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Additive Manufacturing: Simulation of Distortion for Different Processes

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COMSOL
CONFERENCE
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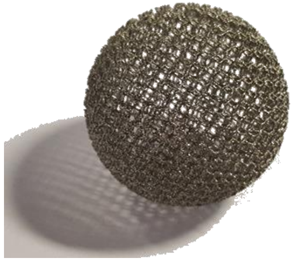
ADDITIVE LAYER MANUFACTURING (ALM)

Powder-Based ALM:

- Selective Laser Melting (SLM)
- Electron Beam Melting (EBM)
- The parts are built-up by locally melting a thin layer of metal powder
- High accuracy
- Localised heat affected zone
- Slow build up time



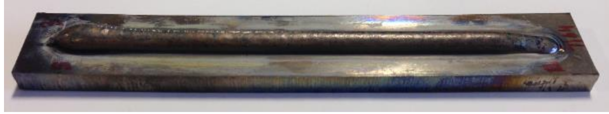
Top: *Hollow sphere built with a 3D lattice*

Bottom: *Calibration specimen used for FEA modelling of Powder-Based ALM*

Shaped Metal Deposition ALM:

- The desired shape is achieved by welding a continuous metal wire onto a substrate
- Larger deposition rates
- Accepts dissimilar materials
- Large heat affected zone

Layer 1: *Neat first deposit*



Layer 2: *Visible sliding of molten layers*

Layer 6: *Observable distortion in substrate*

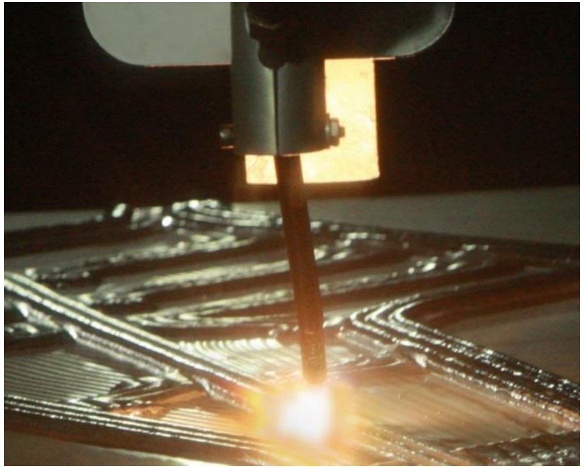
WHY MODEL ALM PROCESSES?

ALM processes are not fully understood due to their complexity

- Many heat cycles are involved, which remove/overwrite temperature history
- Complicated microstructure evolution of alloy materials
- Undesired distortion and residual stresses

Modelling can help identify:

- A suitable calibrated material model
- Methods to reduce residual stresses and distortion
  - Through parametric studies of key process parameters, which can include heating or cooling effects



http://additivemanufacturing.com/2013/03/25/sciakys-dm-solution-game-changing-technology/

THERMOMECHANICAL MODEL

- Domain ODE + previous solution
  - The field variable controls the “activation” of the newly molten material based on the tool position and current layer height; maintaining it active once the pass is complete
- Heat Transfer
  - Moving heat source
  - External convection/radiation to the environment
- Structural Mechanics
  - Clamping and unclamping of the part
  - Elastoplastic material model
- Thermal Expansion Coupling
- Sequentially-coupled
  - Activation → Heat Transfer → Structural Mechanics

