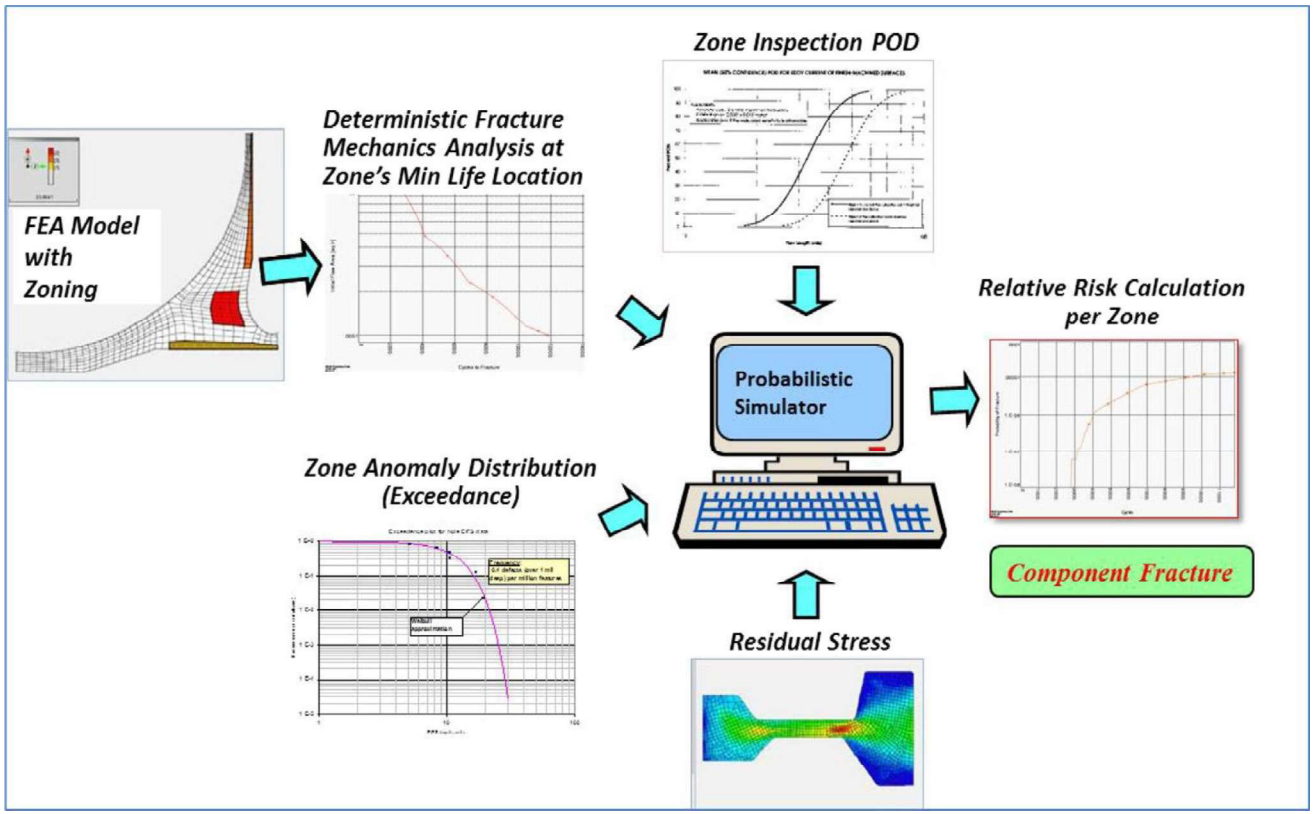
- Residual strength and fatigue life not compromised by the damage
- Repair needed to restore:
  - Form, fit and function
  - Corrosion protection
  - Surface finish

Structural

- Damage is such that static strength and/or fatigue life margins are compromised
- Need to demonstrate that the repair restores structural integrity, in addition to the geometry restoration requirements

Design, Substantiation and Certification - Structural Repairs

- High fidelity, accurate modelling essential
- Key aspects include:
  - Residual stress
  - Crack propagation

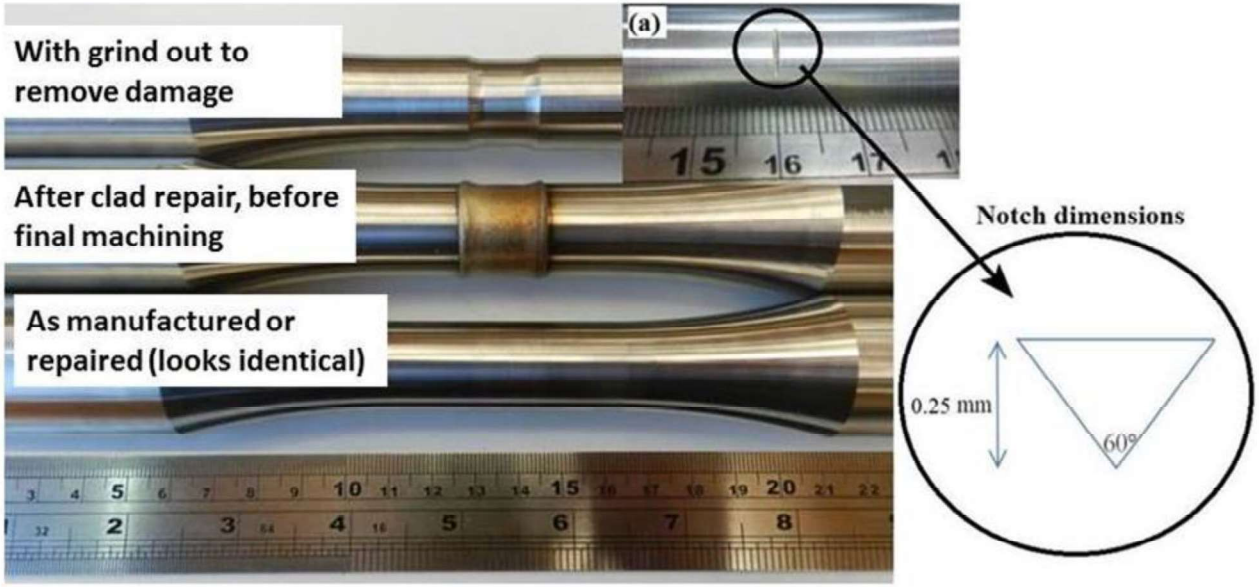


Source: Gorelik, M., International Journal of Fatigue 94 (2017) 168-177

Previous work with AerMET®100 Steel

Structural Repair of AerMet®100 Steel

- AerMet®100 32/20 mm dia round bar samples
- Baseline: no repair, with 0.25 mm deep crack starter
- Repair: 0.5 mm deep, 10 mm long groove, repaired by cladding with TRUMPF TrueLaser Cell 7020 System, without crack starter



Walker, K.F., Lourenco, J.M., Sun, S., Brandt, M., and Wang, C.H., *Quantitative fractography and modelling of fatigue crack propagation in high strength AerMet100 steel repaired with a laser cladding process.* International Journal of Fatigue, 2017.

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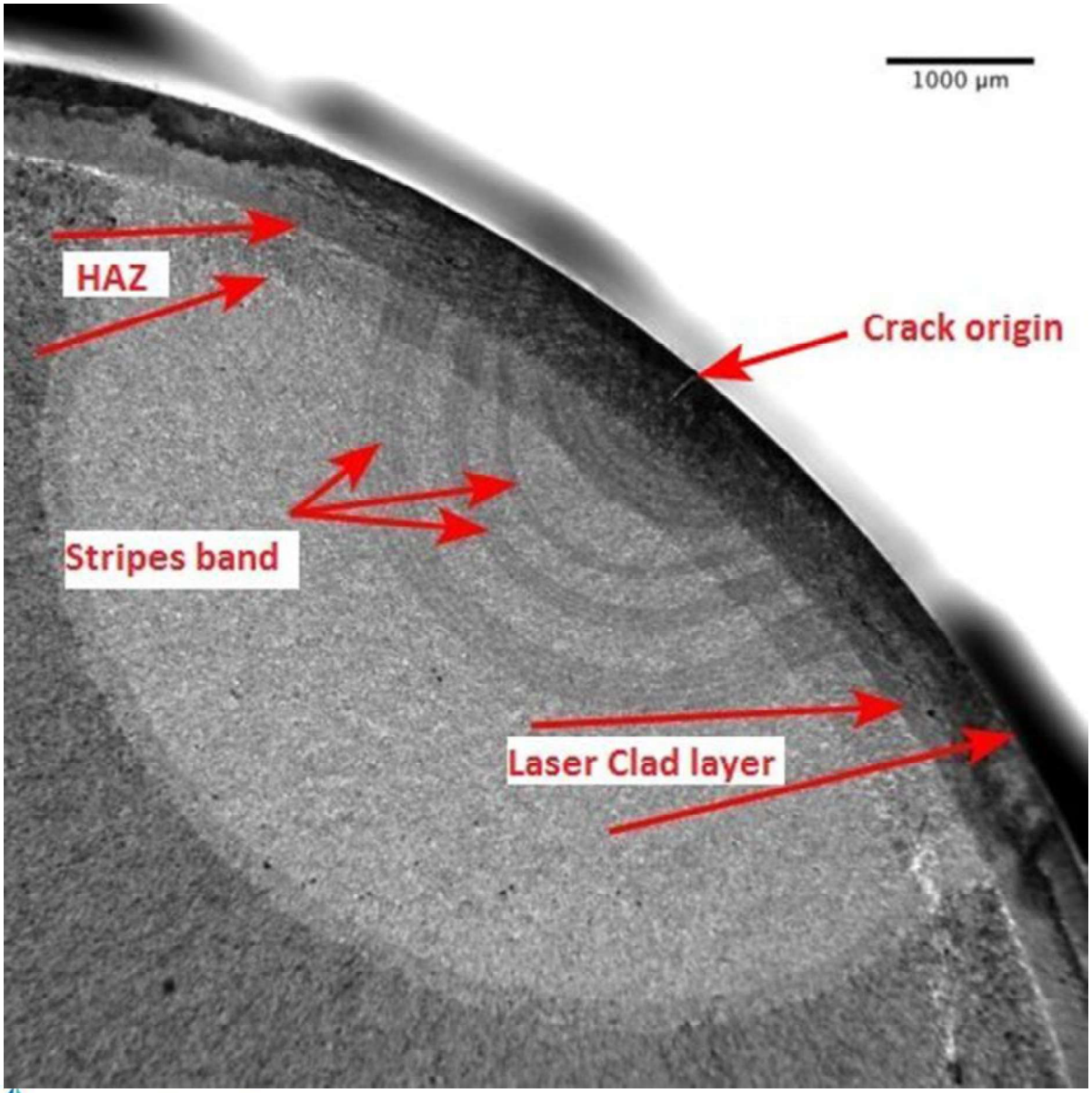
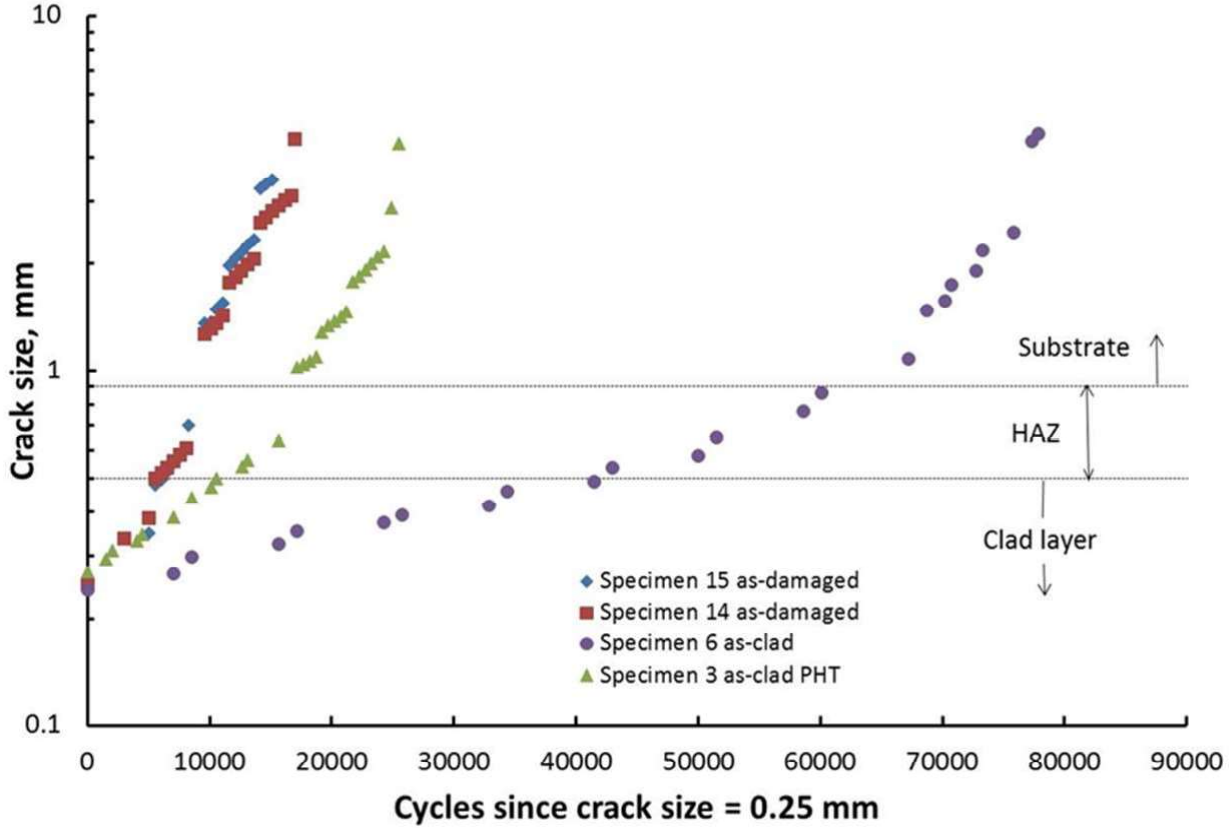
Test Results : As-clad



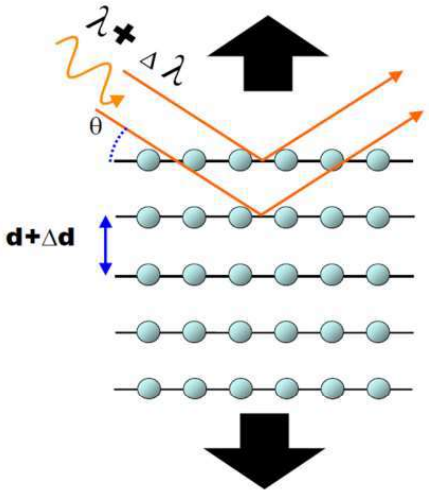
Test Results – Comparison of all three test cases



- Clad repair - fatigue crack growth life improvement by more than a factor of four
- Due to beneficial residual compressive stress
- Crucially important to understand and quantify those residual stresses in order to accurately model the process

Residual stresses measured by three methods

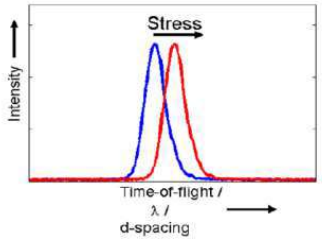
- Neutron diffraction



With residual strain/stress

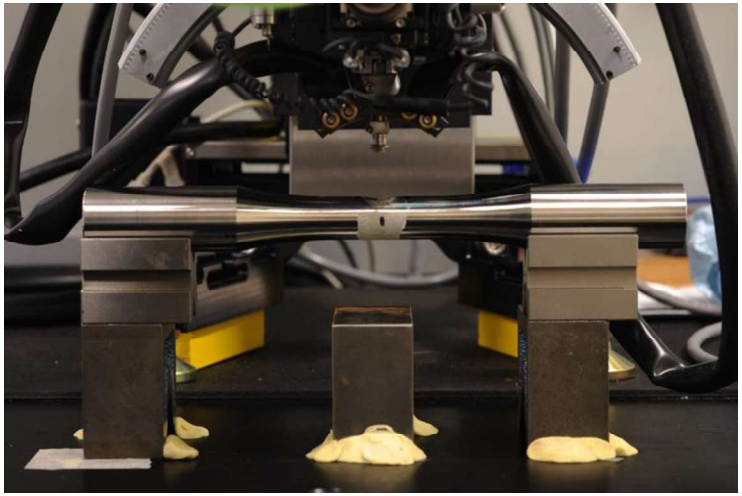
Bragg's Law:
$d = \lambda / (2 \sin\theta)$

Fixed angle θ: $\varepsilon = \frac{\Delta d}{d} = \frac{\Delta \lambda}{\lambda}$

