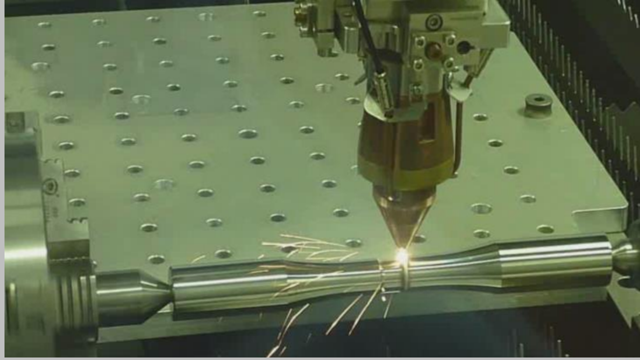
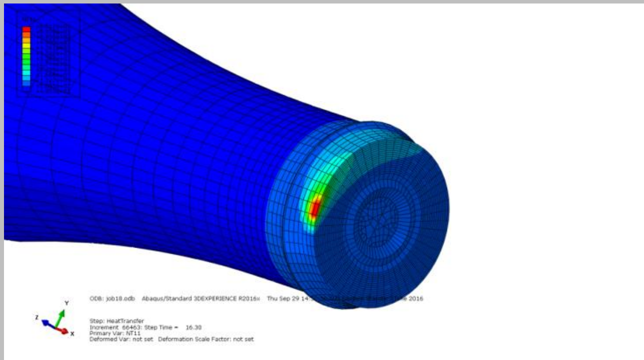
Additive Manufacture Simulation - Laser Deposition





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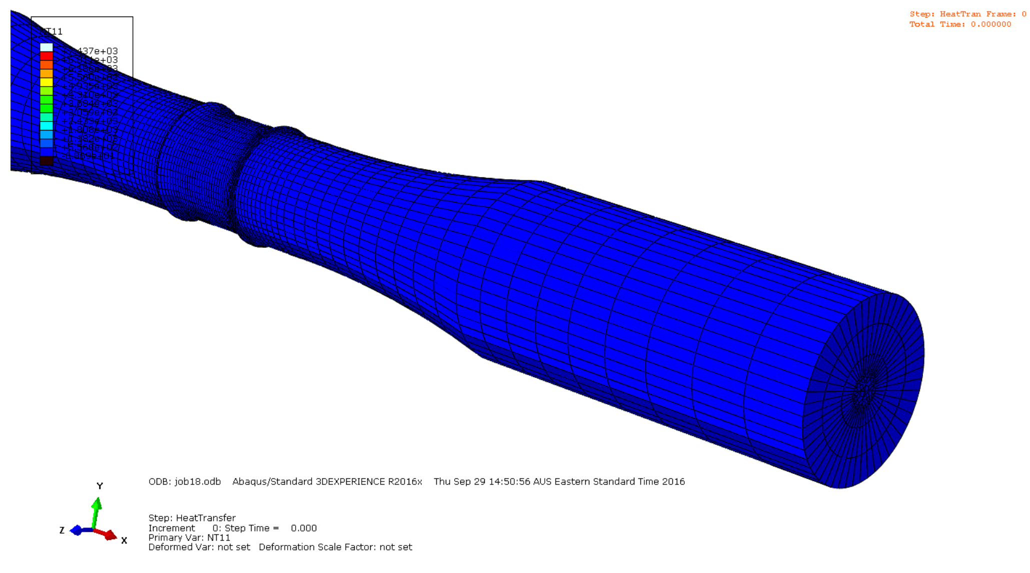
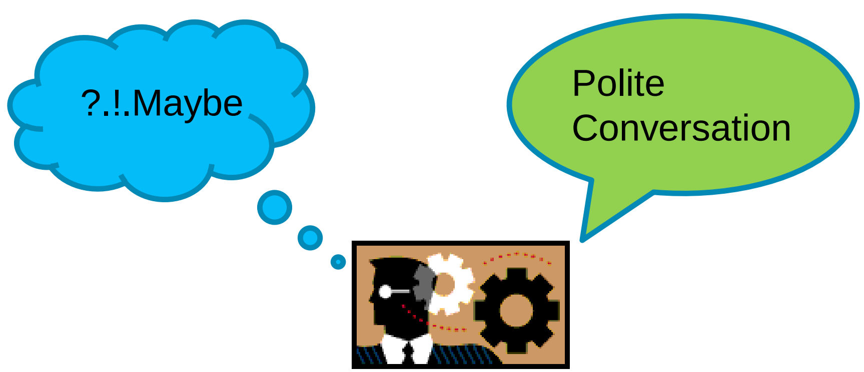
Outline

1. Background
2. Introduction
3. Material Model Development
4. Thermal Loads Development
5. Thermal Analysis
6. Residual Stress Analysis
7. Correlation
8. Literature Review
9. Evaluation
10. The Next Steps