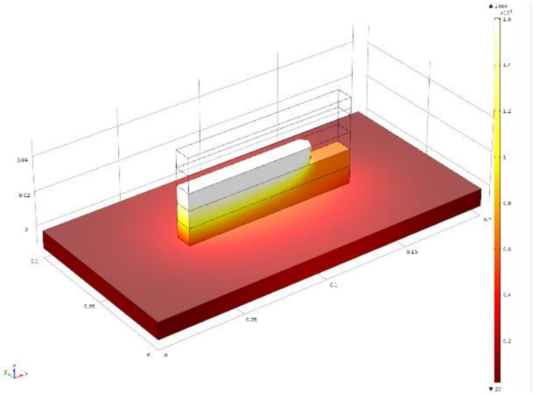


Figure 1: *Component temperature and active elements during the build up*

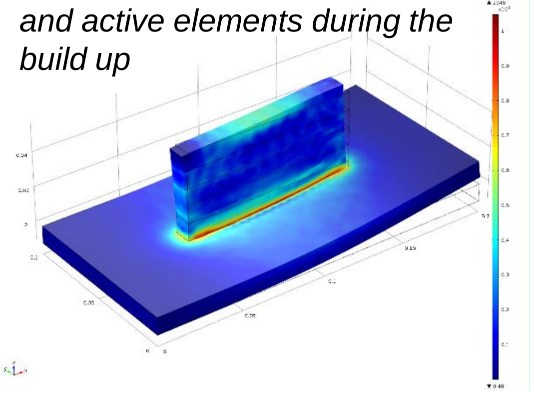
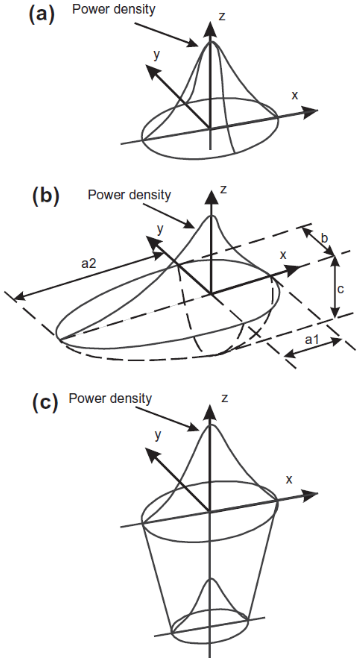


Figure 2: *Residual stresses after release (Von Mises)*

HEAT SOURCE MODELS



a) Surface Disk Source

$$q(r) = q(0)e^{-Cr^2}$$

b) Goldak Double Ellipsoid Source

$$q_f(x,y,z,t) = \frac{6\sqrt{3}f_f Q}{abc_f\pi\sqrt{\pi}} exp\left(-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{\left(z-(vt)\right)^2}{c_f{}^2}\right)\right)$$

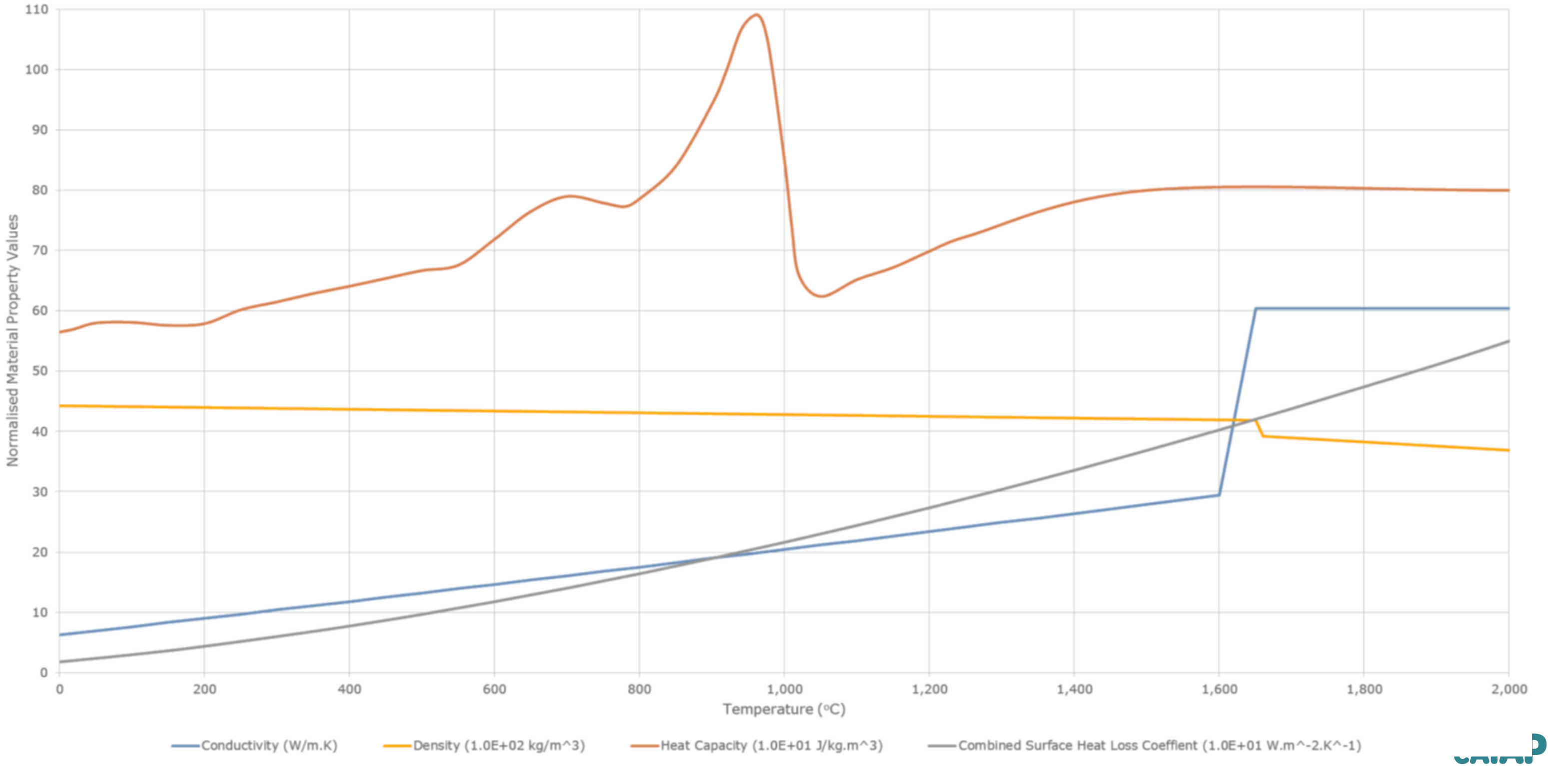
$$q_r(x,y,z,t) = \frac{6\sqrt{3}f_r Q}{abc_r\pi\sqrt{\pi}} exp\left(-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{\left(z-(vt)\right)^2}{c_r{}^2}\right)\right)$$

