Simulation of Laser Powder-bed Fusion Additive Manufacturing Process with the COMSOL Multiphysics® Software

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COMSOL CONFERENCE
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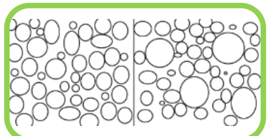
AM Simulation Module

Input

Material parameters

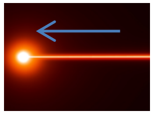
Powder size



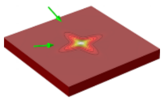
Chemical composition

Process parameters

Laser scan speed



Power density

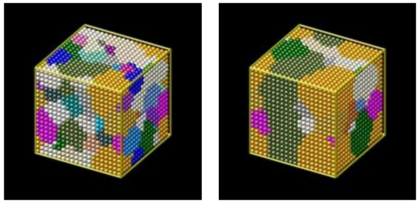


AM Simulation Module

Microstructure module

Thermal history

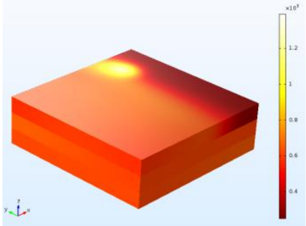
Material thermal and mechanical properties



Micro-scale

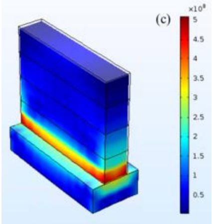
In-house thermo-mechanical simulation software + COMSOL

Heat transfer module



Meso-scale

Residual stress module



Macro-scale

- Microstructure composition / Phase fraction
- Grain size distribution
- Porosity / density distribution
- Temperature and melt pool distribution
- Surface roughness distribution
- Residual stress distribution

Performance Module

Mechanical performance module

Elastic modulus   Plastic properties, yield stress   Fracture toughness and fracture stress

Mechanical performance distribution: Elastic, plastic, and fracture properties distribution

Validation

Experimental results on material properties and mechanical performance

AM Heat Transfer

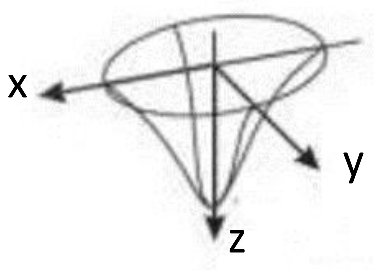
- The localized heating of powder is modeled by conductive heat transfer

$$\rho C_p \frac{dT}{dt} = k\nabla^2 T + \varphi$$

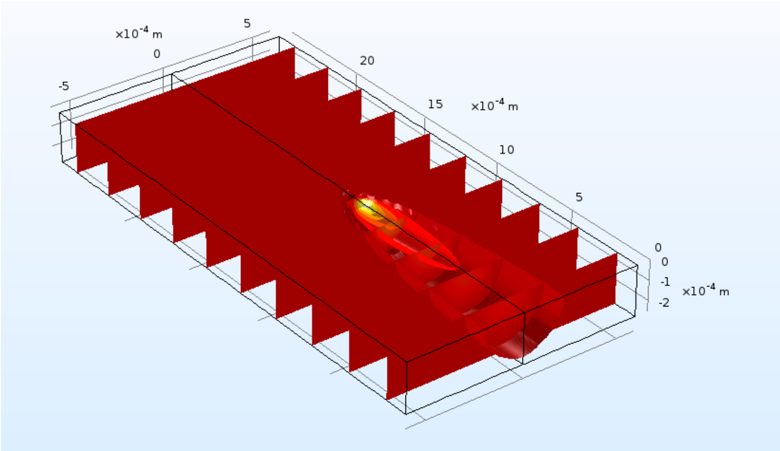
- T is the temperature, t is time, k is thermal conductivity, ρ is the density, C_p is the specific heat and φ is the heat source term
- The thermal interaction between the domain and surroundings can be represented as

$$-k\frac{dT}{dn} = -h(T_{amb} - T) + \sigma\varepsilon(T^4 - {T_{amb}}^4)$$

- h is the heat transfer coefficient, T_{amb} is the temperature of the environment, ε is the emissivity of the material and σ is the Stefan-Boltzman constant

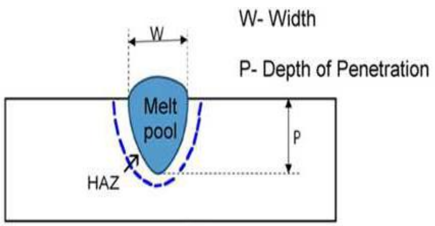


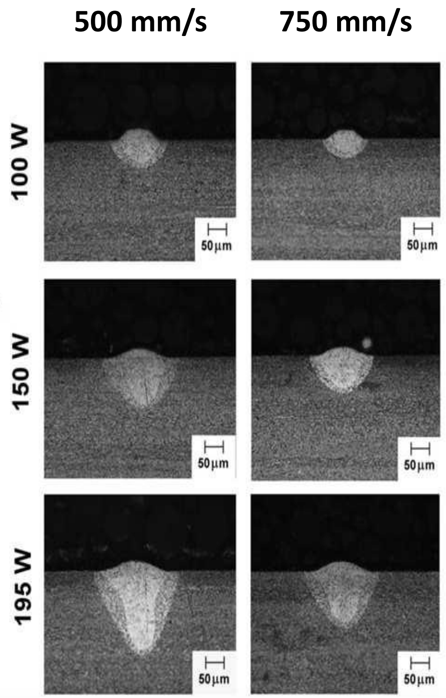
$$q(x,y,z,t) = \frac{6\sqrt{3}\alpha P}{abc\pi\sqrt{\pi}} e^{-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)}$$