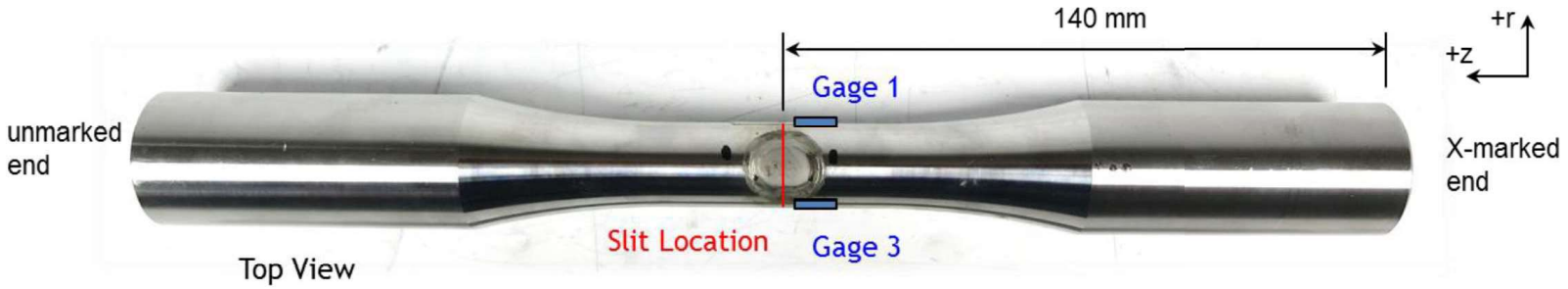


Diffraction peak shift is used to determine residual strain and stress

- X-ray diffraction



- Slitting



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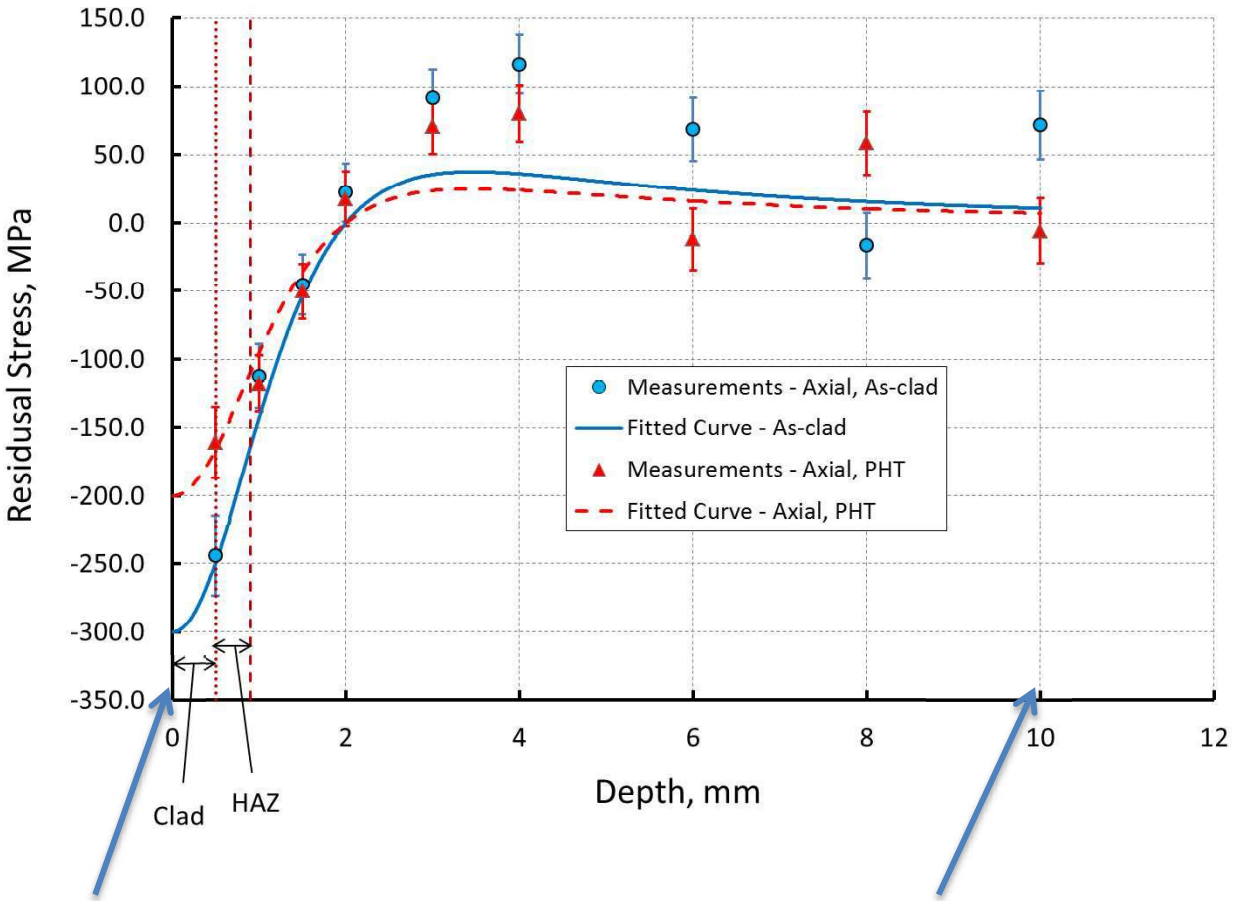
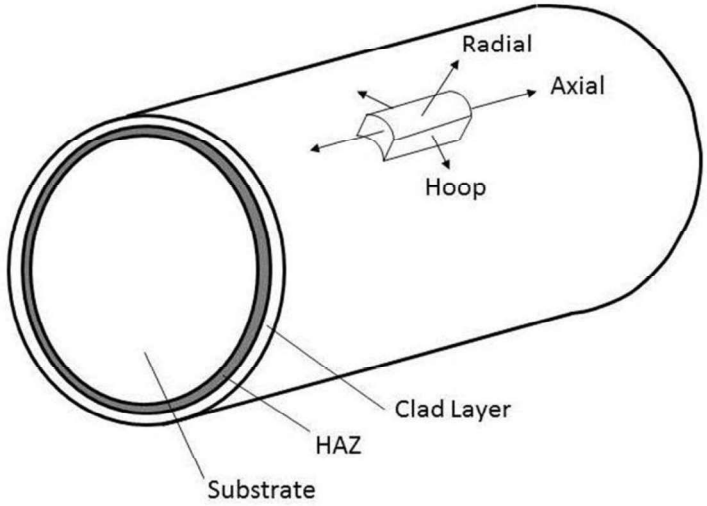
Residual Stress Measurement – Neutron Diffraction





$$\sigma_R(z) = \sigma_{R,\max} \frac{1-(z/d)^2}{\left[1+(z/d)^2\right]^2}$$

Satisfies the zero net force condition

$$\int_0^\infty \sigma_R(z)dz = 0$$

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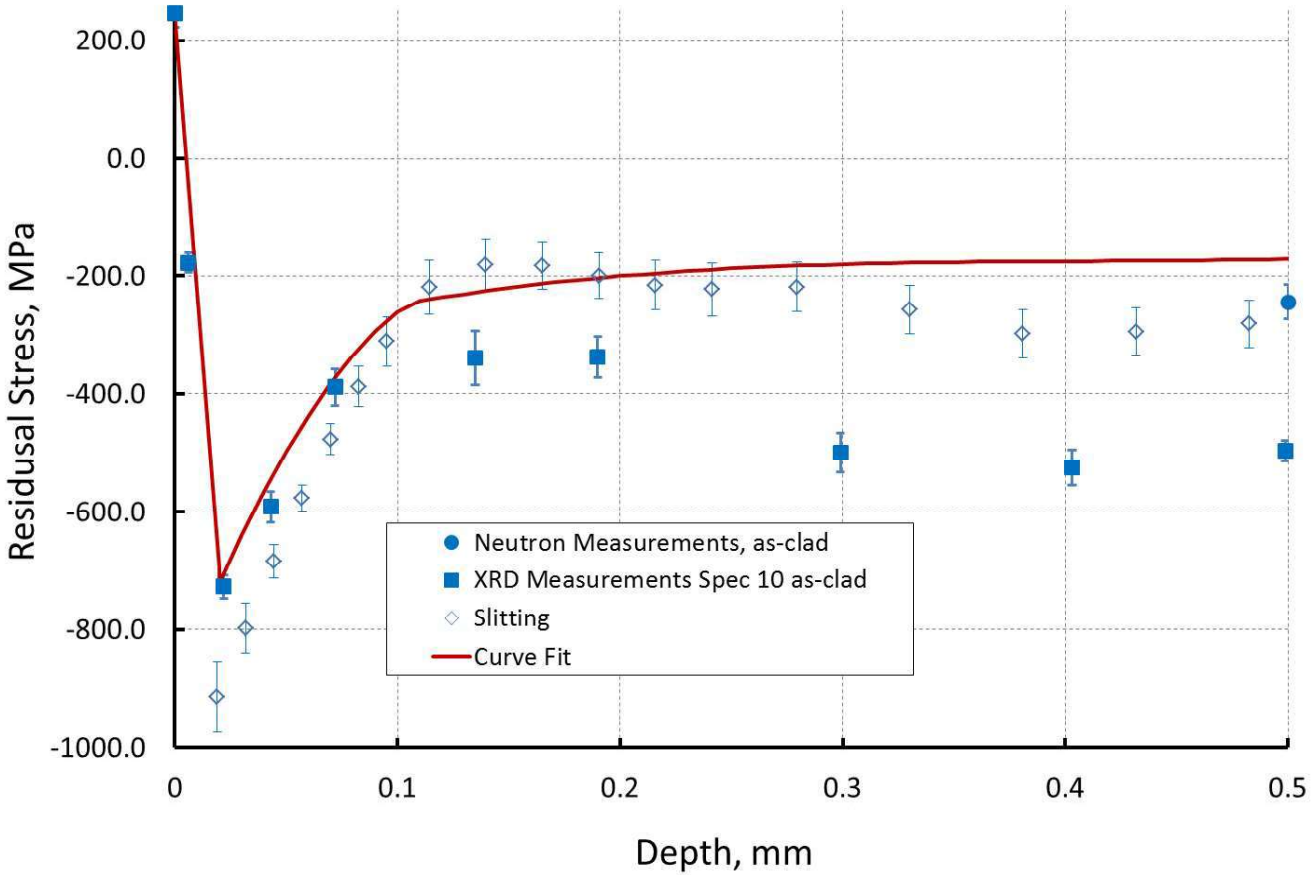
Neutron, X-Ray, Slitting Results – Clad Layer

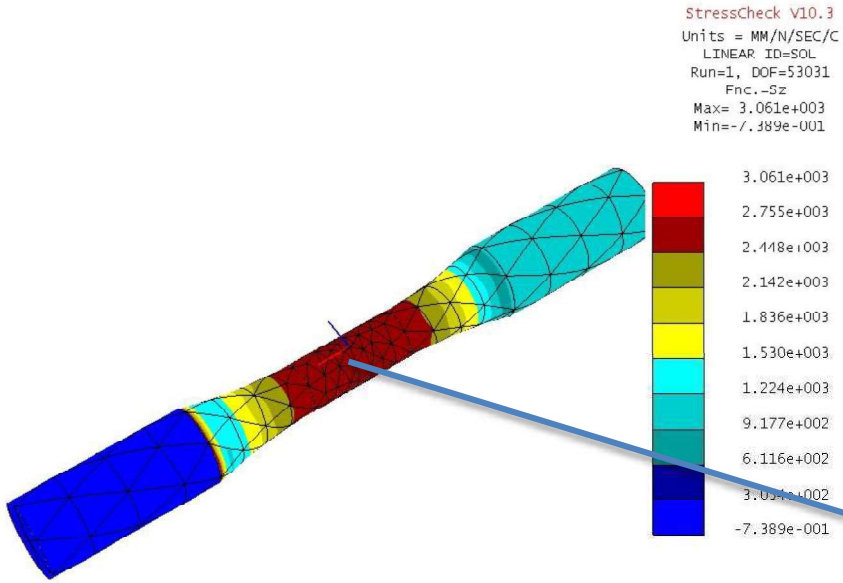


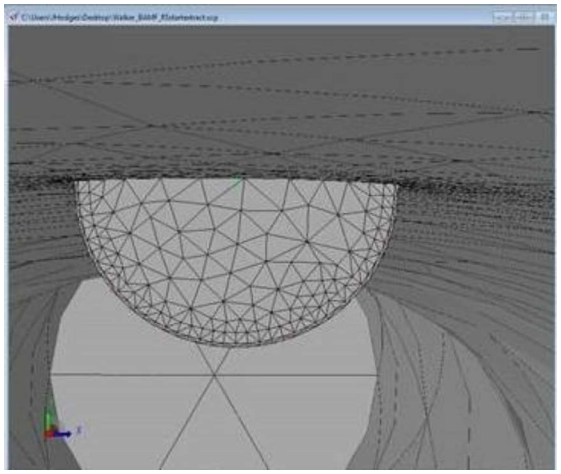
- Shown for the area of interest near surface, in the clad layer
- Some disagreement between X-Ray and slitting, but slitting agreed better with neutron result at 500 µm
- Slitting samples all around the circumference and gives an average result

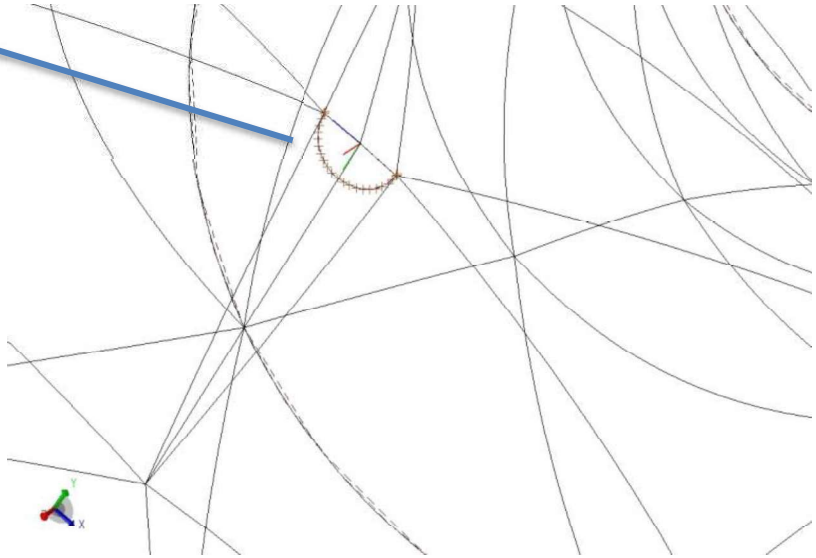
BAMF/AFGROW/StressCheck Model

- BAMF – Broad Area for Modelling Failure
- USAF sponsored code, managed and being further developed/validated by Hill Engineering
- BAMF is a “plug-in” for the AFGROW fatigue crack growth analysis code
- StressCheck p-element FE code used here for stress intensity factor (SIF) solution development
- StressCheck model runs to calculate SIF, this is fed to AFGROW for the crack growth (FASTRAN model in this case). Crack is grown by an incremental amount, and new shape returned to StressCheck to update SIF solution
- Iterative process continues to advance the crack through to final failure

BAMF/AFGROW/StressCheck Model Overview 1







StressCheck FE Model

Crack Detail

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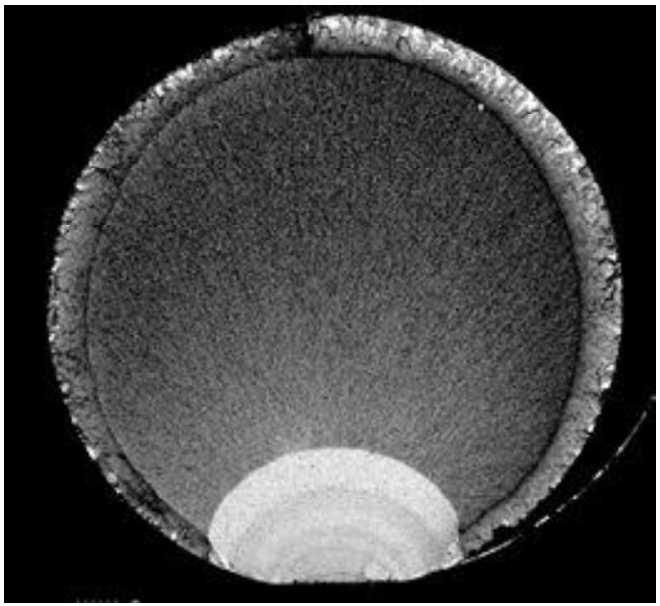
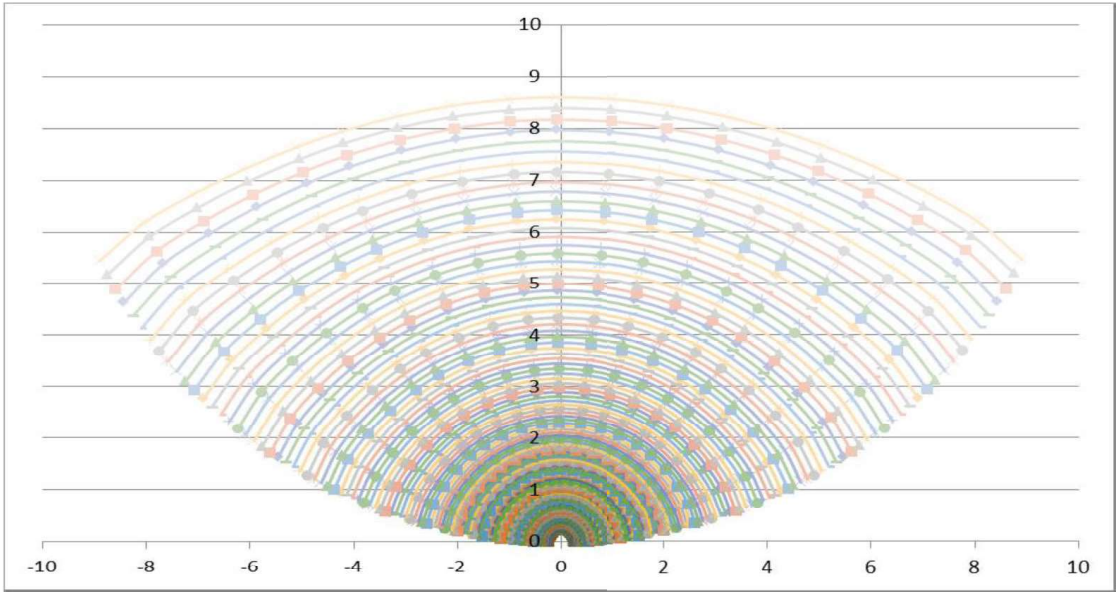
BAMF/AFGROW/StressCheck Model Overview 2