c) Conical Heat Source

$$q_v(x,y,z,t) = \frac{2\eta\beta Q}{\pi r_0^2 d_0} exp\left[1-\left(\frac{x^2+\left(z-(vt)\right)^2}{r_0^2}\right)\right]\left(1+\frac{y}{d_0}\right)$$

P. Lacki, K. Adamus, K. Wojsyk, M. Zawadzki, Z. Nitkiewicz, Modelling of Heat Source Based on Parameters of Electron Beam Welding Process, *Archives of Metallurgy and Materials* 56 (2) (2011) 455-462.

MATERIAL PROPERTIES (THERMAL)



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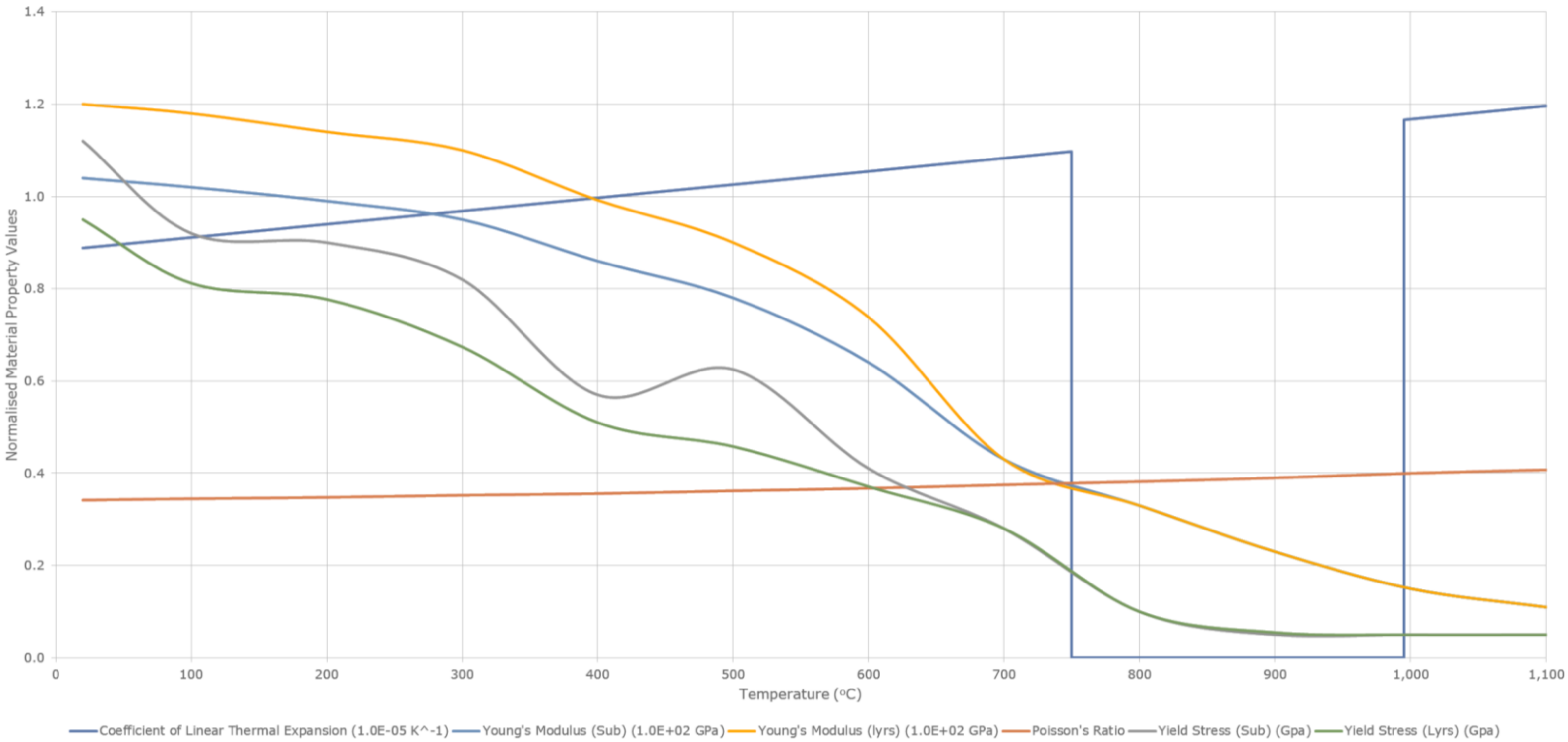
MATERIAL PROPERTIES (STRUCTURAL)