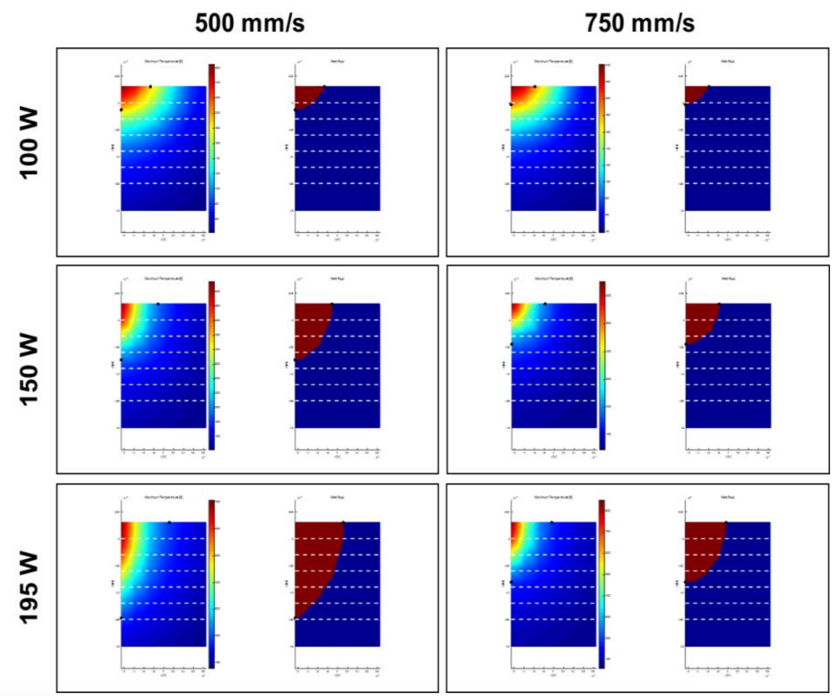


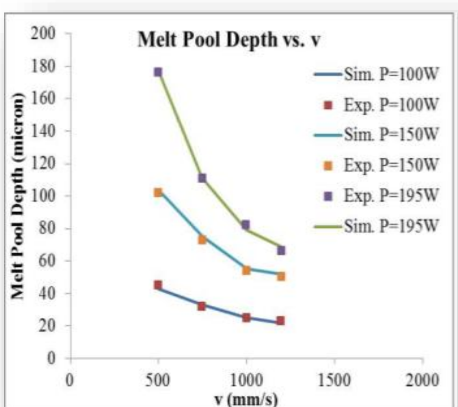
Melt Pool Simulation

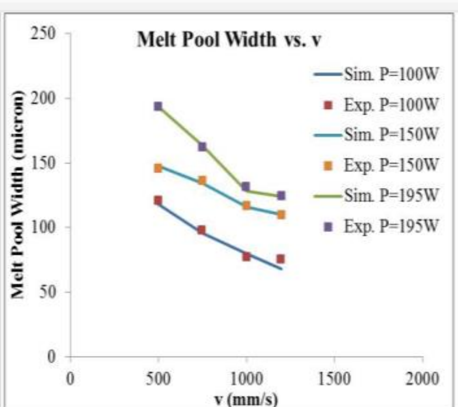
Dilip. Influence of processing parameters on the evolution of melt pool, porosity, and microstructures in Ti-6Al-4V alloy parts fabricated by selective laser melting.