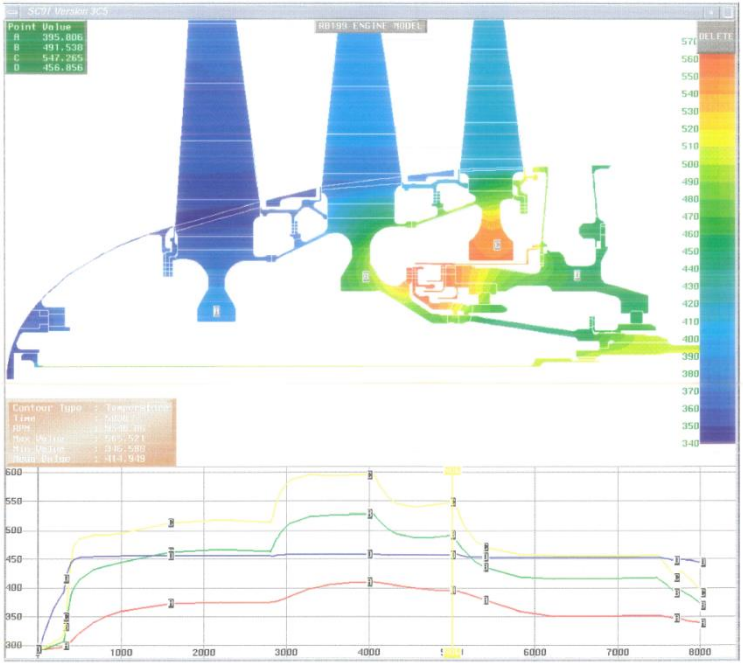


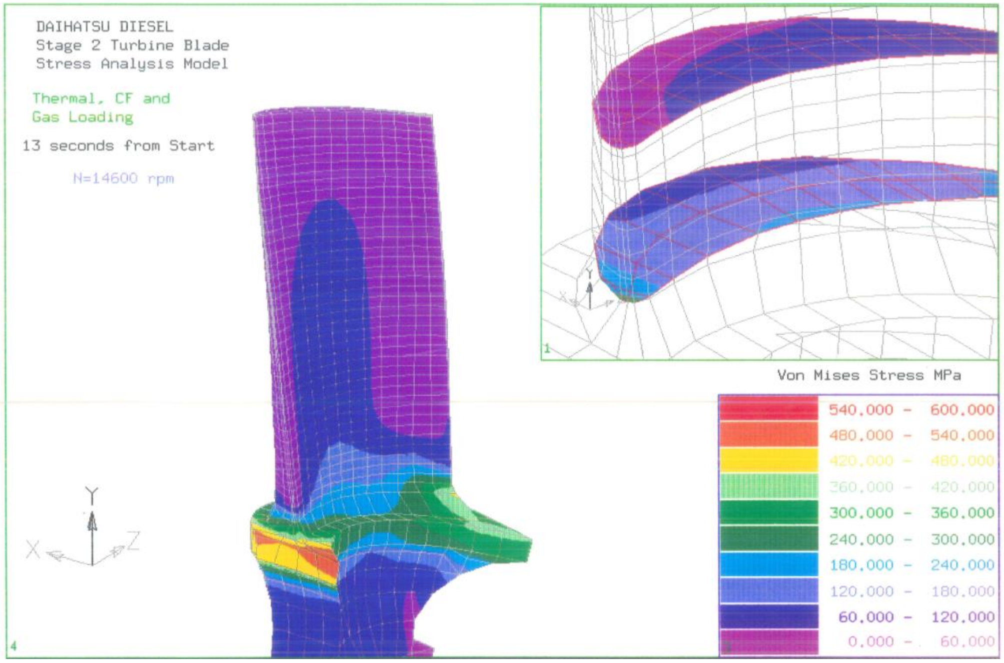
1. Background

- In July 2015 Kevin Walker mentioned in conversation one of his current areas of interest in additive manufacturing and part restoration for the Aero Division at DST Group
- Kevin is looking at the processes of additive manufacturing applied to part restoration by the addition of material by the melting of metal powders (with a laser heat source), and is interested in the residual stresses this process incurs
- From a background of experience in carrying out transient thermo-mechanical analyses using Finite Element Analysis on gas turbines, I suggested to Kevin that we might have a good chance of being able to analytically predict the residual stress – if we construct a good thermal model coupled to an elastic-plastic non-linear structural model representation



1. Background





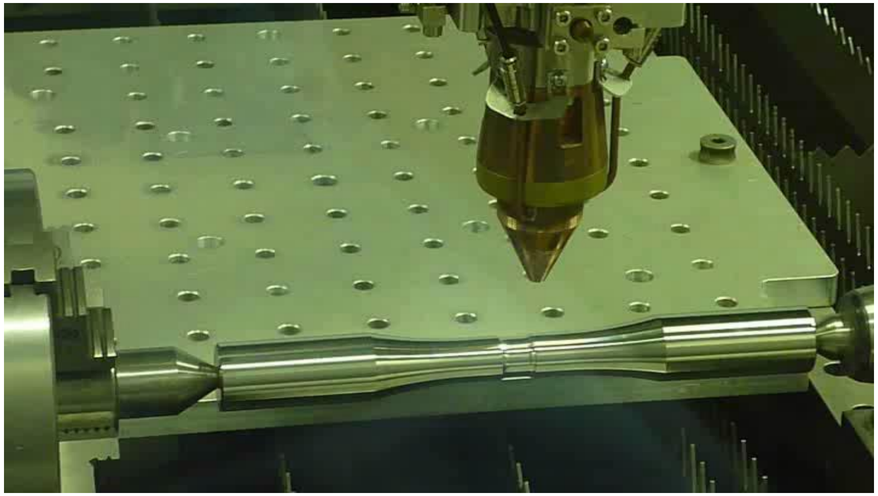
- Kevin obtained task funding in 2016, and we (QinetiQ) started on modelling his AIRMET 100 and 4340 laser additive manufactured test samples, using ABAQUS
- In 2017 we obtained further internal research and development funding from QinetiQ (under the QinetiQ IRAD program) to enable further work to be done – this is planned as a joint collaborative venture with DST Group

2. Introduction

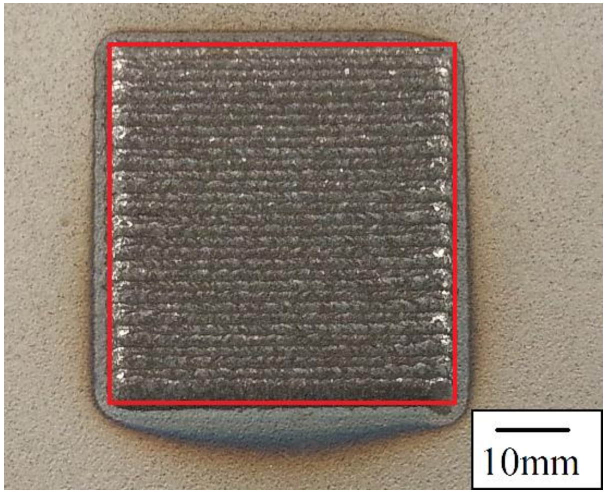
In 2016 DST Group tasked QinetiQ to develop a Finite Element Analysis (FEA) Simulation of Laser Deposition process

- QinetiQ to simulate laser deposition on
  - AirMet 100 Cylindrical Bar Test Specimens
  - AISI 4340 Steel Rectangular Plate Samples
- Test data (thermal profiles and measured residual stresses) available

