A numerical approach to fabricate defect free and structurally sound components by additive manufacturing

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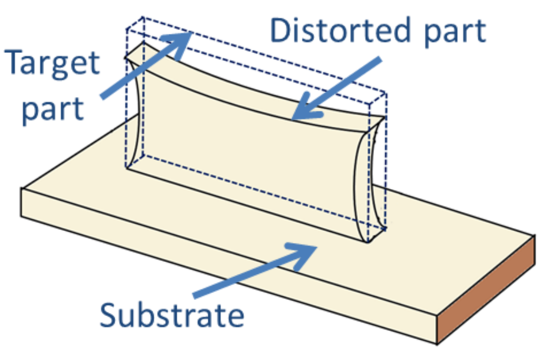
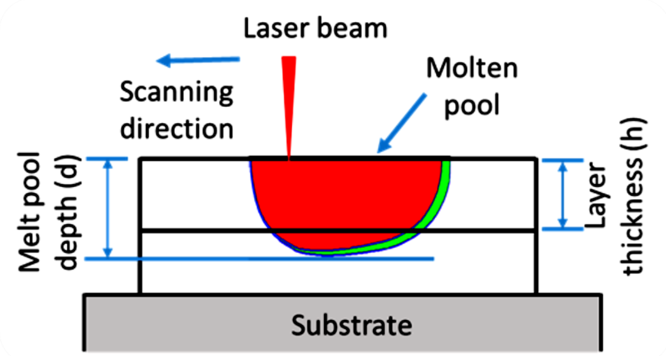
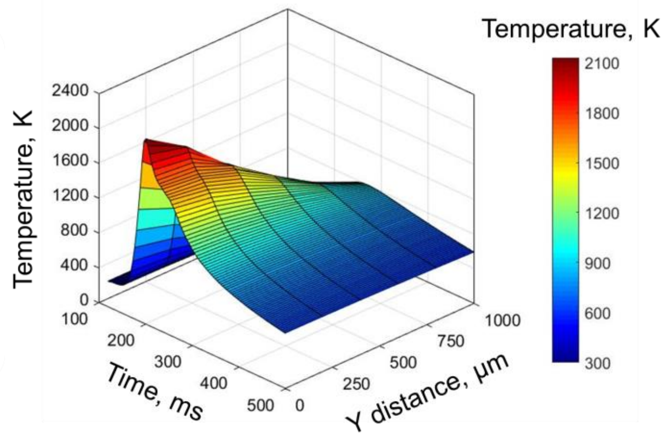
Influence of transport phenomena on structure, property and defect

Heat transfer and fluid flow model to capture the real time physics

Dimensional analysis and back of the envelope calculations







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AWS Professional Program at FABTECH, Chicago, IL, USA, November 6-9, 2017

Main objectives

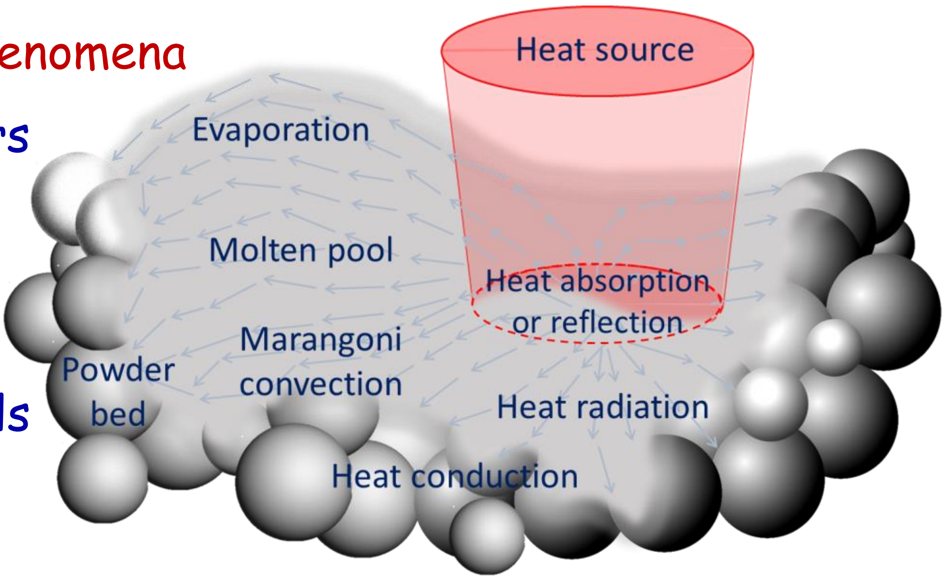
Understanding the role of transport phenomena

=> Cooling rate, solidification parameters

=> Distortion, lack of fusion

Selection of proper process conditions

=> Reduces expensive experimental trials



DebRoy et al. 2018
Progress in Materials Science.

Approach:

3D transient heat transfer and fluid flow model

=> Calculates important metallurgical variables

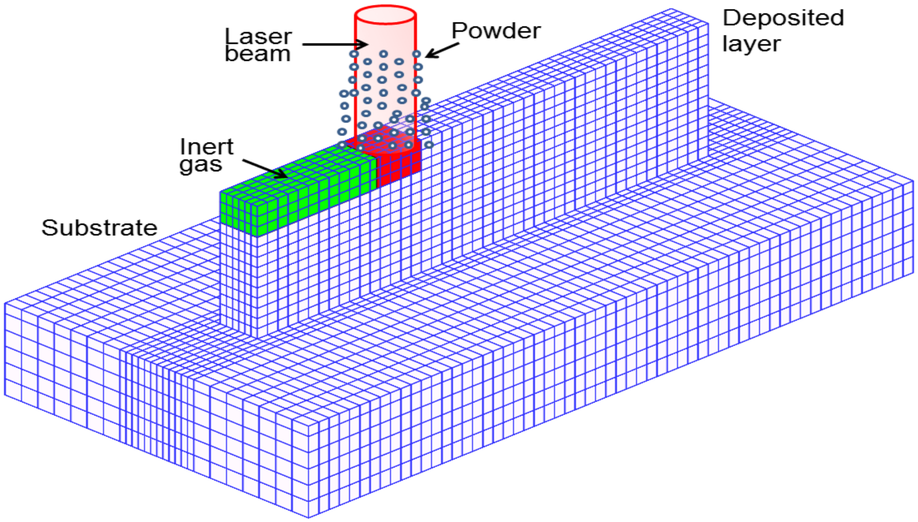
Dimensional analysis and back of the envelope calculations