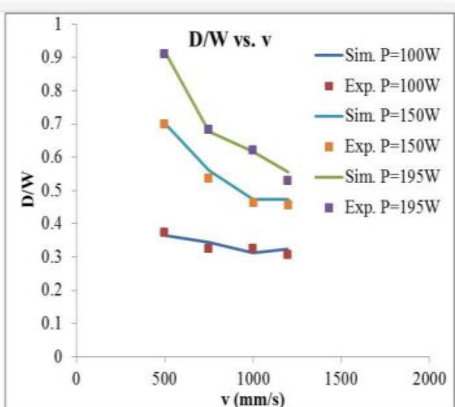




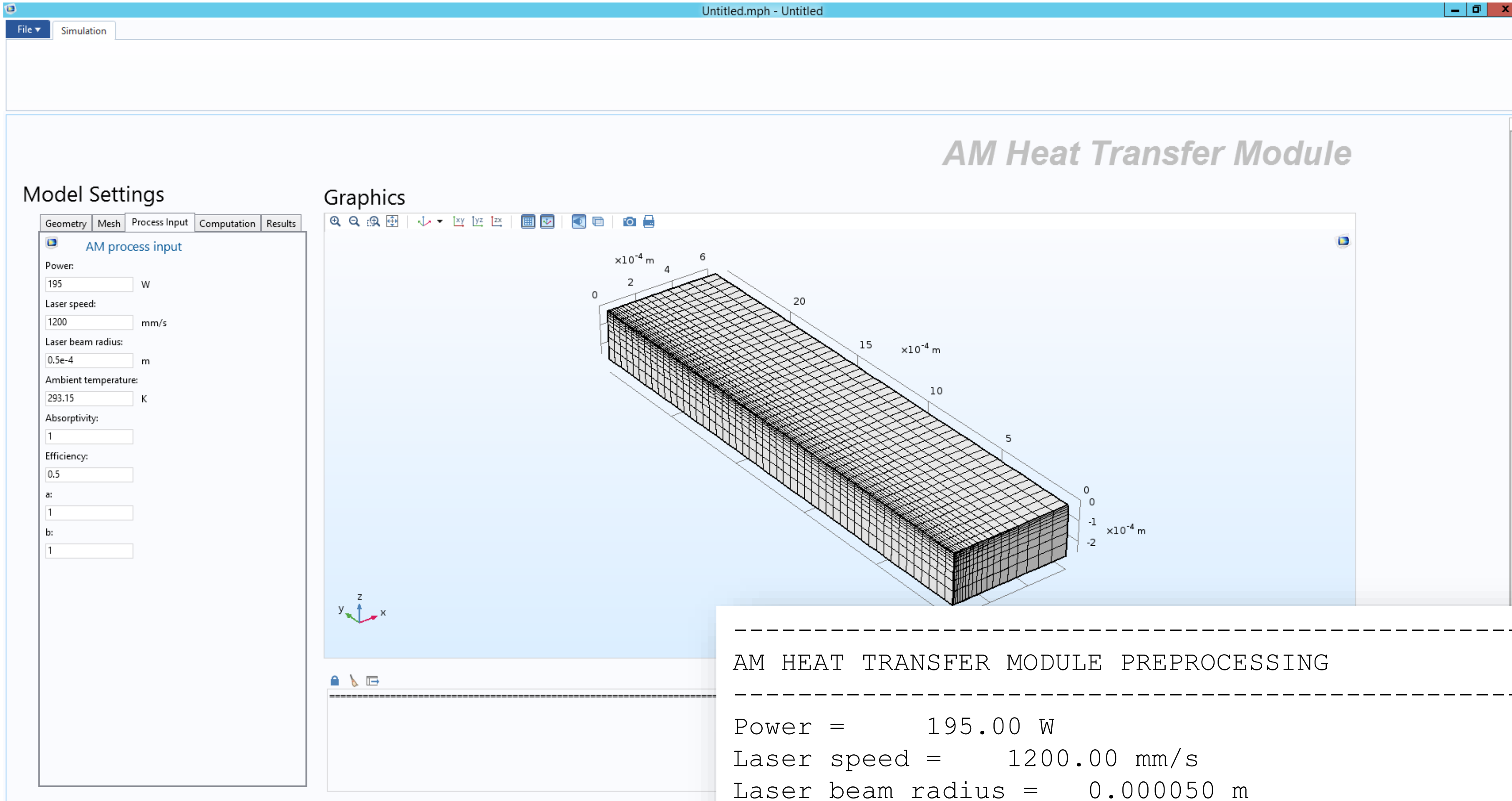








AM Heat Transfer Module

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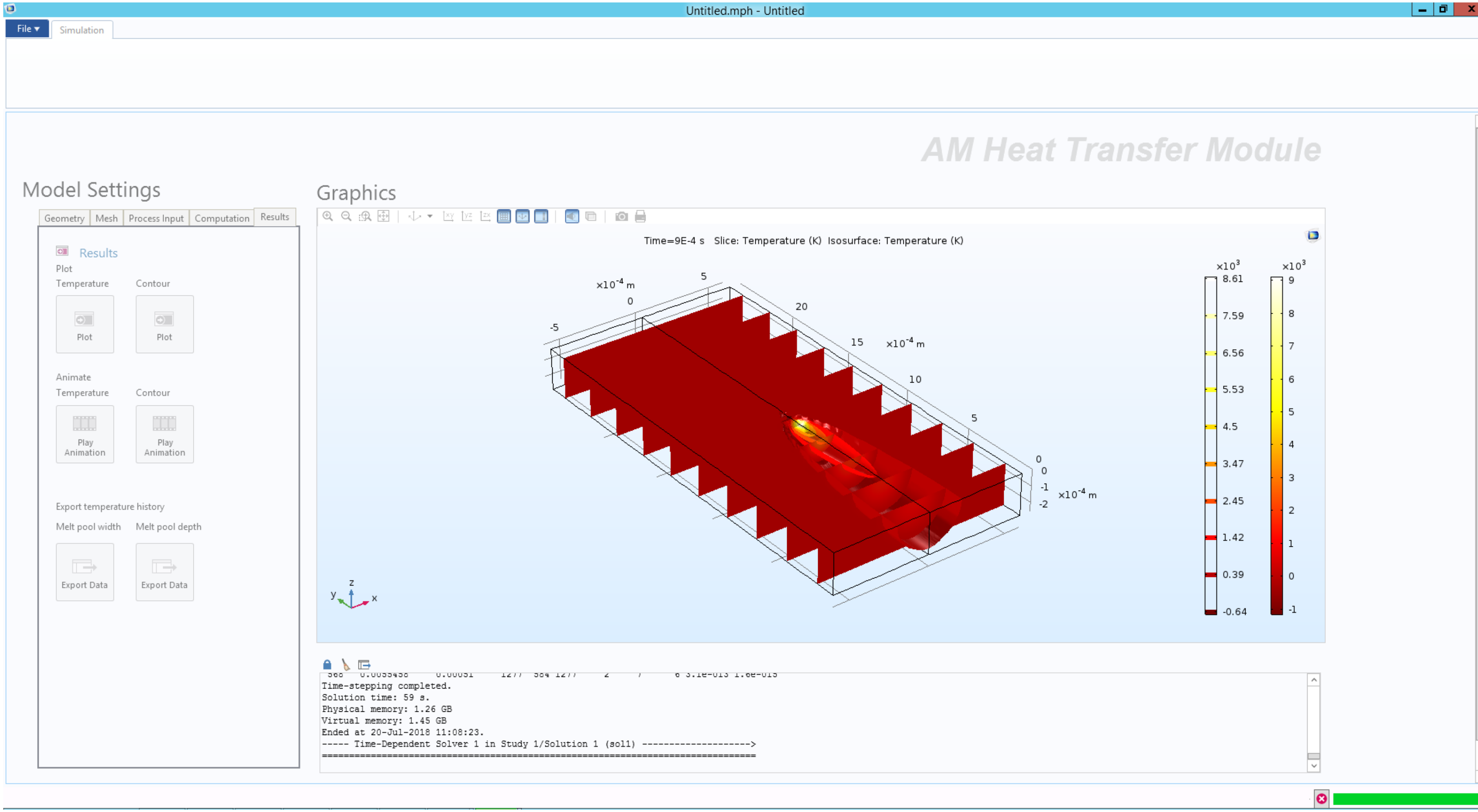
-------------------------------------------------
AM HEAT TRANSFER MODULE PREPROCESSING
-------------------------------------------------
Power =     195.00 W
Laser speed =     1200.00 mm/s
Laser beam radius =    0.000050 m
Ambient Temperature =      293.15 K
Absorptivity =        1.00
Efficiency =        0.50
a =        1.00
b =        1.00
-------------------------------------------------
```

AM Heat Transfer Module



Demonstration of heat transfer module

HT output.mp4

AM Heat Transfer Module

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----------------------------------------------------