AIRMET 100



AISI 4340 STEEL



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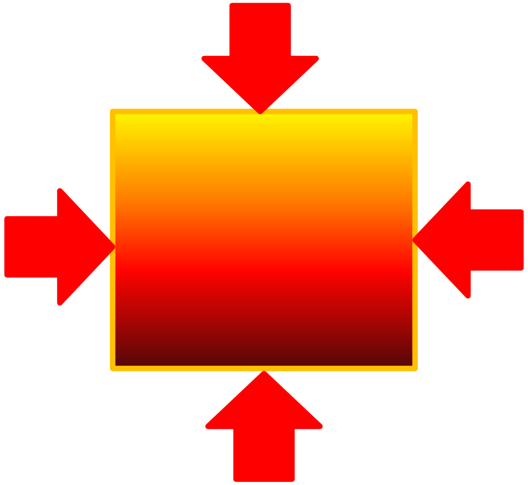
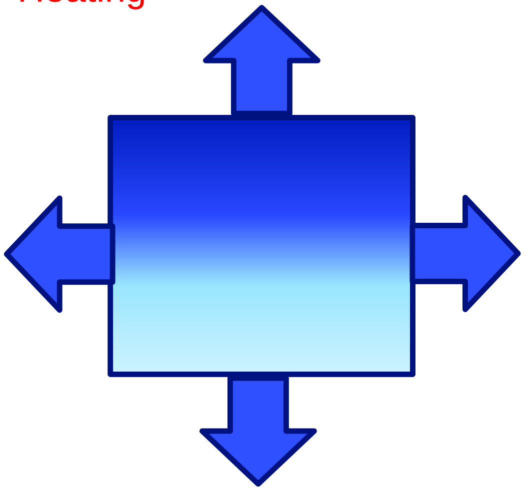
2. Introduction

Fundamentally, the expectation is that the final residual stress state is primarily governed by plastic yielding under constrained transient thermal growth and contraction, and the process of melt-pool dynamics and other complexities associated with material addition need not be included in the model - to obtain residual stresses



Constrained Expansion under Heating



Constrained Contraction under Cooling

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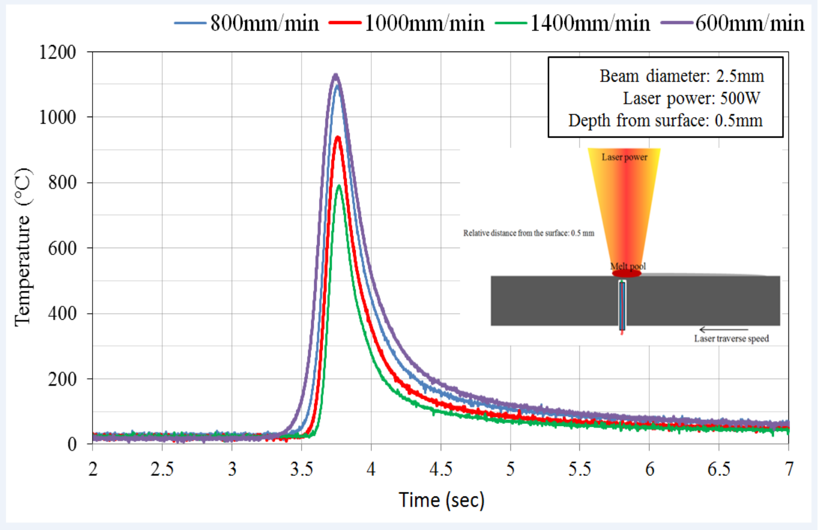
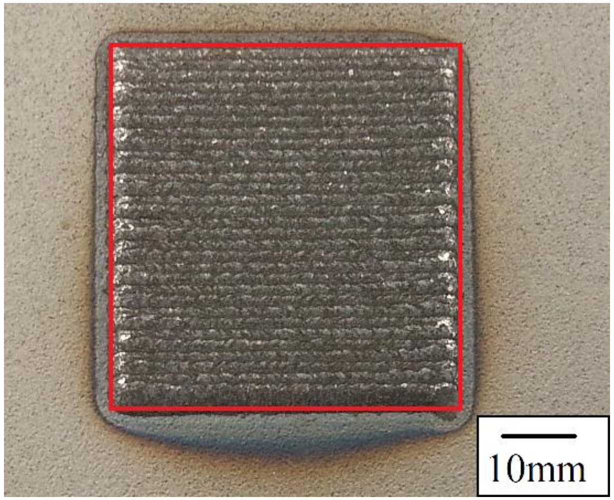
2. Introduction

- Additional 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





3. Material Model Development

- Make use of Material Data in the Public Domain
  - Thermal conductivity
  - Thermal expansion coefficient
  - Specific heat
  - Retained yield strength
  - Elastic modulus
  - Stress- strain curve (room temperature only)
- Additional Material Data Requirements
  - Stress-strain curve as function of temperature, strain rate
  - Material model development required

