A quantitative approach to reduce the residual stresses and distortion in additively manufactured parts

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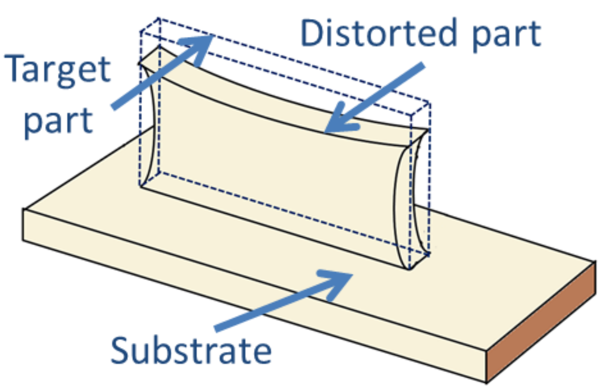
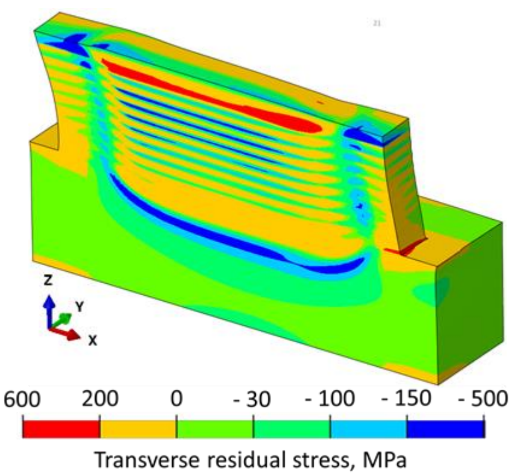
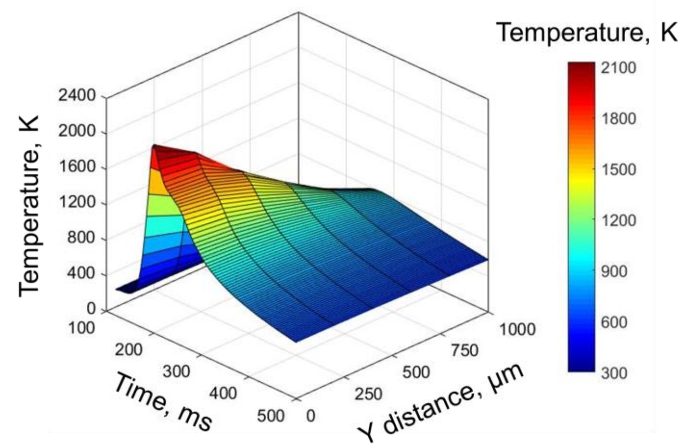
Why distortion and residual stresses in additive manufacturing ?

Calculation of accurate distortion and residual stress fields

Susceptibility of different alloys to distortion and residual stresses







Funding sources: AWS research fellowship, US Department of Energy NEUP

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Main objectives

Estimation of accurate residual stresses and distortion

=> Dimensional inaccuracy

=> Delamination, buckling, warping

=> Affect mechanical properties

Understand the relative susceptibility of different alloys to distortion

=> Printability of different alloys

Approach:

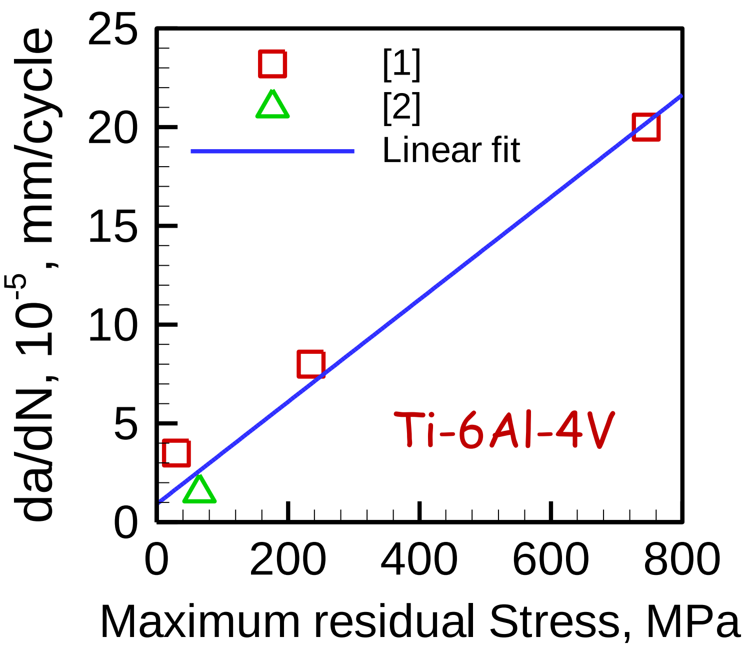
3D transient thermo-mechanical model

=> Transient temperature and the velocity field

=> Stresses and strain fields

Analytical method with non-dimensional no.

=> Compare the thermal distortion for different alloys



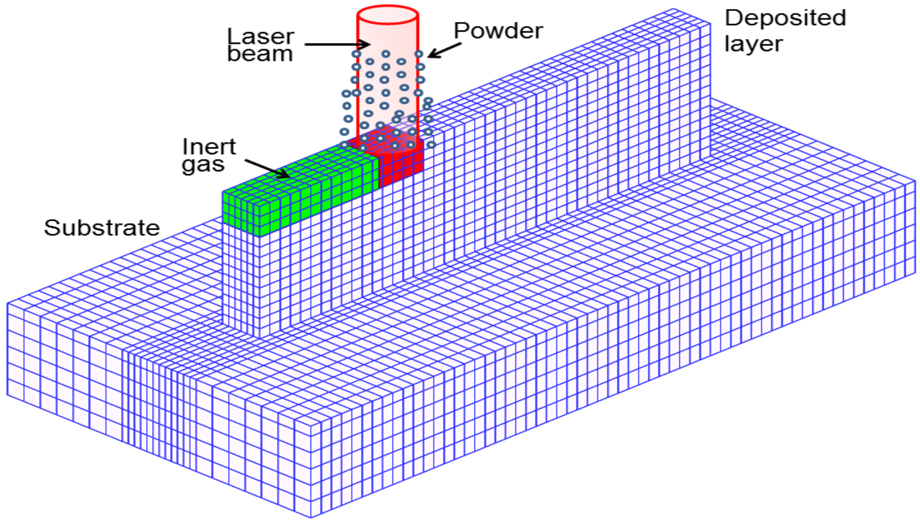
[1] Leuders et al. Int. J. Fatigue. 2013

[2] Edwards et al. J. Manuf. Sci. Eng. 2013

Heat transfer and fluid flow model

Solve equations of conservation of mass, momentum and energy

INPUT
Process parameters
Material properties



OUTPUT
Transient temperature & velocity fields, solidification parameters ...