=> Better understanding of process-structure-property relationship

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

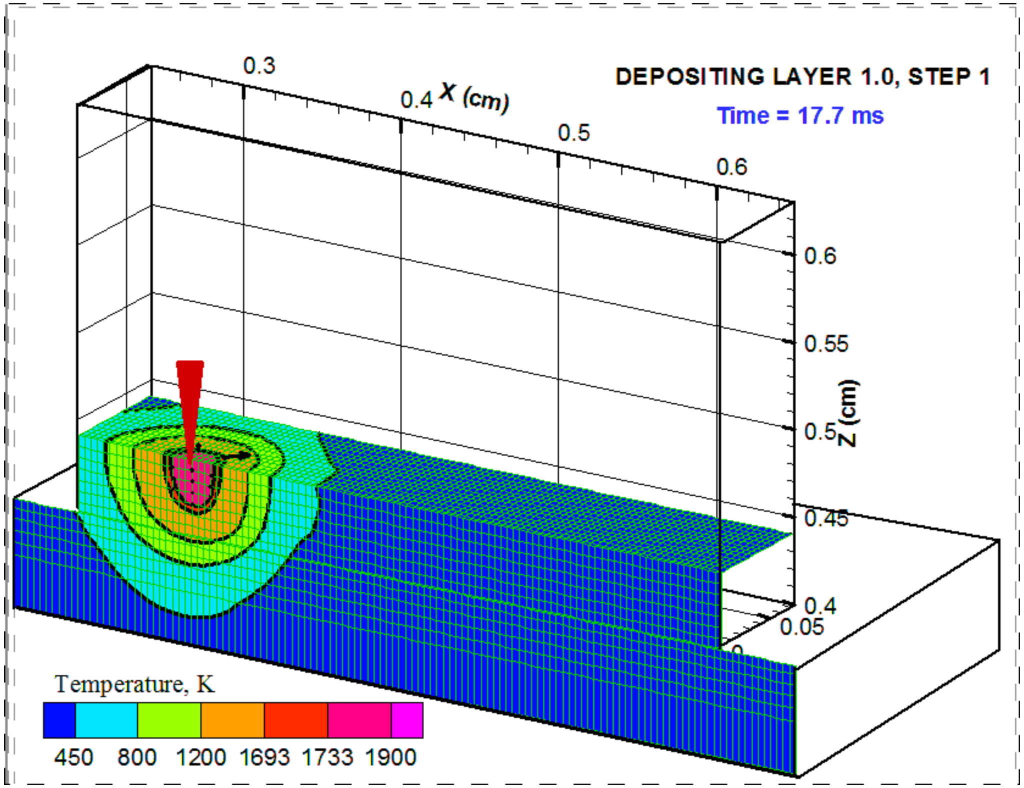
1.25 million algebraic equations (250000 x 5)

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

1000 time step => 125 billion total equations

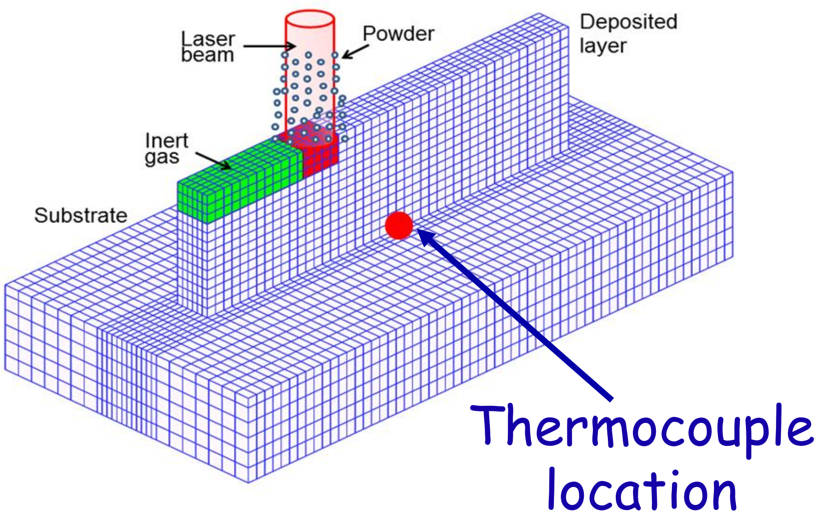
Manvatkar et al. J Appl. Phys. 2014

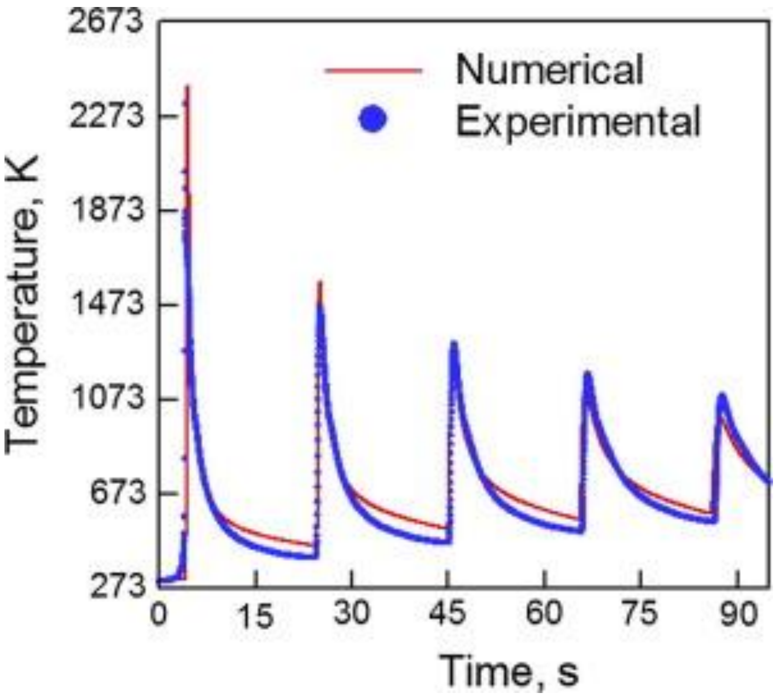
3D transient temperature distribution



Material	Laser power (W)	Beam radius (mm)	Scanning speed (mm/s)	Layer thickness (mm)	Substrate thickness (mm)
SS 316	210	0.5	12.5	0.38	4