MODEL SUITABILITY

Shaped Metal Deposition ALM:

- Melt pool / layer dimensions are not too small compared to overall part
- Larger heat affected zones can see a benefit to using detailed material models
- Full 3D models can be solved within a reasonable timescale (~ 1 day)

Powder-Based ALM:

- Powder layer thickness is typically tens to hundreds of microns
- Industrial components have typically tens of centimetres
- Real industrial example:

Design: 25 cm x 20 cm x 20 cm = 0.01 m^3

Regular element: $(50\ \mu m)^3$ = 1.25E-13 m^3

Required elements: 8E10

- Not a suitable solution, an alternative is required

LUMPED THERMAL STRESS MODEL

- When using a lumped layer approach we are no longer explicitly modelling the real process
- We have to use a specimen geometry to calculate the equivalent thermal strain required per lumped layer to deform the component as observed in reality
- The MTC approach involves calibrating an analytical temperature field to induce the appropriate thermal strain

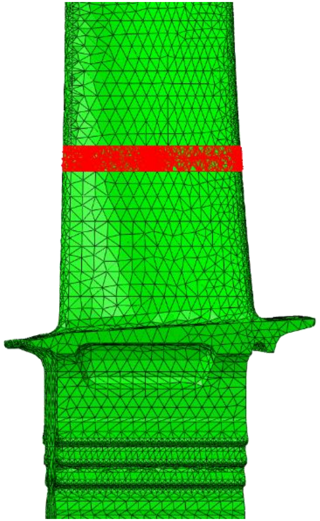


Figure 2: *3D blade geometry with highlighted lumped layers, corresponding to 6 real powder layers in this thickness*

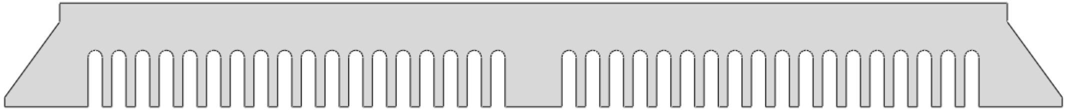


Figure 1: *2D calibration specimen geometry*

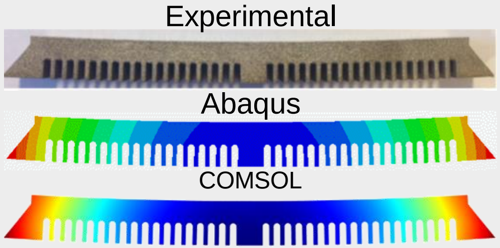
Calibration Specimen

Run calibration model
Measure predicted vertical displacement

Predicted distortion matches experimental observation?