Calculation domain: about 250,000 cells

Five main variables: three components of velocities, pressure & enthalpy

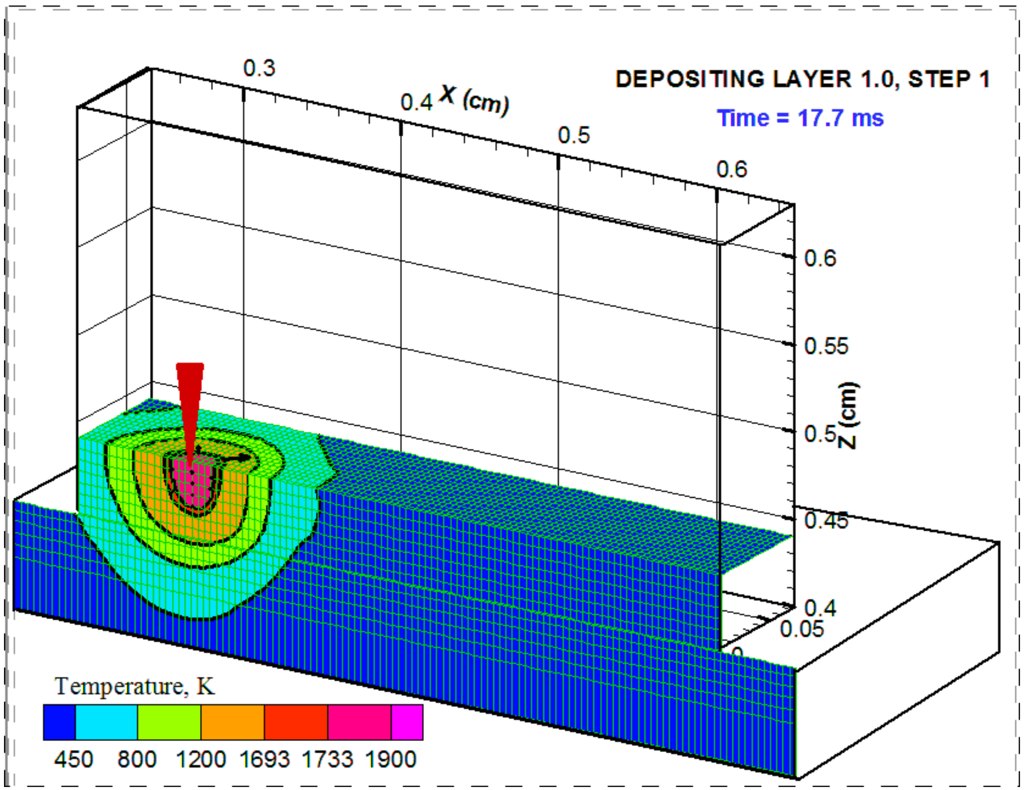
1.25 million algebraic equations (250000 x 5)

100 iteration at any time step => 0.125 billion equations/time step

1000 time step => 125 billion total equations

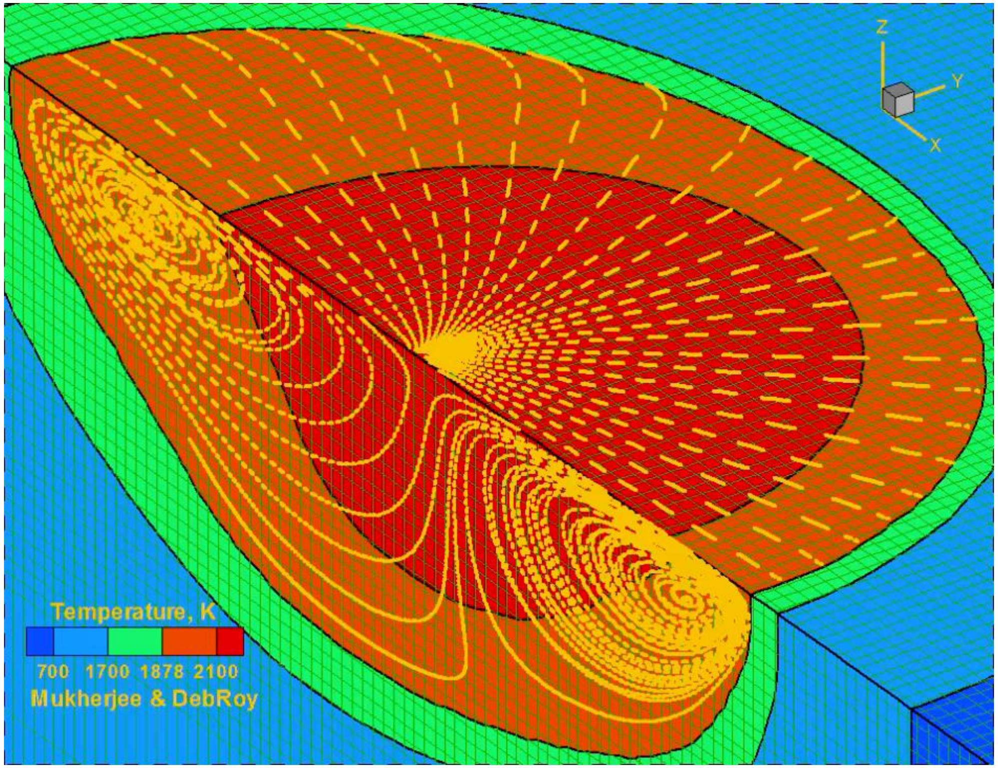
Manvatkar et al. J Appl. Phys. 2014

3D transient temperature distribution



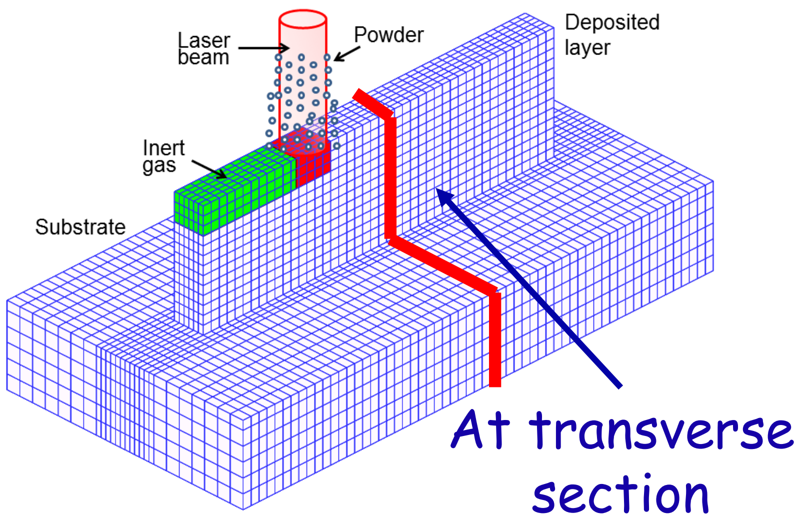
Laser power (W)	Beam radius (mm)	Scanning speed (mm/s)	Layer thickness (mm)	Substrate thickness (mm)
210	0.5	12.5	0.38	4

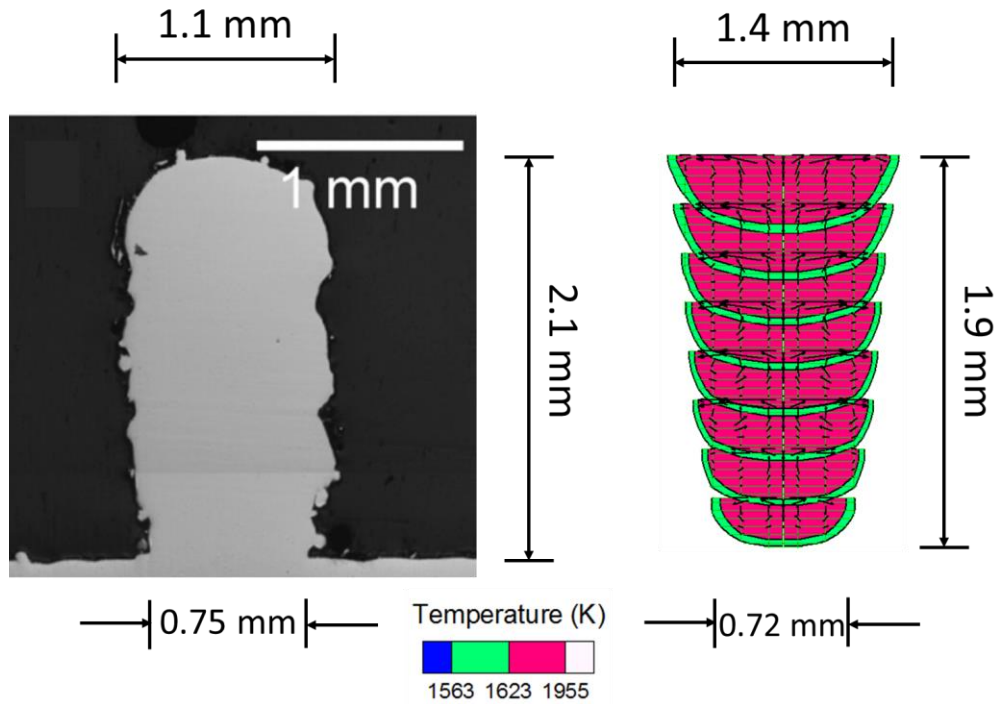
3D transient molten metal velocity field



Laser power (W)	Beam radius (mm)	Scanning speed (mm/s)	Layer thickness (mm)	Substrate thickness (mm)
210	0.5	12.5	0.38	4

