George W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology

ME3210

3-D Printing

Assigned Reading:

10.12.

Methods

Prototyping: The making of parts, as opposed to mass production

Prototyping: CNC machining, however, internal and intricate features are hard to accomplish.

Virtual Prototyping: Virtual reality. No physical part is produced.

Prototyping: point-by-point and layer-by-layer building up of parts by resin curing or metal re-solidification.

3-D Printing

Additive Prototyping/Manufacturing, Prototyping, Manufacturing, Fabrication:

a process by which a solid physical part is made directly from a 3-D CAD drawing through point-by-point or layer-by-layer material .

Advantages:

(1) Short fabrication preparation time for niched part, requiring no set-up and ______ time,

(2) Very little limitation by part geometry complexities. Even ______ features that cannot be made otherwise is possible.

Difficulties:

(1) ______ fabrication cycle time for each part, cannot justify batch production,

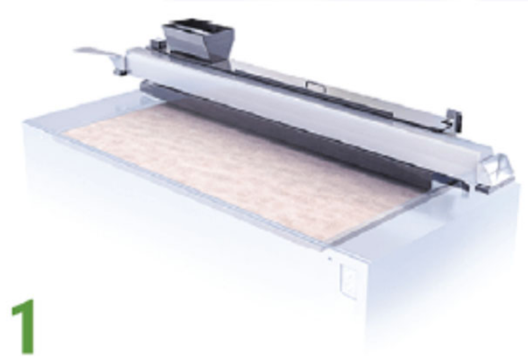
(2) Part finish and dimensional accuracy are not as great,

(3) Part mechanical performance may be inconsistent.

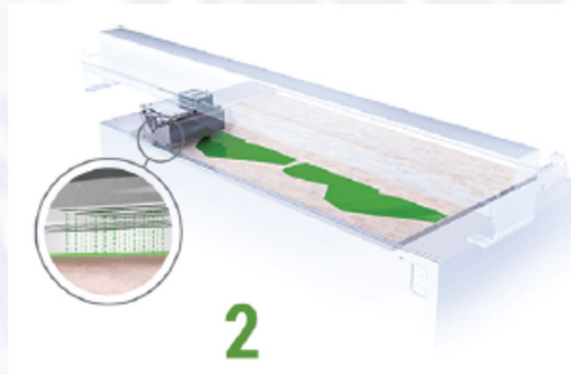
Binder Jetting

For sand, ceramic, and metal parts

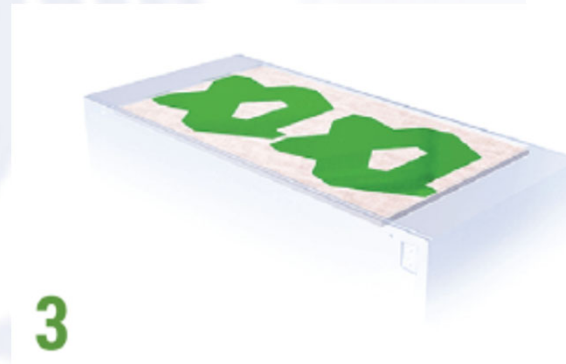
Depositing Powder



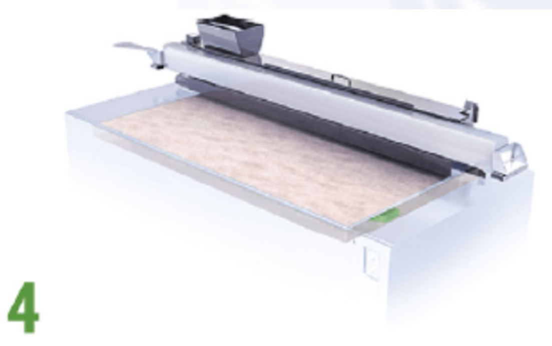
Applying Binder



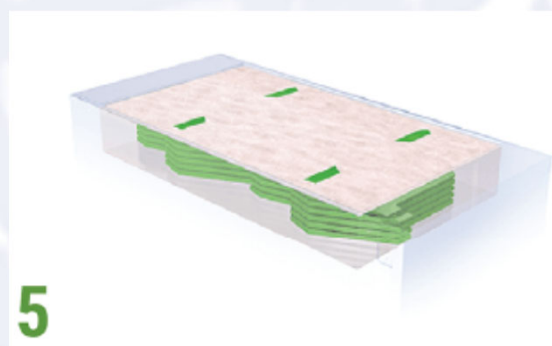
Printing Layer



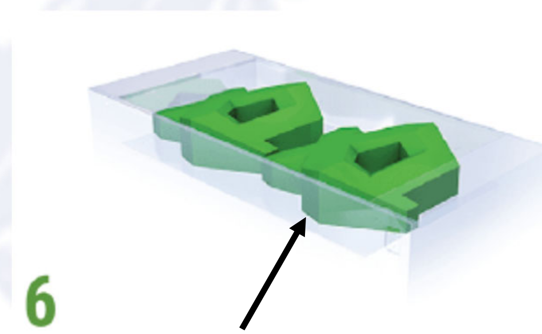
Drying/Recoating



Repeating Process



Completing



weak and brittle

Post-Jetting Steps

-Curing: Oven hardening at 200^{o}C for several hours, typically on the printing bed with loose powders still in place, to polymerize the binder and strengthen the green;

-[ ]: removing the loose powers with compressed air, vibration, or vacuum;

-Debinding and Sintering: Furnace heating at 250~500^{o}C for 1~2 days, to burn off the binders then to fuse the powders by thermal diffusion;

-[ ]: Applying molten bronze to fill voids in the part, reduce porosity, and further strengthen parts.

https://www.youtube.com/watch?v=L6Rd9dilkrs

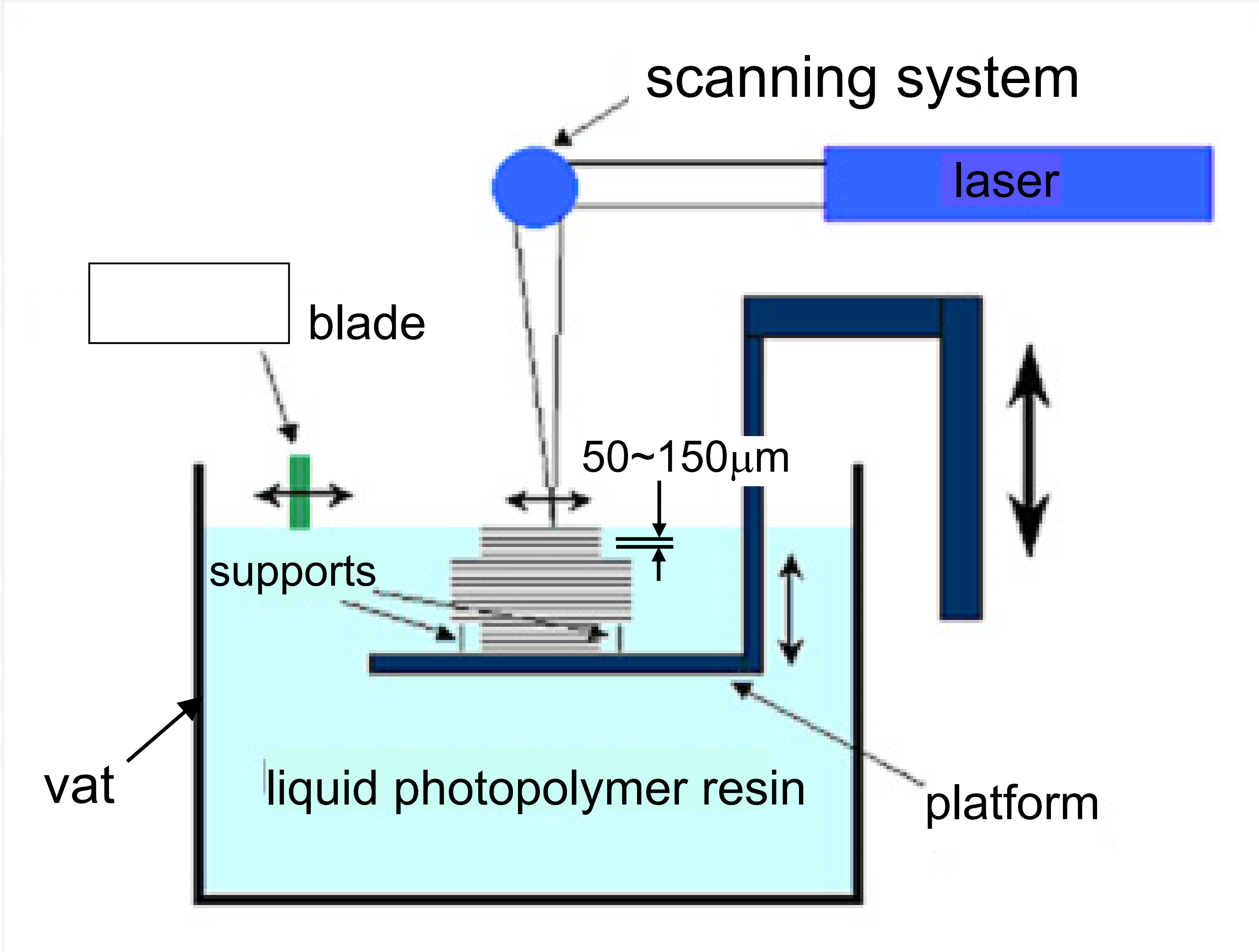
Advantages of Binder Jetting:

- [ ] parts are possible;
- Parts stronger than LOMed ones;
- Used powders are recyclable.
- No residual stress from thermal gradient

Difficulties:

- Surface finish is hard to control, in lack of [ ];
- Dimensions hard to control, due to shrinkage in sintering
- Post-processing requires significant time

(SLA)



http://www.youtube.com/watch?v=iceiNb_1E0I

Part Materials (UV curable liquid): photopolymer resin

UV Light Source: Laser

Build Platform (elevator): $\boxed{}$ axis positioning table.