Crack Surface

BAMF Crack Model

- SIF Calculated at 20 points around crack front
- Crack size incremented by 3% per step

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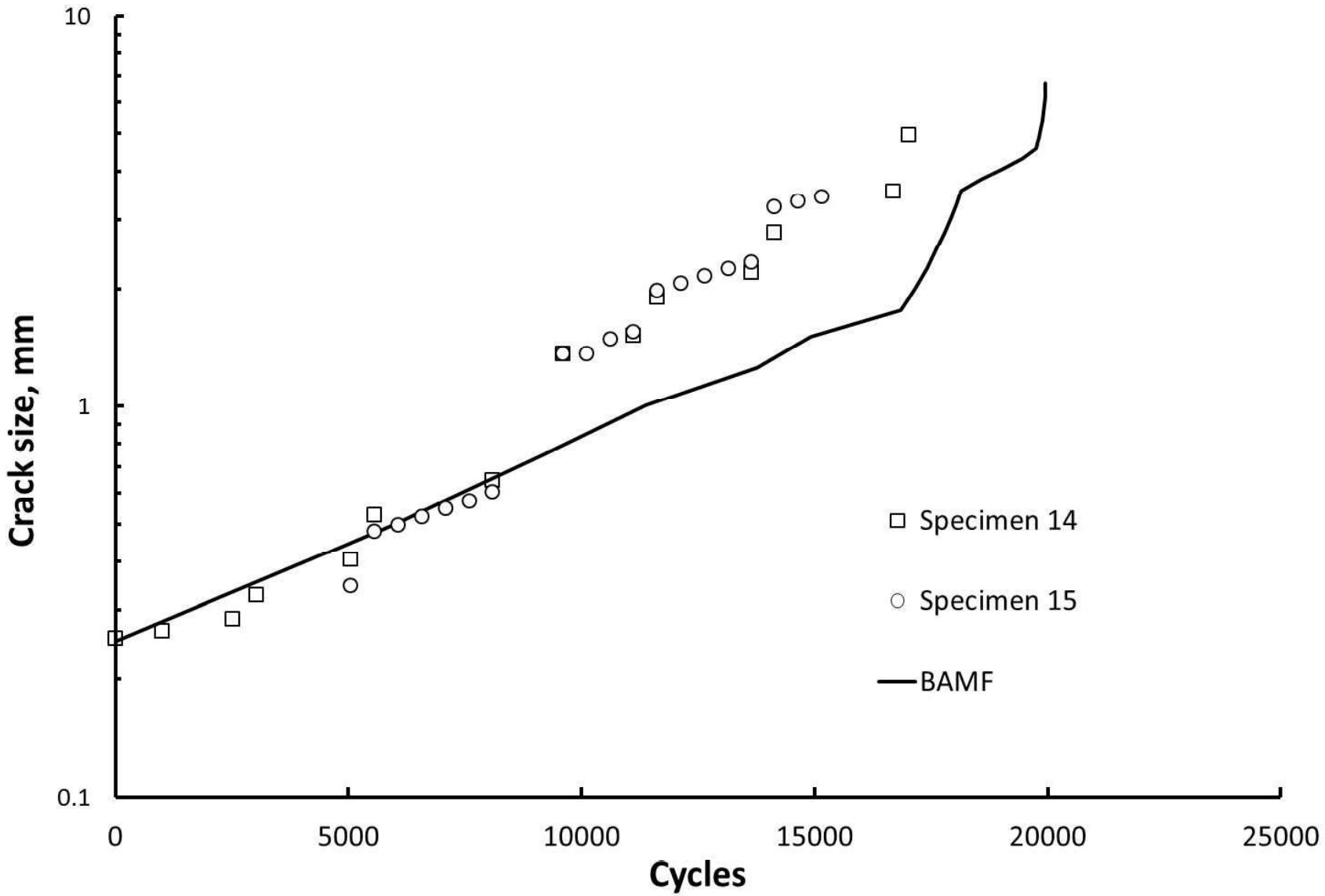
Full BAMF Model Results : Baseline



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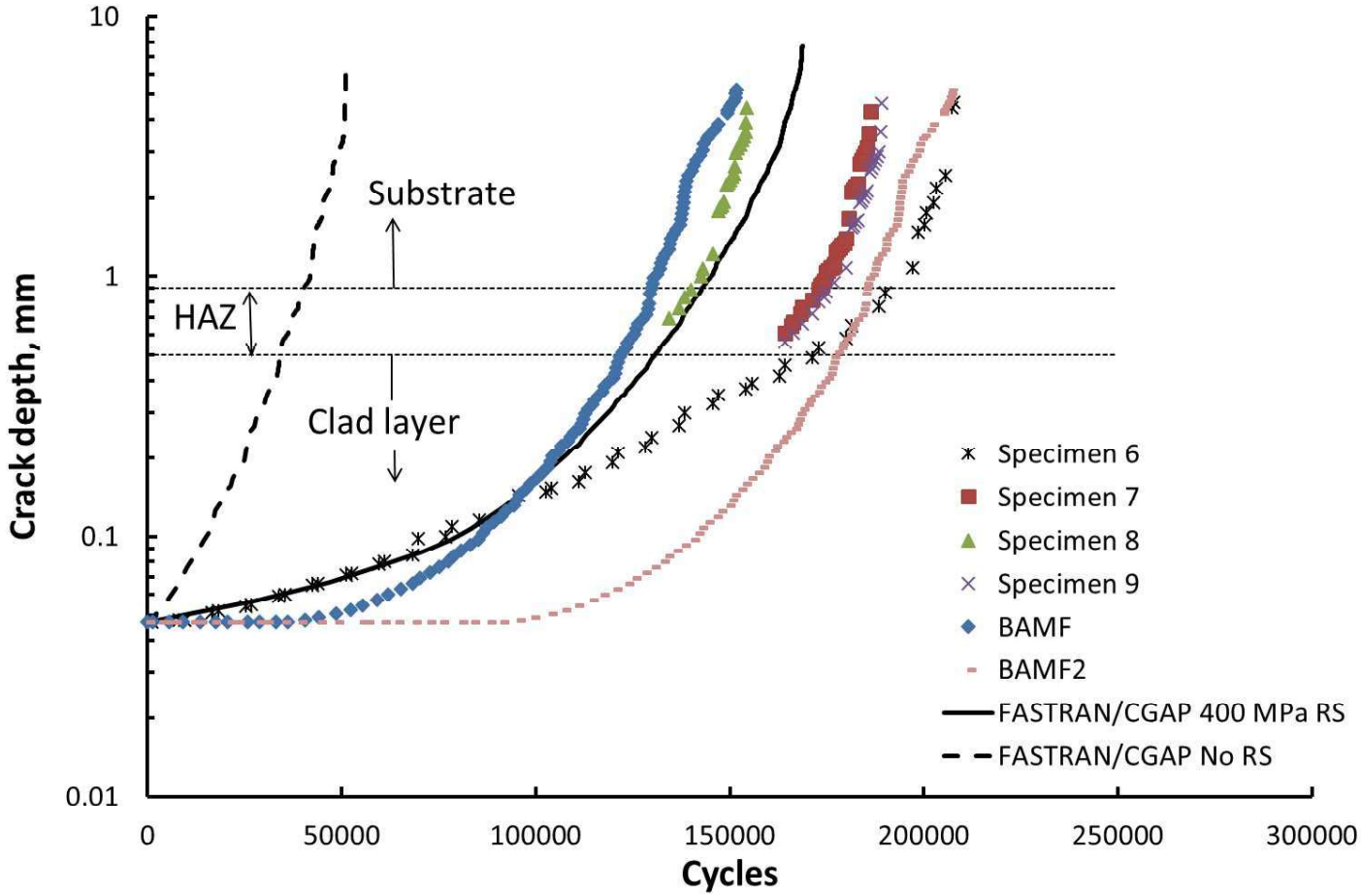
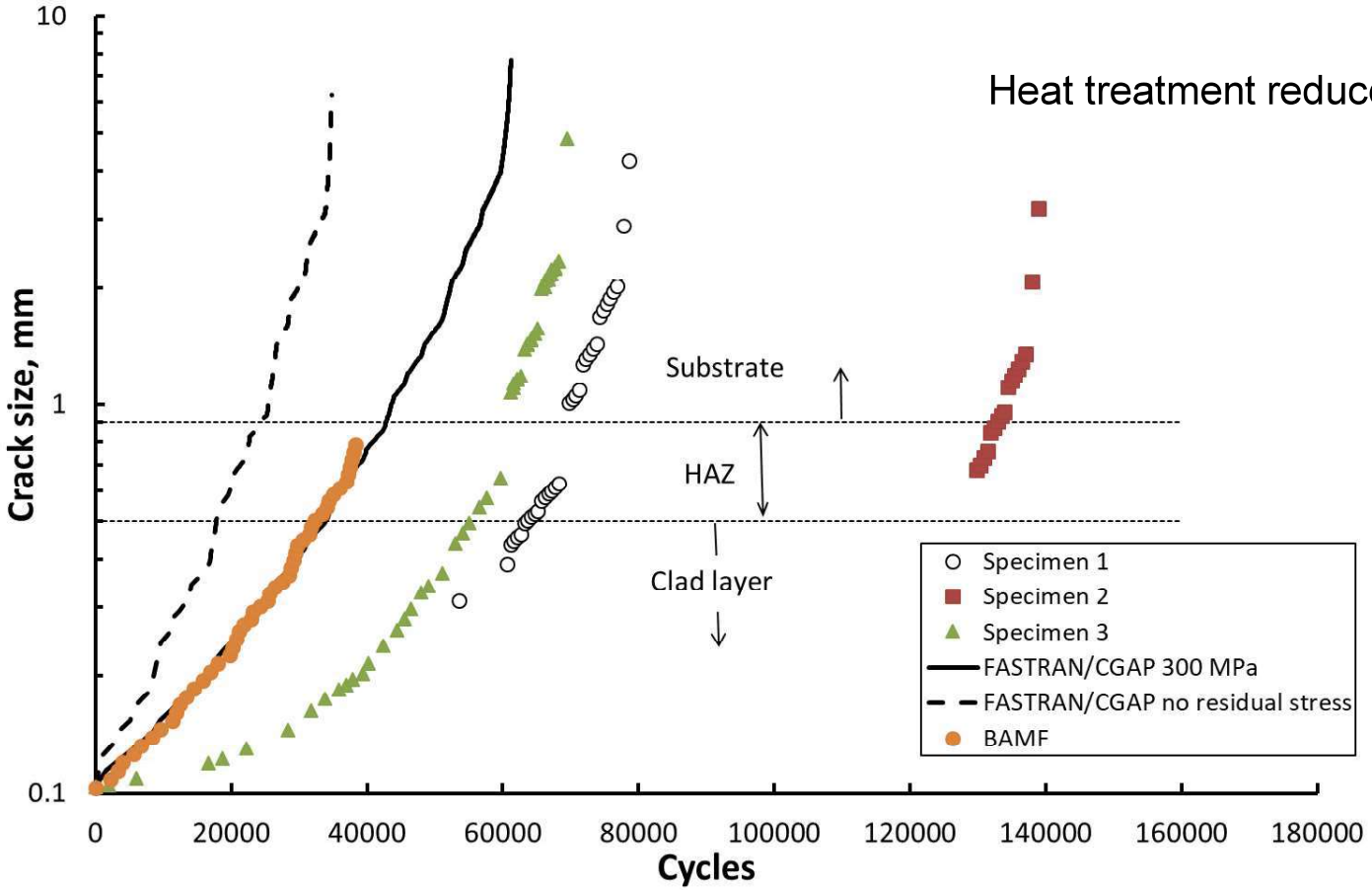
FASTRAN/CGAP/BAMF Modelling Results: As-clad



- Both BAMF and CGAP/FASTRAN modelling correlated well
- BAMF modelling still being reviewed, particularly in the early stage of growth

FASTRAN/CGAP Modelling Results: PHT



- Full BAMF modelling still in development/review
- BAMF results appear consistent with simplified FASTRAN/CGAP approach at this stage

Summary thus far with AerMet®100

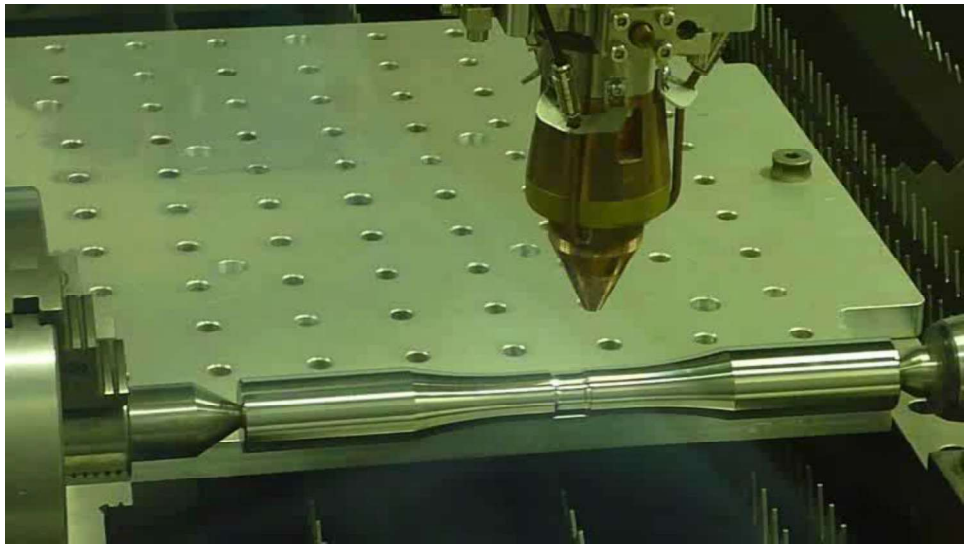
- Can measure residual stress and crack growth
- Can model the crack growth, including through the residual stress field
- For a complete modelling capability, also need to model the residual stress field.