AM HEAT TRANSFER MODULE POSTPROCESSING
----------------------------------------------------
Melt pool half width along scan path (micron):
Average =  63.86.
Median =  64.00.
Standard deviation =   1.27.
Maximum =  66.00.
Minimum =  57.00.
- - - - - - - - - - - - - - - - - - - - - - - - - -
Melt pool depth along scan path (micron):
Average =  63.84.
Median =  64.00.
Standard deviation =   1.25.
Maximum =  66.00.
Minimum =  57.00.
- - - - - - - - - - - - - - - - - - - - - - - - - -
Melt pool depth to width ratio along scan path:
Average =   0.50.
Median =   0.50.
Standard deviation =   0.00.
Maximum =   0.50.
Minimum =   0.49.
----------------------------------------------------
```
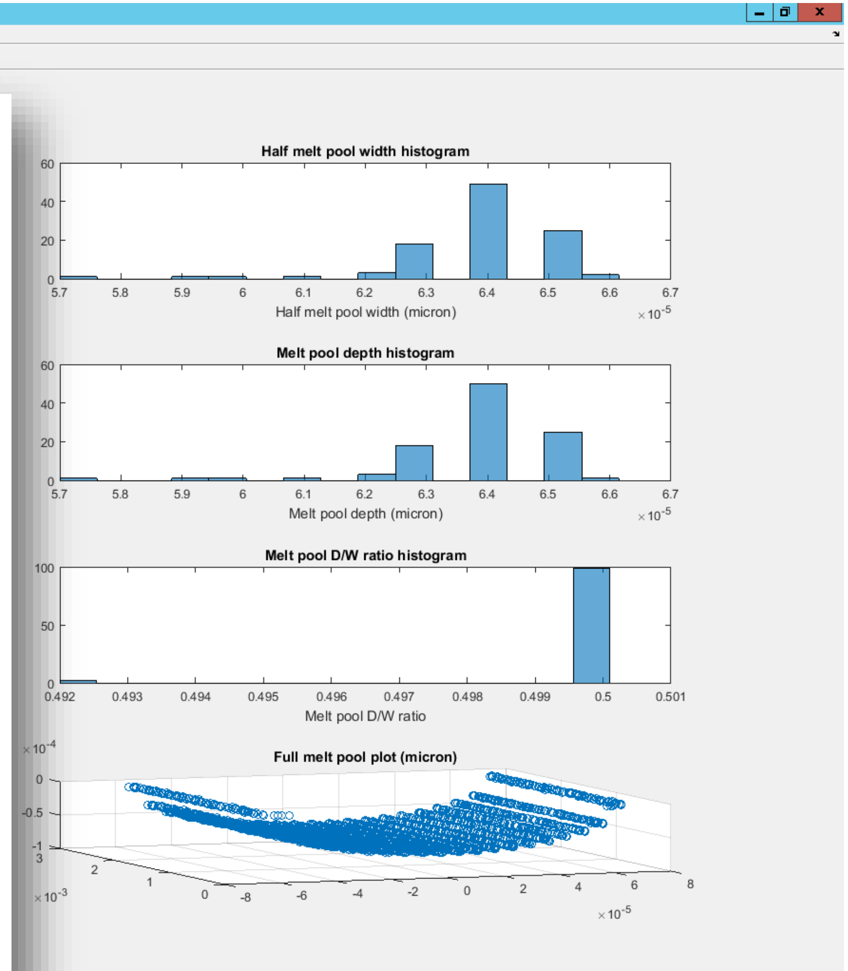
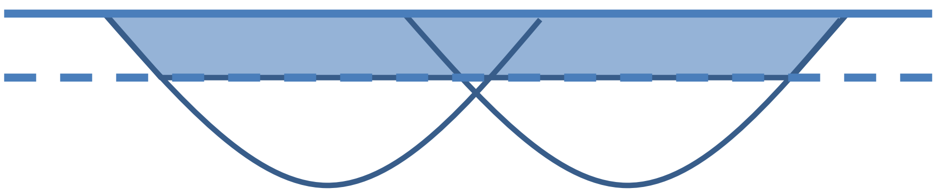
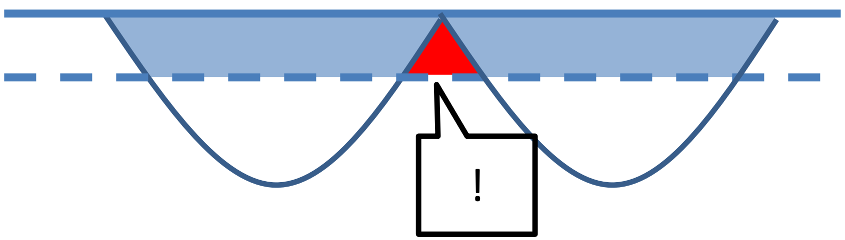