Recoater Blade: a reciprocating sweeper

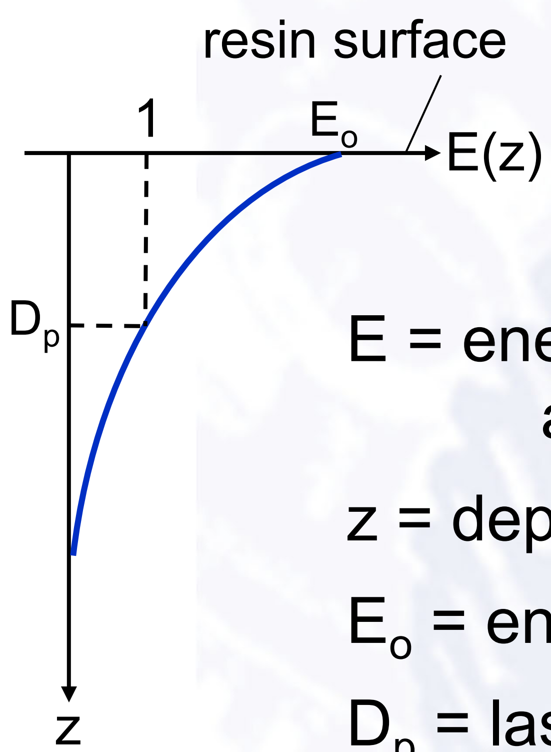
Supports: to sustain overhanging features

The platform starts from its $\boxed{}$ position. The liquid at the laser focus cures and forms a cross section while the platform traverses (or the scanner traces) on the X-Y plane. After the blade moves across the cross section to smooth it, the platform lowers by a certain height ($\boxed{}$ thickness) and the process repeats.

SLA Energy and Curing

Liang

Energy Exposure by Beer-Lambert Law:



$$E(z) = E_0 \boxed{}$$

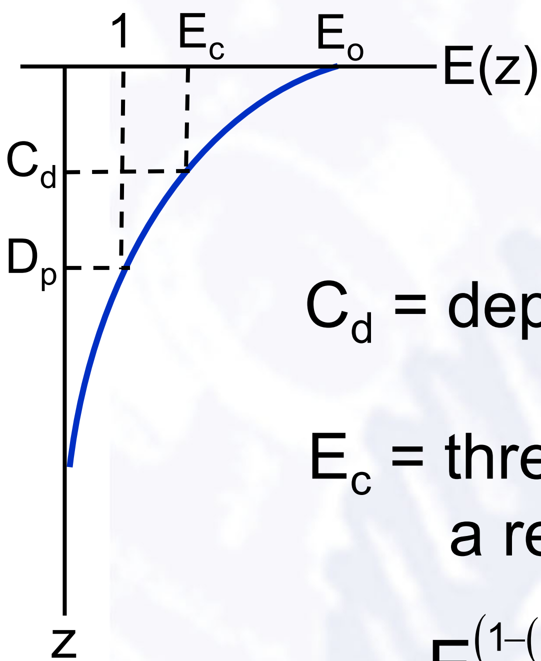
(*Text Eq10.27 is mistaken*)

E = energy exposure per unit area (energy density) at depth z into material;

z = depth into the material;

E_o = energy density at the surface

D_p = laser penetration depth where the laser energy density reduces to a $\boxed{}$. It's a resin material property, indicating the level of ease for laser to penetrate, inversely indicating the energy absorption ability at that laser wavelength.

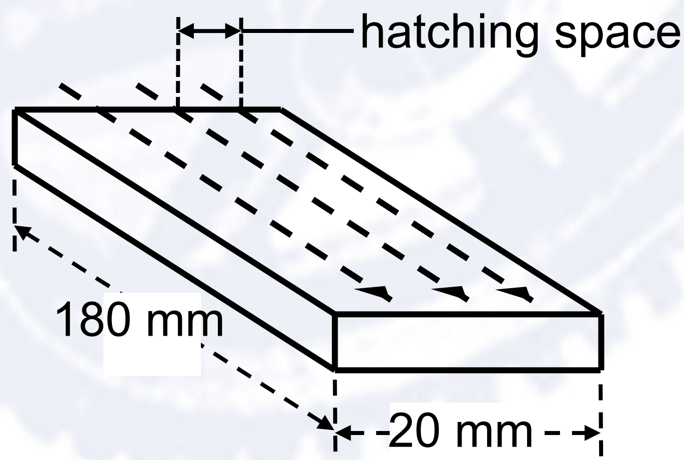


C_d = depth of curing

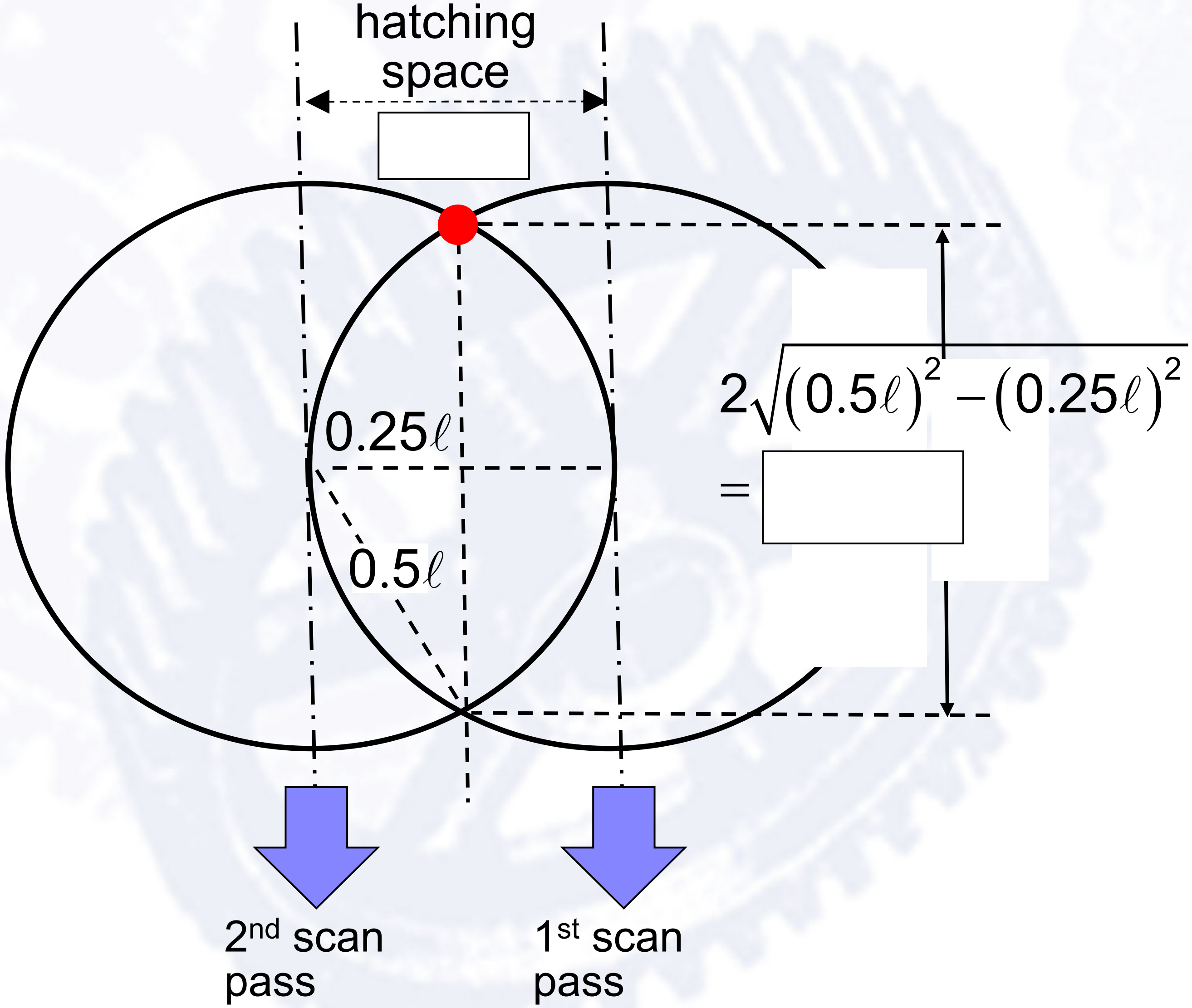
E_c = threshold energy density for curing to occur.
a resin material property

$$= E_0^{\left(1-\left(\boxed{}\right)\right)}$$

Ex: A 10 W (10^4 N-mm/s) laser of 0.5 mm spot diameter is used for stereolithography on an epoxy of 8.4 N/mm threshold energy density and 0.35 mm laser penetration depth. If a rectangular surface area of 180X20 mm^2 is to be cured to a depth of 0.15 mm on one layer, what would be the total amount of time required to cure this layer, using a hatching space of half of laser spot diameter? Consider that the laser spot size does not change with resin depth but its power does.