Aim – Modelling of the Residual Stress

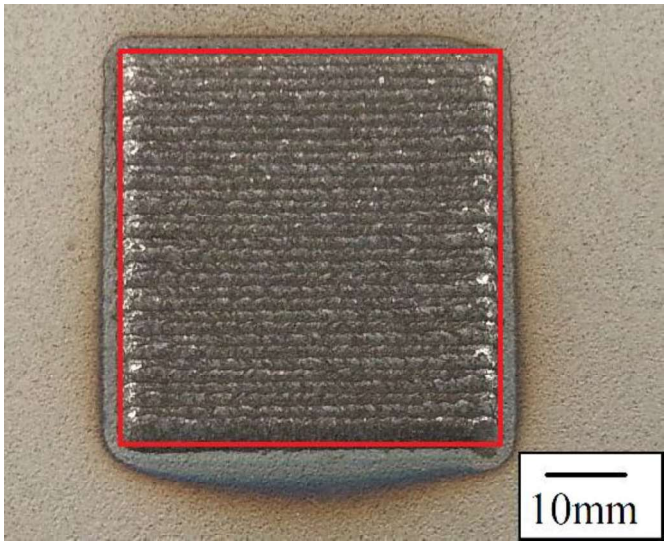
Develop a thermomechanical model of the laser cladding process

- For AerMet®100 Cylindrical Bar Test Specimens
- Start with AISI 4340 Steel Rectangular Plate Samples where test data (thermal profiles and measured residual stresses) available

AerMET®100



AISI 4340 STEEL



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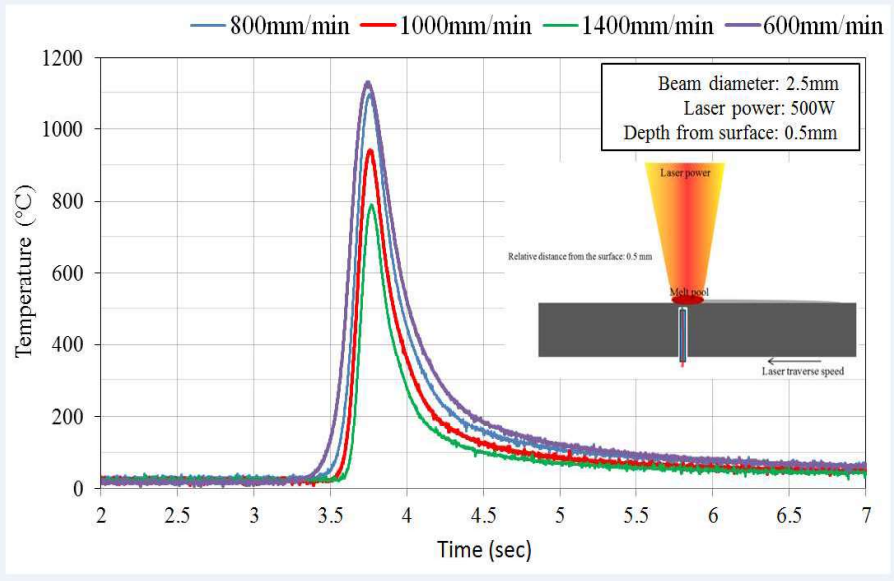
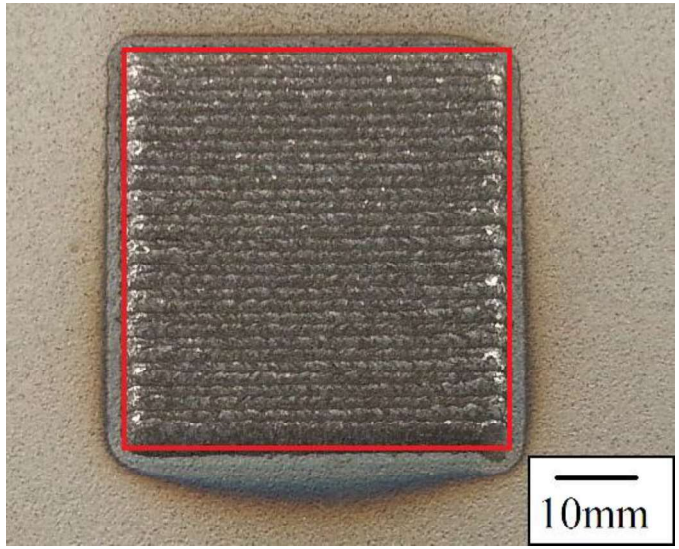
Experimental data available for 4340

- Deposition experiments performed by S. Sun (RMIT) in collaboration with DST Group
- AISI 4340 steel plates (200 x 100 x 10)
  - Thermocouple experiments
    - No deposition
    - Temperature history at 0.5 mm depth
  - Residual stress experiments
    - AISI 4340 material deposited
    - Residual stress evaluation using Neutron Diffraction

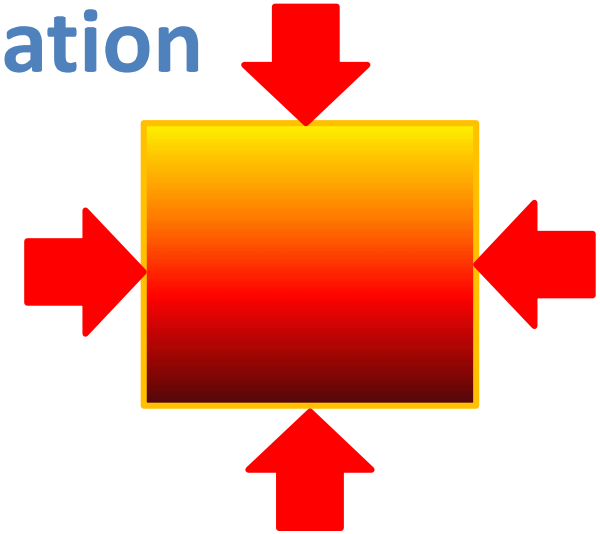




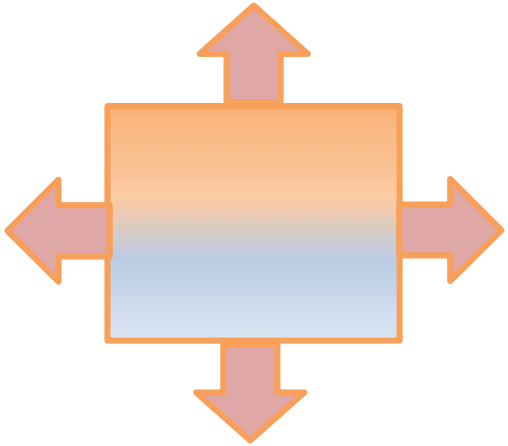
Mechanism of Residual Stress Formation

Residual stress state is primarily governed by plastic yielding under constrained transient thermal expansion and contraction.

It is anticipated that the highly local (to the laser heated melt-pool) effects of liquid metal flow need not be modelled discreetly to capture the final residual stress state.



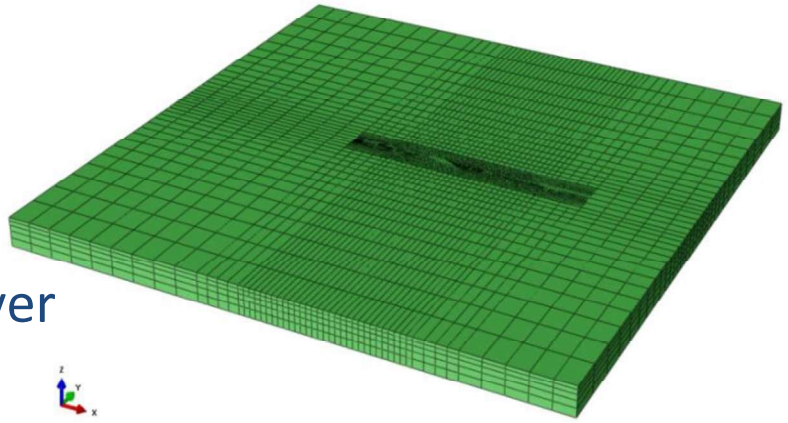
Constrained Expansion under Heating



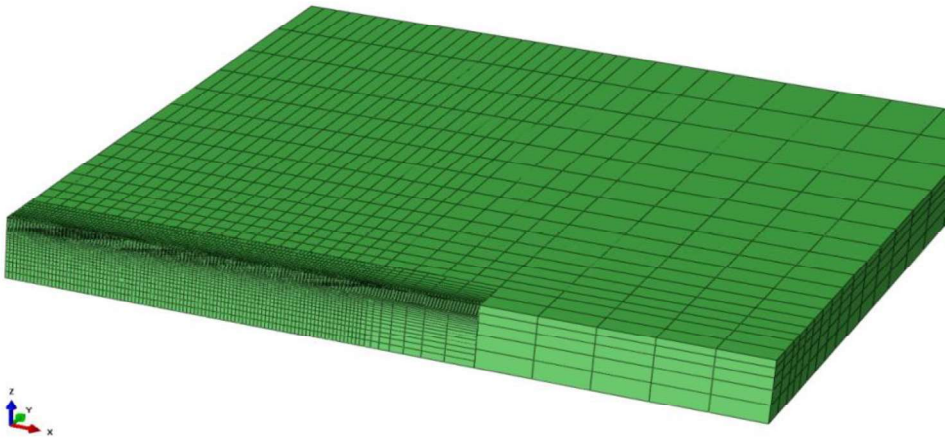
Constrained Contraction under Cooling

Thermal Model

Transient Thermal Finite Element Analysis



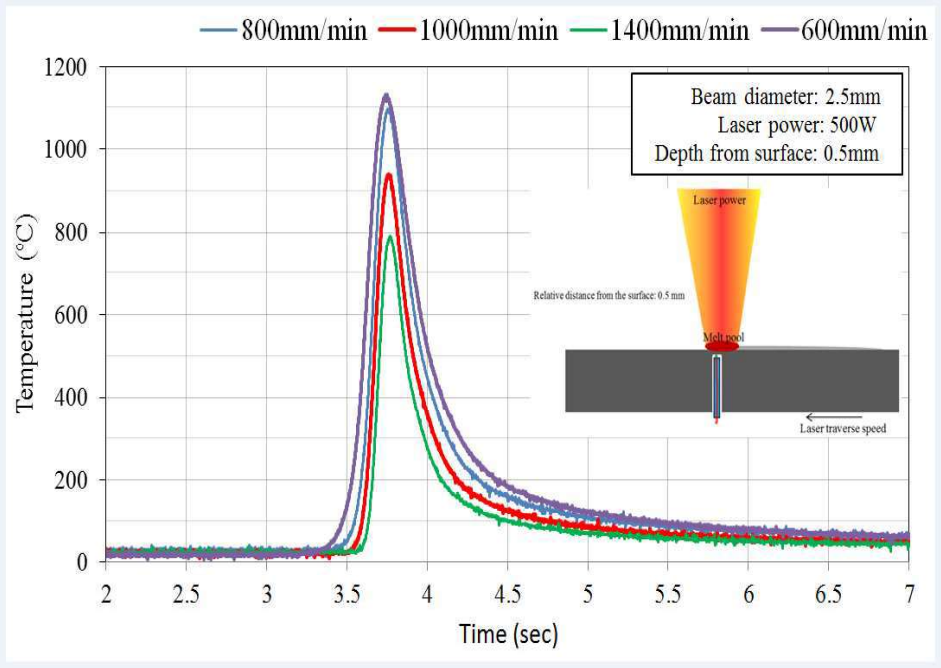
- ABAQUS 2016 Software
- Temperature field modelled using explicit solver
  - Decoupled from displacement field
- Thermal load scaled from laser beam profile interpolation
- Conduction out through Plate Supports shown to have negligible effects in the time-frame considered
- Convection & radiation heat transfer to ambient conditions ignored
- Total 7.5 second simulation
  - 2.5 second laser scan
  - 1400, 1000, 800, 600 mm/min
  - 5.0 second cool down



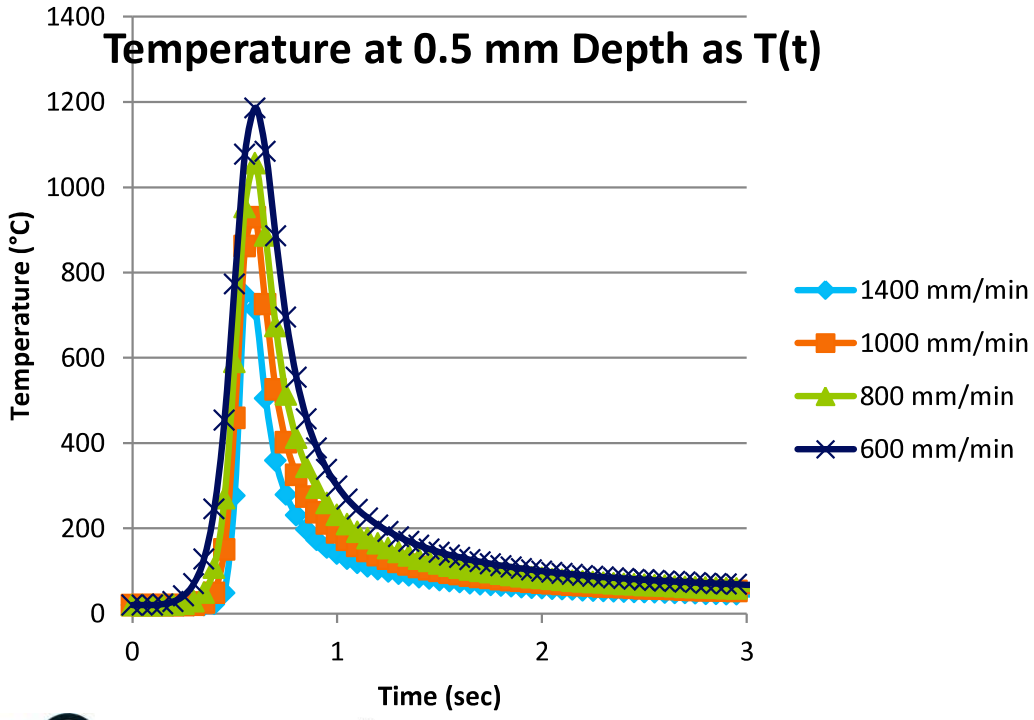
Thermal Model Correlation

- Single pass, no material deposition
- Strong agreement of temperature transients (rise/decay profiles and rates)
- Quantitative agreement to within 7 % against peak temperature
  - Achieved using heat source amplitude scaling
  - Equivalent to setting an effective absorptivity

EXPERIMENT



SIMULATION



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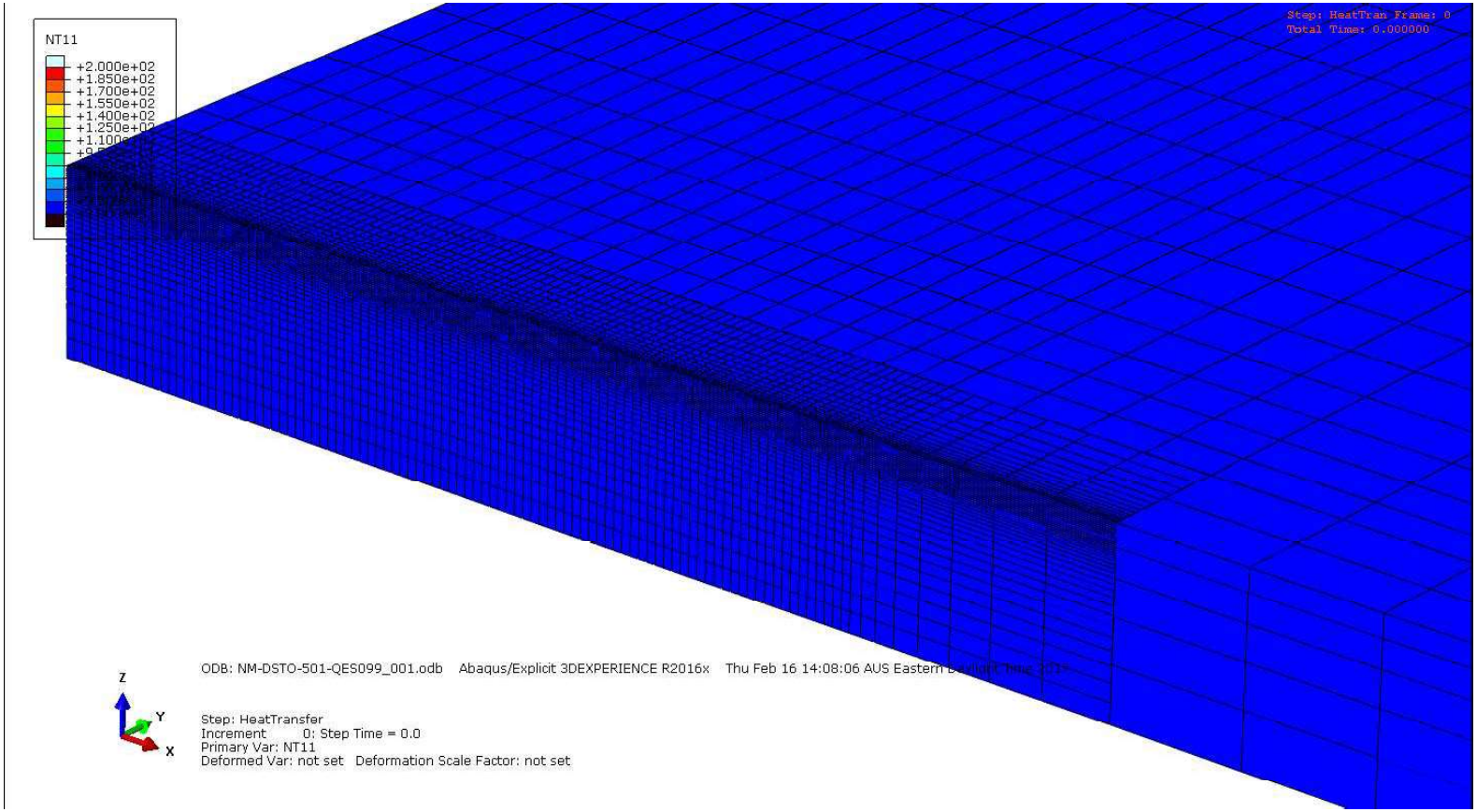
Thermal Analysis – Results