All with temperature dependence

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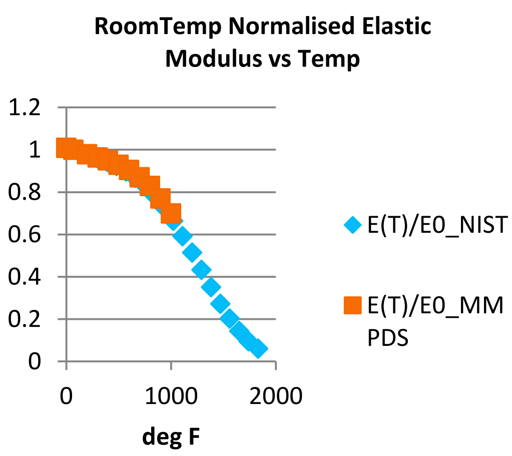
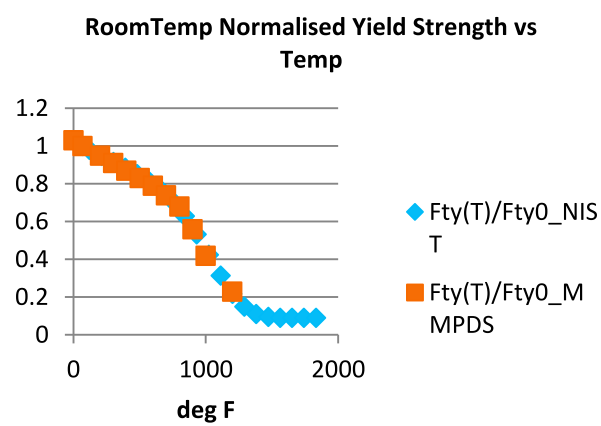
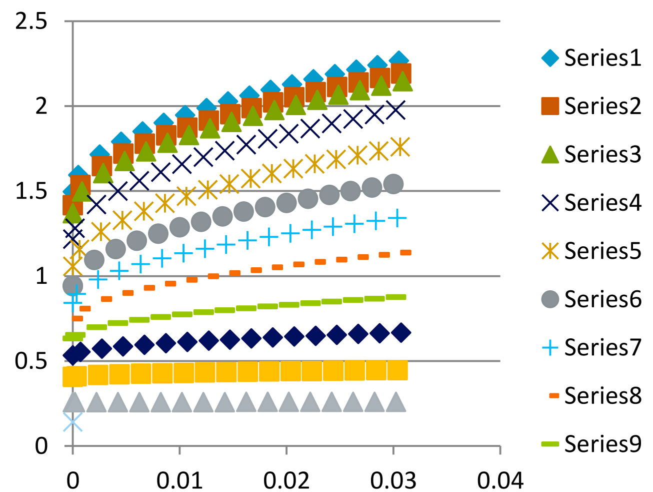
3. Material Model Development

- U.S. National Institute of Standards (NIST) and Technology Study
  - Elevated temperature behaviour of 42 structural steels with reference to World Trade Centre collapse
  - Elevated temperature material model extensible to generic structural steels
  - Temperature & strain rate dependencies included
- NIST model customised using AISI 4340 specific data (from MMPDS)
  - Parameters adjusted to achieve best fit against available data
  - Stress-strain curve obtained as function of temperature, strain rate



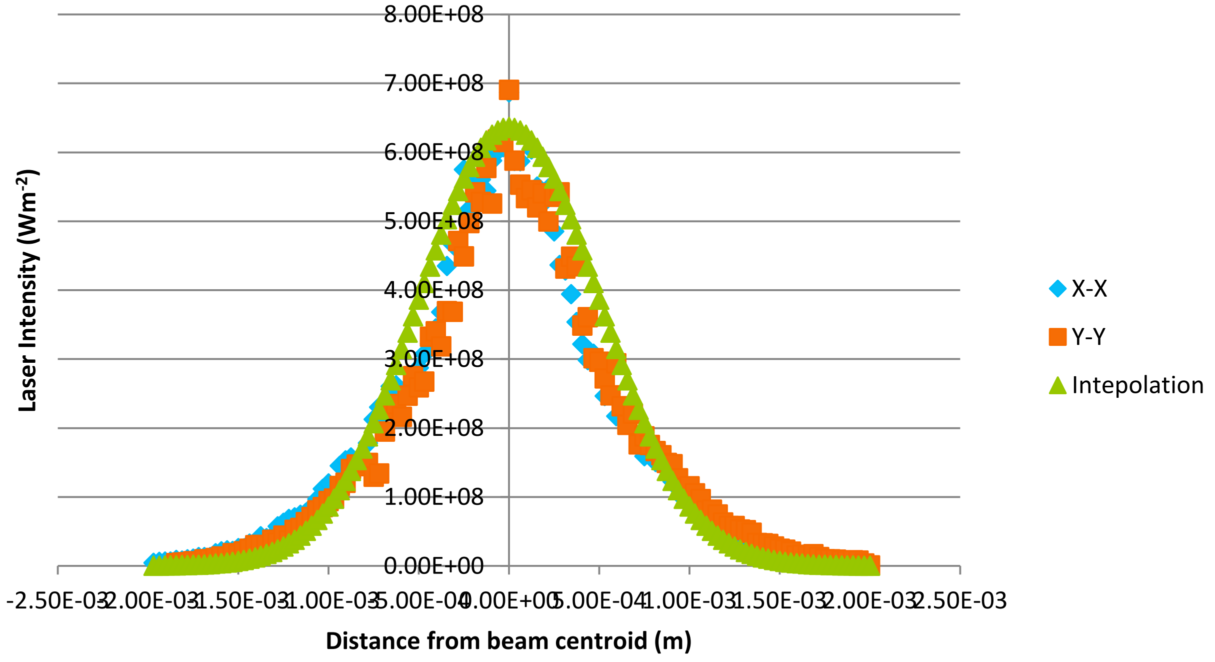




4. Thermal Loads Development

Laser profiling conducted on Rofin Sinar equipment used in AISI 4340 experiments

- Curve fit assuming Gaussian distribution
- Match power under surface

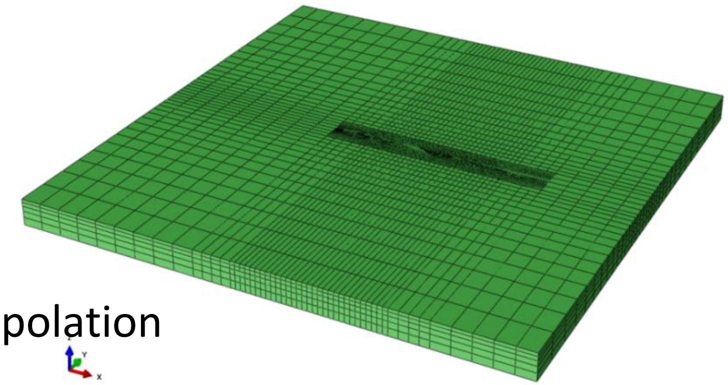


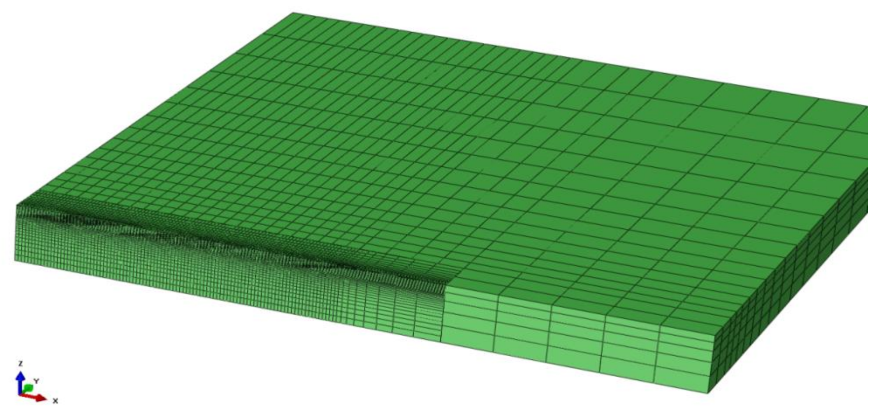
Laser Profile Showing Experimental and Interpolated Curves