Porosity Estimation

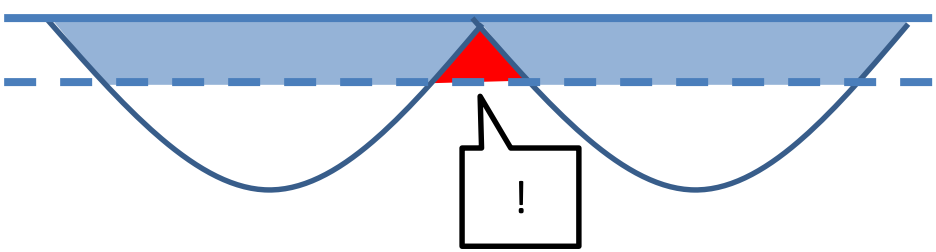
No lack of fusion porosity



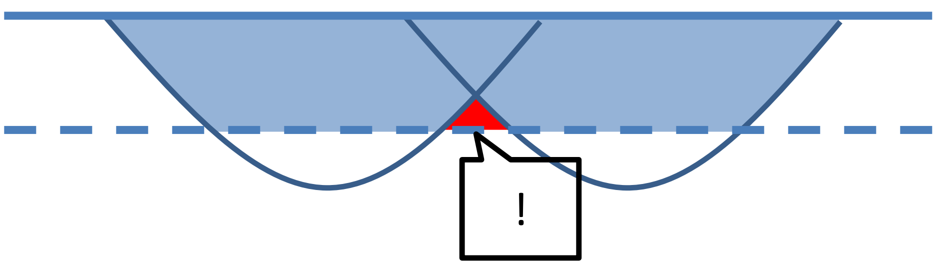
Increase scan speed



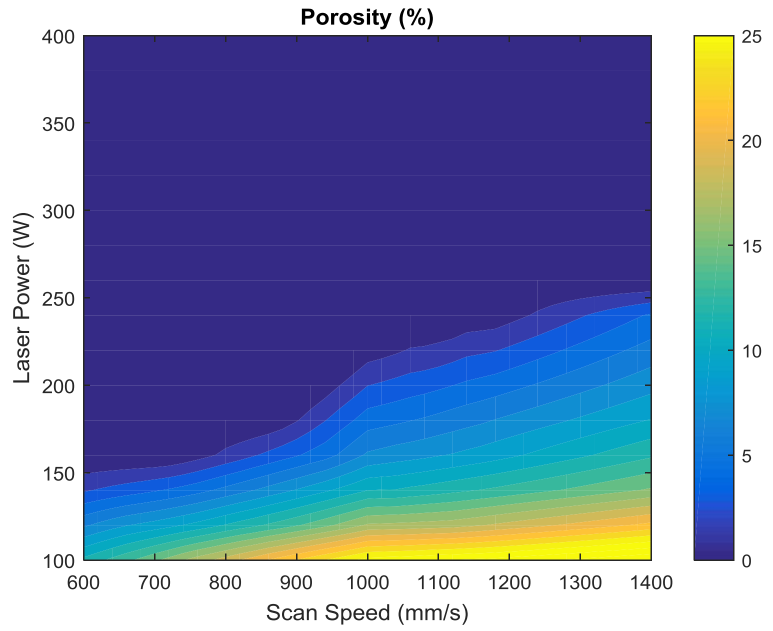
Increase hatch spacing



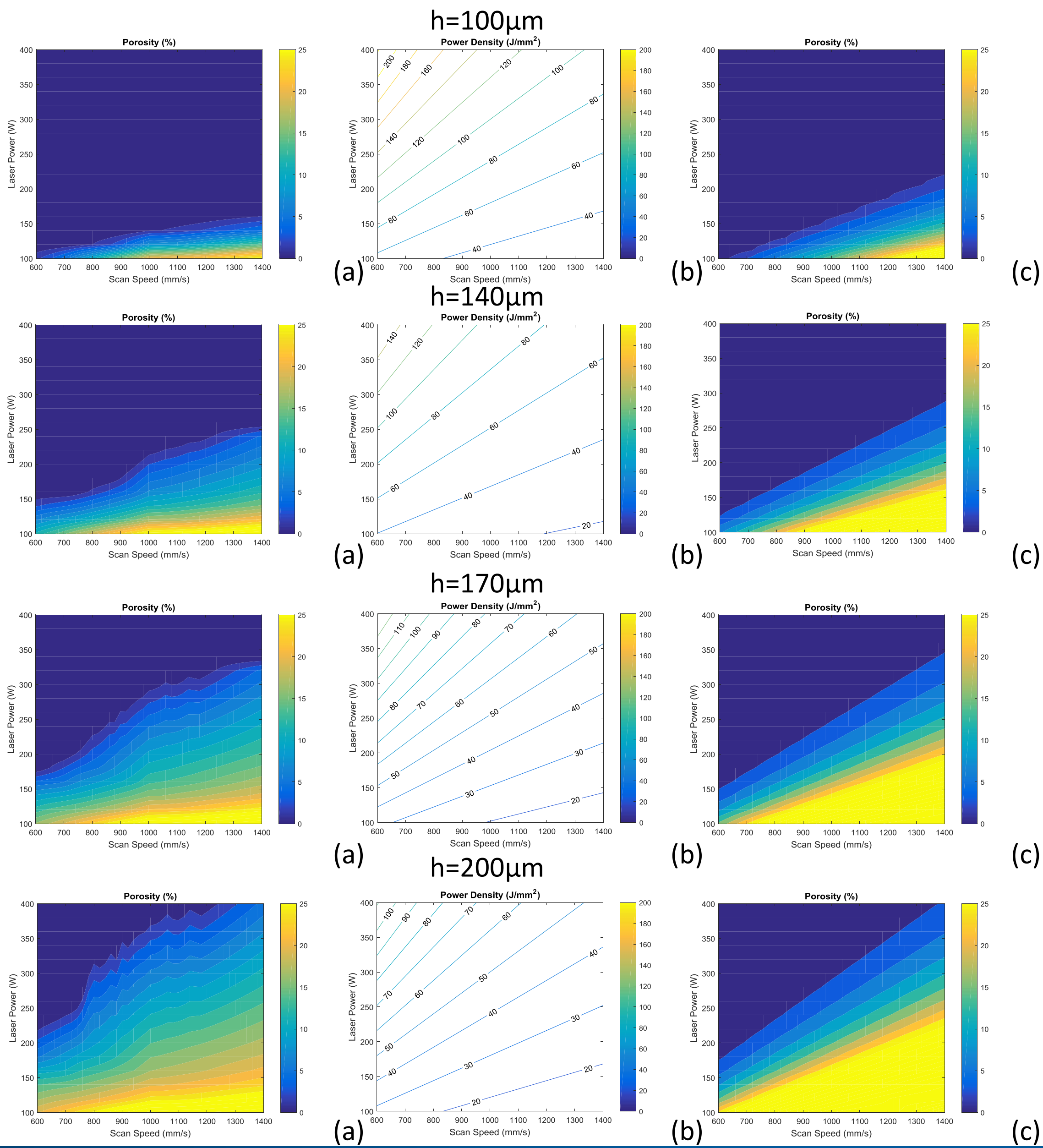
Increase layer thickness

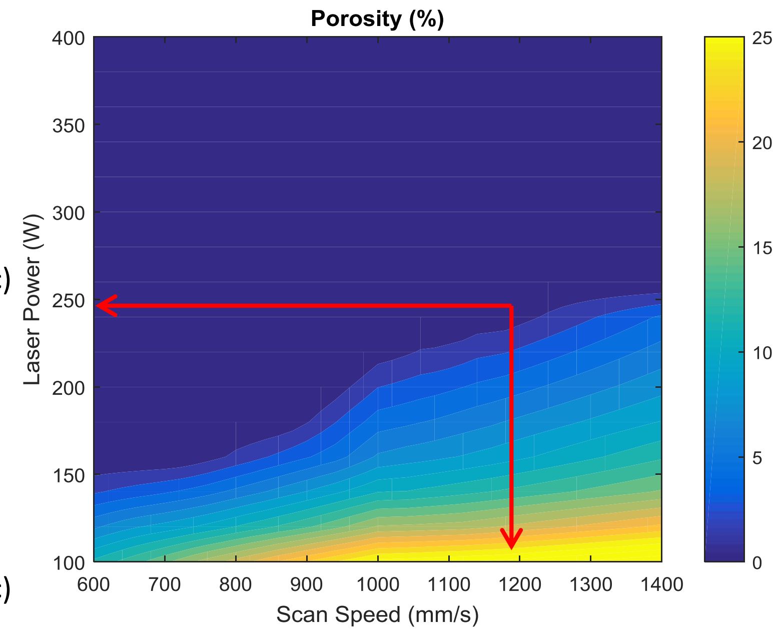


Lack of fusion porosity map

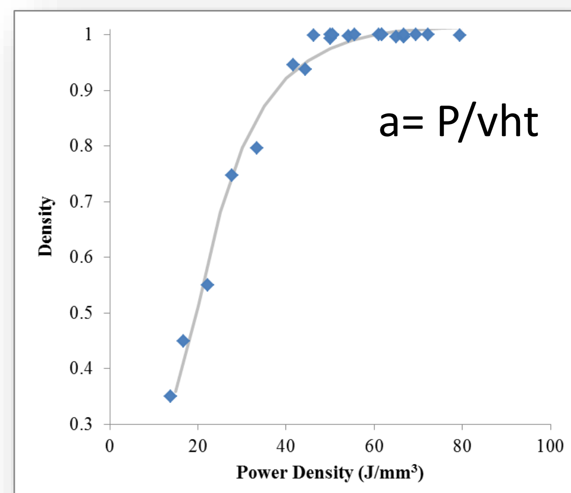


Porosity Estimation



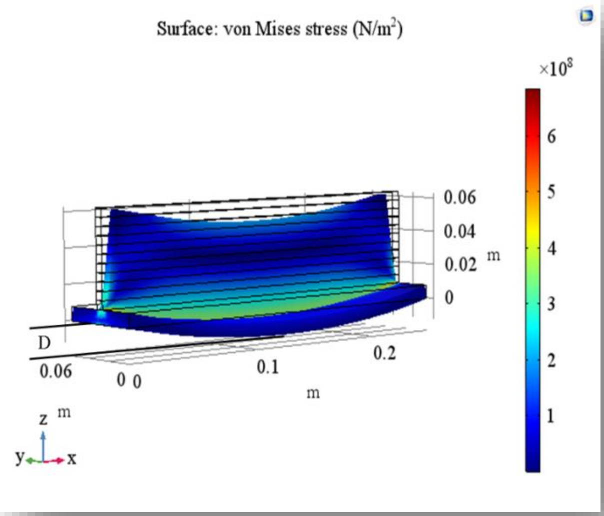


$$\rho = 0.91 + 18.3a - 904a^2 + 7590a^3$$



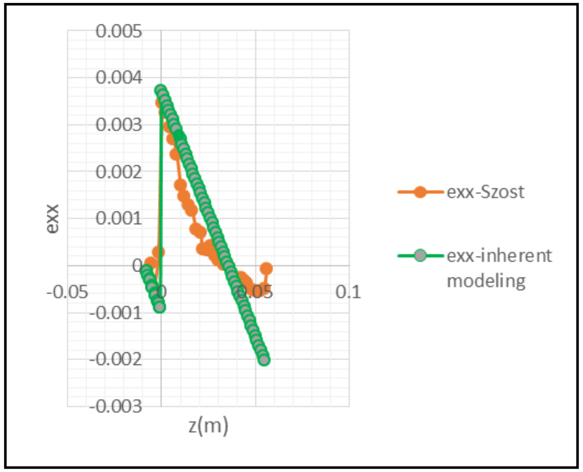
Distortion and Residual Stress