no

Calibrate Analytical Temperature Field

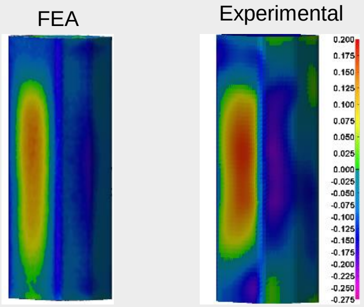


yes

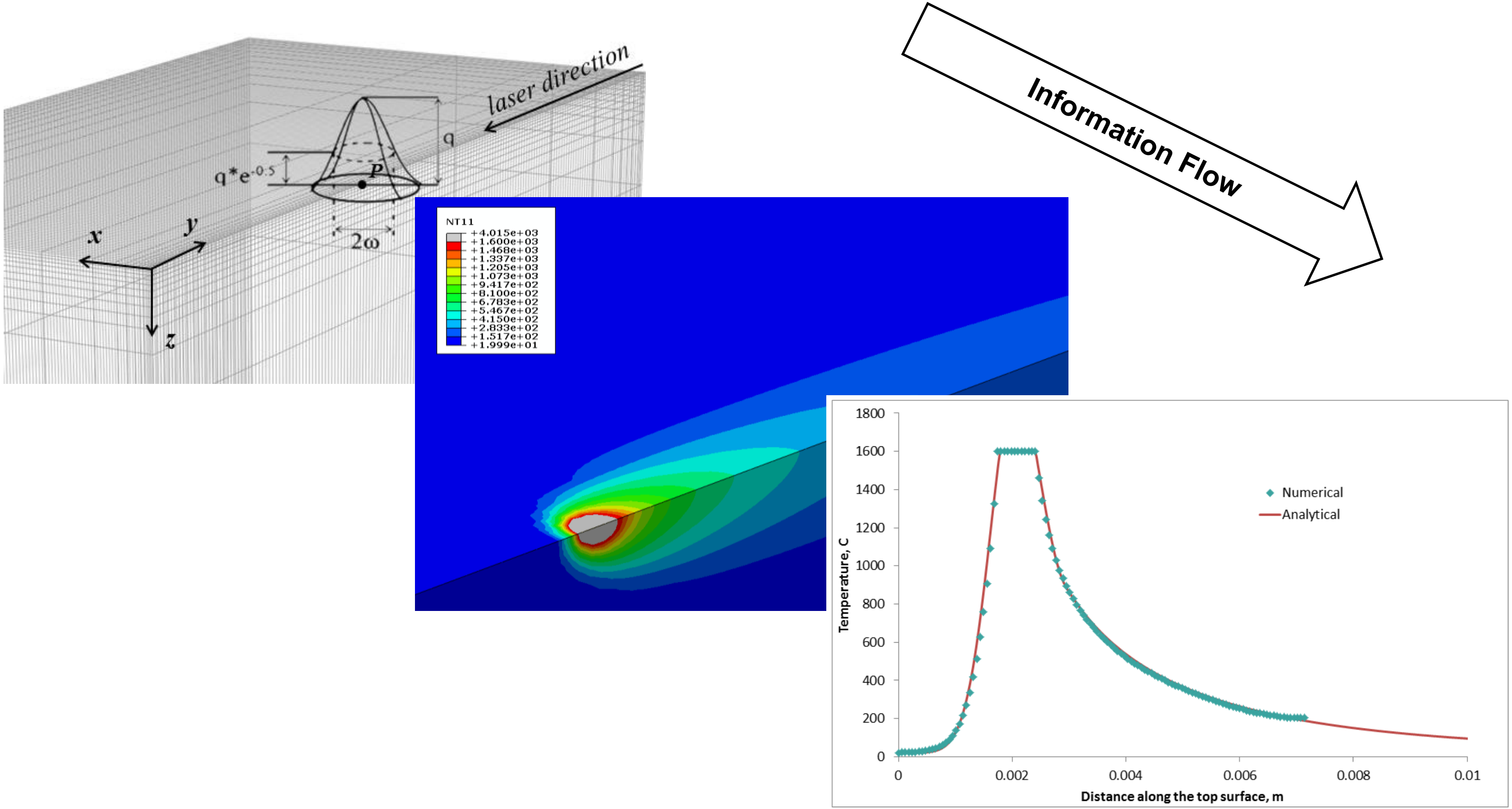
Component Model

Calibrated temperature field
Layer slicing and meshing
Toolpath definition
Run model