Sol:


hatching space
0.25ℓ
0.5ℓ
$2\sqrt{(0.5\ell)^2-(0.25\ell)^2}$
$=$
2nd scan pass
1st scan pass

At z=0.15mm,

Time (t_1) for any point to receive sufficient curing energy

$t_1 = E_c/P_a$; where P_a is laser power density=P/ $\boxed{}$

At depth of 0.15 mm,

$$P_a(0.15) = P_a(0)^{\left(1-\left(Z/D_p\right)\right)} = \frac{10^4}{\left(\pi * 0.5^2\right)/4}^{\left(1-\left(0.15/0.35\right)\right)} = 489 \text{ N/mm-s}$$

$$\Rightarrow \quad t_1 = 8.4/489 = 0.017 \text{ sec}$$

Maximum feed rate for spot to travel for one overlap length

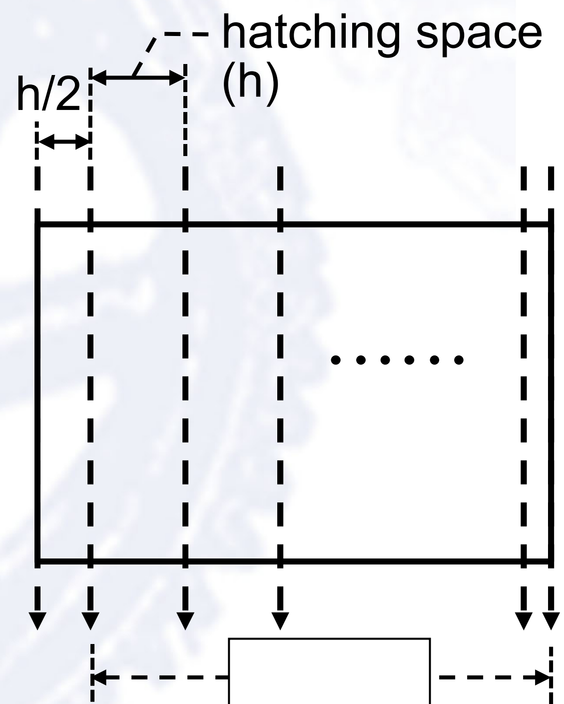
= ($\boxed{}$)/t_1 = 0.866(0.5)/0.017 = 25.47 mm/s

Time to cure one straight line (t_2)

$= 180/\boxed{\qquad\qquad\qquad} = 180/(25.47) = 7.07$ sec

$$\text{No of scans} = \text{int}\left[\frac{20-(h/2)}{h}\right]+2$$

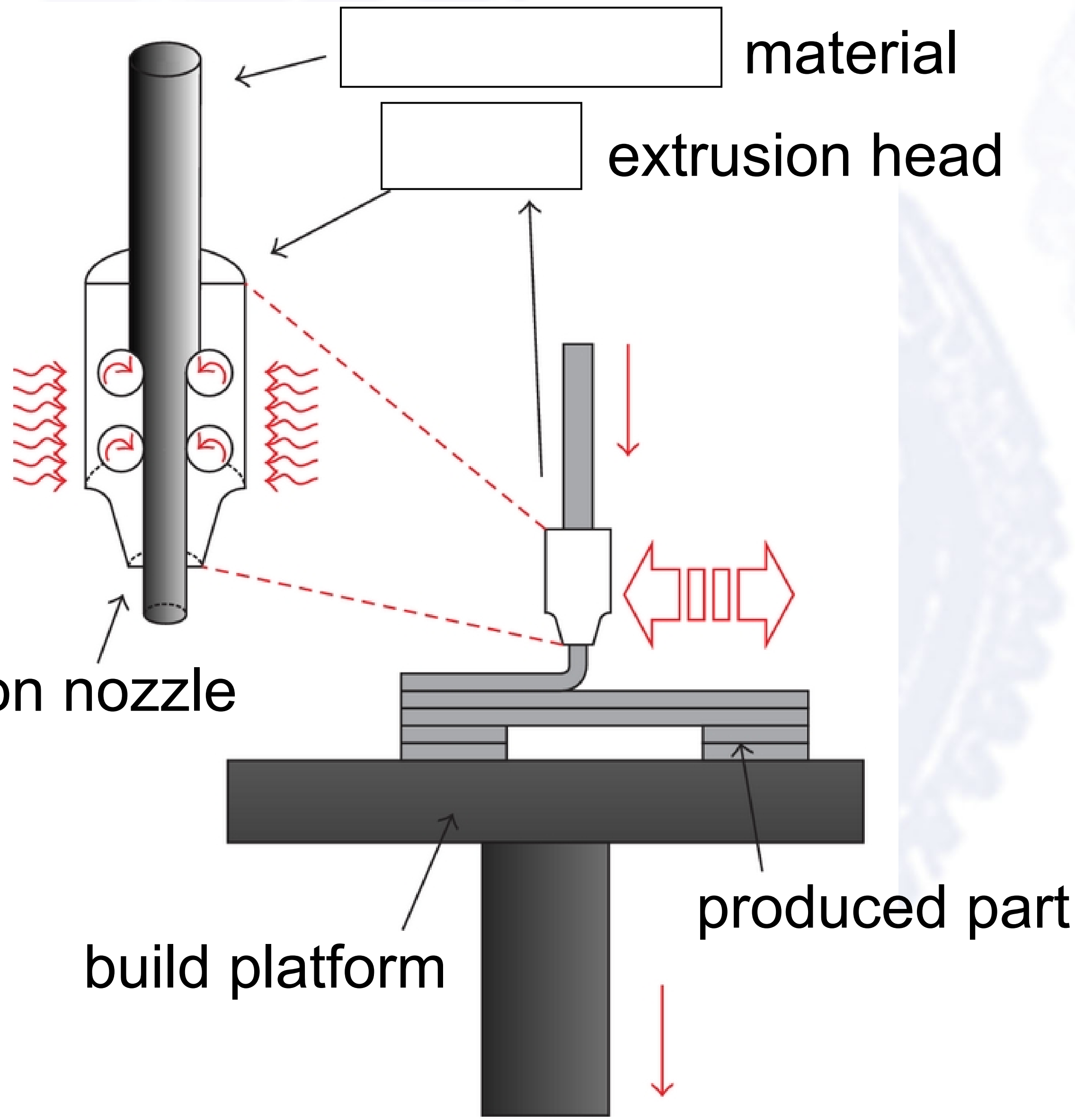
$$=\text{int}\left[\frac{20-(0.25/2)}{0.25}\right]+2=81$$

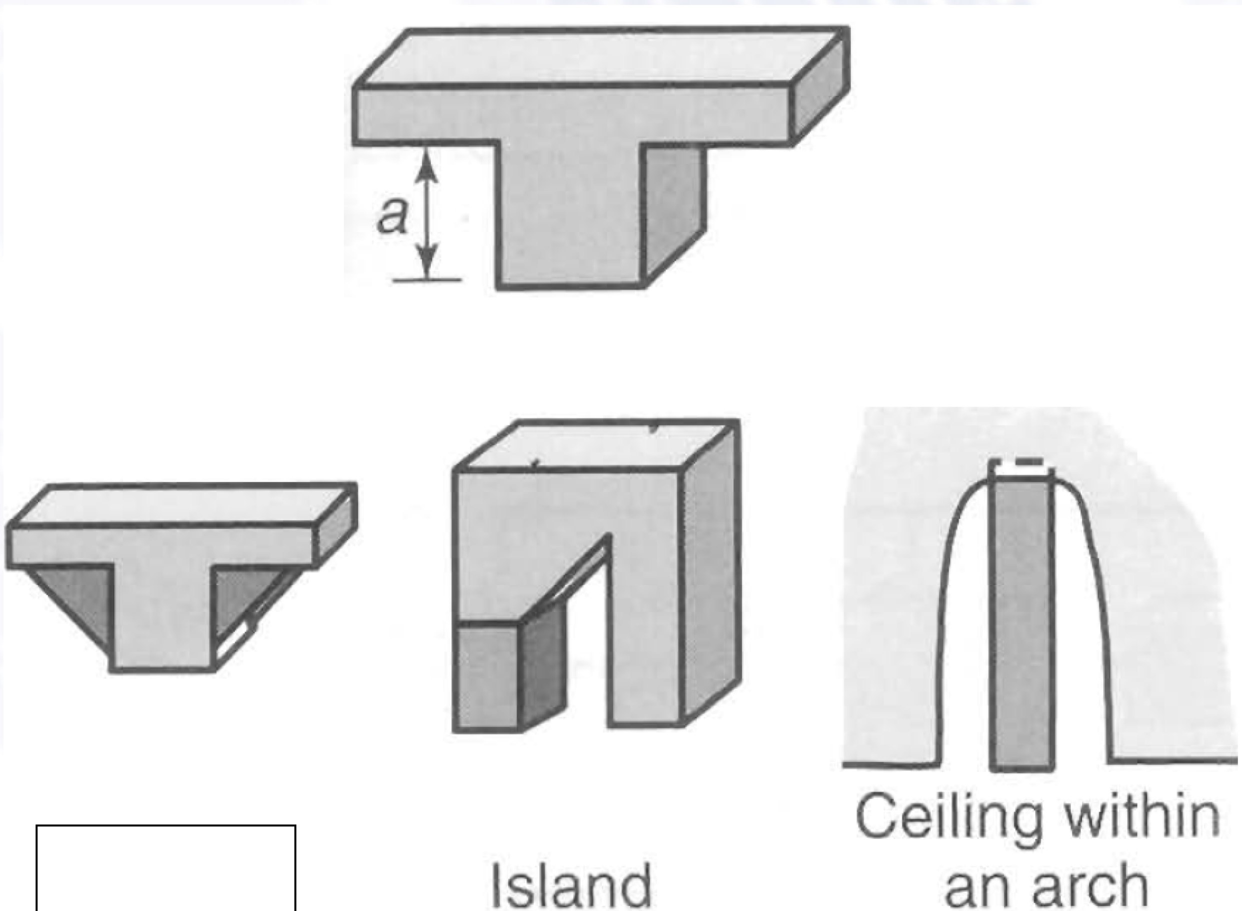


Time to cure entire surface

$= (t_2)\ (\boxed{\qquad\qquad\qquad}) = (7.07)\ (81) = 572.67$ sec

Fused- Modeling (FDM)