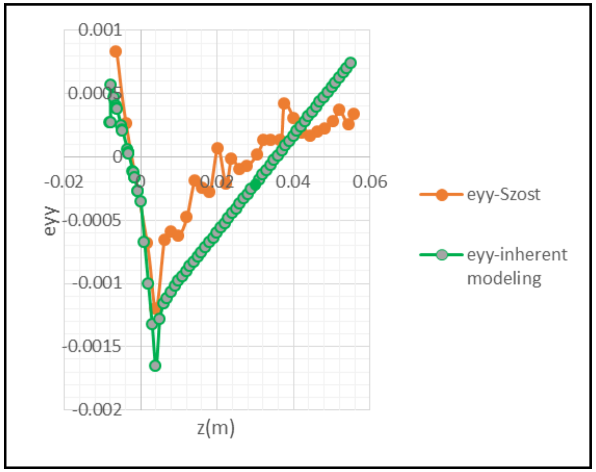
- Residual stress built up in Ti–6Al–4V AM components produced by laser cladding process (CLAD) is compared with inherent strain method.
- In the experimental study of Szost et al., 65 layers of approximately 0.85 mm high and 250 mm long of Ti–6Al–4V were deposited on a 250 × 60 × 8 mm baseplate.
- Same geometry has been modeled in COMSOL software. Compressive inherent strain with magnitude equal to the half of the ratio of the yield stress over the modulus of elasticity, at room temperature, have been prescribed in the longitudinal directions.