Experimental validation: Thermal cycle



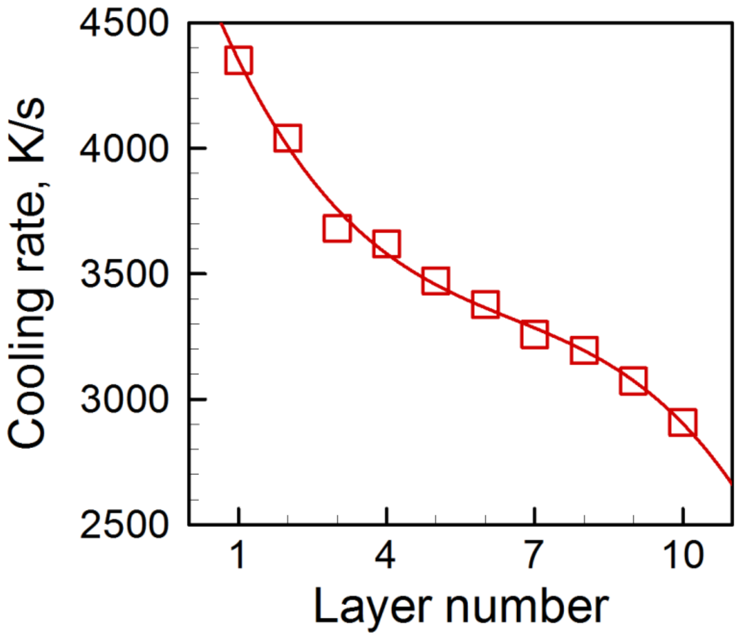


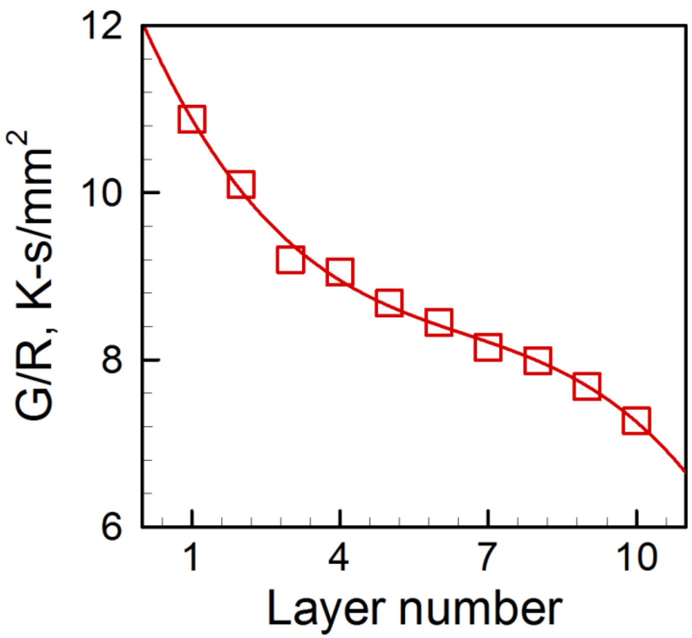
Liquidus temperature = 1878 K

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.

Cooling rates and solidification parameters





=> Temperature gradient => G
Solidification growth rate => R

=> Cooling rates are calculated during solidification

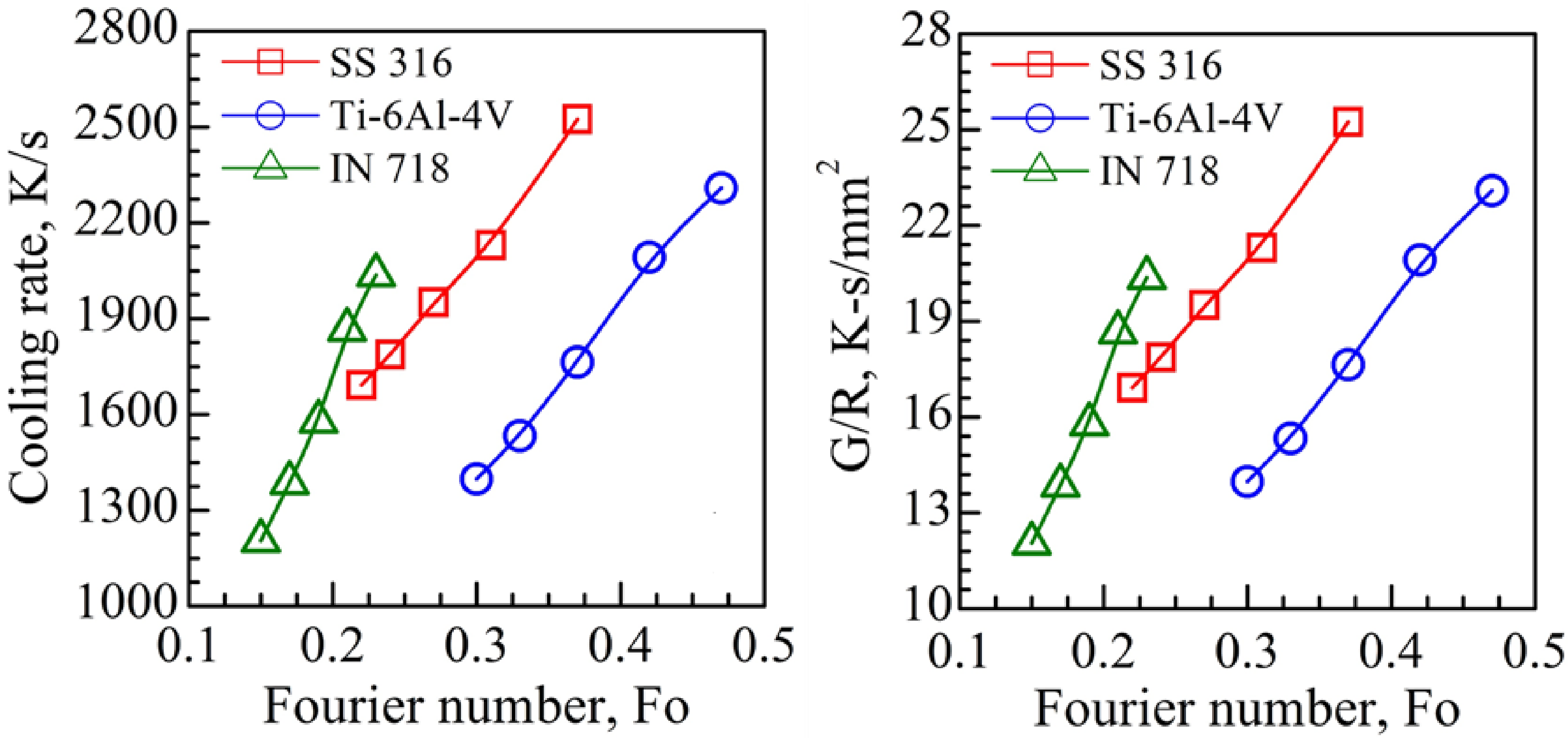
=> Calculations are done at mid-length of the deposit just below the laser beam