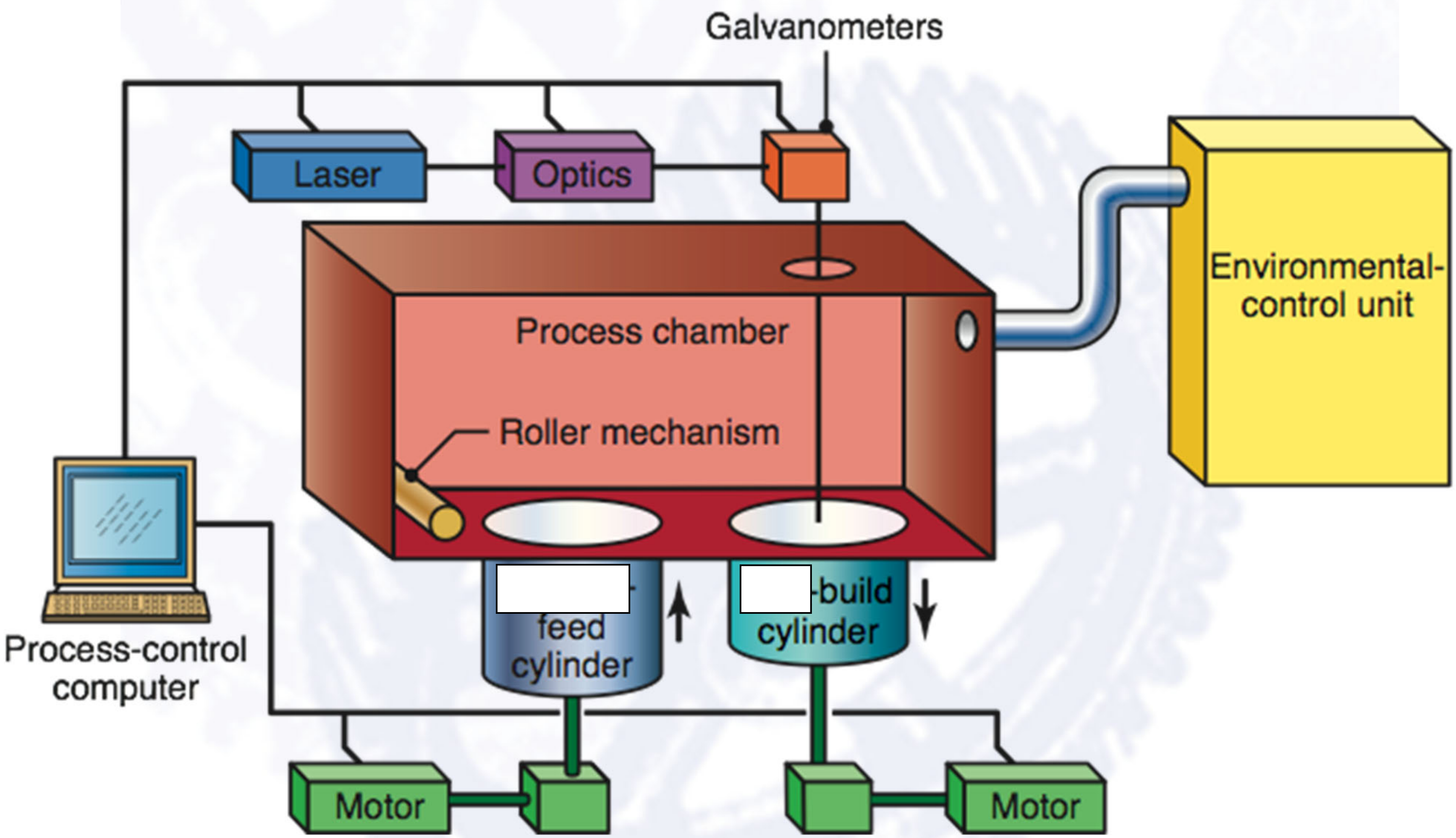
http://www.youtube.com/watch?v=0pPvAjwq6qM

The thermoplastic filament leaves the nozzle as a softened paste. It hardens immediately on contact with the part. The support filament is a wax (positioned prior to printing) to build the gussets, island, and arch to support the part above “a”. The wax can be removed easily afterwards.

Advantage: no toxic chemicals, $\boxed{}$, or a messy vat.

Disadvantage:
(1) accuracy as limited by the $\boxed{}$ size (0.12 to 0.33 mm);
(2) only a few types of materials work.

Selective Laser [ ] (SLS)



http://www.youtube.com/watch?v=9E5MfBAV_tA

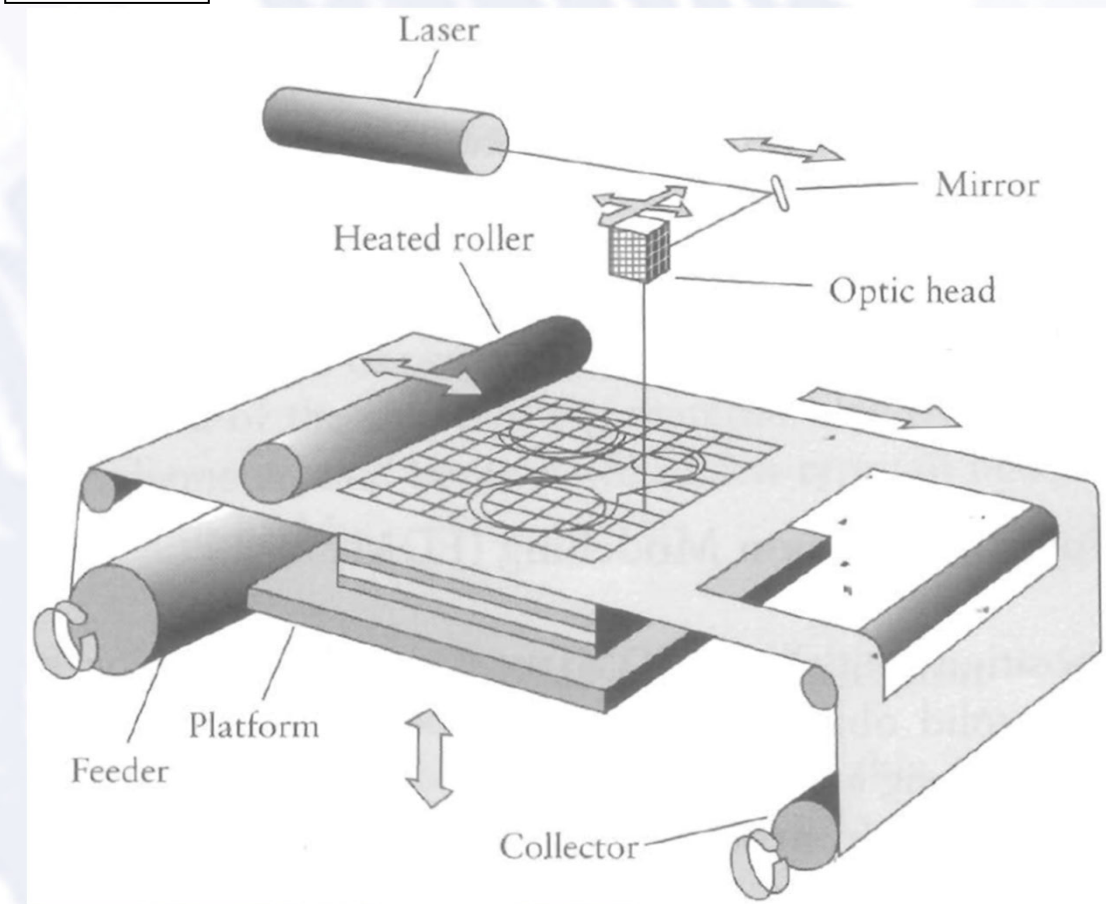
Initially a very thin layer of heat fusible powder (metallic or nonmetallic) is placed in the ______ cylinder. The CO_2-laser scans over the cylinder and fuses (sinters) the powders at selected locations. Then the part-build cylinder is lowered by one step, some more powder is scraped from the powder-feed cylinder to the part-build cylinder by a roller or a blade.