5. Thermal Analysis - Inputs

Transient Thermal Finite Element Analysis

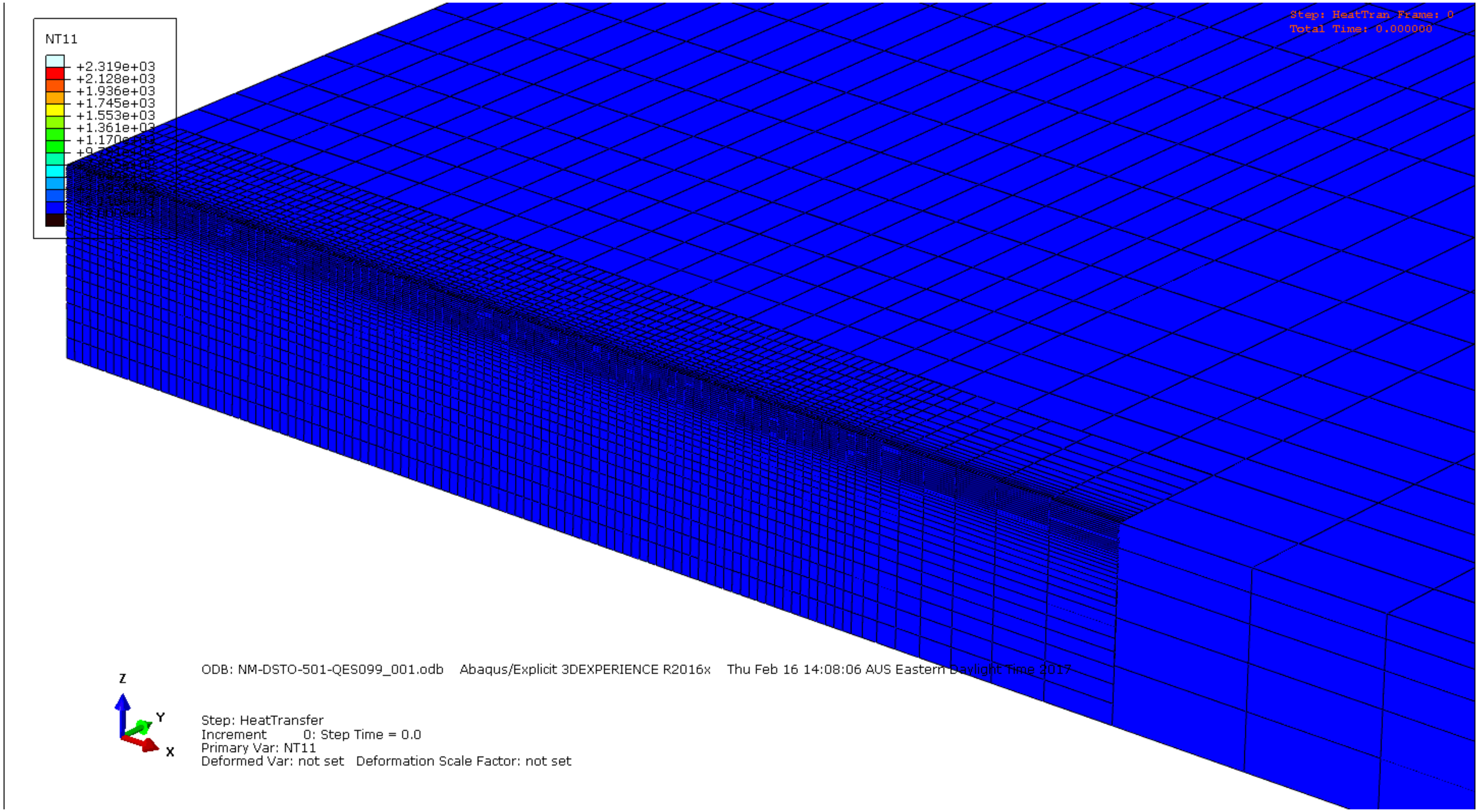
- ABAQUS 2016 Software
- Temperature field modelled using explicit solver
  - Decoupled from displacement field
- Thermal load scaled from laser beam profile interpolation
- Conduction out through Plate Supports shown to have negligible effects in the time-frame considered
- Convection & radiation heat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