=> For the higher layers, heat transfer through the substrate decreases that reduce the cooling rate

Alloy	IN 718
Laser power (W)	600
Beam radius (mm)	0.5
Scanning speed (mm/s)	20
Layer thickness (mm)	0.38
Substrate thickness (mm)	4

Effects of heat dissipation and storage

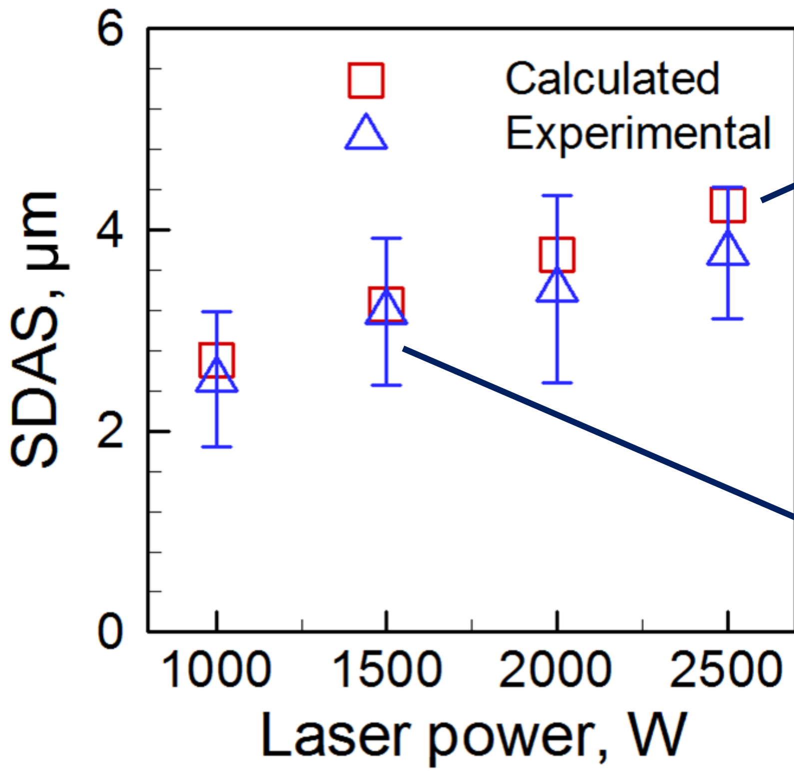
Temperature gradient => G   Solidification growth rate => R

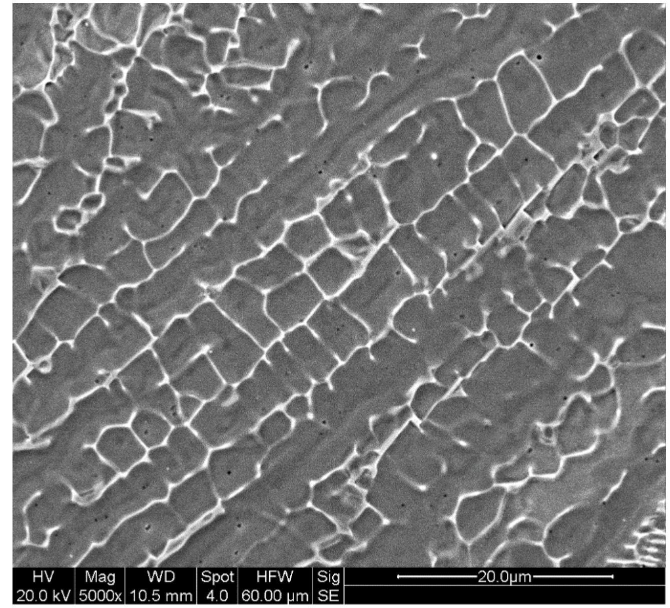


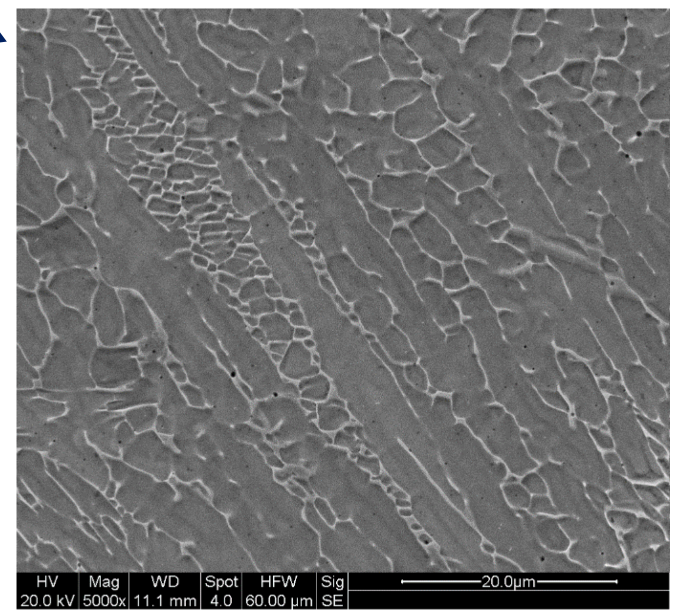
$$\text{Fourier number } (F_0) = \frac{\text{Heat dissipation rate}}{\text{Heat storage rate}}$$

Mukherjee et al. J Appl. Phys. 2017.