Advantages: (1) the non-sintered powder remains loose and serves as natural support for the next layer of powder thus needing no ______ (2) Many kinds of materials can be used including polycarbonate, PVC, nylon, metal, ceramics, and investment casting wax, etc.

Difficulties: (1) surface is usually rough, (2) toxic ______ are generated from sintering.

[   ] Object Manufacturing (LOM)

Laser beam cuts out the contours of a layer from a [   ] foil (or ribbon). The [   ] roller softens the foil and bonds it to the stack below.



http://www.youtube.com/watch?v=Z1WNA6tdfWM

Advantages:

(1) a variety of organic and inorganic materials (paper, plastic, composites, ceramic, etc) can be processed;

(2) the remaining portion serves as support, no additional $\boxed{}$ needed;

(3) cycle time is short and cost is low for $\boxed{}$ parts;

Difficulties:

(1) the bonding strength may not be high enough;

(2) $\boxed{}$ parts can be weak.

Expanding variety of metals available for AM:

Aluminum Alloys (AlSi12, AlSi7Mg,…),

Nickel Alloys (IN718, HastelloyX,…),

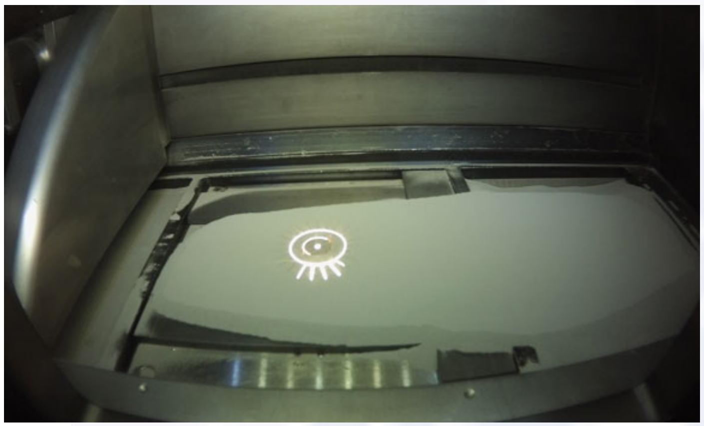
Stainless Steel (SS304, SS440, …),

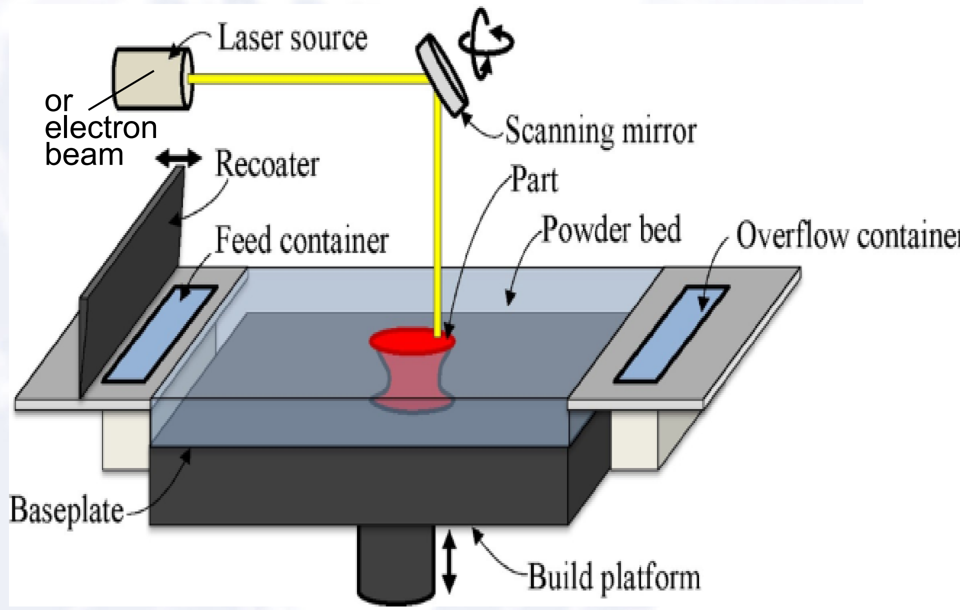
Titanium Alloys (Ti2, Ti64, …),

Precious Metals (Gold, Silver, …)

Powder-[ ] Fusion (Direct Metal Laser Sintering, DMLS)

Liang





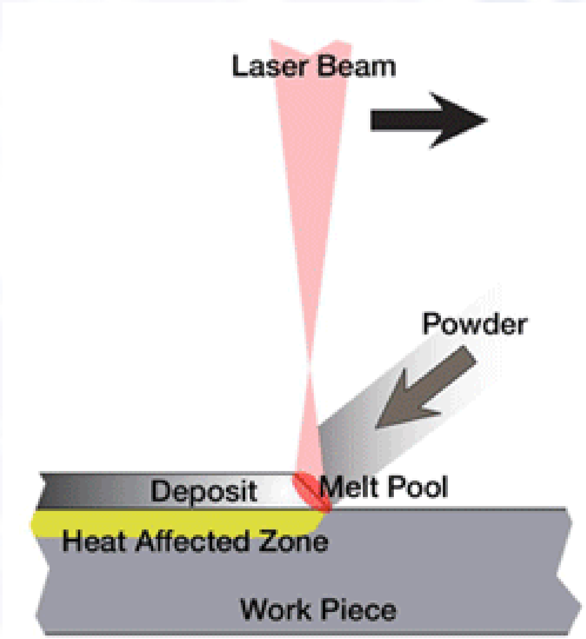
Main Characteristics:

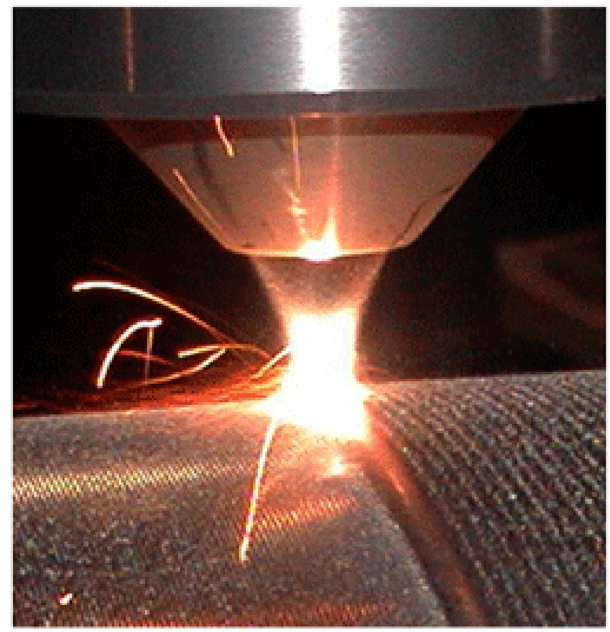
1. High density (~99%);
2. Increased strength;
3. High tensile residual stress;
4. Decreased ductility;
5. Nonequilibrium phase transformations.

https://www.youtube.com/watch?time_continue=3&v=zgYxeMpyLbY (0.38)

Powder- Fusion (Cladding or Laser Metal Deposition)

Liang





Example Applications of 3-D Printing

(a) Communication for Design:

Easier than paper drawing or screen display.

(b) Engineering Analysis and Planning:

(1) Evaluation of aesthetic appeal of the part,

(2) Analysis of fluid flow through physical objects,

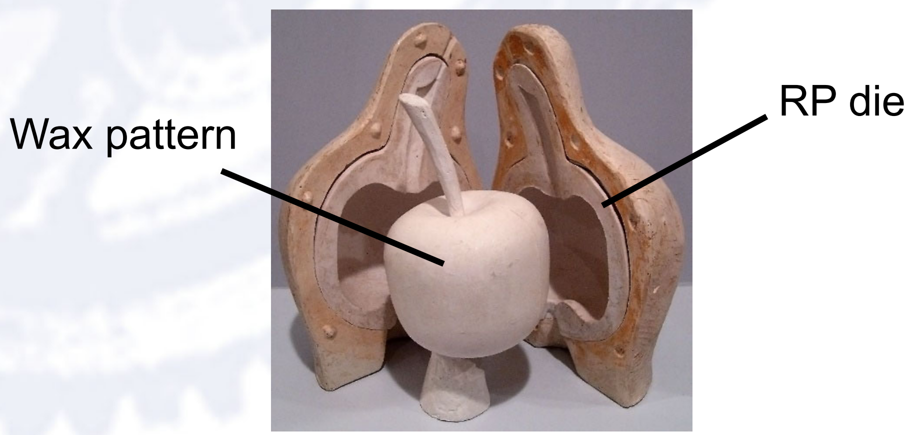
(3) Stress analysis on physical objects,

(4) Help preparing for medical procedure or fabricating implants.