Experimental validation: Shape and size of deposition

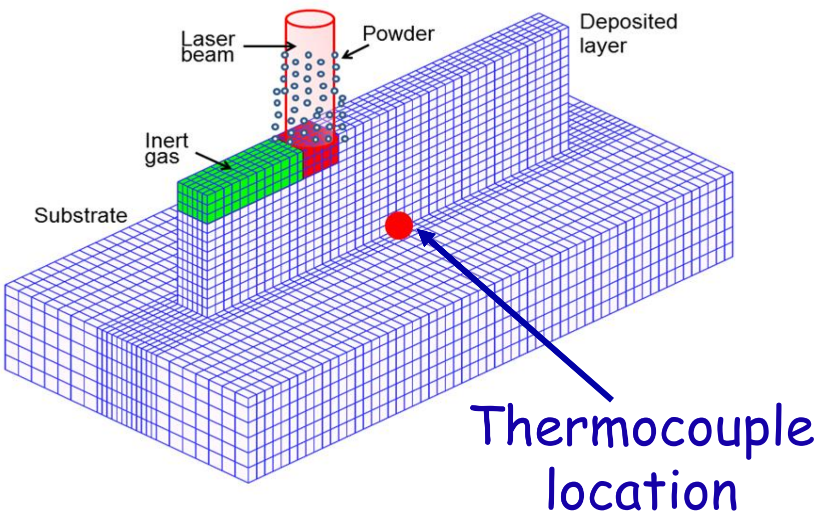


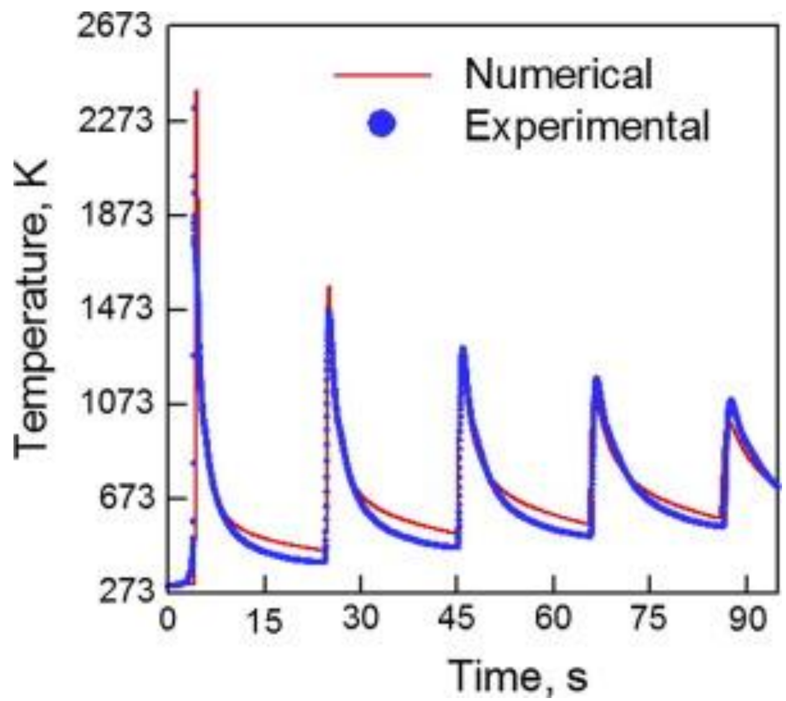


Material	Laser power (W)	Beam radius (mm)	Scanning speed (mm/s)	Layer thickness (mm)	Substrate thickness (mm)
IN 625	600	0.5	7.5	0.25	7

Mukherjee et al. Sci. Rep. 2016
www.nature.com/articles/srep19717

Experimental validation: Thermal cycle





Liquidus temperature = 1878 K

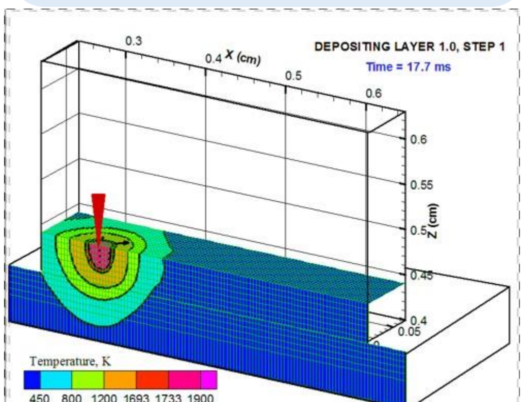
Material	Laser power (W)	Beam radius (mm)	Scanning speed (mm/s)	Layer thickness (mm)	Substrate thickness (mm)
Ti-6Al-4V	2000	1.5	10.6	0.9	10

Mukherjee et al. Comput. Mater. Sci. 2017.