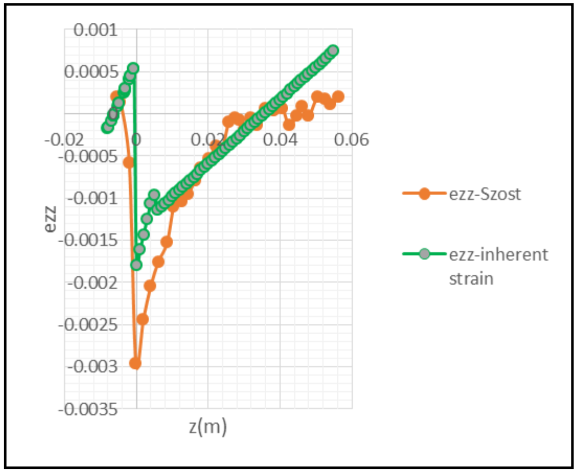


$D_{experimental}$=3.5 mm

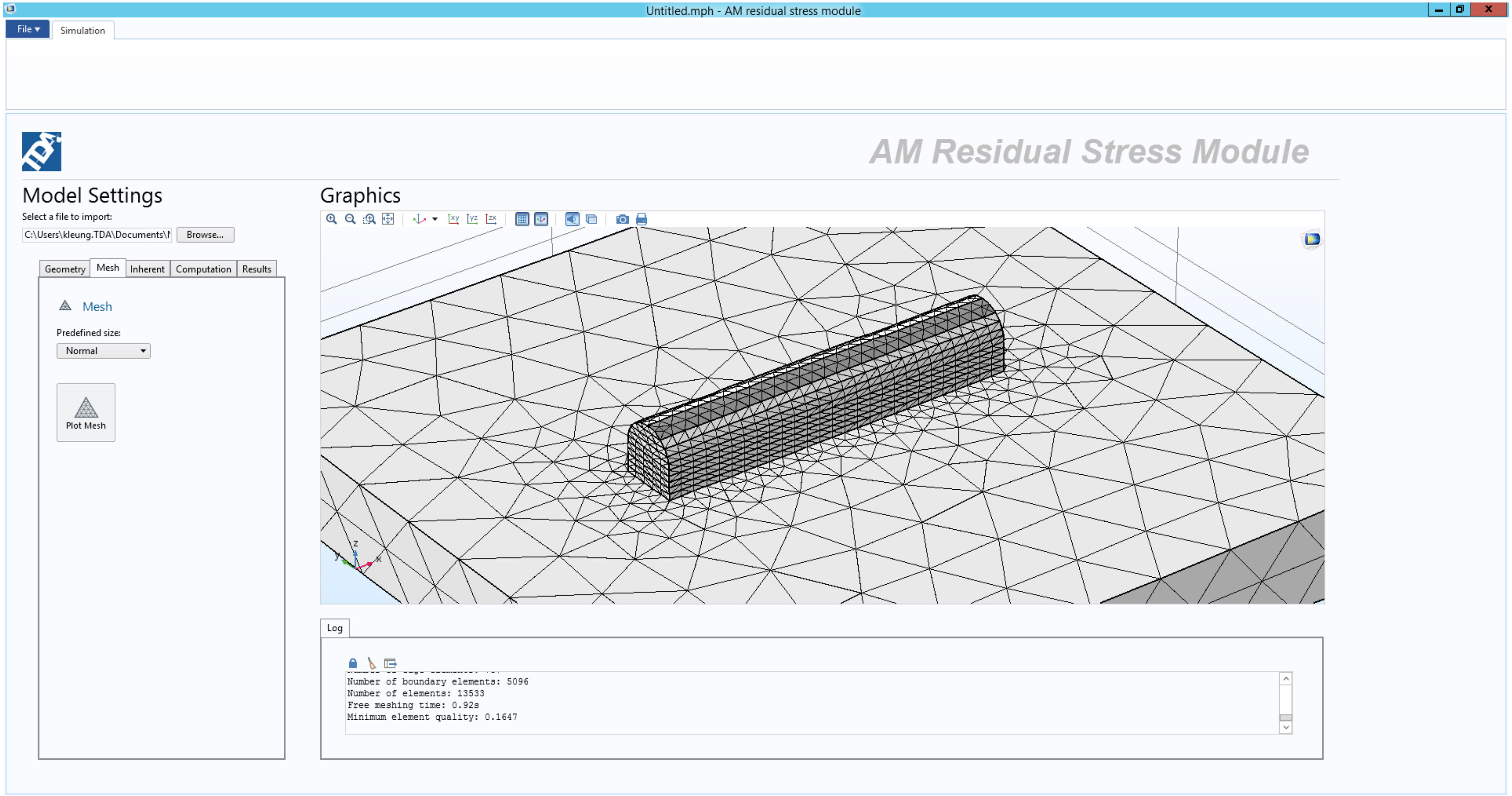
$D_{inherent\ strain}$ =1.5 mm



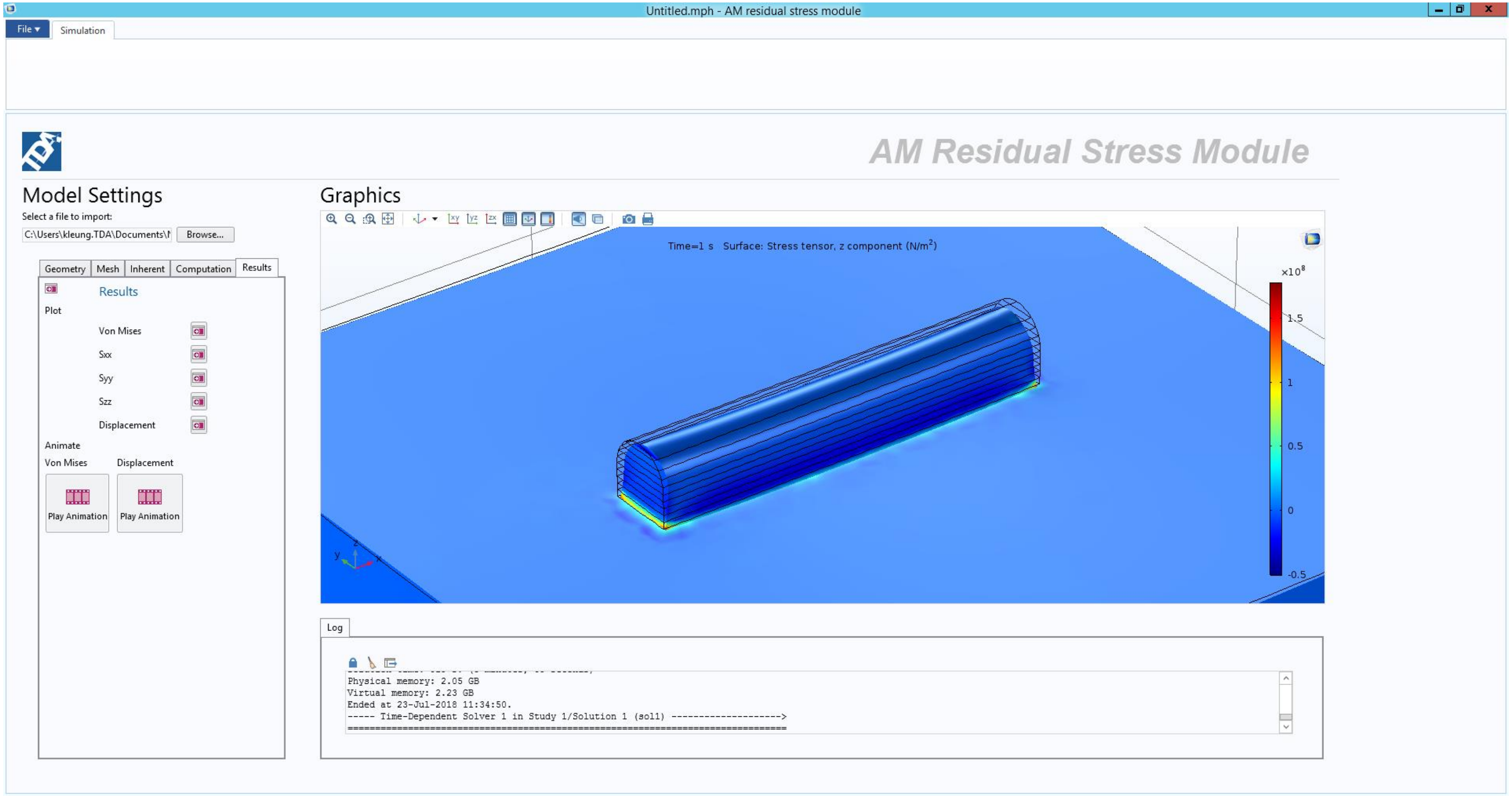




AM Residual Stress Module



AM Residual Stress Module



Demonstration of residual stress module

RS output.mp4

Planned Experiments

(P,V)	Scan Velocity (mm/s)			
	(400,400) [1]	**(400,800) [2]**	**(400,1200) [3]**	**(400,1500) [4]**
Power (W)	(250,400) [5]	(250,800) [6]	(250,1200) [7]	(250,1500) [8]
	(100,400) [9]	(100,800) [10]	(100,1200) [11]	(100,1500) [12]

Hatch Spacing (H) = 140 µm   Layer Thickness (T) = 30 µm

(P,V,H=150) [13]

(P,V,H=130) [14]

(P,V,T=40) [15]

(P,V,T=20) [16]

For each sample:

- In-situ monitoring to obtain melt pool depth, width and length, and temperature history (for tensile sample)
- CT scan of gage section to obtain porosity and size of defects (for tensile sample)
- Surface roughness measurement of gage section (for tensile sample)
- Microstructure analysis: phase fraction of α and β, α lathe size and prior β size (for tensile sample)
- Stress-strain curve (for tensile sample)
- Bridge samples to measure distortion (for bridge sample)