5. Thermal Analysis – Results 1

AISI 4340 Plate Quarter Model – Full Scale Temperature Range



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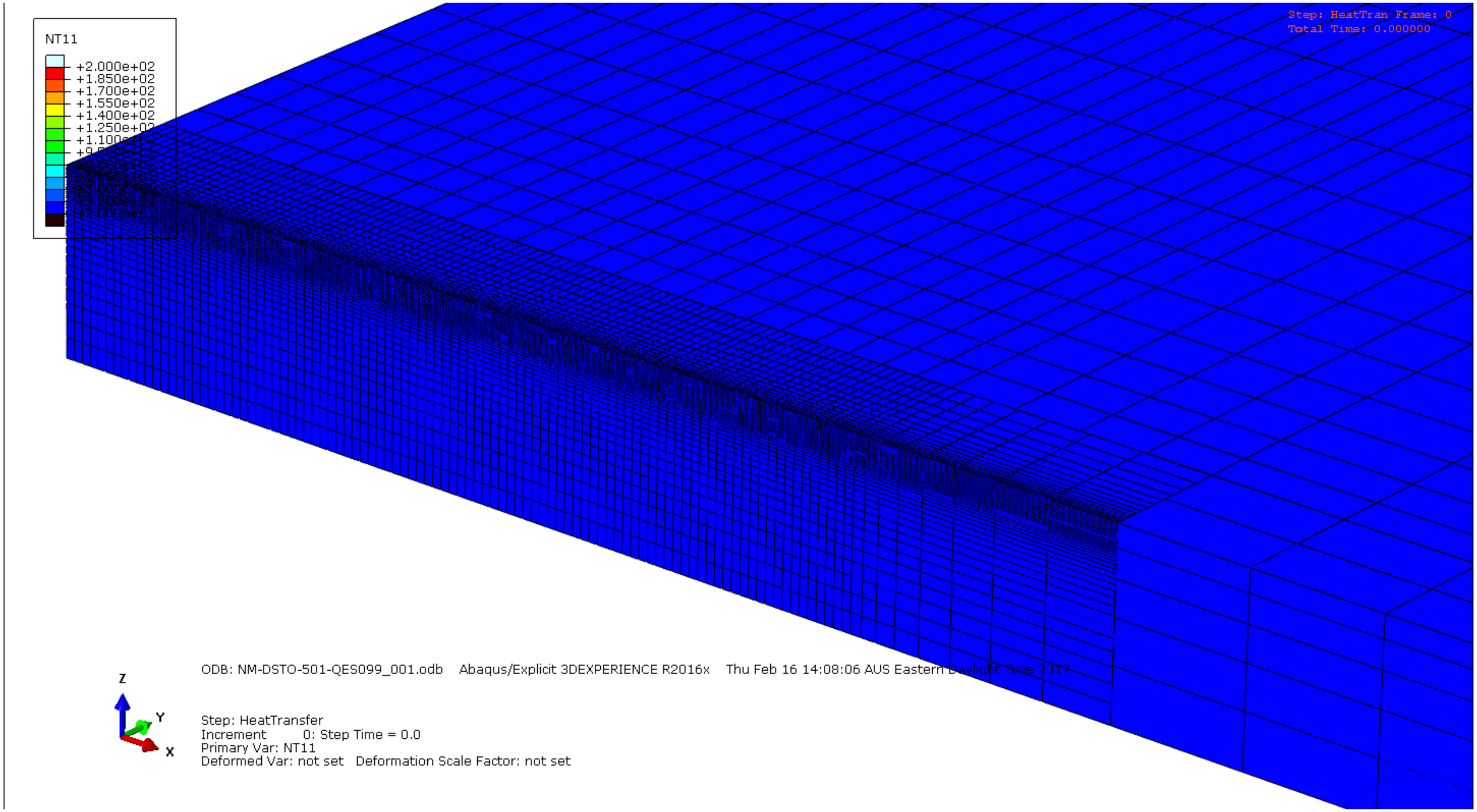
5. Thermal Analysis – Results 2

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



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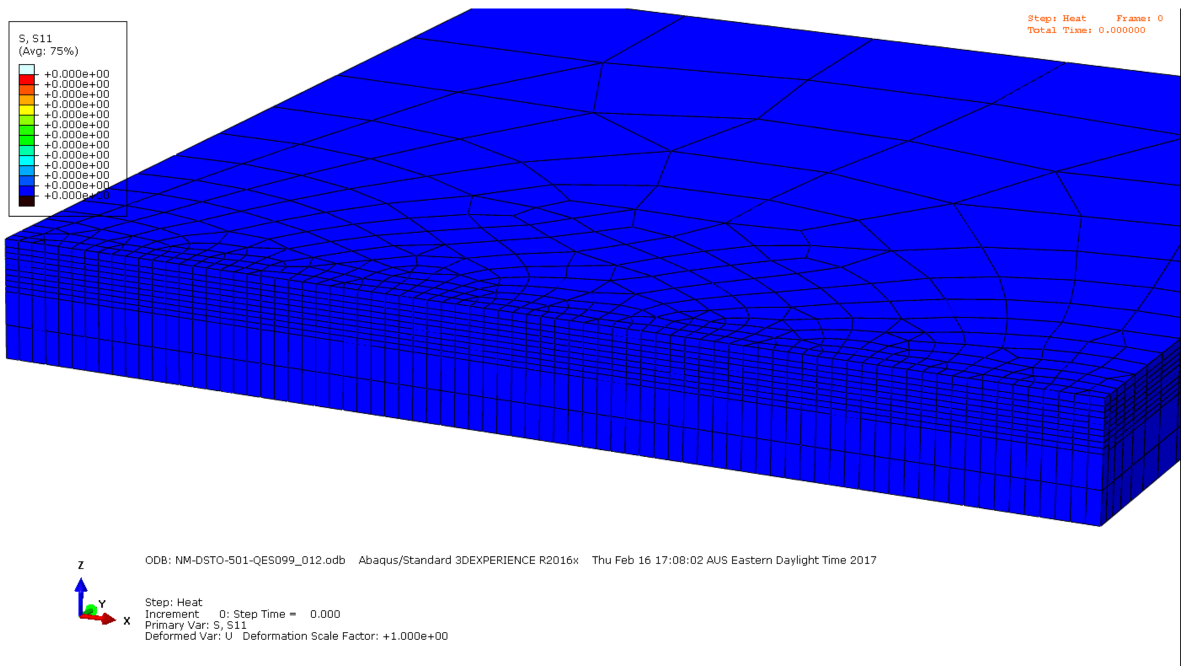
6. Residual Stress Analysis - Results