Calculation of distortion and residual stresses

3D Transient heat transfer and fluid flow model

Temperature and velocity distribution for the domain

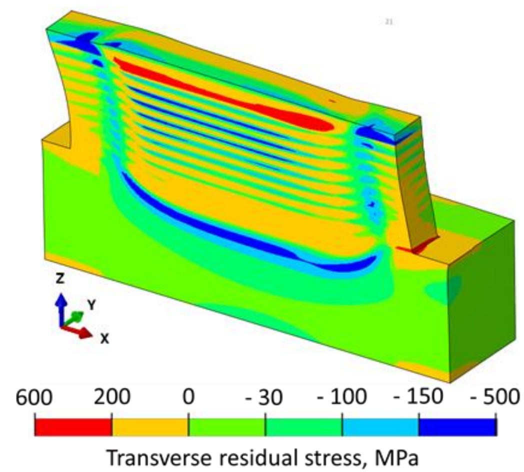


Thermal strain, stress, deformation for the domain

Abaqus output database (.odb) file

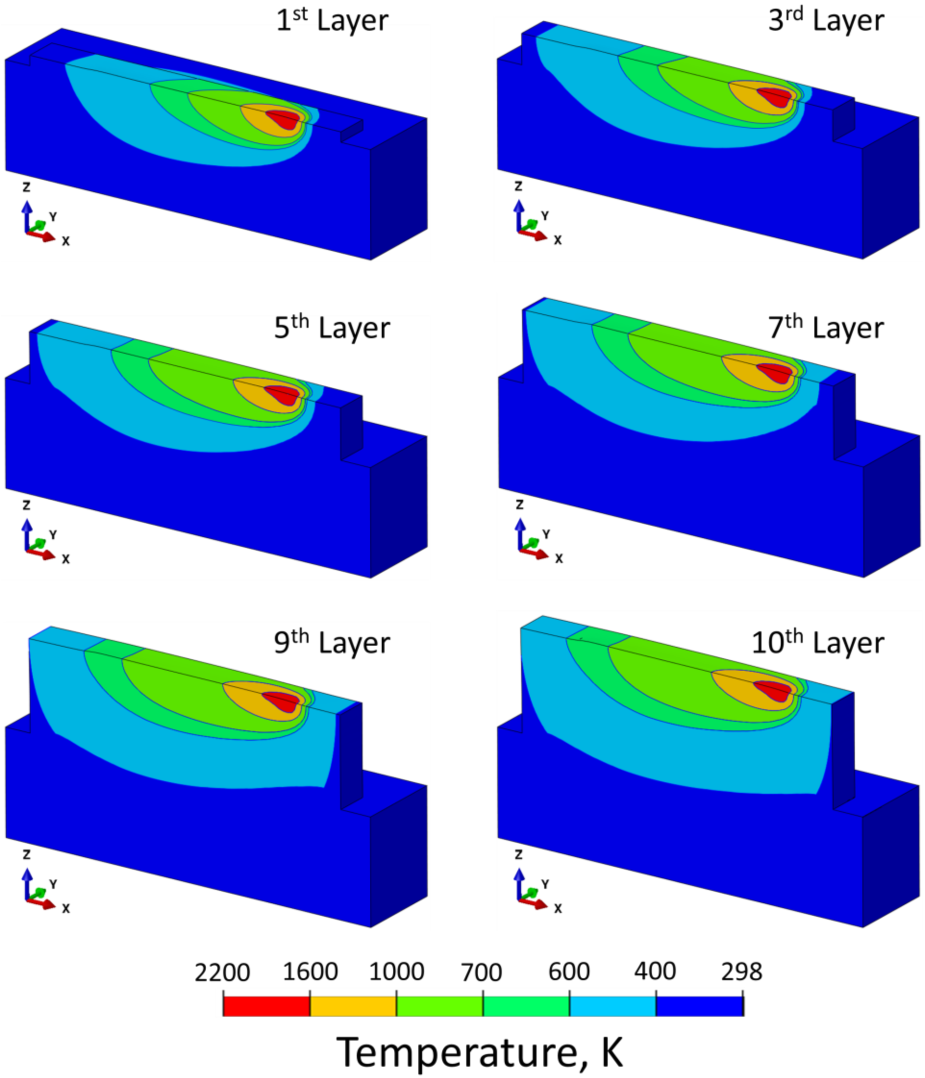
Using a Python script

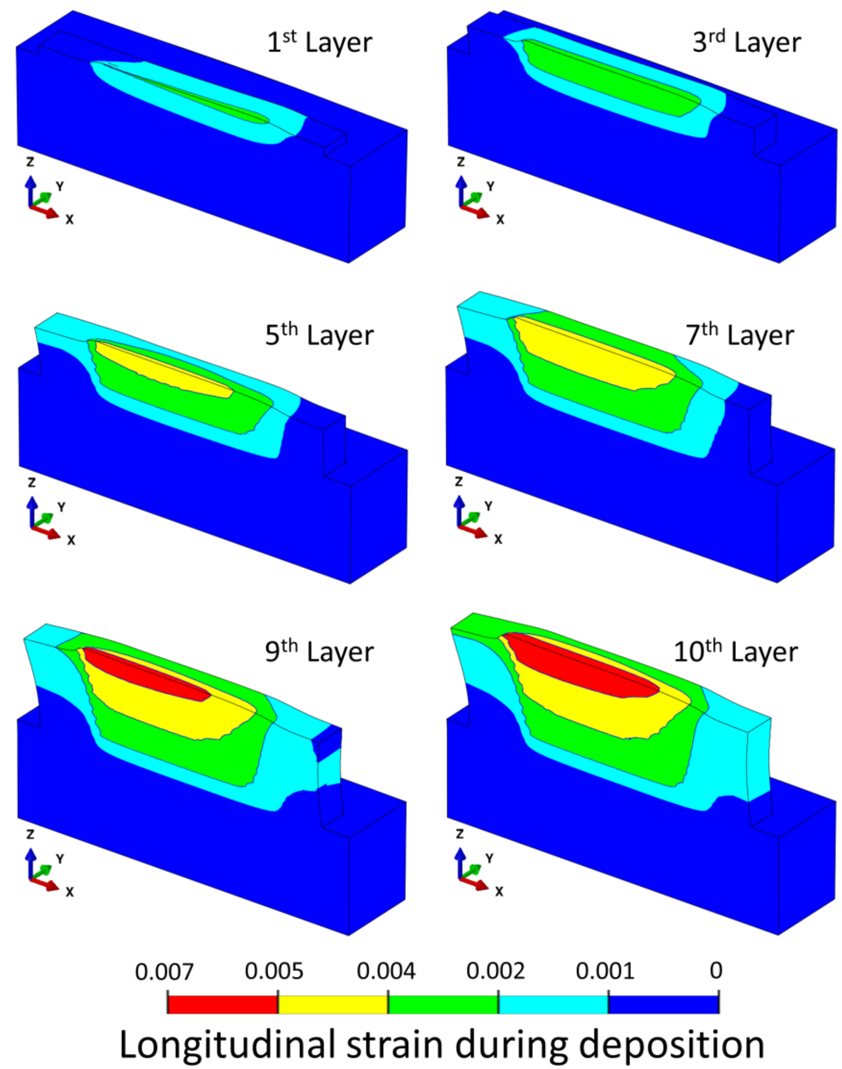
Geometry, mesh and temperature field



Mukherjee et al. Comput. Mater. Sci. 2017.

Calculated thermal strain from temperature field





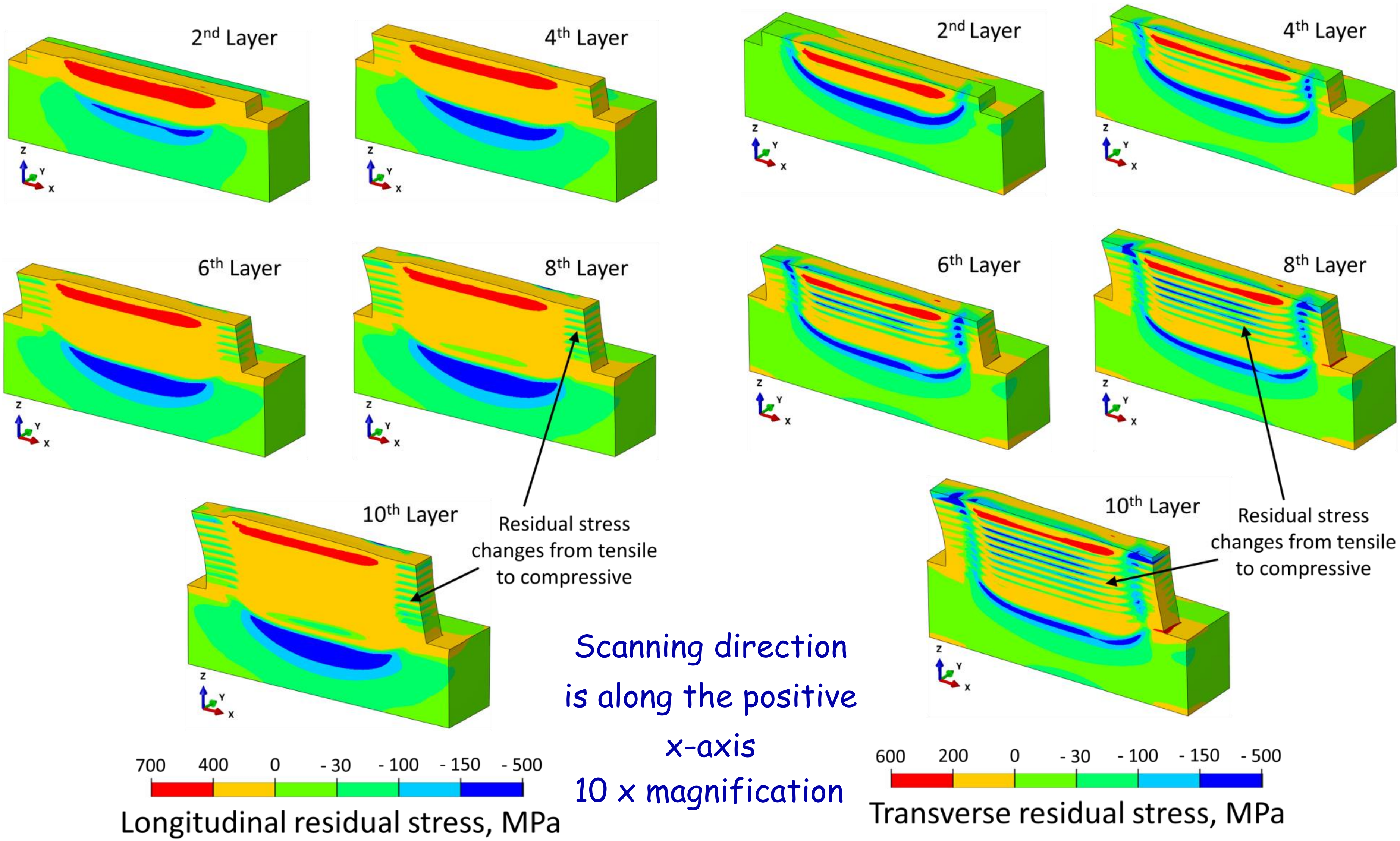
Alloy: Inconel 718, Laser power: 300 W, Speed: 15 mm/s

Scanning direction is along the positive x-axis

Mukherjee et al. Comput. Mater. Sci. 2017.