Experiments

On mechanical properties

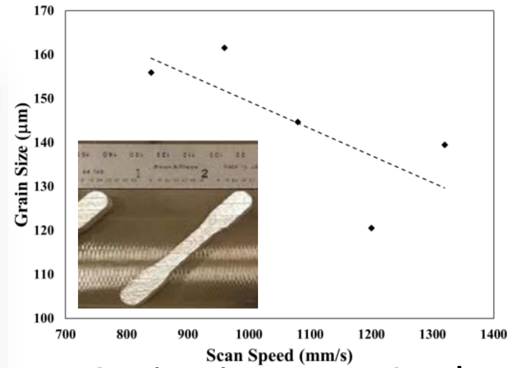
Tensile properties

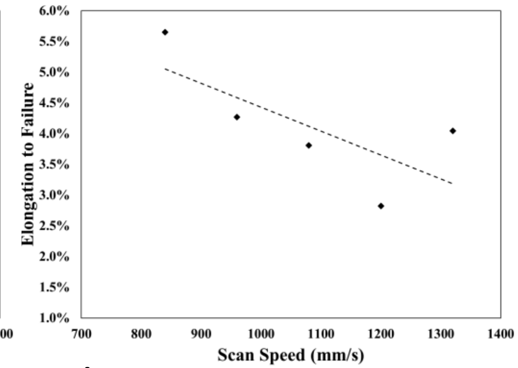
Parameter2	E	σ_y	UTS	Elong.	σ_f	ε_f
	MPa	MPa	MPa	%	MPa	%
1	95775	1084	1133	3.40%	1170	3.28%
2	101988	1079	1130	2.83%	1168	3.31%
3	102414	1111	1169	3.88%	1213	3.78%
4	98976	1063	1112	3.81%	1153	3.65%
5	98015	1071	1127	4.04%	1158	3.65%
6	97647	1074	1136	4.60%	1183	4.35%
7	99504	1066	1133	5.35%	1186	4.98%
10	95847	1050	1123	3.04%	1156	2.95%
11	99399	1068	1137	4.24%	1183	4.07%
13	100275	1052	1118	4.27%	1165	4.08%
14	97331	1073	1136	5.65%	1189	5.35%
16	94935	1073	1144	4.72%	1185	4.23%

Parameter	Long.	CS-90°	CS-0°	Average
	µm	µm	µm	µm
1	98.44	220.47	111.15	143.35
2	91.97	181.71	88.08	120.59
3	67.86	160.11	109.05	112.34
4	133.61	209.93	90.62416	144.72
5	123.33	222.10	107.66	151.03
6	112.30	210.45	98.03	140.26
7	109.93	287.01	127.92	174.95
10	109.62	237.23	129.29	158.72
11	123.98	218.72	106.5306	149.74
13	166.65	196.01	121.98	161.55
14	175.00	157.34	135.49	155.94
16	104.77	203.54	80.03	129.45

Microstructure properties

Scan speed -> grain size





Grain size -> UTS, elongation