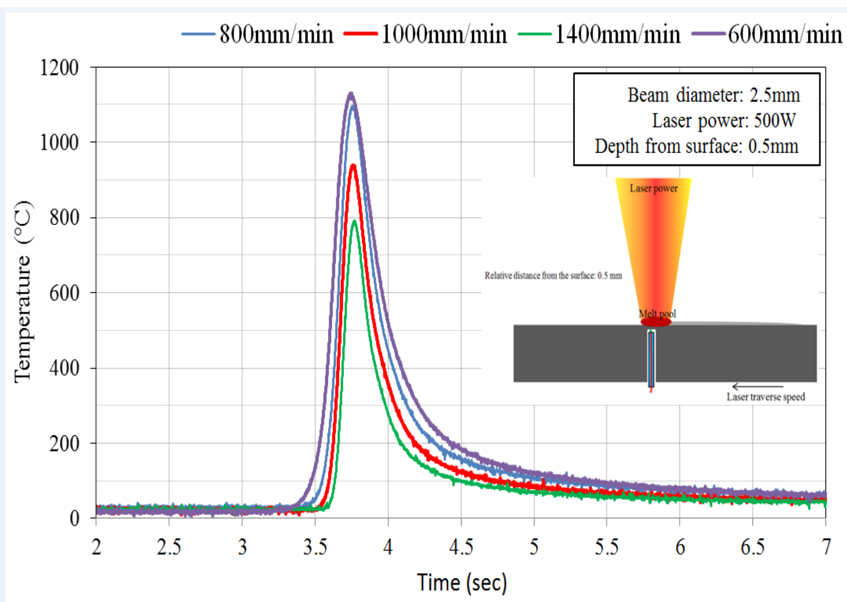
- Displacement (strain) field modelled using ABAQUS 2016 implicit solver
  - Sequentially coupled to temperature field
- Distributed time-point body temperature from transient thermal analysis
- Stress development from constrained thermal expansion/contraction
- Total 7.5 seconds of simulation



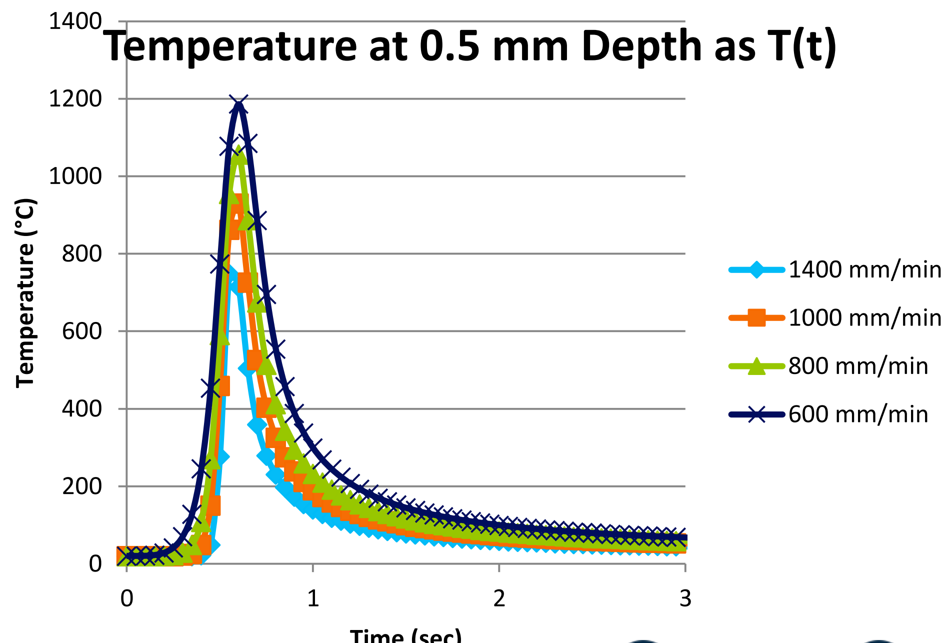
7. Thermal Model Correlation

- 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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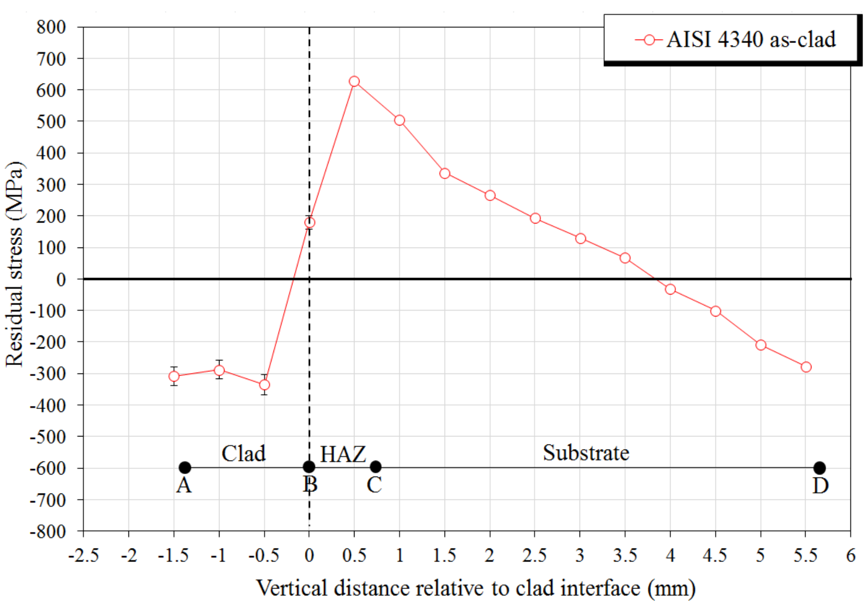
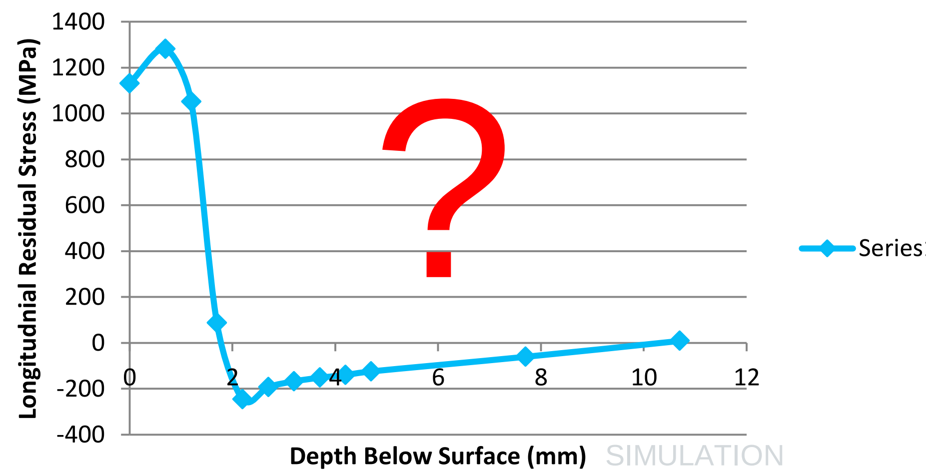
7. Residual Stress Model Correlation