Secondary dendritic arm spacing (SDAS) for SS 316







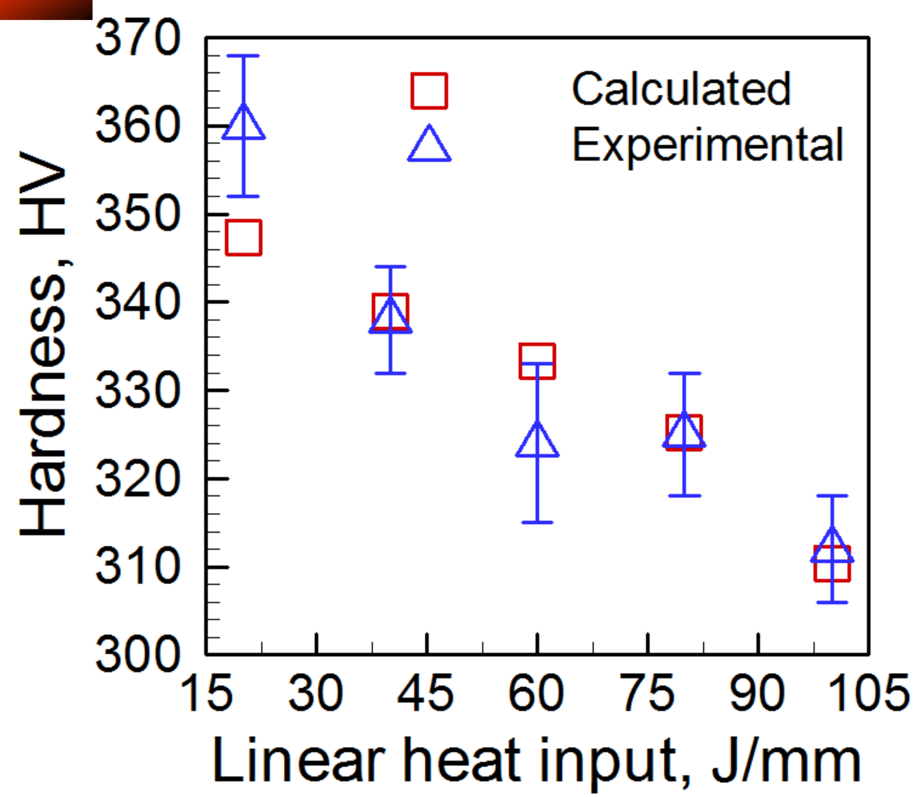
$$\lambda = 50(GR)^{-0.4}$$

λ = Secondary dendritic arm spacing, µm

GR = Cooling rate, K/s

Knapp et al. Acta Mater. 2017.

Hardness of SS 316



$$\text{Linear heat input} = \frac{\text{Laser power}}{\text{Scanning speed}}$$

$$\sigma_y = \sigma_0 + K_y (\lambda)^{-0.5}$$

σ_y = Yield strength, MPa

σ_0 = 240 Mpa, K_y = 279 MPa (μm)$^{0.5}$

λ = Secondary dendritic arm spacing, μm

$$H_v = 3\sigma_y (0.1)^{-0.25}$$

H_v = Vicker's hardness

More heat deposited per unit length => Slow cooling => Large SDAS => Low hardness (SS 316)

Experimental data are taken from Zhang et al. Mater. Des. 2014.

Mukherjee et al. J Appl. Phys. 2017.

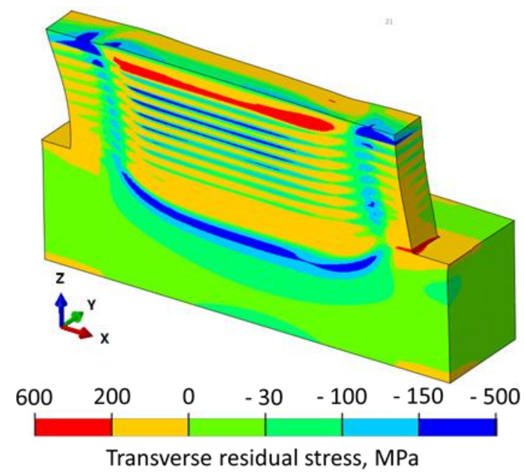
Calculation of distortion and residual stresses

3D Transient heat transfer and fluid flow model

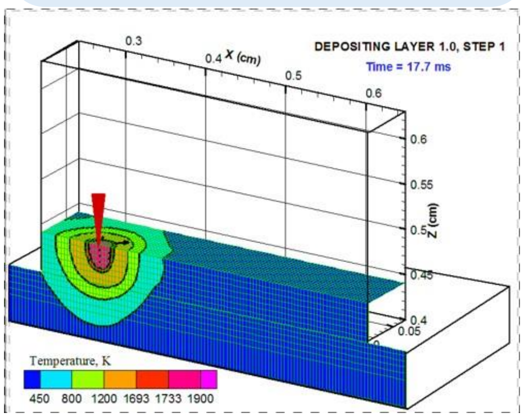
Thermal strain, stress, deformation for the domain