(c) Tooling and manufacturing:

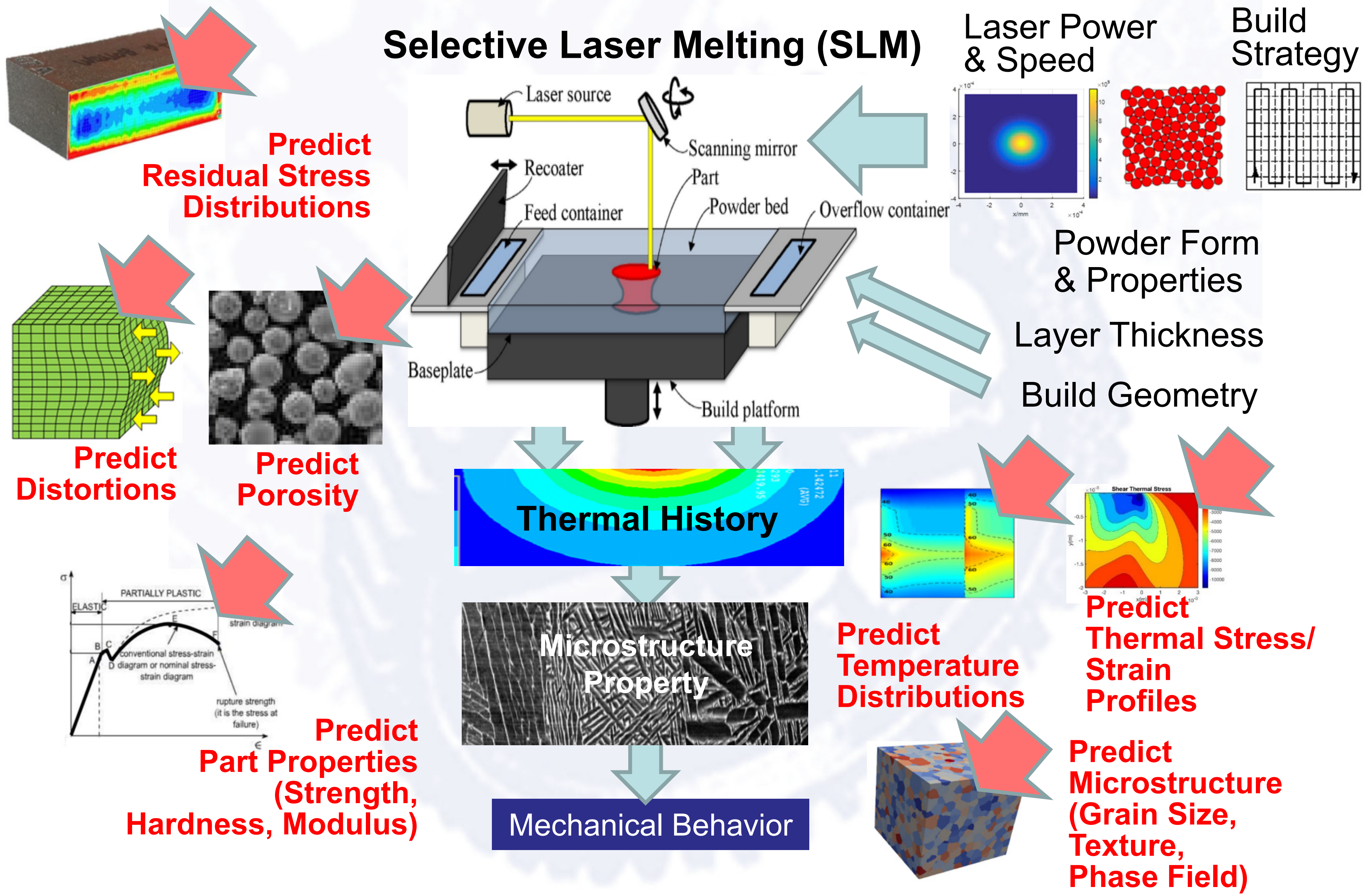
(1) Direct [   ] tool making (RTM): to make a tool, such as molds, dies, cores, or insets

(2) Indirect RTM: to make a [   ] for later use of making the tools. For example: RP-fabricated master for later high-volume making of wax pattern that is subsequently used to produce mold. Or to RP-fabricate a pattern for making sand molds or wax molds.