Validation



TEMPERATURE FIELD CALIBRATION



ANALYTICAL TEMPERATURE FIELD

- The temperature field used in the MTC model is given by:

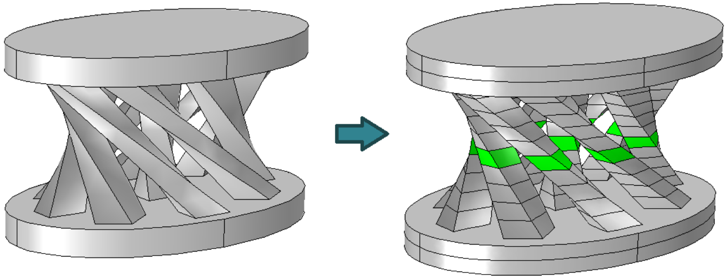
$$T(x,y,z) = T_{amb} + \frac{2Q}{C_p\rho\left(4\pi a t_{ref}\right)^{\frac{3}{2}}} exp\left(-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4at_{ref}}\right)$$

T_{amb}	Ambient temperature
Q	Heat source power*
ρ	Material density (room temperature)
C_p	Material heat capacity (room temperature)
a	Material thermal diffusivity $(k/\rho C_p)$ (room temperature
t_{ref}	Reference time*
$\{x', y', z'\}$	Current heat source centre coordinates

* Parameters which are used to calibrate temperature field

FULL COMPONENT SLICING AND MESHING

- Once the temperature field is calibrated it can be applied to the actual component
- Before meshing, the geometry needs to be sliced to the thickness of the layer lumping used for the calibration specimen
- The part can then be meshed using a similar element size to the specimen

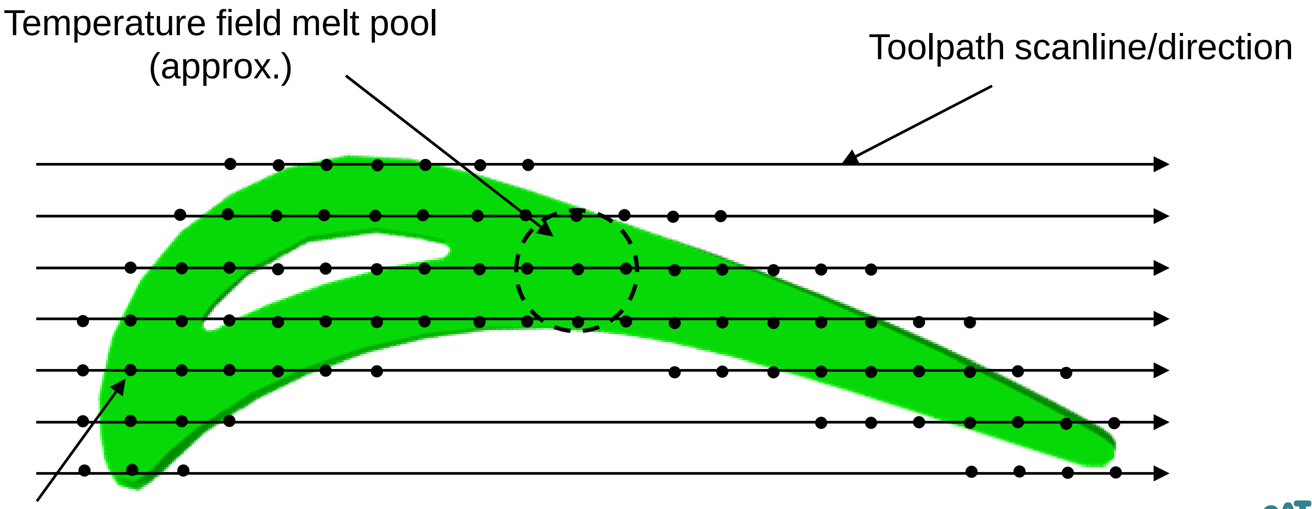


Left: *Original geometry*

Right: *Sliced geometry using a COMSOL App. The domains of one slice are highlighted.*

TOOLPATH GENERATION

- From observation, the toolpath has little impact on the overall result and we have found that toolpath waypoints lying on simple linear ‘stripes’ are suitable