10 x magnification

Calculated residual stresses

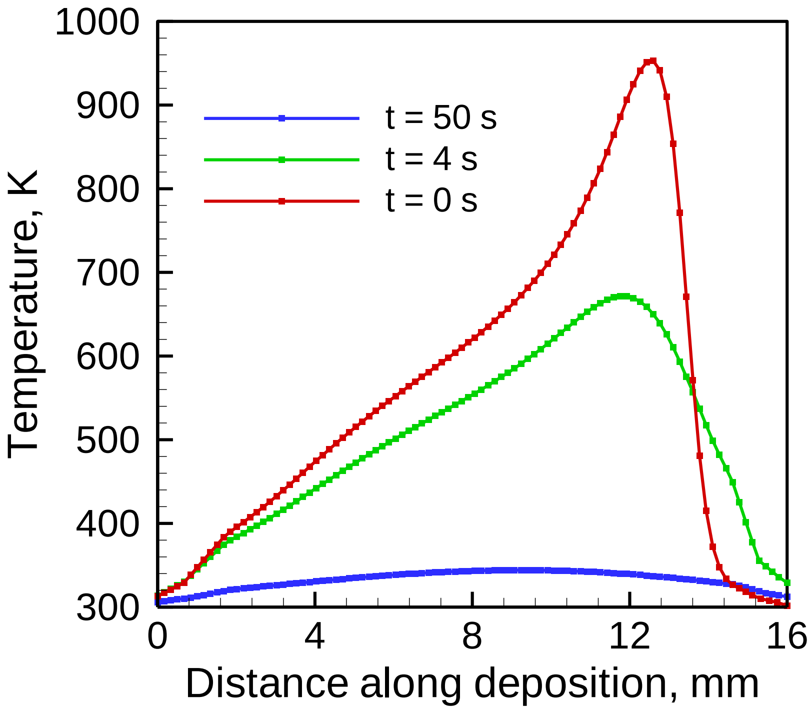


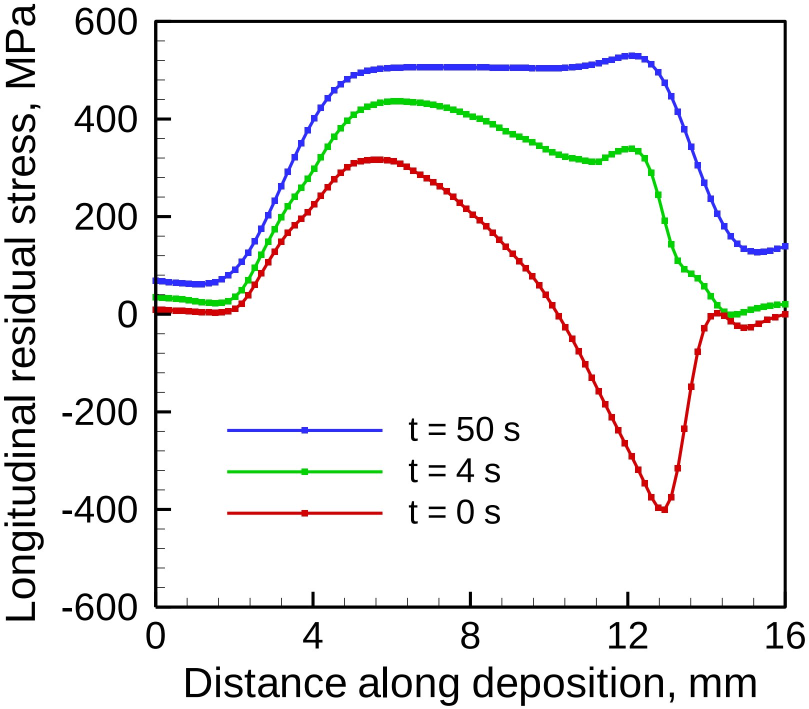
Scanning direction is along the positive x-axis
10 x magnification

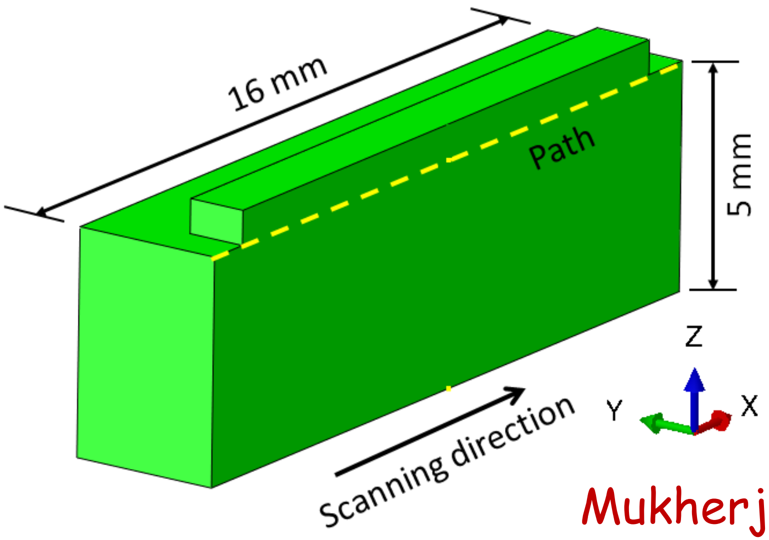
Alloy: Inconel 718, Laser power: 300 W, Speed: 15 mm/s

Mukherjee et al. Comput. Mater. Sci. 2017.

How residual stresses evolve during cooling?







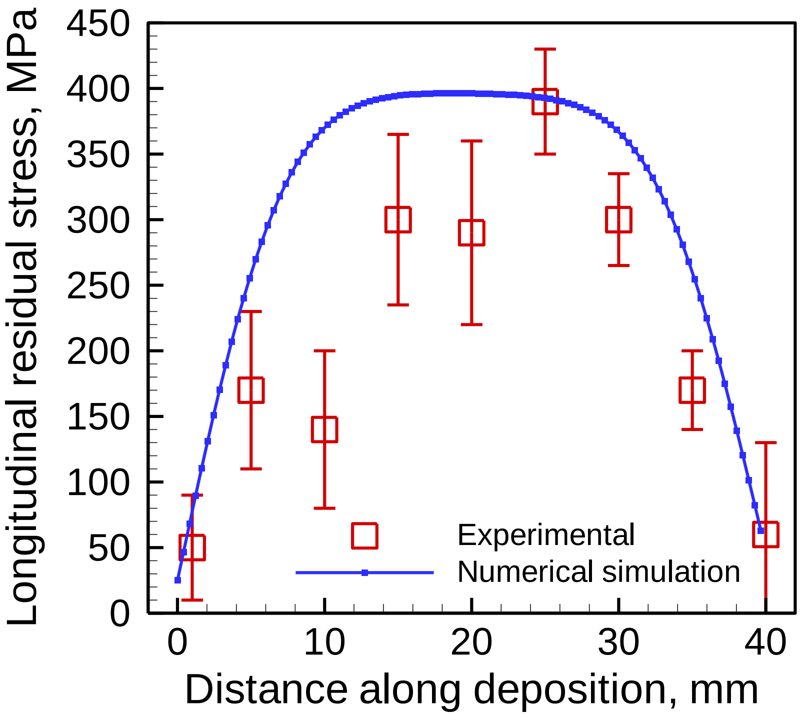
=> Time 't' is after the end of deposition

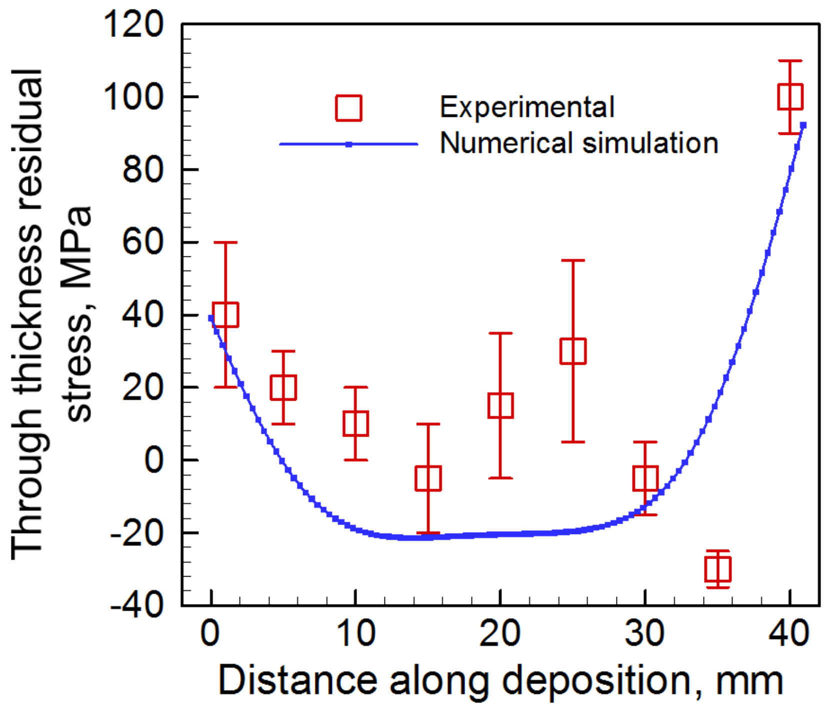
=> Longitudinal stress along the path may cause buckling and warping