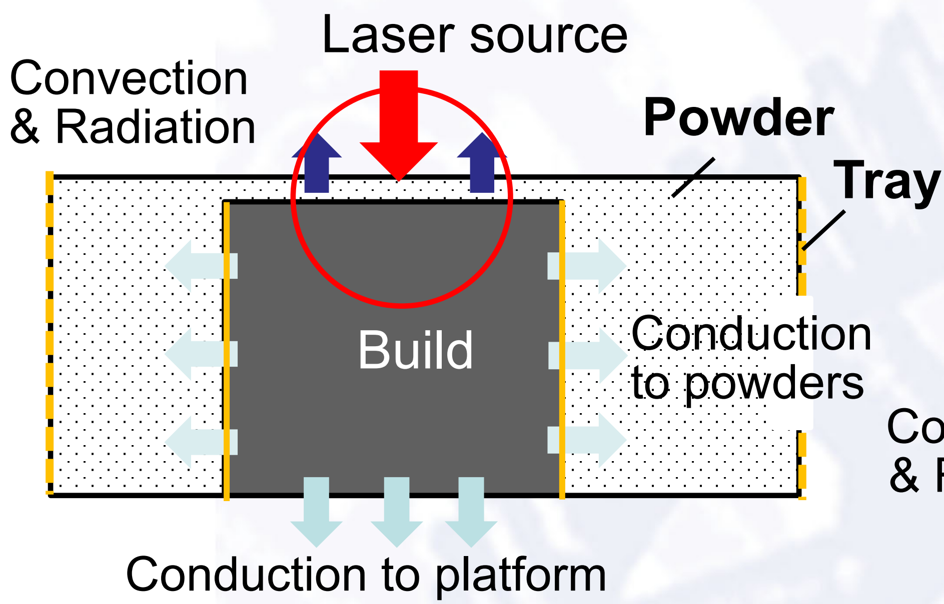


Georgia Tech Precision Manufacturing Lab Research Goals

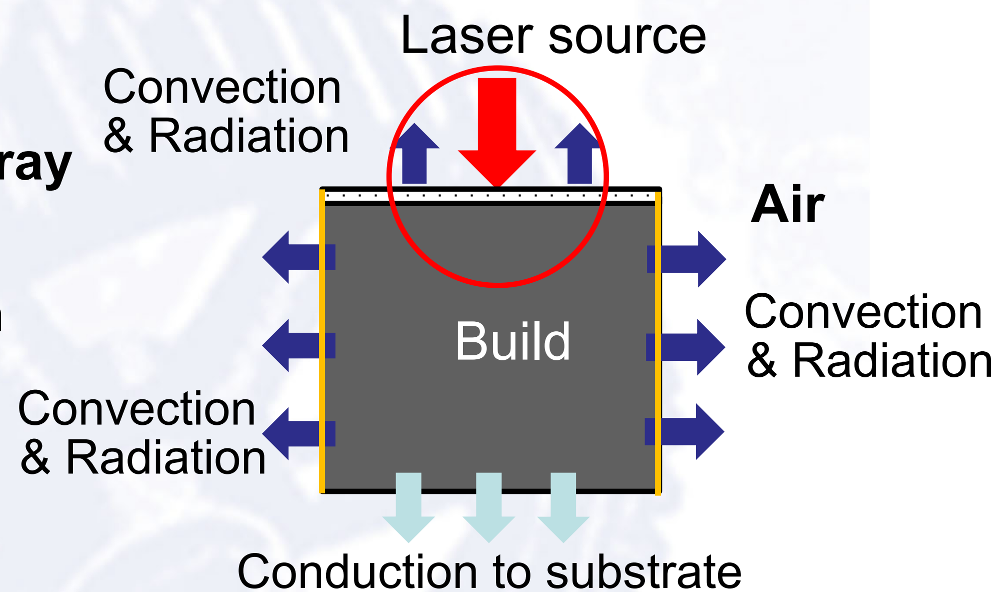
Liang

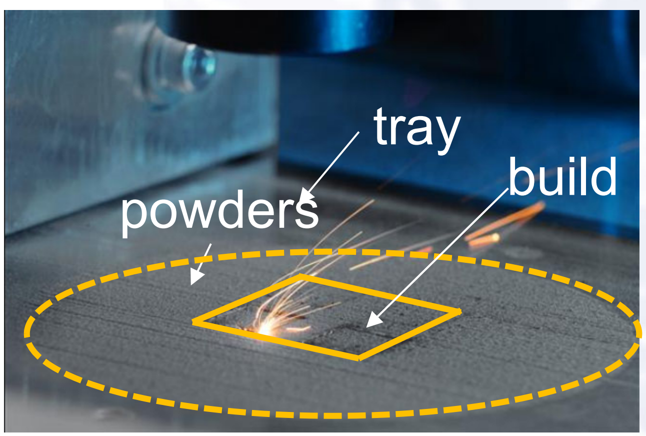


Powder Bed

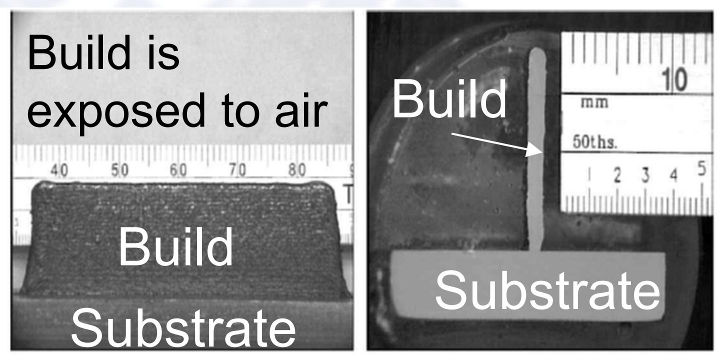


Powder Feed

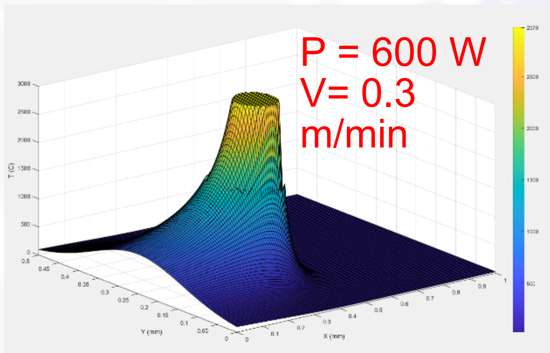


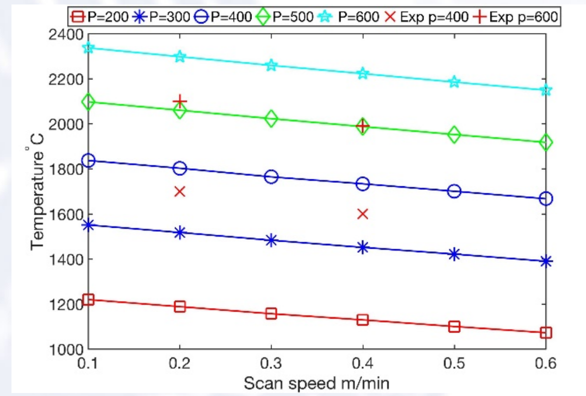


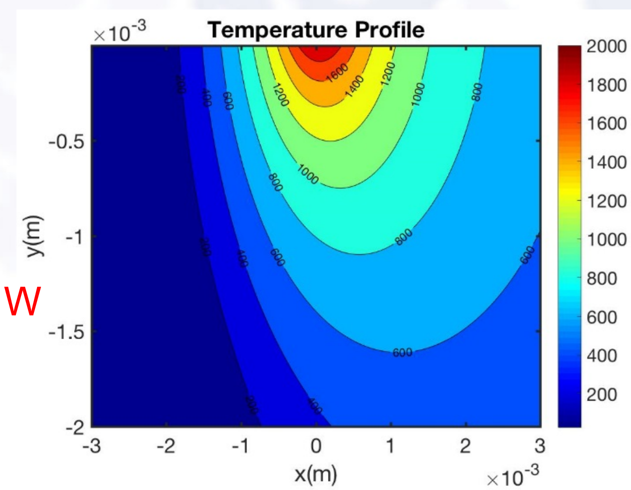
Build is embedded inside powder



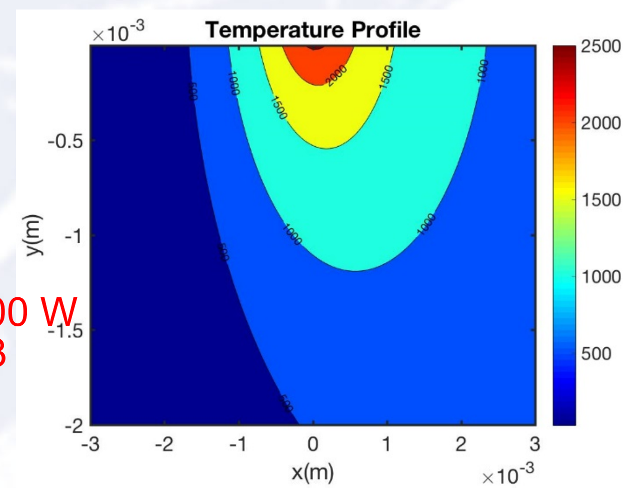
Temperature Profile by 3-D Moving Heat Source Analysis (Ti-6Al-4V) – GT Lab







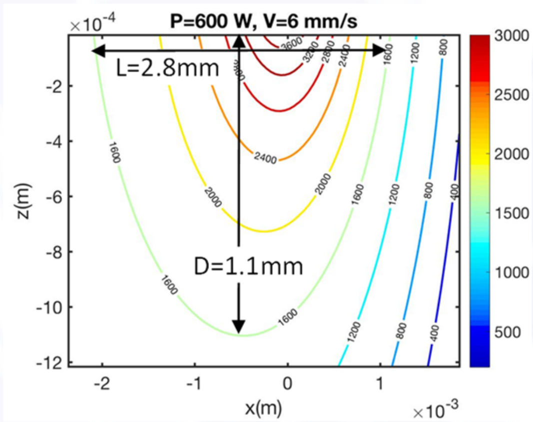
P = 400 W
V= 0.3
m/min

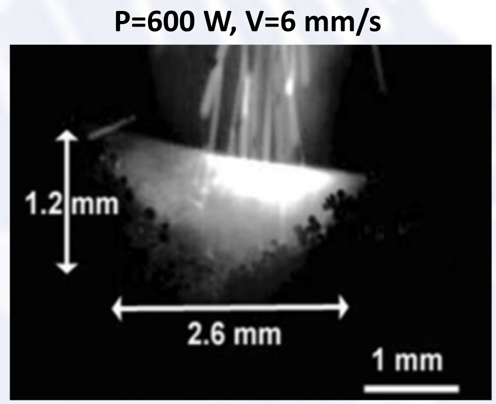


P = 600 W
V= 0.3
m/min

Computational Accuracy Advantages – GT Lab

Liang



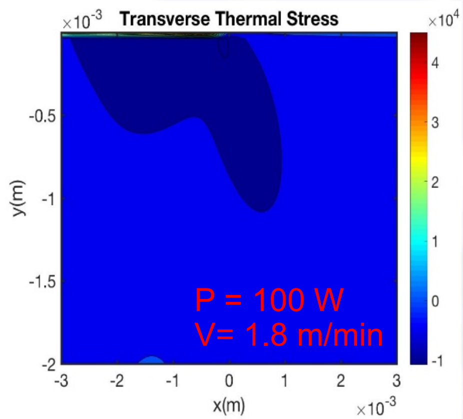


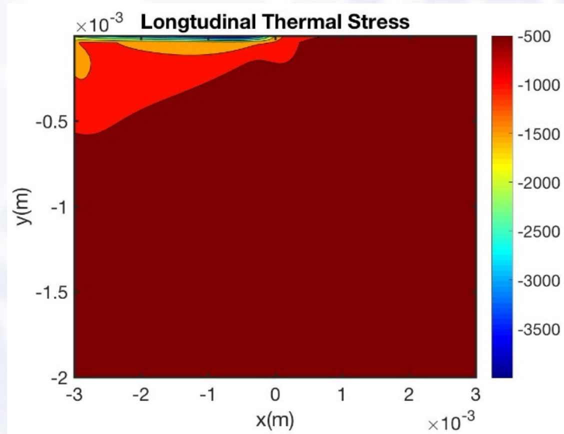
Melt Pool: Analytically Predicted *Experimentally Measured*

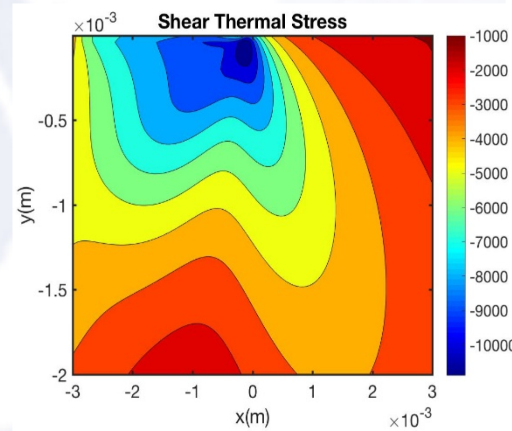
P (W)	V (mm/s)	Melt pool length (mm) Model	Melt pool length (mm) Experimental	Melt pool depth (mm) Model	Melt pool depth (mm) Experimental	Error in length	Error in depth
600	6	2.80	2.60	1.10	1.20	**7.6%**	**2.0%**
360	100	-	-	0.29	0.30	-	**3.4%**
300	100	-	-	0.26	0.27	-	**3.7%**
240	100	-	-	0.22	0.20	-	**1.0%**

Thermal Stress Distributions (AISI 316L) – GT Lab

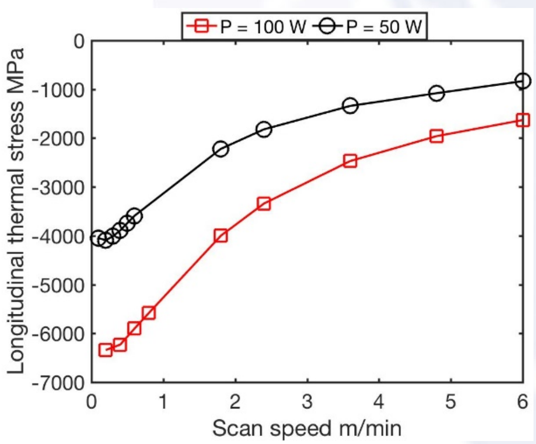
Liang

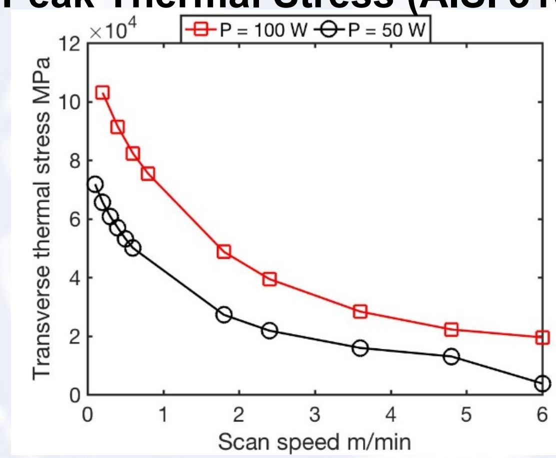


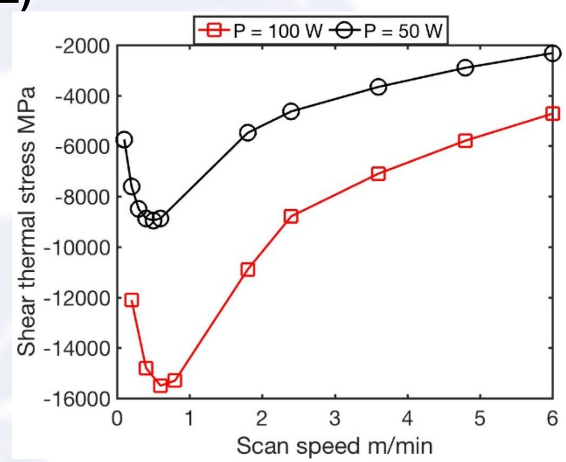




Peak Thermal Stress (AISI 316L)