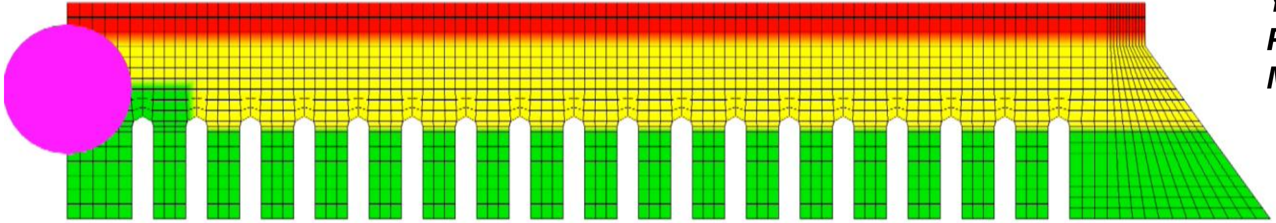
Temperature field melt pool (approx.)

Toolpath scanline/direction

Top-down view of slice

ACTIVE, SOFT AND HARD ELEMENTS

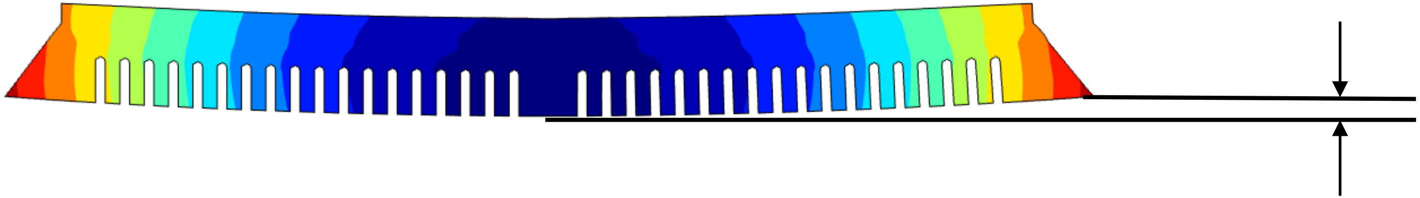
- Layers which are above the current heat source location are treated as deactivated or “quiet” and are given soft properties
- The current layer starts in an inactive state and a search radius is applied around the temperature field centre to activate nearby elements as they are deposited
- In the real process, the laser will always scan in the expected location of the target geometry regardless of any deformation experienced
- To emulate this, a soft element layer connects the current layer with a rigid and constrained area.



Green: *Active*
Yellow: *Soft (quiet)*
Red: *Rigid*
Magenta: *Melt pool*

SPECIMEN EXPERIMENTAL BUILD AND MEASUREMENT

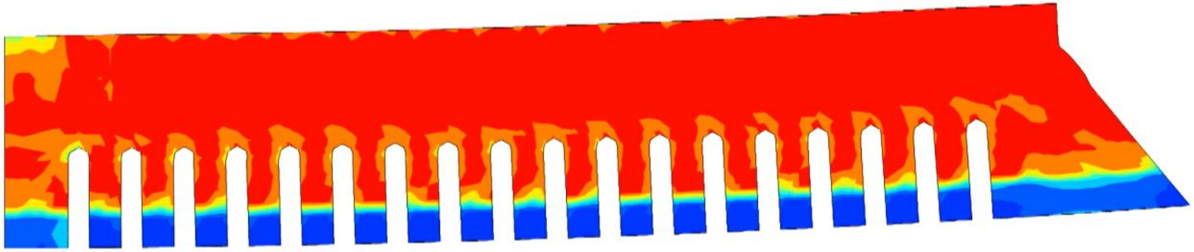
- The specimen should be built using the same machine scan strategy and parameters which are intended for use in the real component
- The bending of the cantilever part should be measured in the build direction