AISI 4340 Plate Quarter Model – 0 to 200ºC Temperature Range



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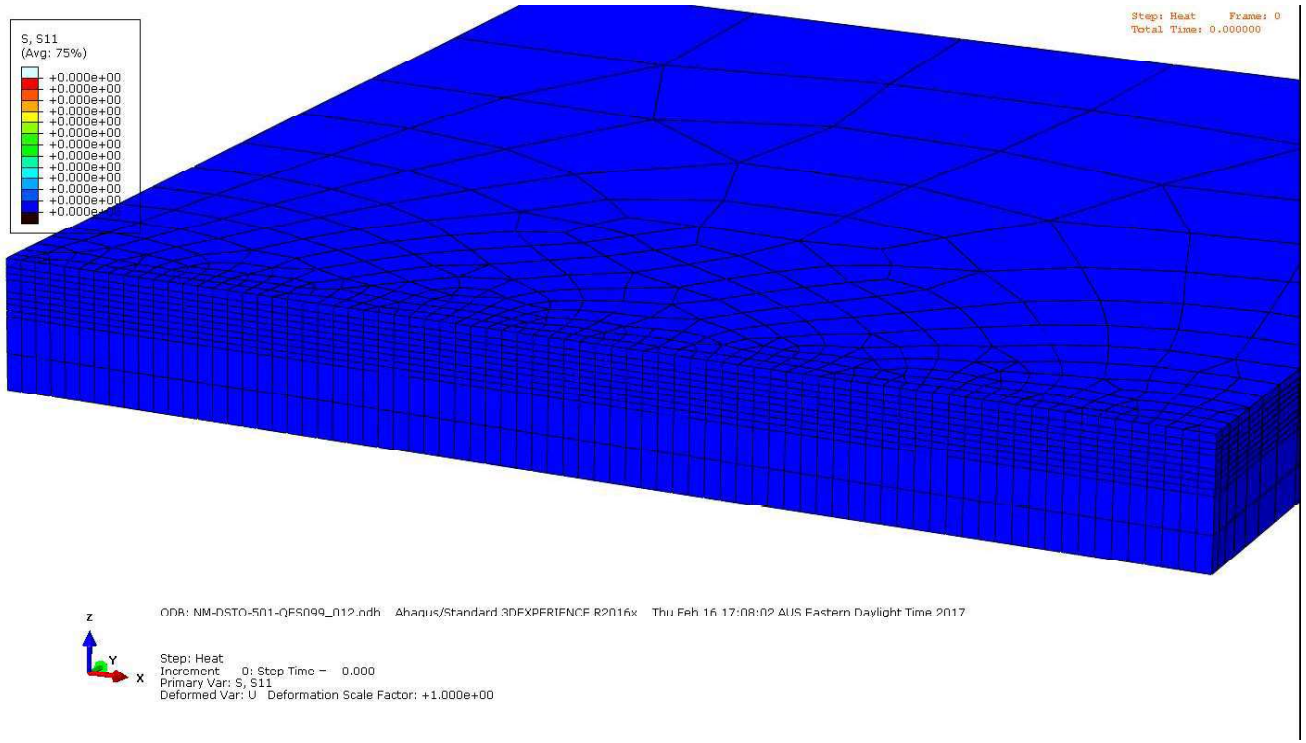
Residual Stress Analysis - Results

- Displacement (strain) field modelled using ABAQUS 2016 implicit solver
- Sequentially coupled to temperature field
- Distributed time-point body temperature from transient thermal analysis
- Stress development from constrained thermal expansion/contraction
- Total 7.5 seconds of simulation

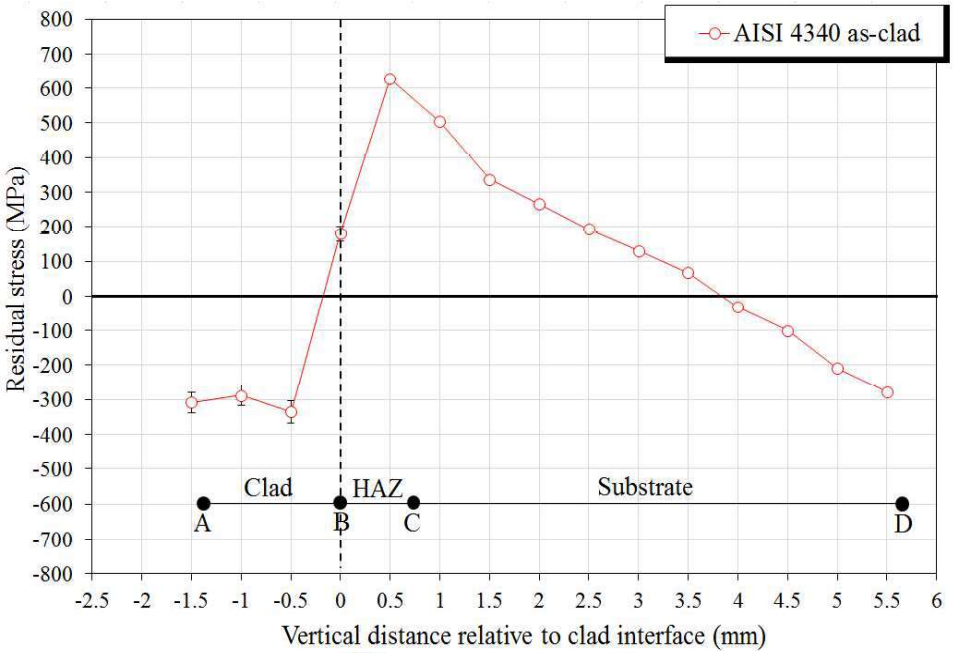


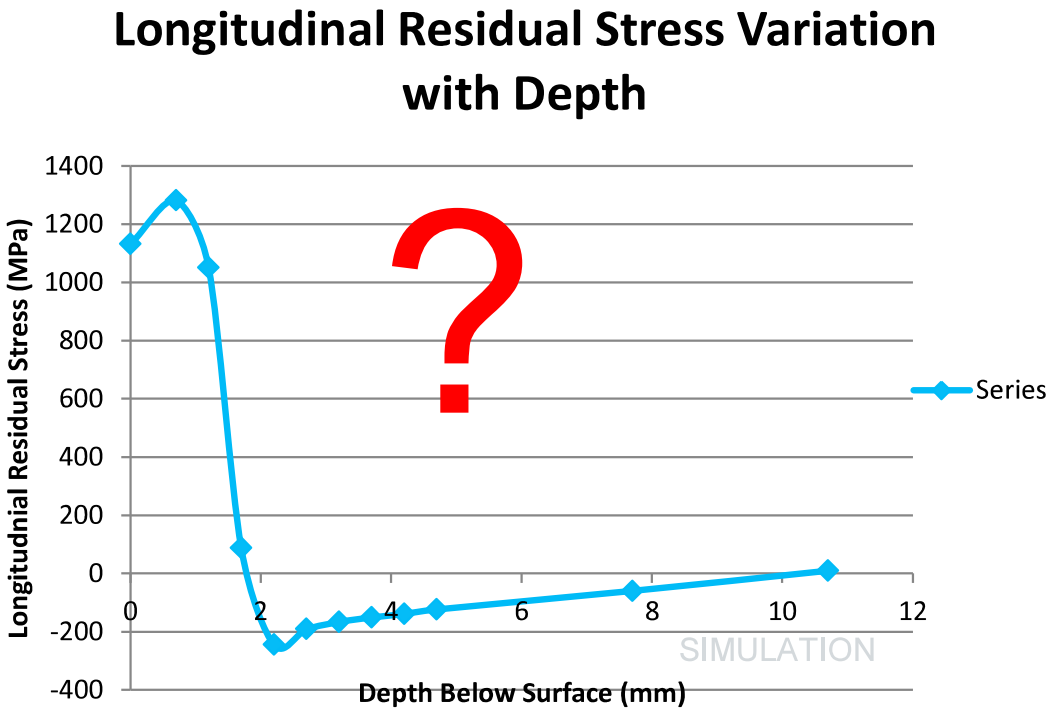
Residual Stress Model Correlation

- Measured and modelled residual stress profiles are different. Why? Where did we go wrong?
- We did not model addition of material, or multiple passes. However, we believe there is something else even more important which we haven't accounted for.

SIMULATION

EXPERIMENT





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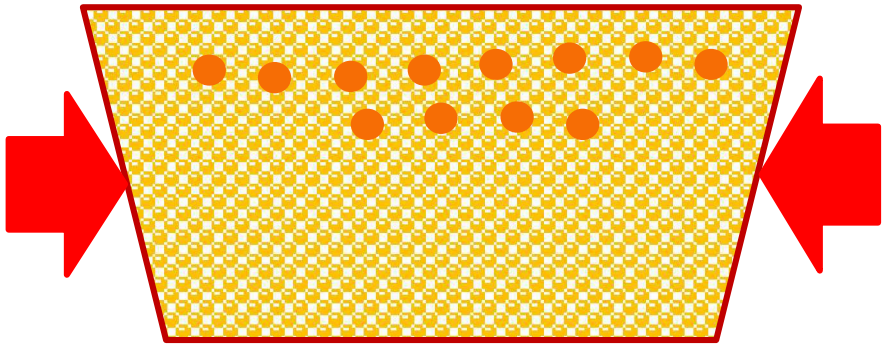
Evaluation- What's Happening?

- Residual stress can be driven by two mechanisms
  - Constrained thermal expansion and contraction, plus local material yielding
  - Phase transformation, with associated step volume changes
- For cases dominated by thermal expansion – results in primarily tensile residual stresses at the surface
- For cases dominated by material phase change – results in primarily compressive residual stresses at the surface (when phase change on cooling results in volume increase)
- A given material may be subject to both effects, given the right temperature and transient temperature conditions
  - This varies from point to point in test article
  - Being a function of local temperature, local temperature transients and bulk material constraint
  - Also a function of material composition, heat treatment history

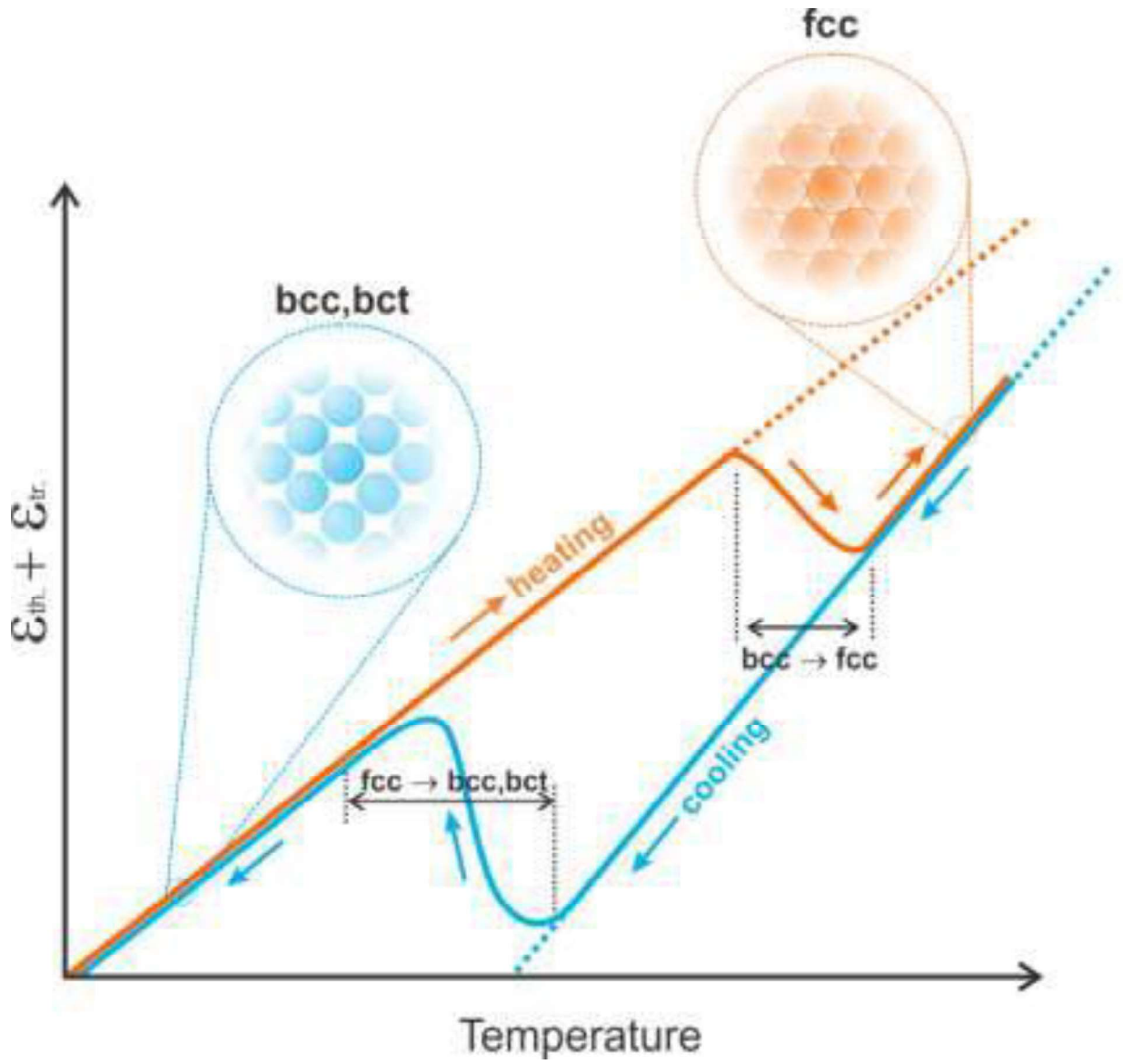
However, current model does not include the added material



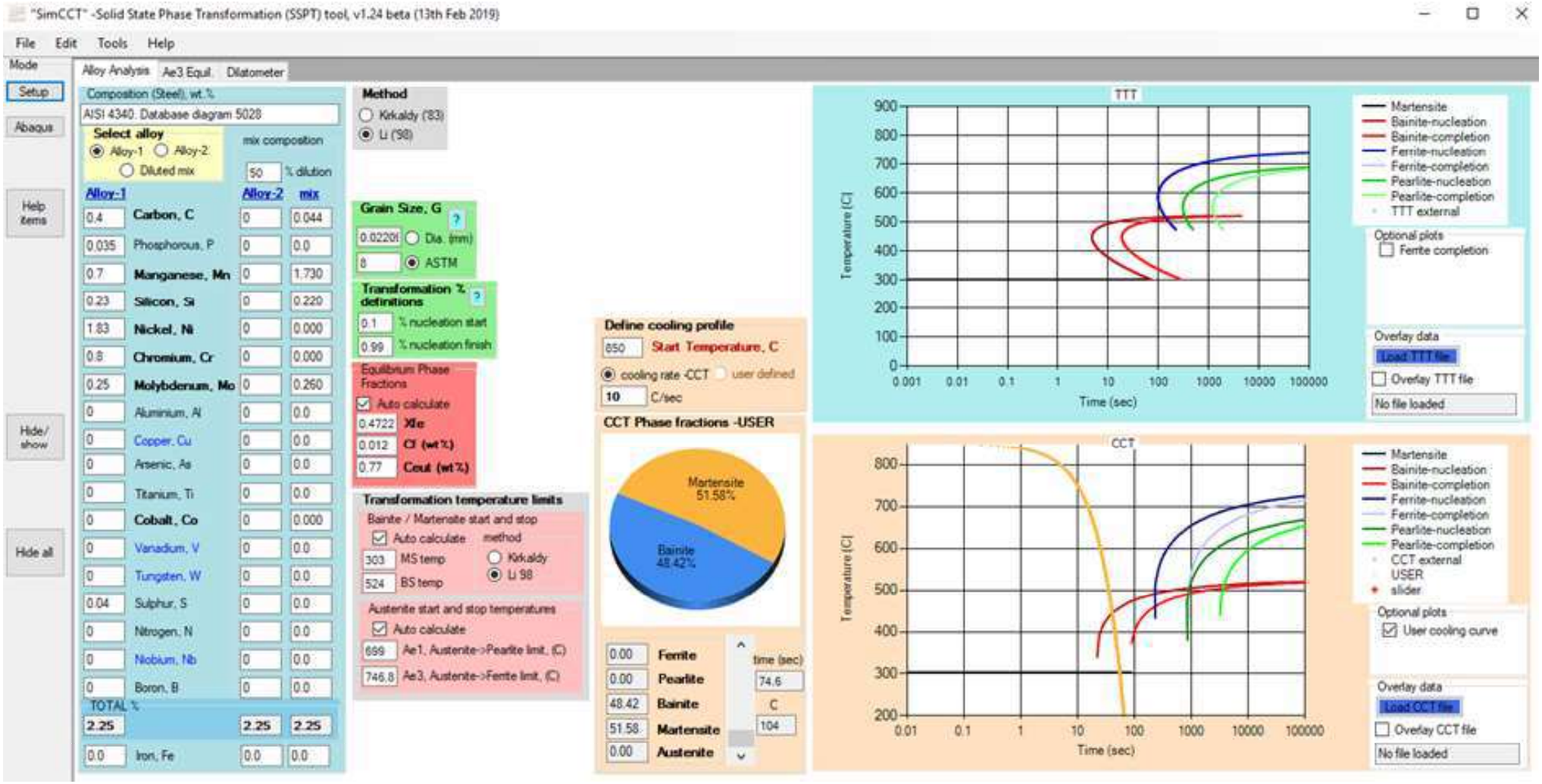
Development of Model Accounting for Phase Change Effects

- Entered collaboration with ANSTO (Dr Ondrej Muransky and Dr Phil Bendeich)
- Devised heavily instrumented baseline experimental program on two steels:
  - 316L Austenitic Stainless Steel (no phase change)
  - 300M Ultra-high strength steel (undergoes Phase change to Martensite)
- Addition of ANSTO phase change model to existing QinetiQ/DST model. Initially for 4340 case, then to be extended to 300M

Accounting for Solid State Phase Transformation (SSPT)