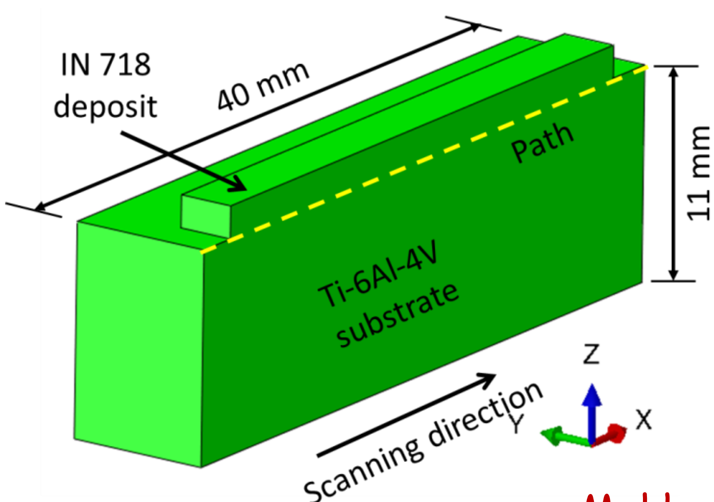
=> Alloy: Inconel 718, Laser power: 300 W, Speed: 15 mm/s

Mukherjee et al. Comput. Mater. Sci. 2017.

Experimental validation of residual stresses







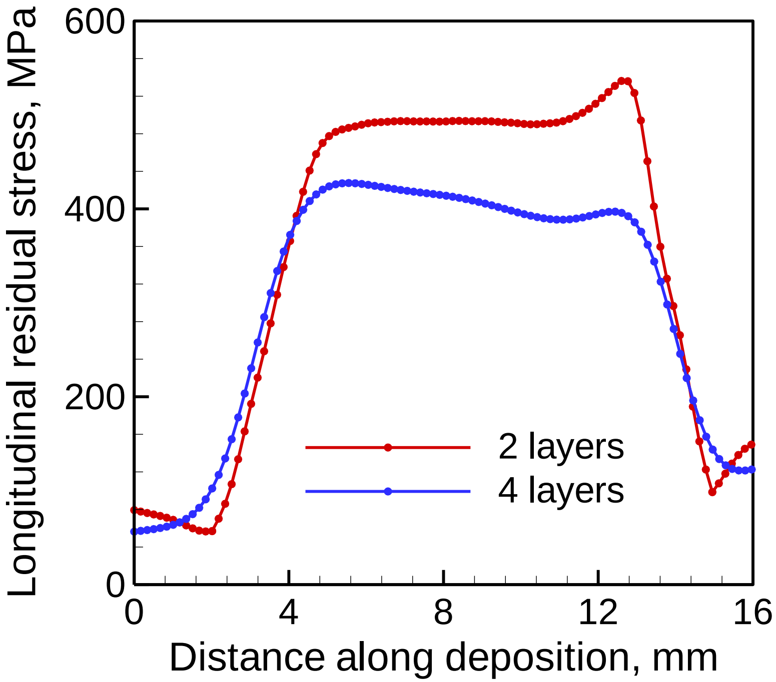
=> Experimental data are from Shah et al. Sci. World J. 2014

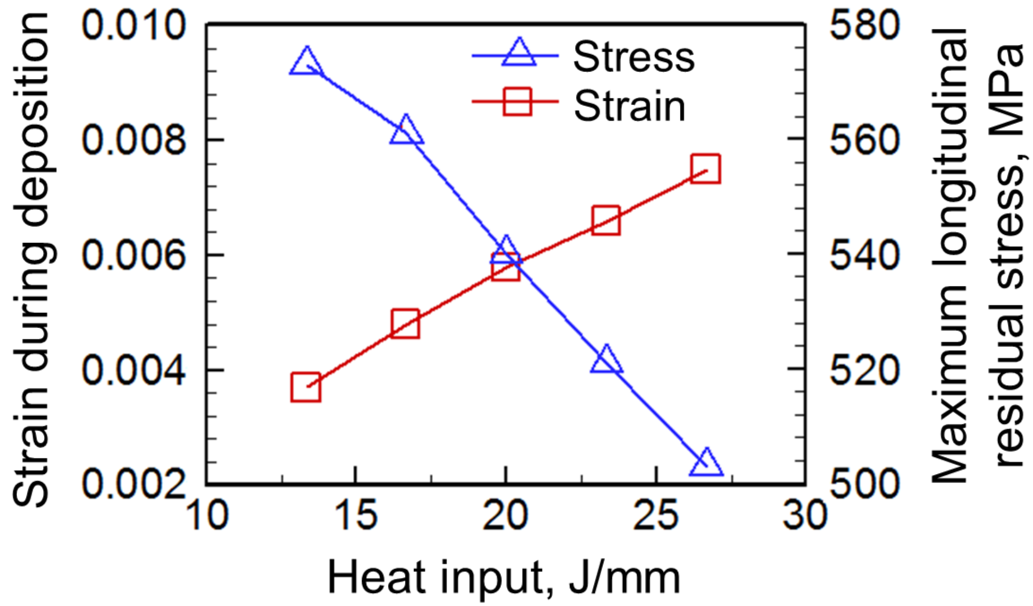
=> Laser power: 600 W, Speed: 4 mm/s

=> Slight mismatch could be caused by the measurement difficulty and the modeling assumptions

Mukherjee et al. Comput. Mater. Sci. 2017.

Effects of layer thickness and heat input





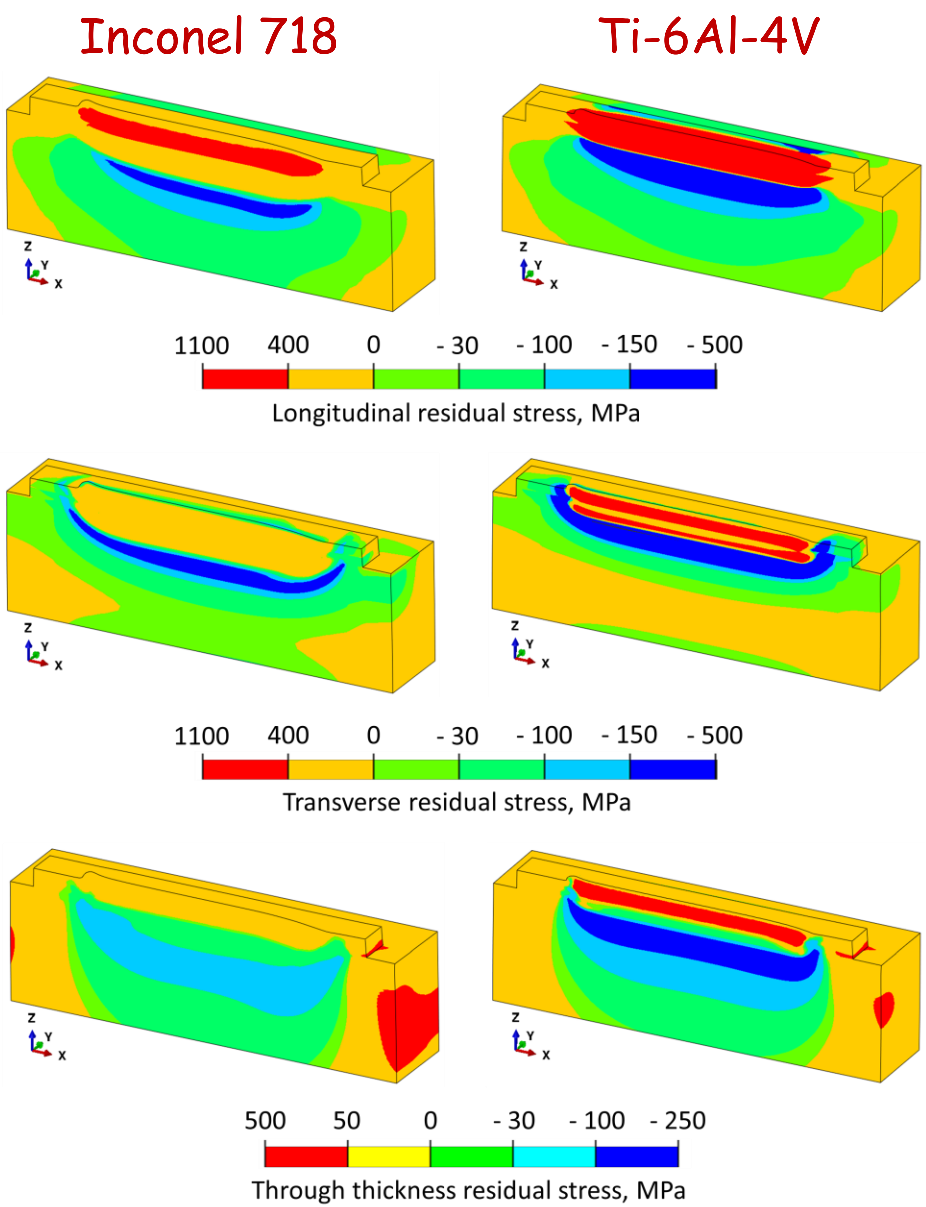
=> Residual stresses can be decreased as much as 30% by doubling the number of layers to build the same height.