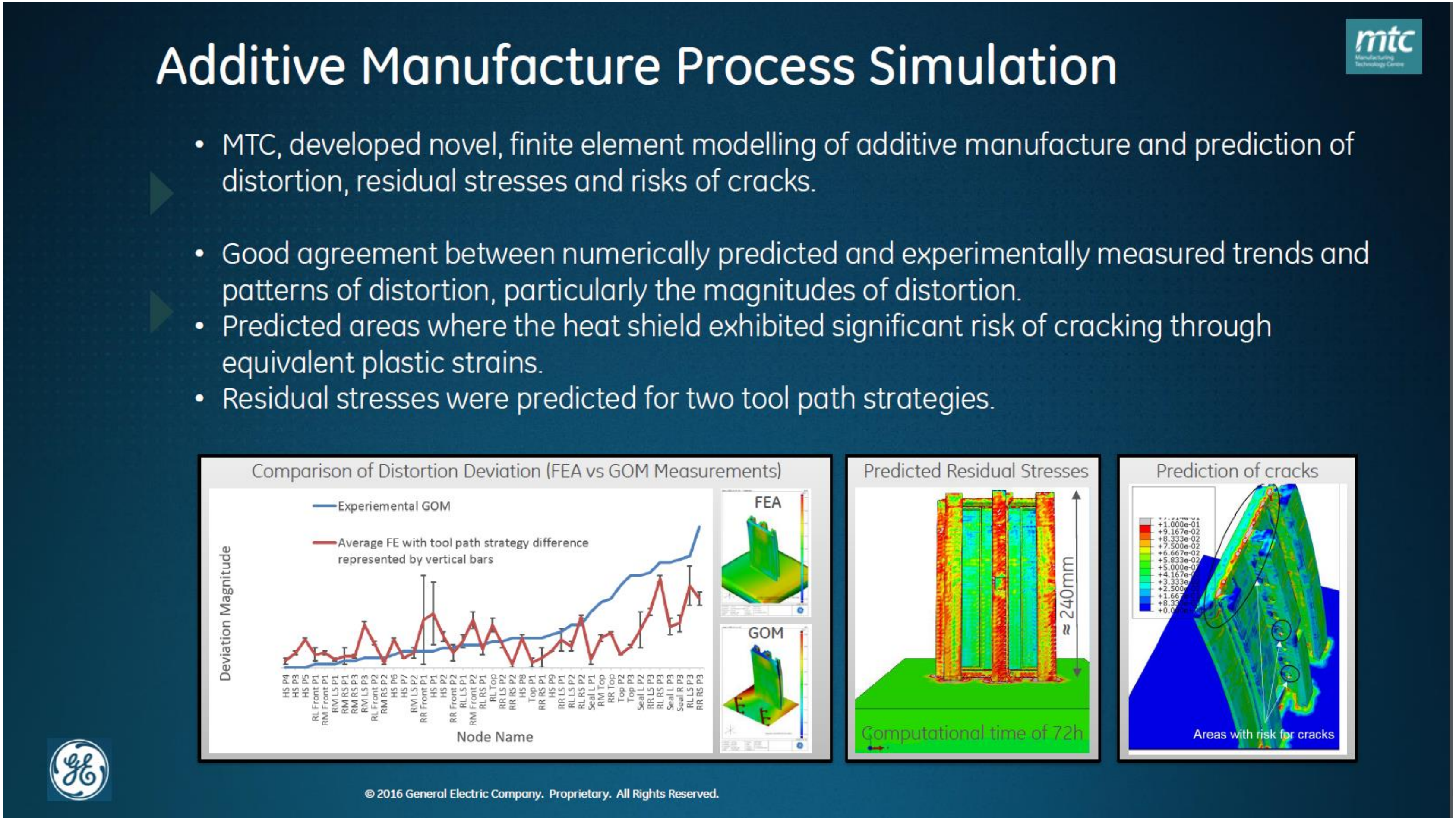
Measured bending against experimental specimen

CALIBRATION MODEL

- The calibration model can make use of the 2D plane stress element formulation
- This allows very quick iterations (typically 1-2 minutes) of the temperature field to calibrate against experimentally observed deformation
- Symmetry can be exploited



Video: *Von Mises stress during build and release.*



Additive Manufacture Process Simulation

- MTC, developed novel, finite element modelling of additive manufacture and prediction of distortion, residual stresses and risks of cracks.
- Good agreement between numerically predicted and experimentally measured trends and patterns of distortion, particularly the magnitudes of distortion.
- Predicted areas where the heat shield exhibited significant risk of cracking through equivalent plastic strains.
- Residual stresses were predicted for two tool path strategies.

Comparison of Distortion Deviation (FEA vs GOM Measurements)

Predicted Residual Stresses

Computational time of 72h

Prediction of cracks

Areas with risk for cracks

Case study: *Presented at NAFEMS Conference in June 2016 by Charles Soothill (*Senior Vice President of Technology and Chief Technical Officer at GE Power*)*

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