ANSTO SSPT Model



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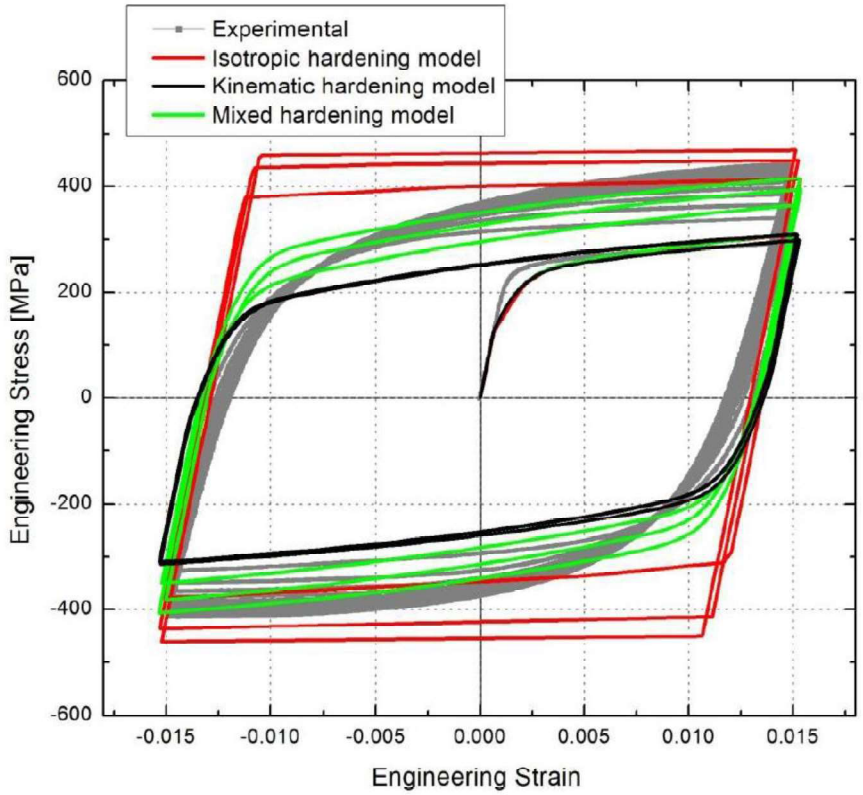
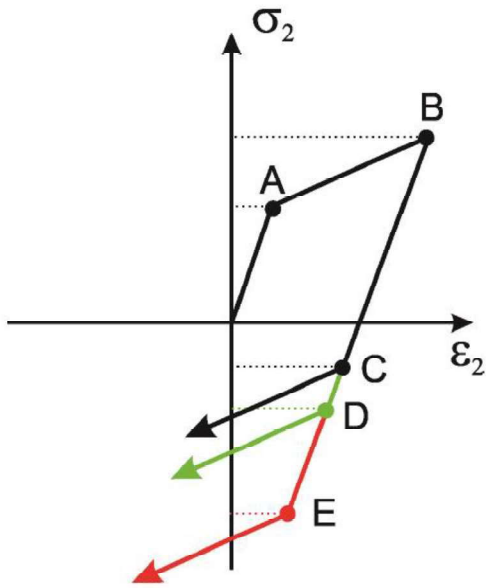
Hardening Model

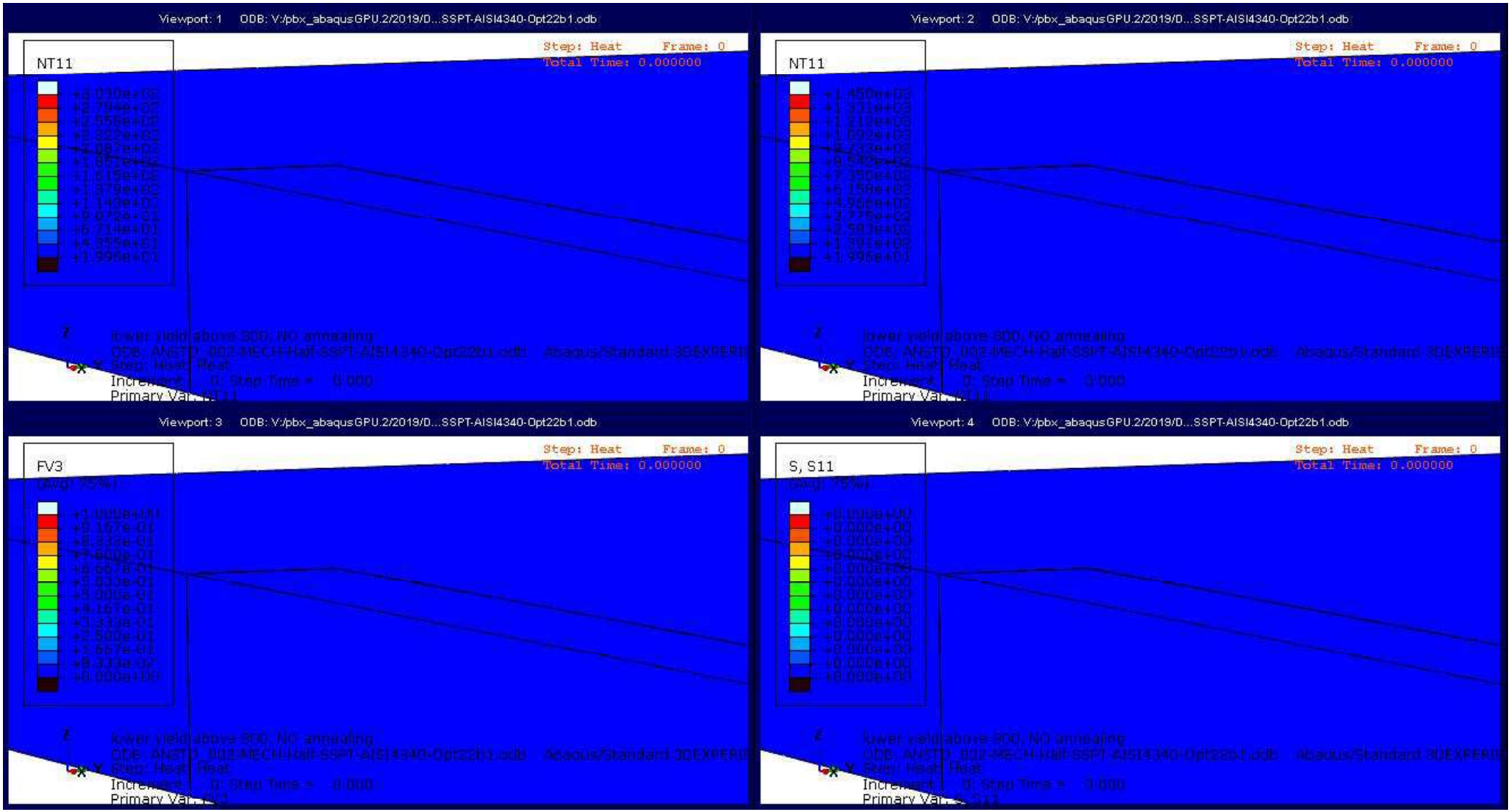
Material Model: 1) Isotropic Hardening
2) Kinematic Hardening
3) Mixed (Isotropic-Kinematic) Hardening





Reversal Yielding

Updated 4340 Model



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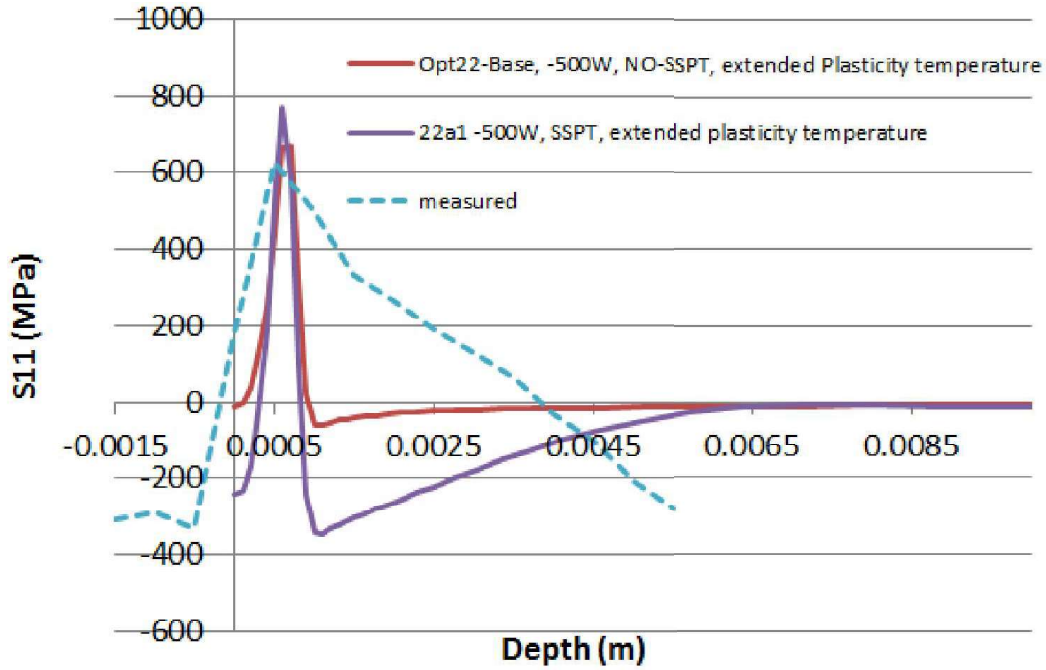
Preliminary Results for 4340 Model with ANSTO SSPT Routine



- Do see compression when SSPT is included
- Several aspects not yet modelled, i.e.:
  - Deposition of material
  - Multiple overlapping passes

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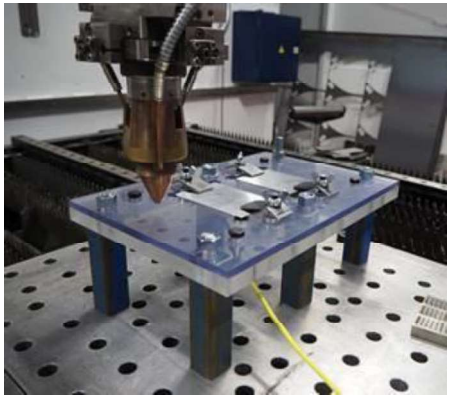
Comprehensive investigation into 316L and 300M Steels

- Experimental program
- Thermocouple measurements
- Infrared Camera Measurements
- Residual stress measurements including:
  - Contour
  - Neutron diffraction
- Metallography including:
  - Hardness maps
  - Microstructure and fusion zone assessment

Experimental Program with 316L and 300M Steel

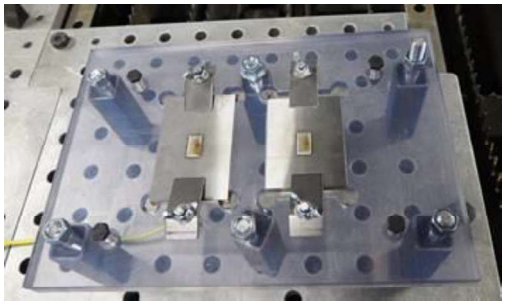
- 8 material samples for testing (4 x 300M, 4 x 316L)
- Mounting/retaining system to securely hold instrumented samples during the LD process
- Bespoke Data Acquisition Systems, each capable of logging 8 thermocouples at 100Hz for a five minute test period, one system per instrumented sample
- Tests of 8 material samples (4 x 300M, 4 x 316 S/S) undergoing LD in the Trumpf Laser at RMIT, Melbourne. Two of each material type were thermocouple instrumented, two were “dumb” samples subject to the same LD process. All samples were subjected to thermal imaging during the LD process
- Measurement of LD induced residual stresses in the “dumb” 300M and 316 Test Samples after LD, using 2 methods
  - The Contour (sectioning) method, and
  - The Neutron Diffraction method

Mount System



DAQ and Instrumented Sample

Two Samples after Deposition



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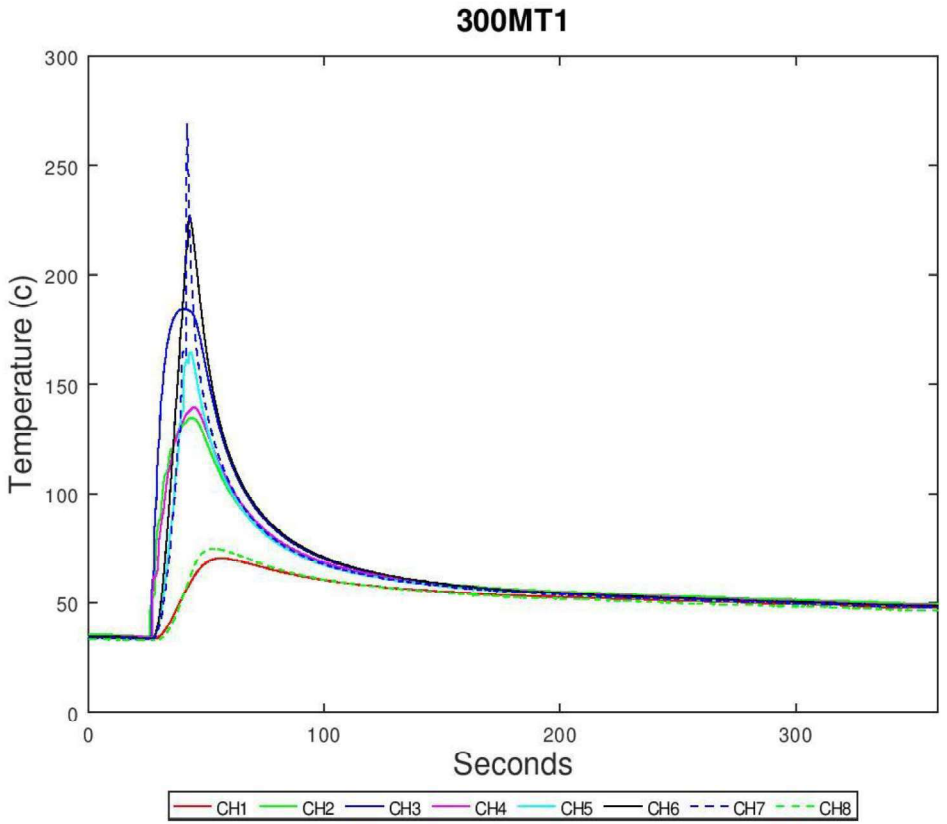
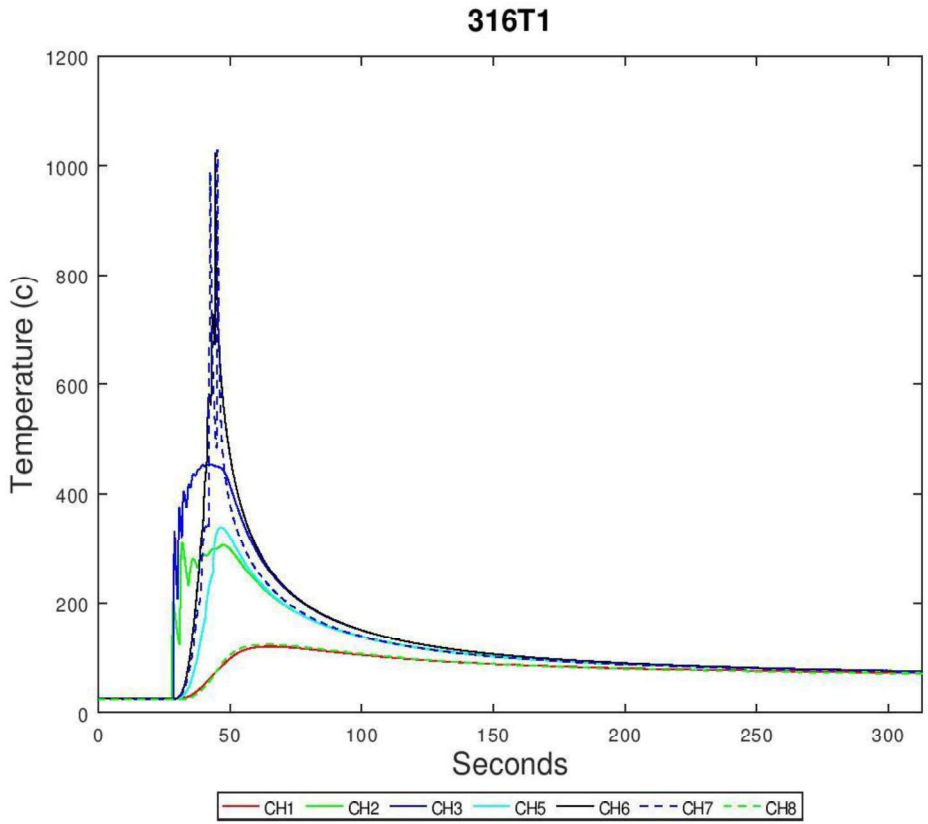
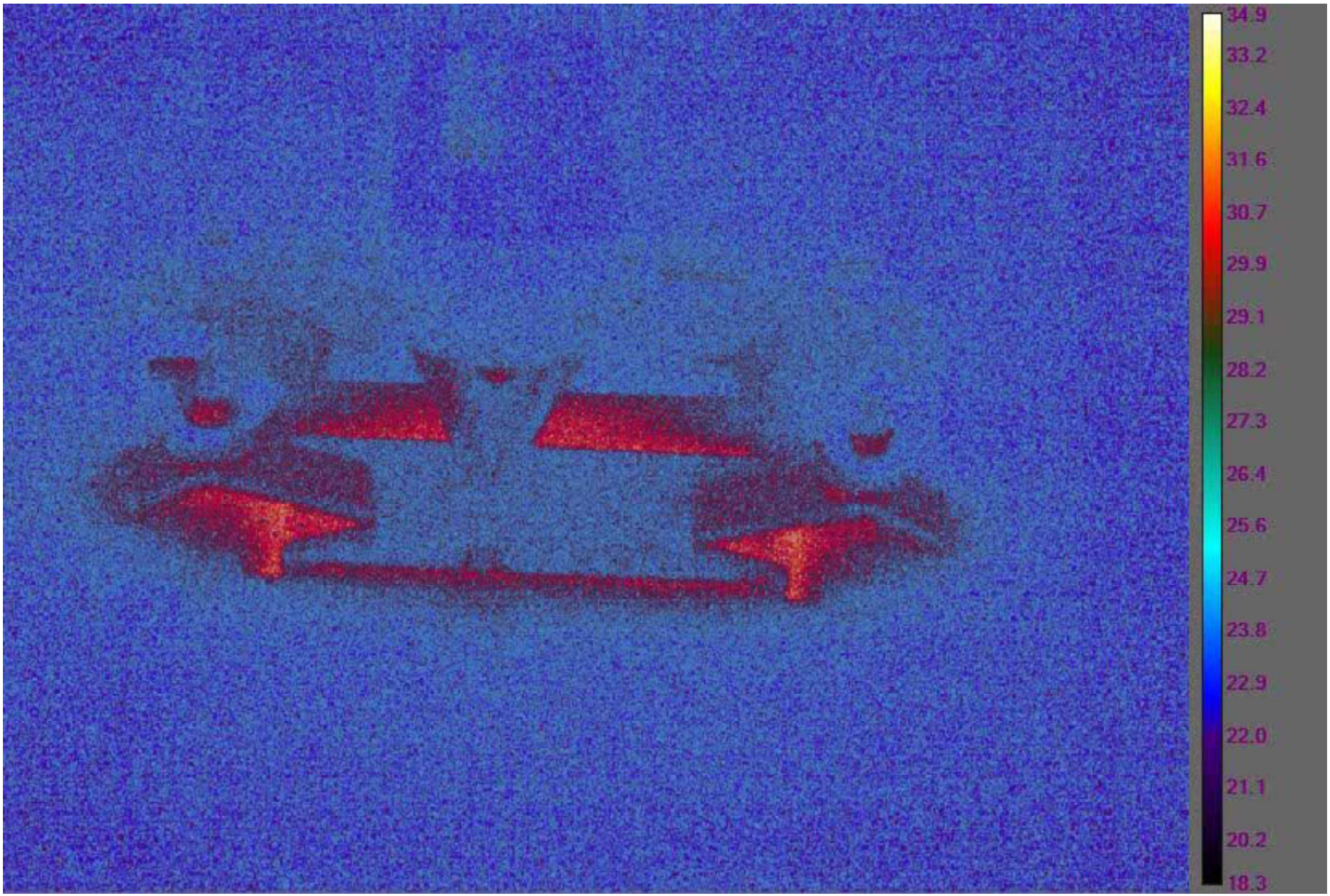
Typical thermocouple data