=> Doubling the heat input reduces the residual stresses by about 20% and enhances the distortion by about 2.5 times.

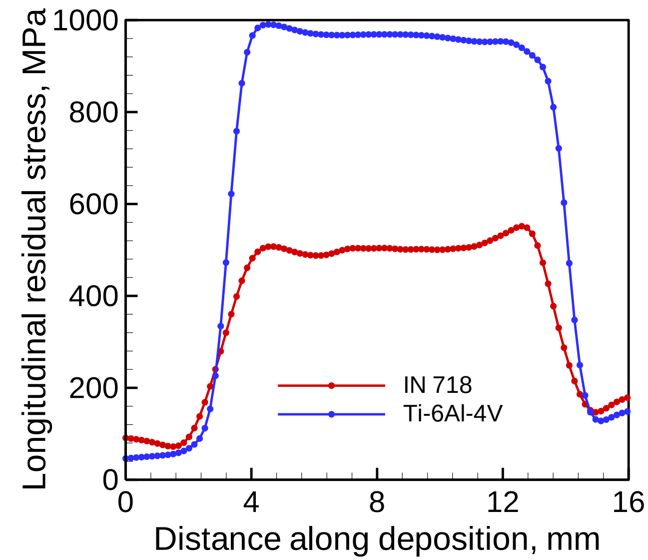
=> An appropriate heat input should be selected by trading off both distortion and residual stresses.

Mukherjee et al. Comput. Mater. Sci. 2017.

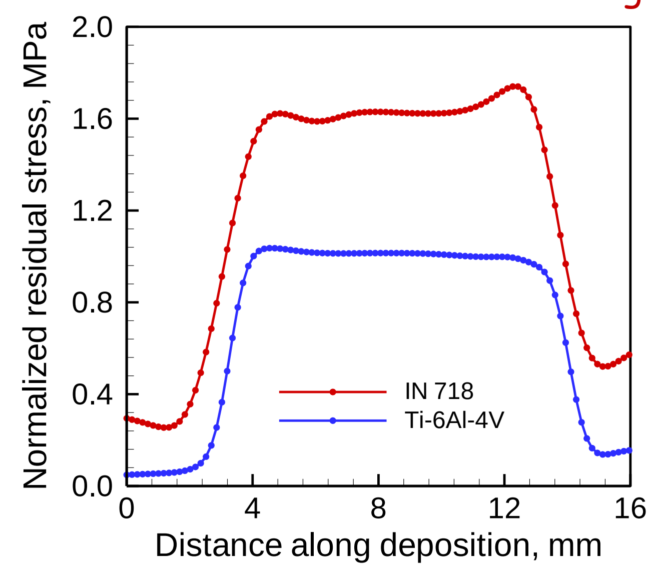
Residual stresses: Inconel 718 vs Ti-6Al-4V



Laser power: 600 W, Speed: 4 mm/s



$$\text{Normalized stress} = \frac{\text{Residual stress}}{\text{Yield strength}}$$



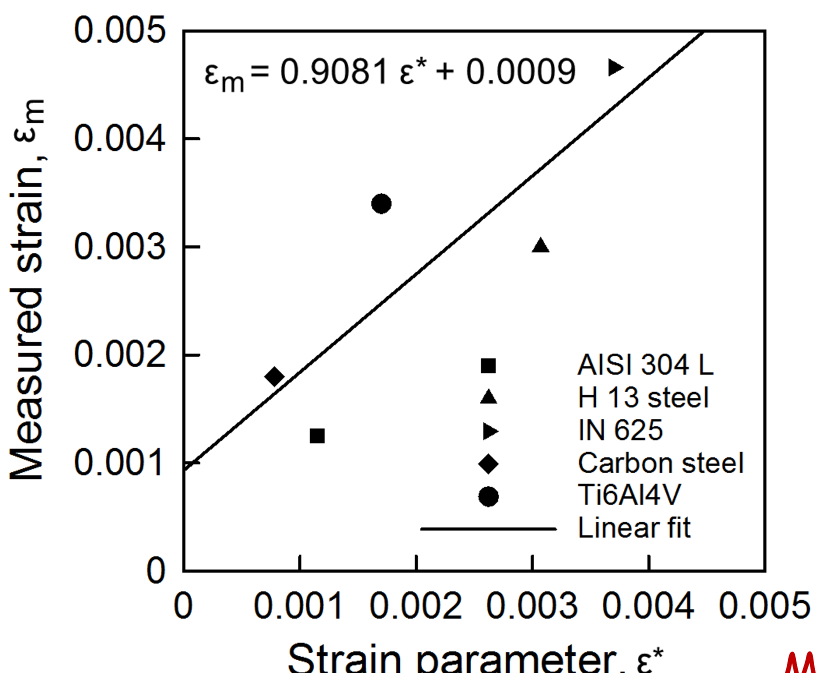
Mukherjee et al. Comput. Mater. Sci. 2017.

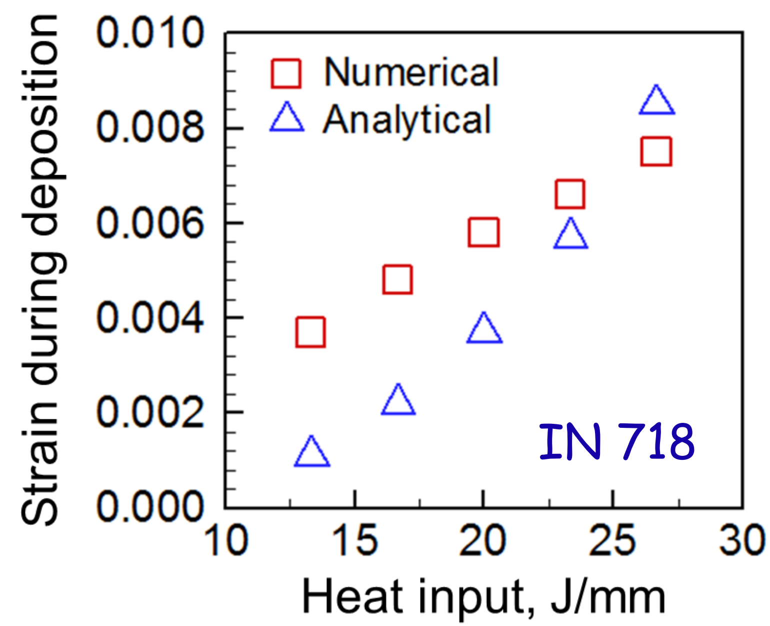
Measure of thermal distortion: Strain parameter

$$\varepsilon^* = \frac{\beta \Delta T}{EI} \frac{t}{F\sqrt{\rho}} H^{3/2}$$

Variables	Symbols
Thermal expansion coefficient	β
Temperature difference	ΔT
Fourier number	F
Heat input per unit length	H
Total time	t
Flexural rigidity of substrate	EI
Density	ρ