- Stress profiles appear reflected about horizontal axis
- Apparent similarities
  - Presence of areas above & below zero line indicate static equilibrium
  - 2 inflection points within 2 mm of surface – (~1 and 2 mm depth both cases)

EXPERIMENT



SIMULATION

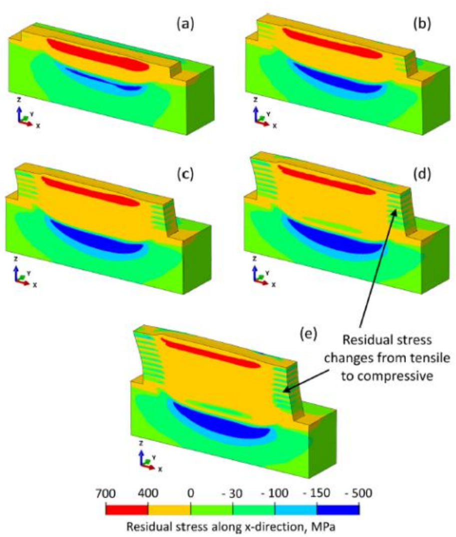


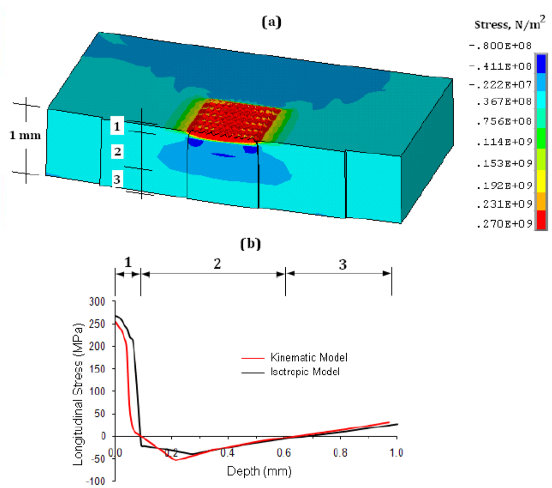
8. Literature Review

Brief literature review to try and understand the differences in results

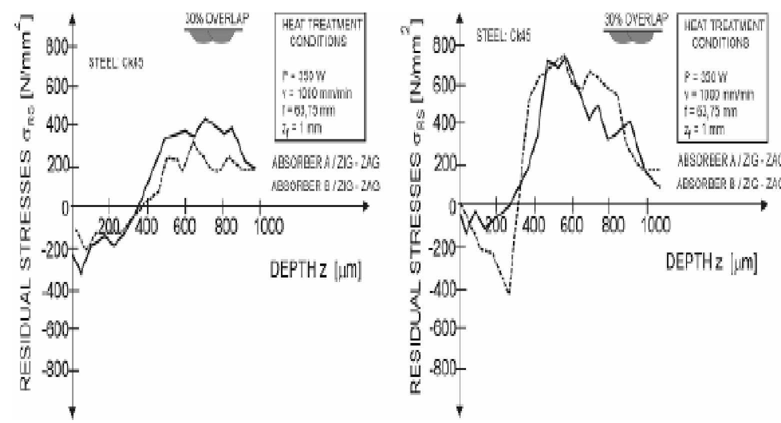
- Both profiles (surface tension/sub-surface compression, surface compression/sub-surface tension) represented in literature from both analysis and measurement
  - Demonstrated through assortment of additive manufacturing processes
    - Direct Energy Deposition - variations in powder delivery mechanism
    - Wire fed DED / welding
  - None directly comparable to Aermet 100/ 4340 experiments
  - Otherwise sufficiently similar in terms of loading & boundary conditions

SURFACE IN TENSION





SURFACE IN COMPRESSION



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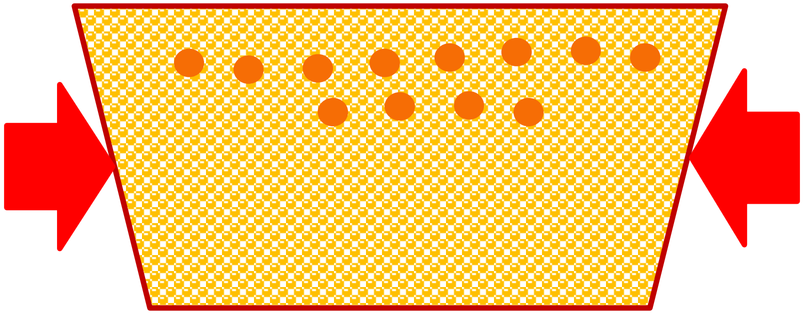
9. Evaluation- What's Happening?

From the case studies reviewed:

- 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
- 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



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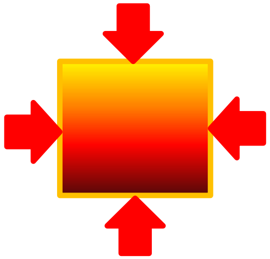
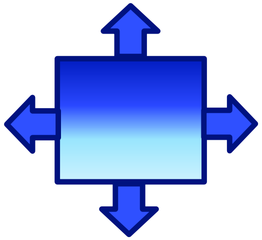
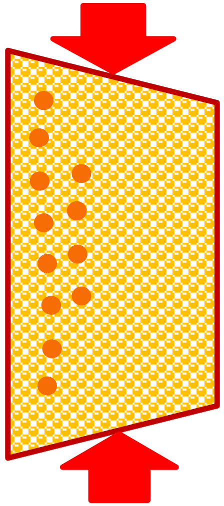
10. The Next Steps

- Test the FEA model:
  - Choose a Material that is not subject to significant Phase Changes
  - Conduct, thermal profile, laser deposition and residual stress measurements on material samples
  - Create FEA Model with appropriate thermal conditions, material model and predict residual stresses
- Extend the existing Material Model to one that can accommodate thermal expansion/contraction induced plastic strains plus temperature transient induced phase changes (causing additional volumetric strain)
  - Local phase changes will depend on local temperature and temperature transients
  - Will cause a step-change in local volume at phase transition of the local material volume
- Test the new Material Model on new analyses and tests for predicted and measured residual stress







Questions
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