Typical Example Infrared Camera Results



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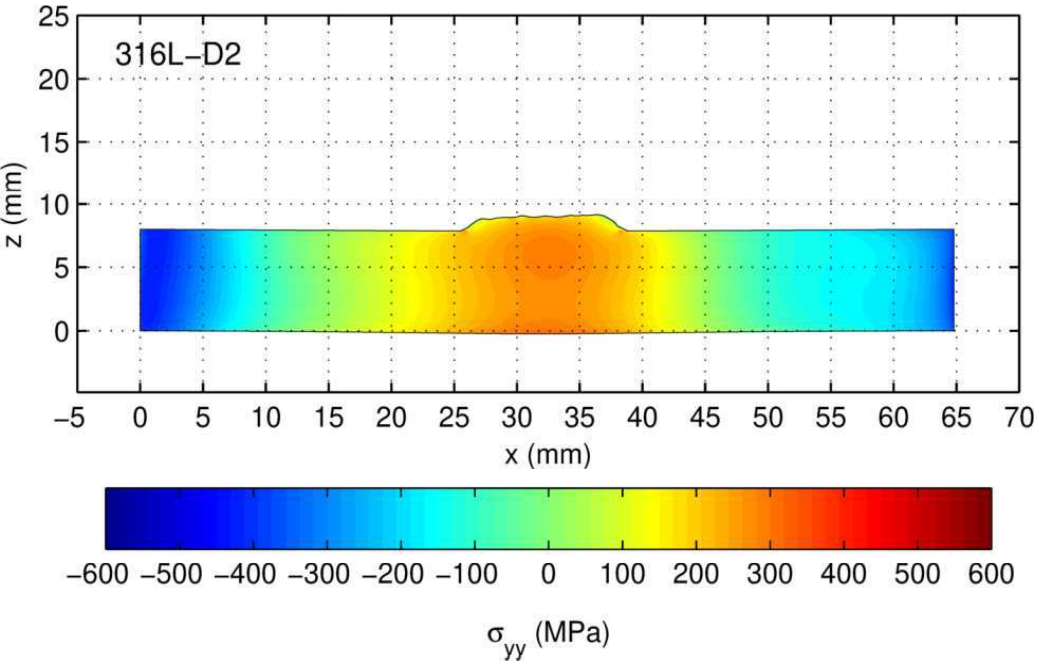
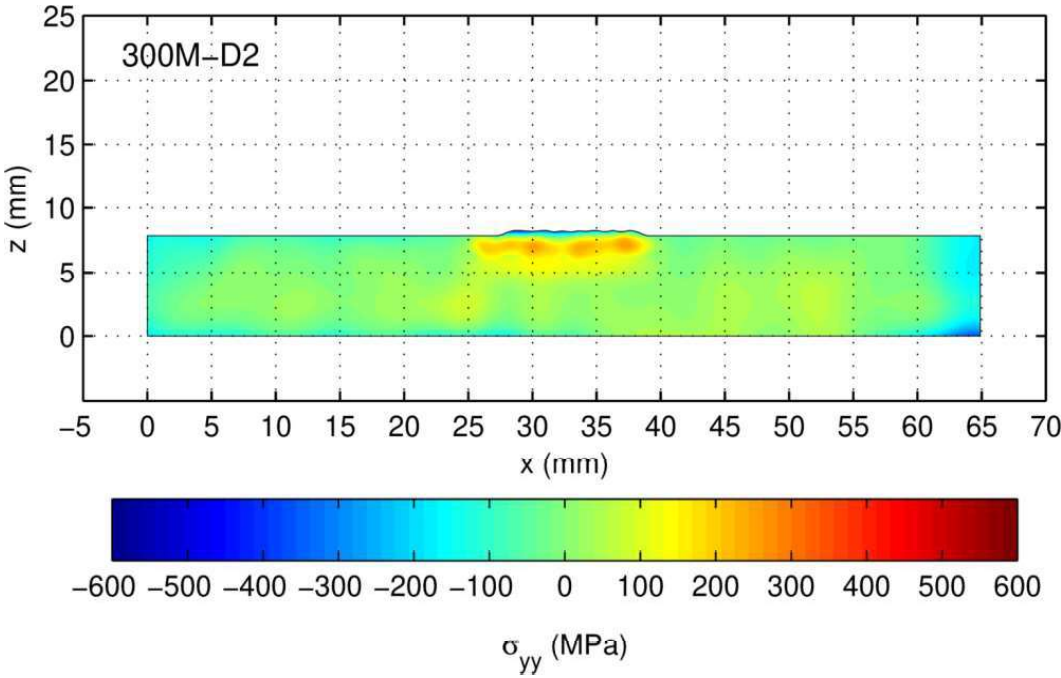
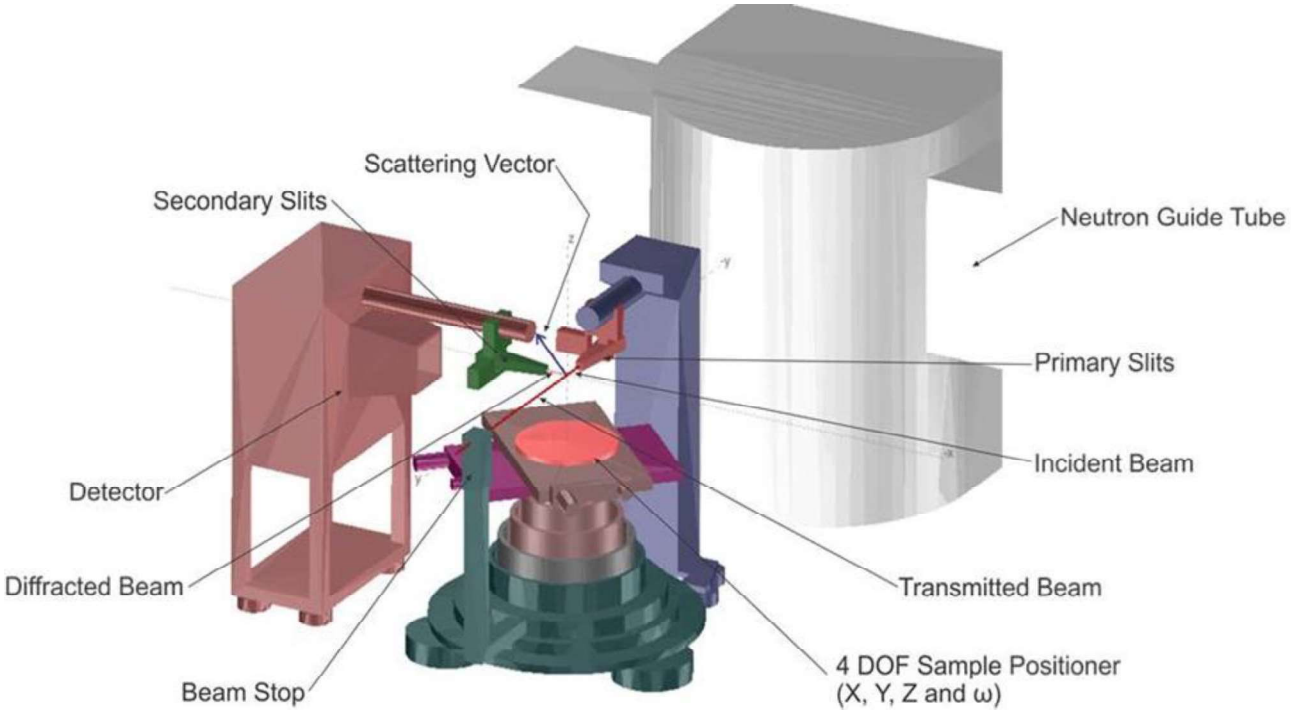
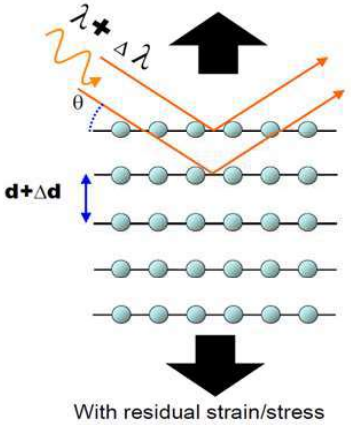
Contour Residual Stress Results





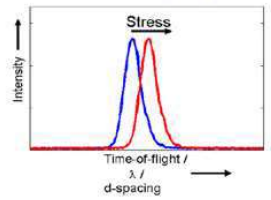
Neutron Diffraction Measurements with Kowari Instrument at ASNTO Lucas heights



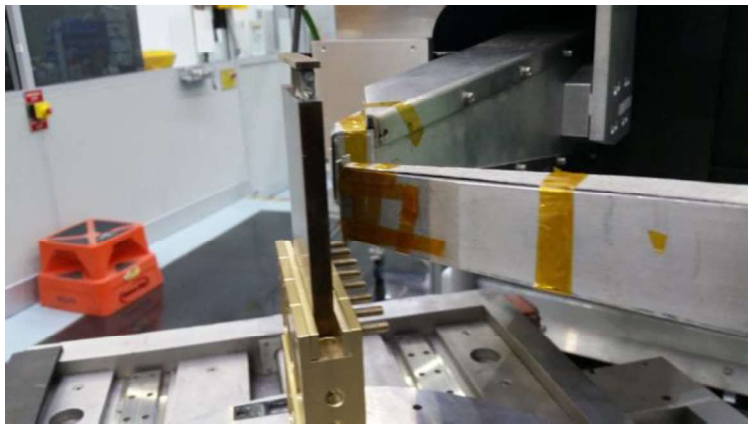


Bragg's Law:
$d = \lambda / (2 \sin\theta)$

Fixed angle θ: $\varepsilon = \frac{\Delta d}{d} = \frac{\Delta \lambda}{\lambda}$



Diffraction peak shift is used to determine residual strain and stress



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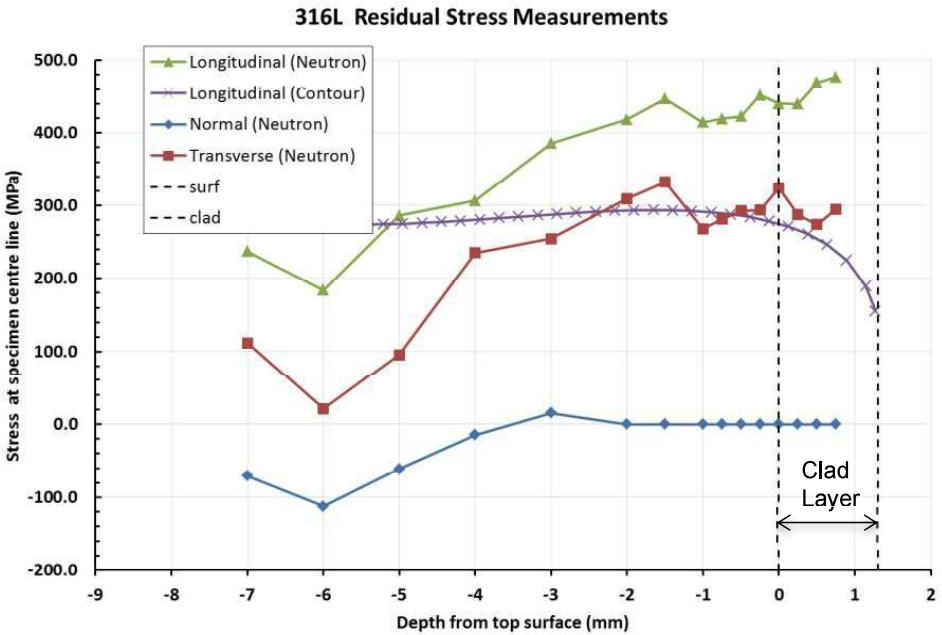
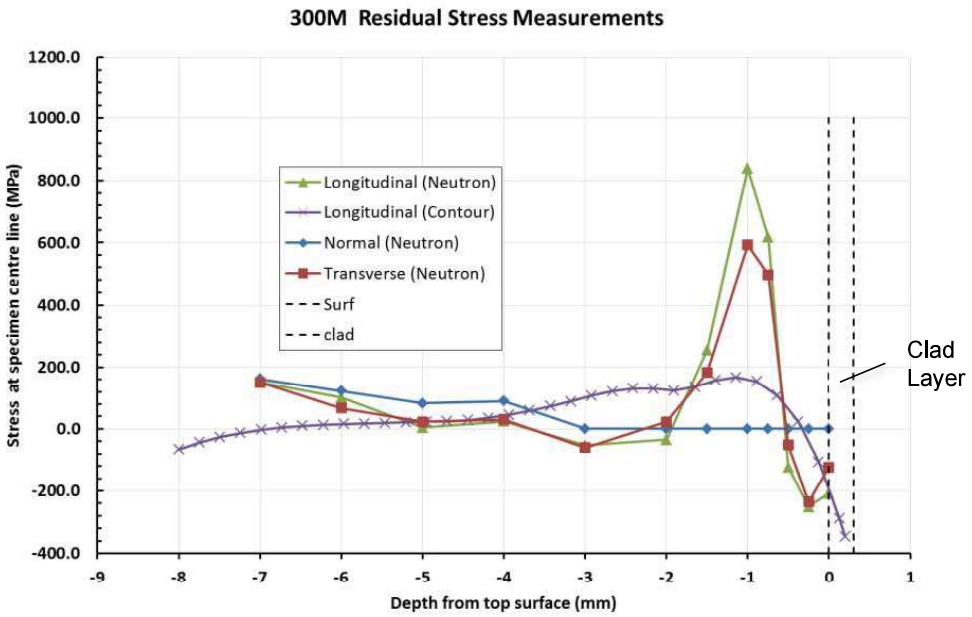
Neutron Diffraction and Contour Measurements