Temperature and velocity distribution for the domain

Abaqus output database (.odb) file



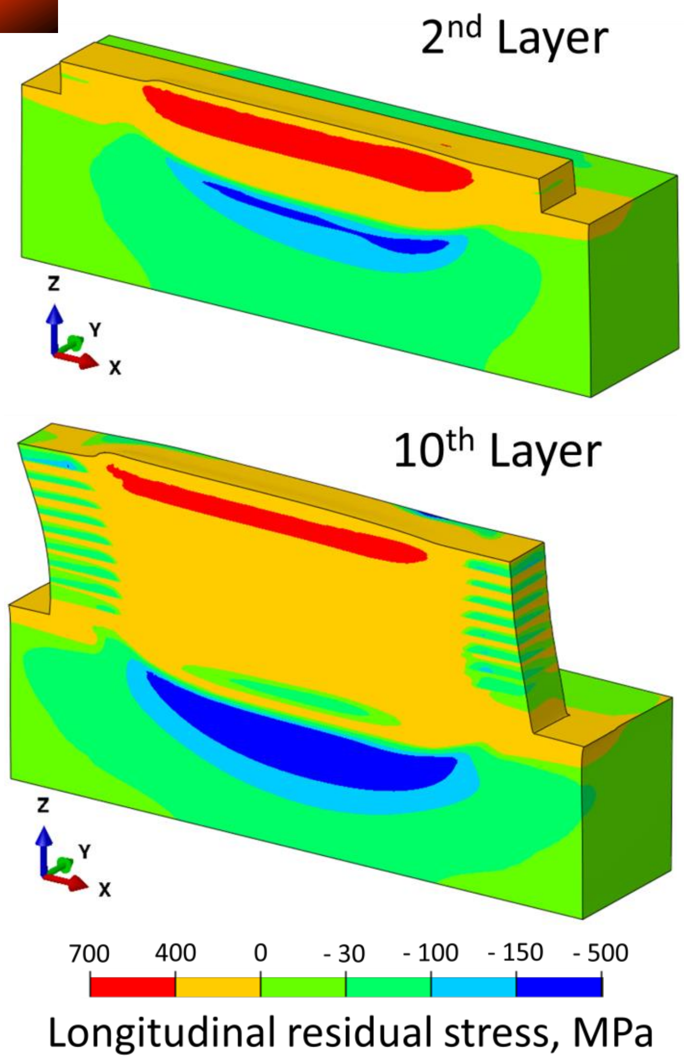
Using a Python script

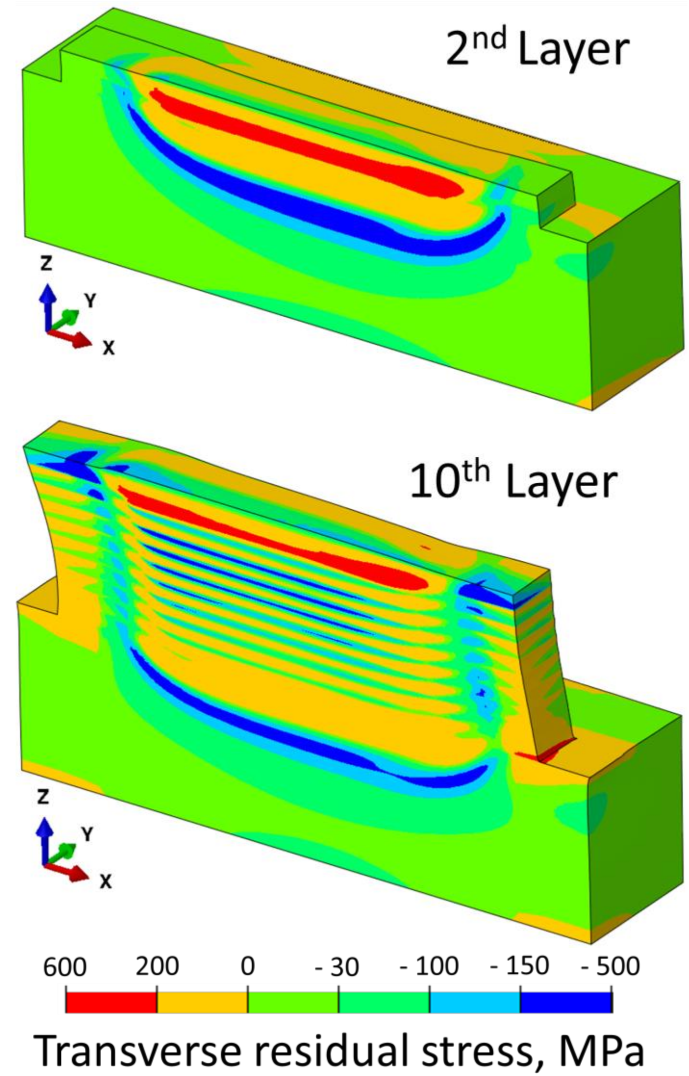


Geometry, mesh and temperature field

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

Calculated residual stresses



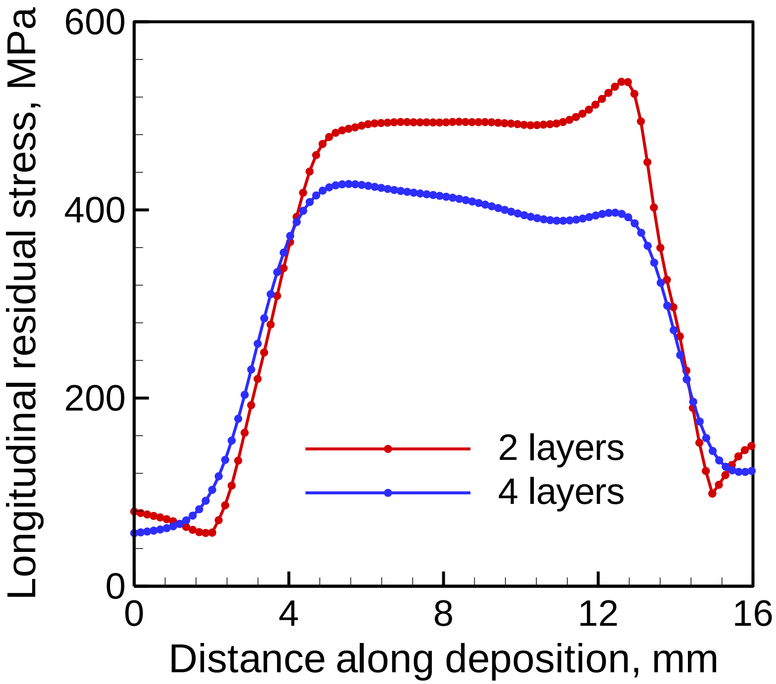


Alloy: Inconel 718,
Laser power: 300 W, Speed: 15 mm/s

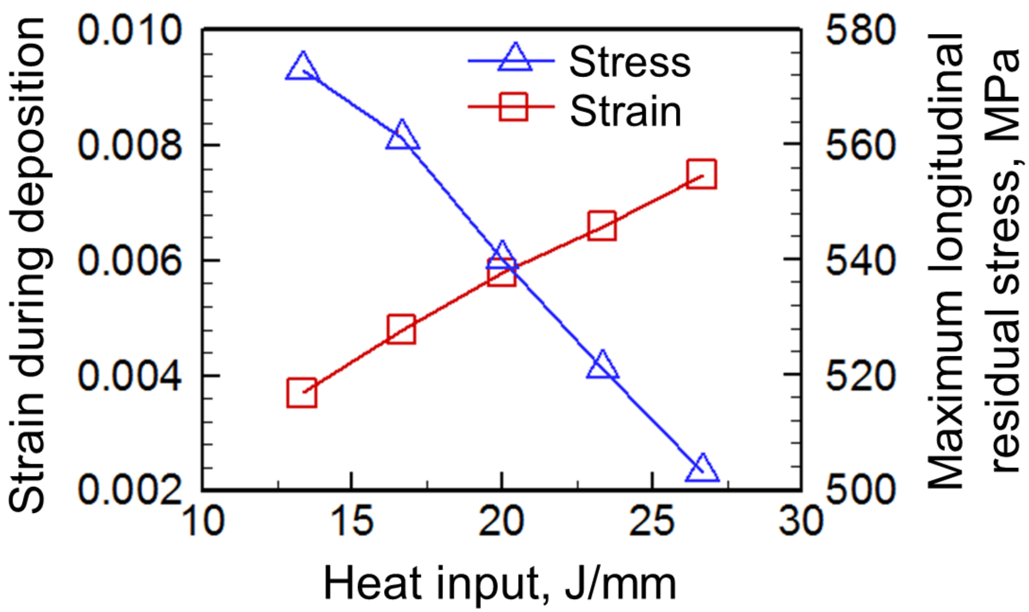
Scanning direction is along the positive x-axis
10 x magnification

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

Effects of layer thickness and heat input



Alloy: Inconel 718



=> 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.