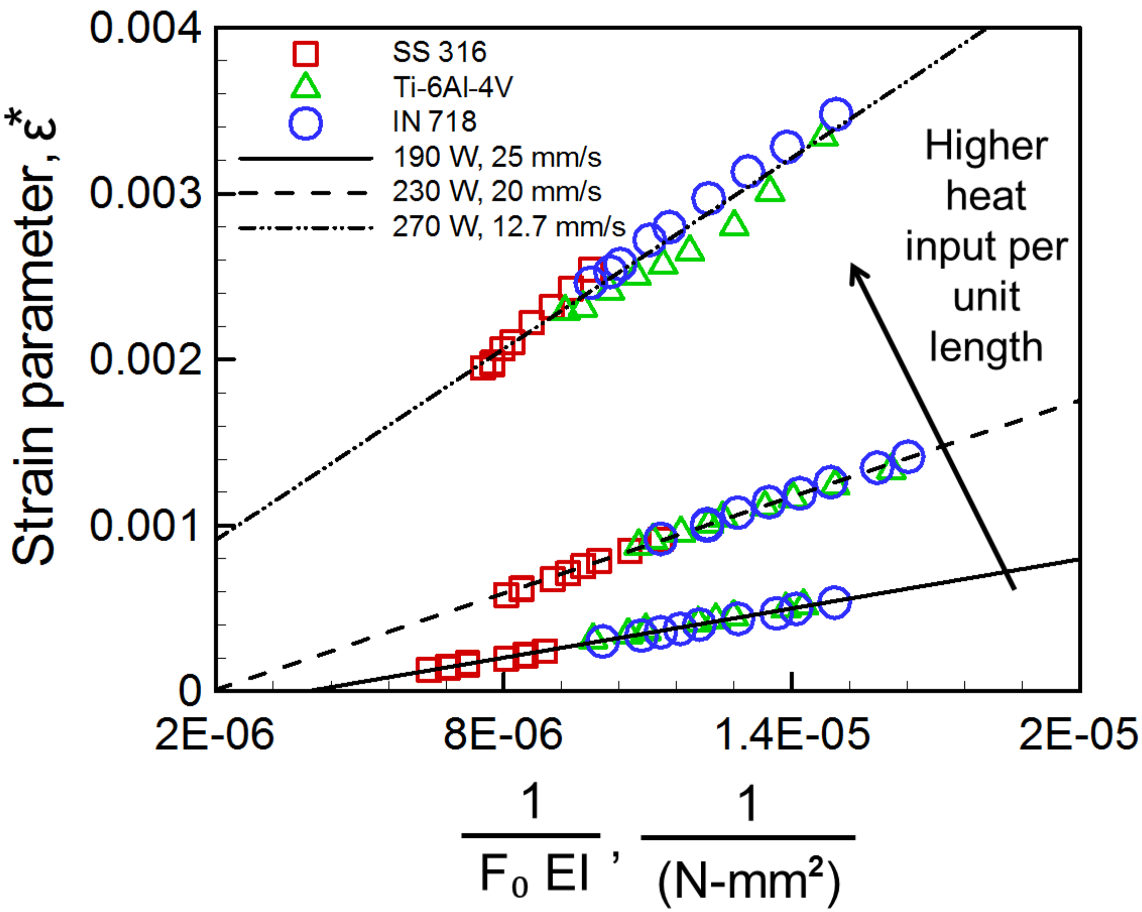
- ε* is obtained by dimensional analysis
- ε* provides insight to thermal strain and distortion in AM
- ε* does not consider any plastic deformation





Mukherjee et al. Scripta. Mater. 2017.

Thermal strain vs. Fourier number



Fourier number (F_0) = $\dfrac{\text{Heat dissipation rate}}{\text{Heat storage rate}}$

EI = Flexural rigidity of the substrate

$$\varepsilon^* = \frac{\beta \Delta T}{EI} \frac{t}{F\sqrt{\rho}} H^{3/2}$$

- Low F_0 => High heat storage => High thermal strain and distortion
- Low EI => Less rigid substrate => High thermal strain and distortion

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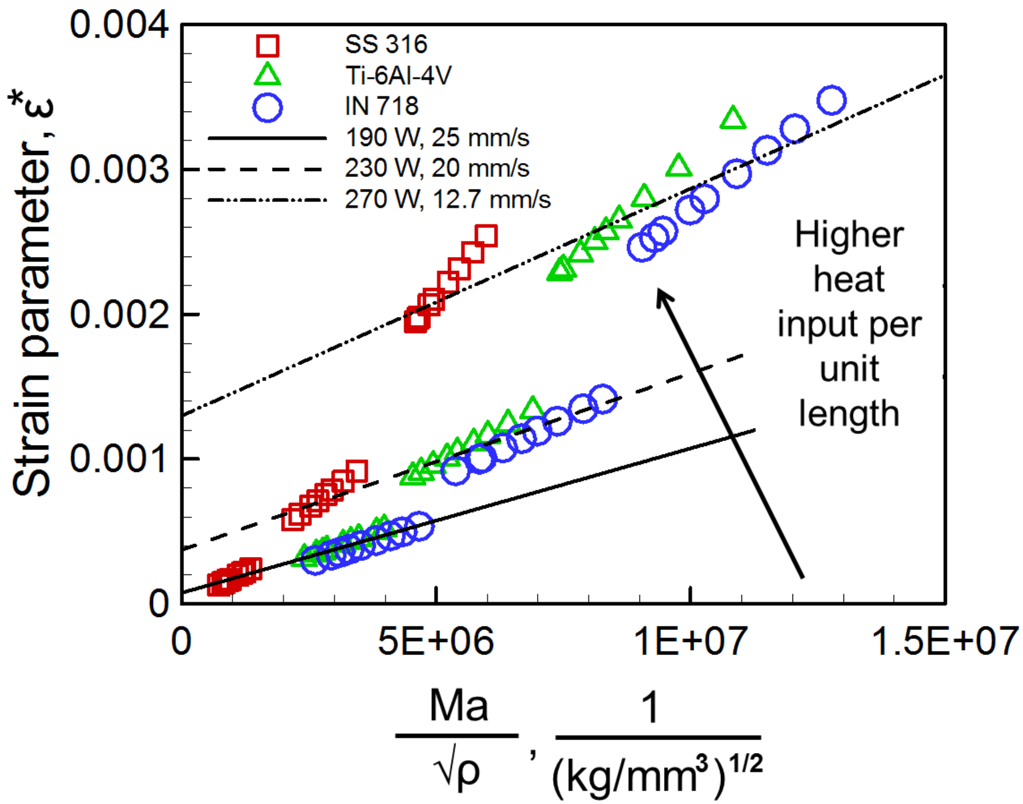
Thermal strain vs. Marangoni number



Marangoni number =

$$Ma = -\frac{d\gamma}{dT}\frac{L\,\Delta T}{\eta\,\alpha}$$

Variables	Symbols
Surface tension gradient	$d\gamma/dT$
Pool length	L
Temperature gradient	ΔT
Viscosity	η
Thermal diffusivity	α

$$\varepsilon^* = \frac{\beta \Delta T}{EI}\frac{t}{F\sqrt{\rho}}H^{3/2}$$

- High Ma => High convective flow inside pool => Large pool => High strain
- Low density (ρ) => High peak temperature => High strain and distortion

Mukherjee et al. Scripta. Mater. 2017.

Summary and conclusions

- A 3D transient heat transfer and fluid flow model is used to calculate the temperature field during the deposition.
- A thermo-mechanical model using Abaqus is used to simulate the residual stress and distortion.
- Lower layer thickness and heat input selected by trading off both distortion and residual stresses are useful to fabricate dimensionally accurate part with minimum residual stress.
- Non-dimensional strain parameter is used to understand the relative susceptibility to distortion of different alloys.
- High Fourier no. (high heat dissipation and low heat storage) and low Marangoni no. (less convective flow inside pool) can effectively reduce thermal distortion.