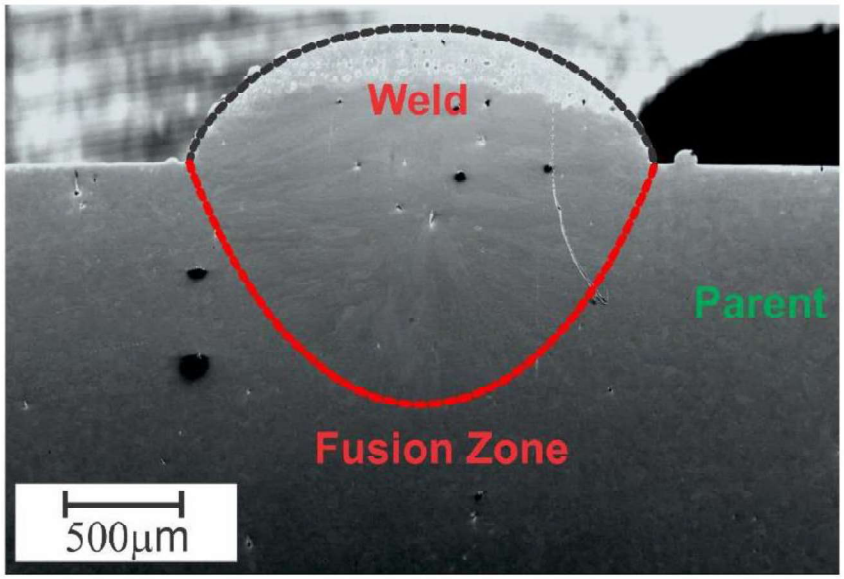


Observations:

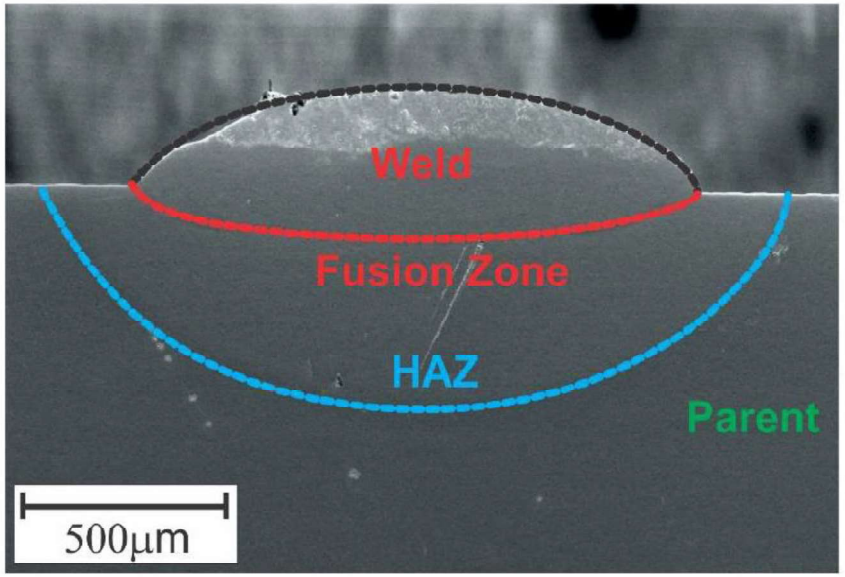
- Contour measurement less reliable near surface
- Both methods detect trend of significant stress gradient from compression to tension in the near-surface for the 300M. Similar to that observed with AerMet®100
- Tension peak for 300M detected with Neutron is localised and may not therefore be detected with the contour method
- Results still being assessed

316L and 300M Fusion Zone

316L Single Pass



300M Single Pass



w/o SSPT

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

elastic strain

plastic strain

thermal strain

w/ SSPT

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

metallurgical transformation strain

transformation-induced plastic strain

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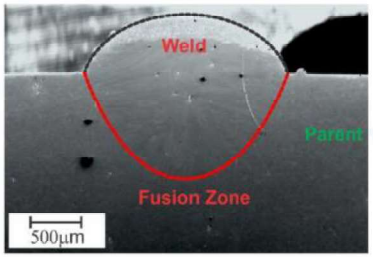
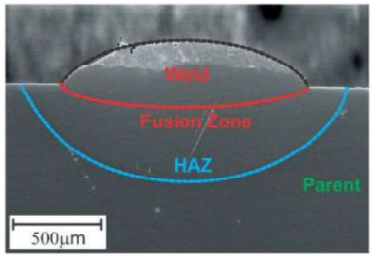
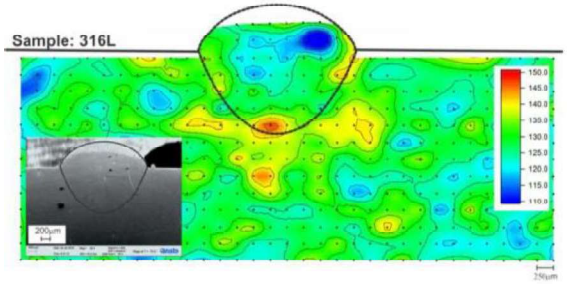
316L and 300M Hardness

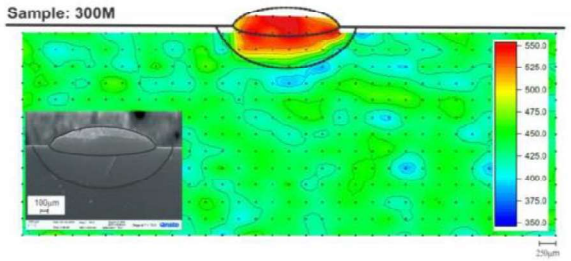
316L Single Pass



300M Single Pass







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Observations:

- Hardness measured with nano-indenter
- Increased hardness in 300M clad due to fast cooling rate which affects phase transformation and final hardness of martensite
- 316L – no phase transformation and therefore hardness is similar across all regions

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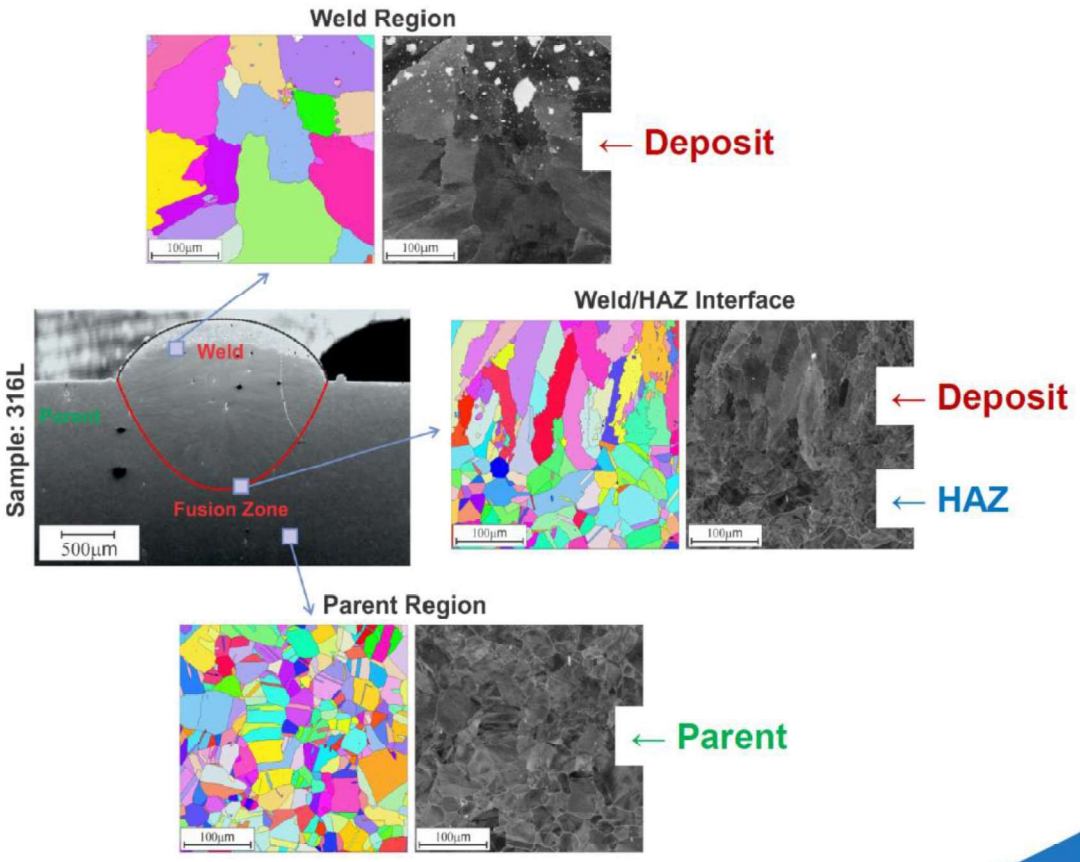
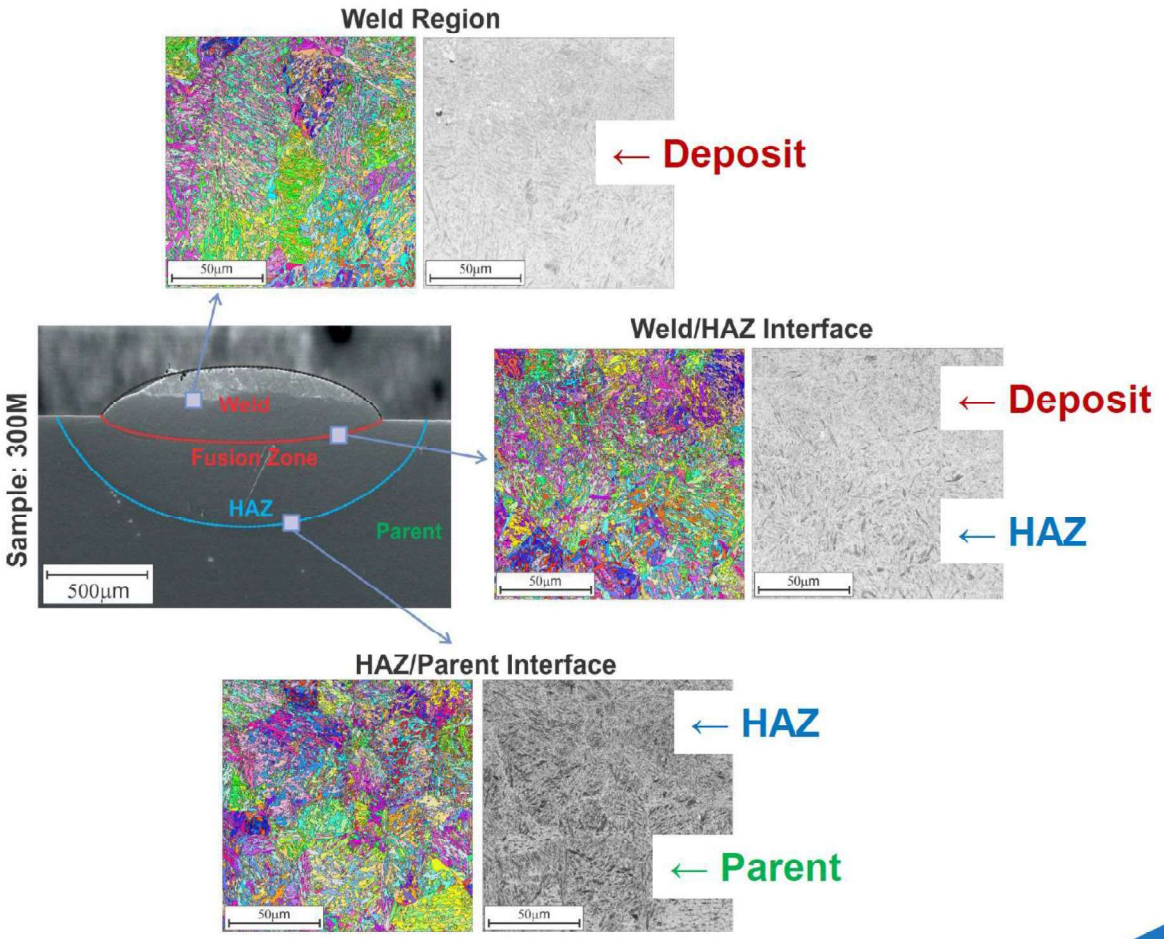
316L Cladding Microstructure



Observations:

- Significantly larger austenite grains in the clad (weld) material compared with the parent
- Austenite grain growth in the direction of heat flow in the weld/HAZ interface region

300M Cladding Microstructure



Observations:

- Microstructure morphology is similar in clad (weld), HAZ and parent
- However, there is evidence of larger prior-austenite grains in the clad (weld) than HAZ and parent material

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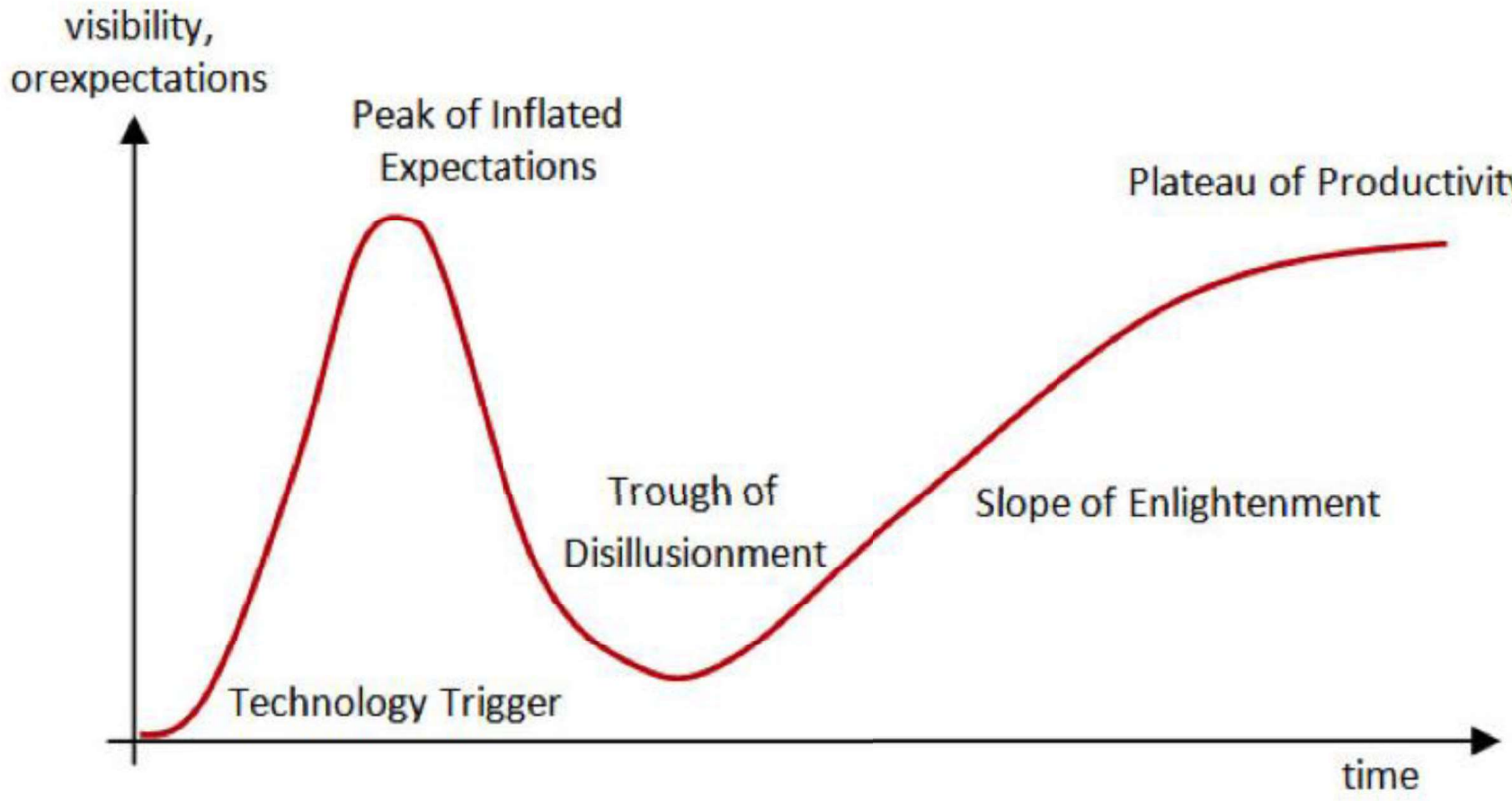
Conclusion and Future Work

- Laser Cladding (LC) is emerging as a viable and attractive structural repair option for critical and expensive steel aerospace components and structures
- Development and validation of modelling to support repair design, substantiation and certification progressing well
- Ongoing and future work includes:
  - Completion of model development for 300M steel
  - Develop the application for an in-service component with representative damage (eg. F-35A nose landing gear piston)
  - Extension to other material systems including Titanium and Aluminium alloys

A Challenge for Laser Cladding Repair Application:

- Avoid the “trough of disillusionment” where ongoing investment is needed to mature the technology



Questions?