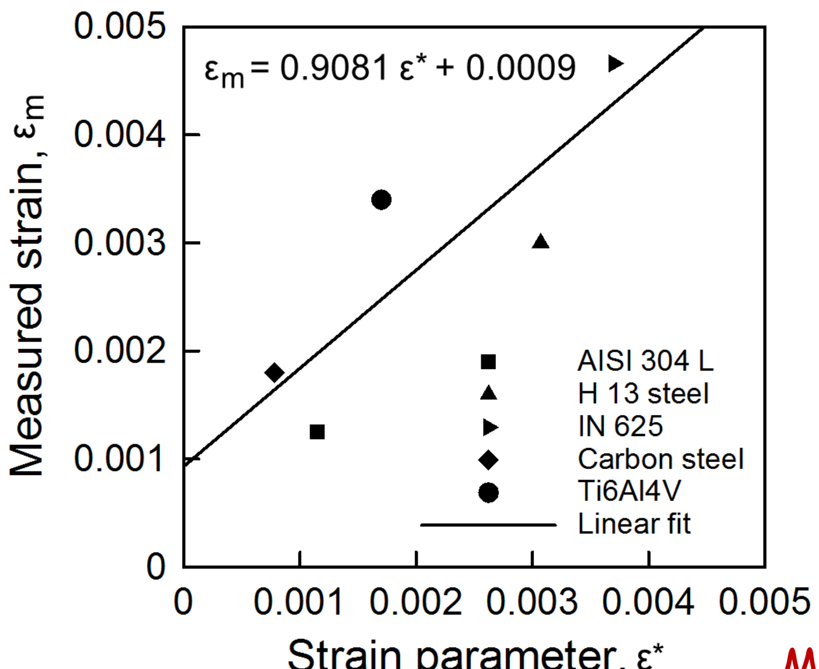
Mukherjee et al. Comput. Mater. Sci. 2017.

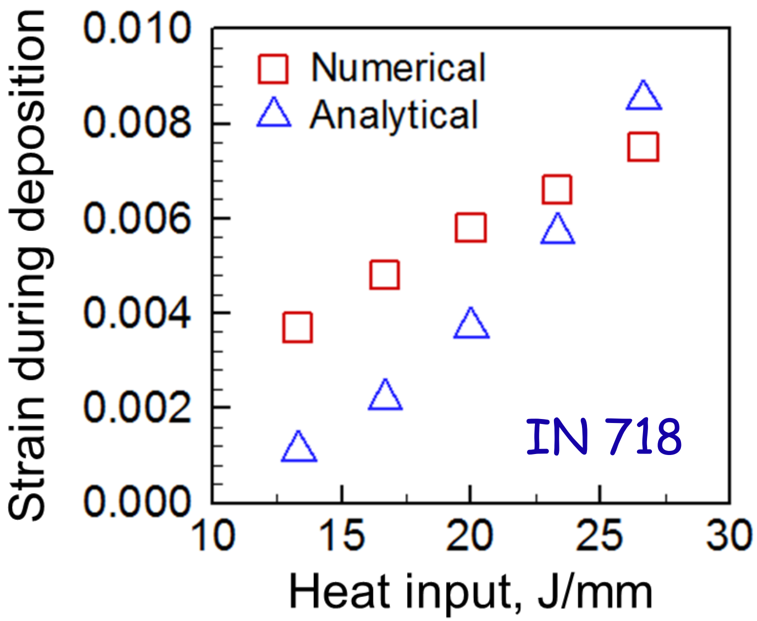
Measure of thermal distortion: Strain parameter

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

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

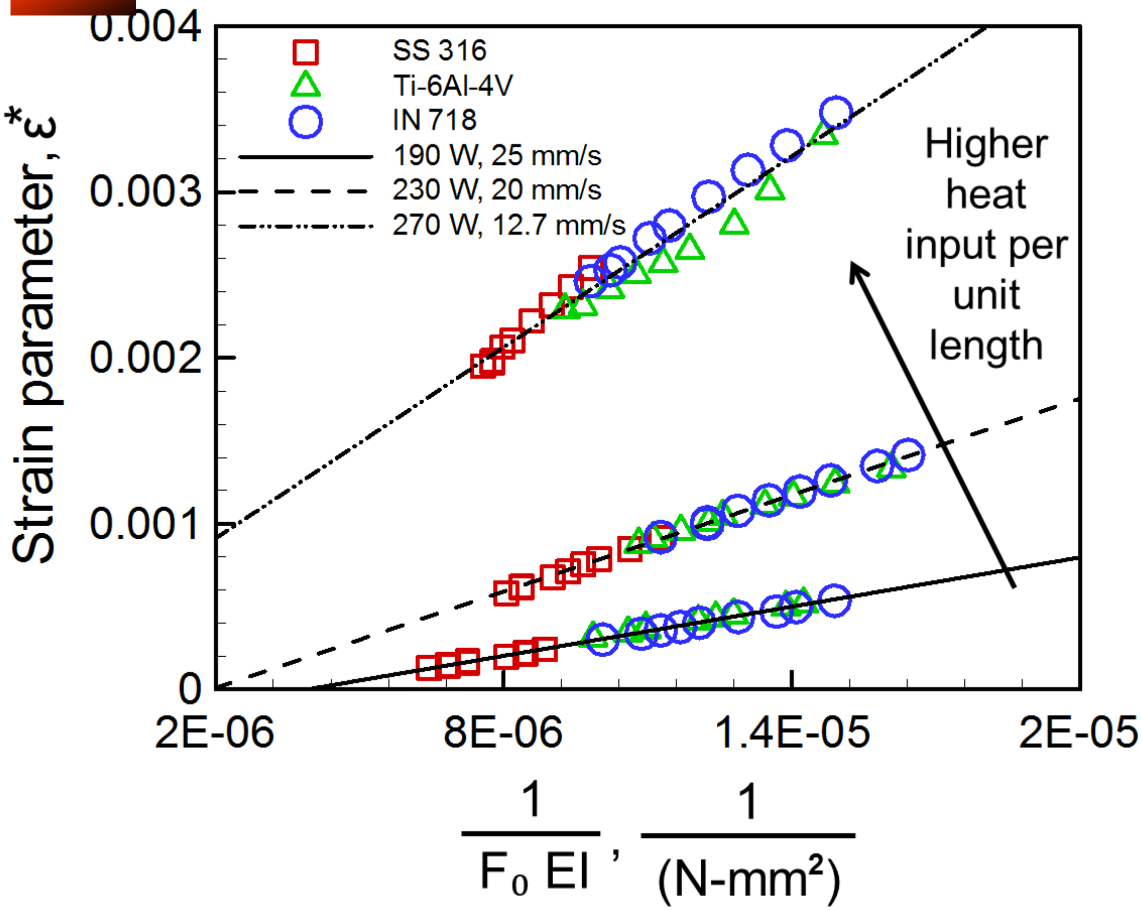
Variables	Symbols
Thermal expansion coefficient	β
Temperature difference	ΔT
Fourier number	F
Heat input per unit length	H
Total time	t
Flexural rigidity of substrate	EI
Density	ρ





Mukherjee et al. Scripta. Mater. 2017.

Thermal strain vs. Fourier number



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

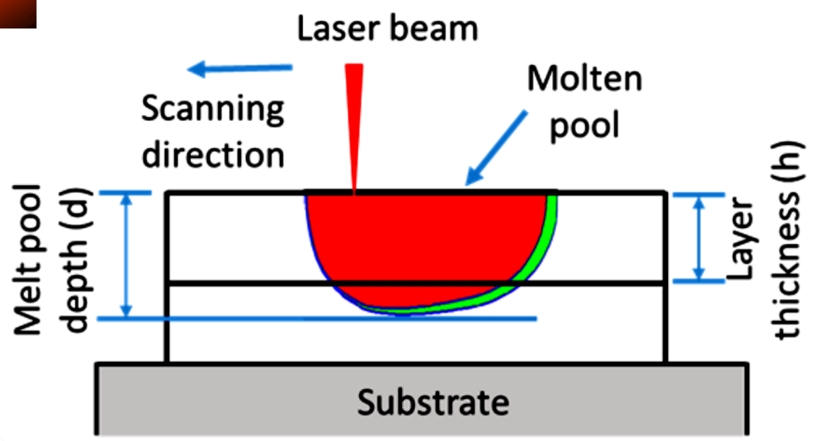
EI = Flexural rigidity of the substrate

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

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

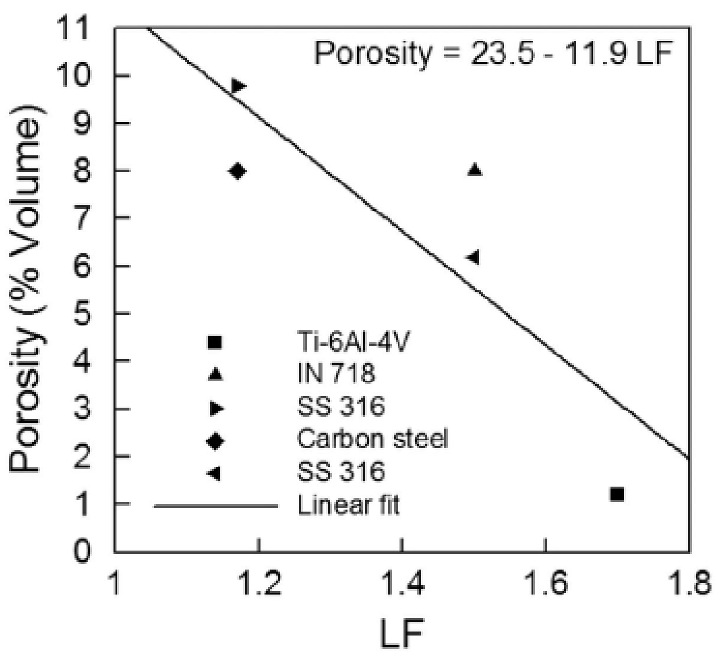
Mukherjee et al. Scripta. Mater. 2017.

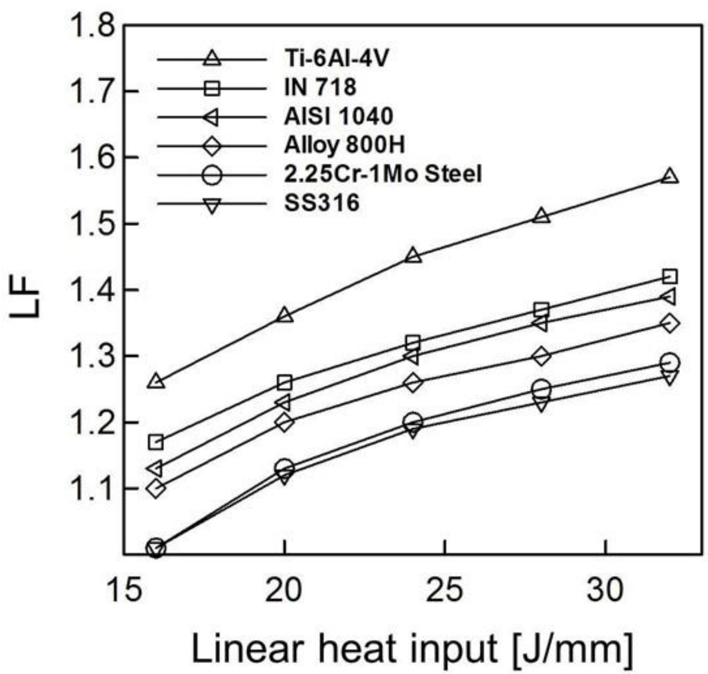
Lack of fusion defect



Lack of fusion index (LF) =

$$\frac{\text{Pool depth (d)}}{\text{Layer thickness (h)}}$$





Mukherjee et al. Sci. Rep. 2016.

Summary and conclusions

- A 3D transient heat transfer and fluid flow model is used to calculate the important metallurgical variables.
- Lower heat input results in faster cooling, smaller grain size and high hardness.
- 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.
- High Fourier no. (high heat dissipation and low heat storage) can effectively reduce thermal distortion.
- Lager molten pool at higher heat input ensures proper fusional bonding between layers.