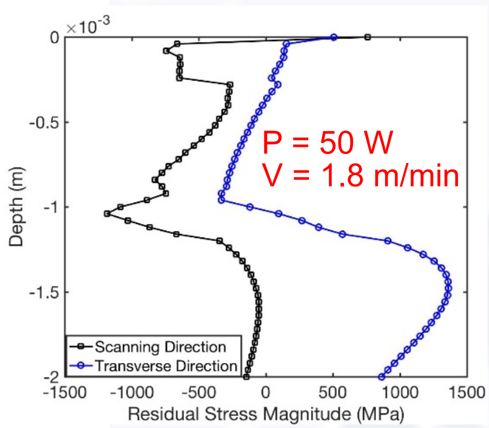


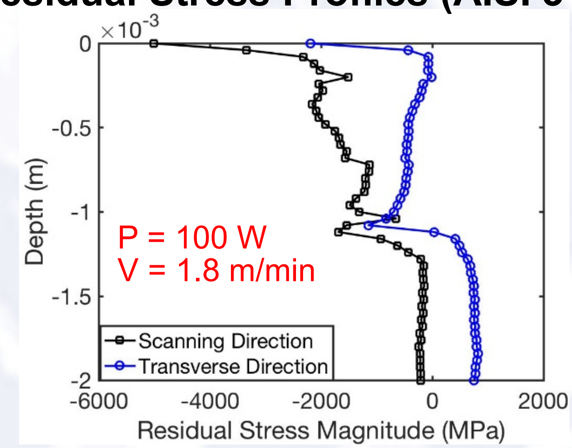


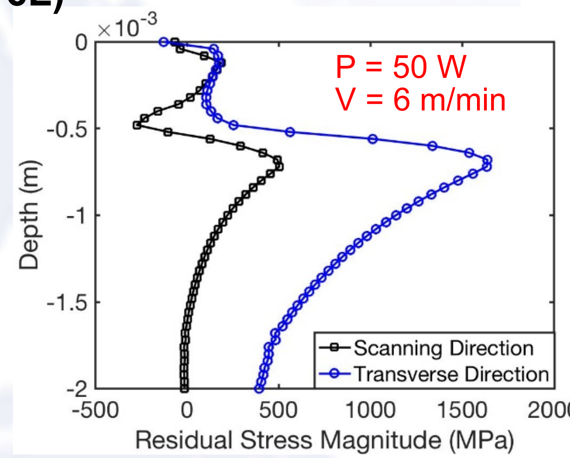
Post-Printing Residual Stress Profiles – GT Lab

Liang

Residual Stress Profiles (AISI 316L)

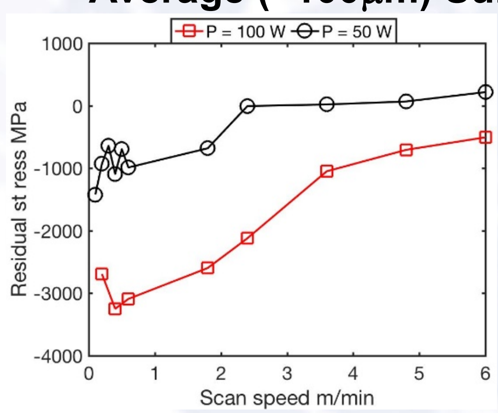




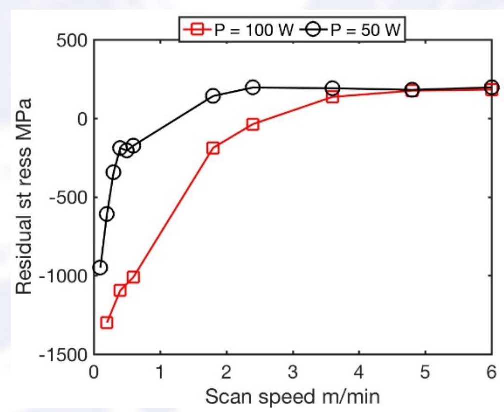


Average (<100μm) Surface Residual Stress (Ti-6AL-4V)

Scanning Direction

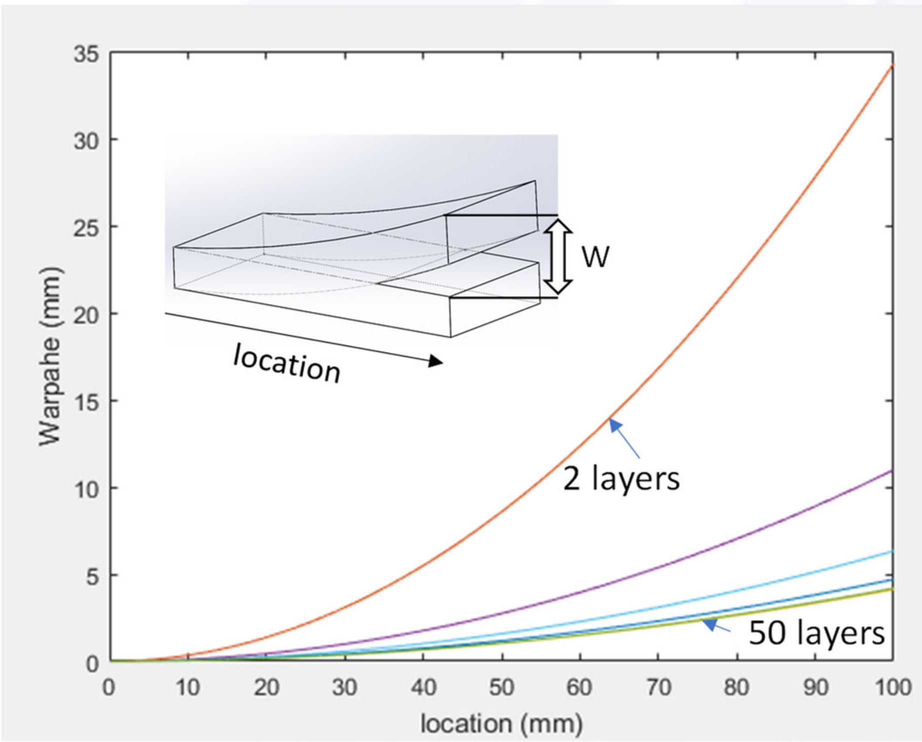


Transverse



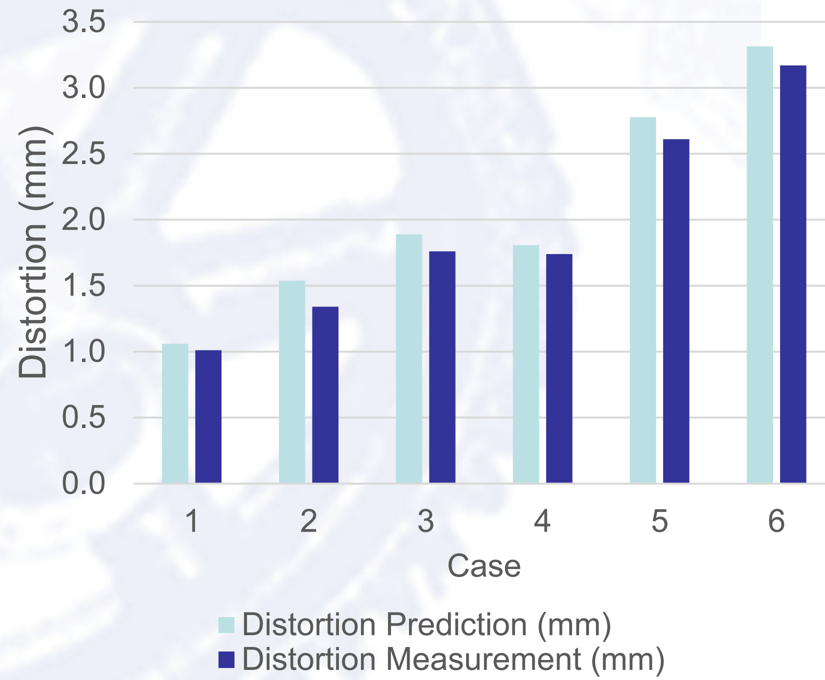
Distortion with Various Build Layers – GT Lab

Liang

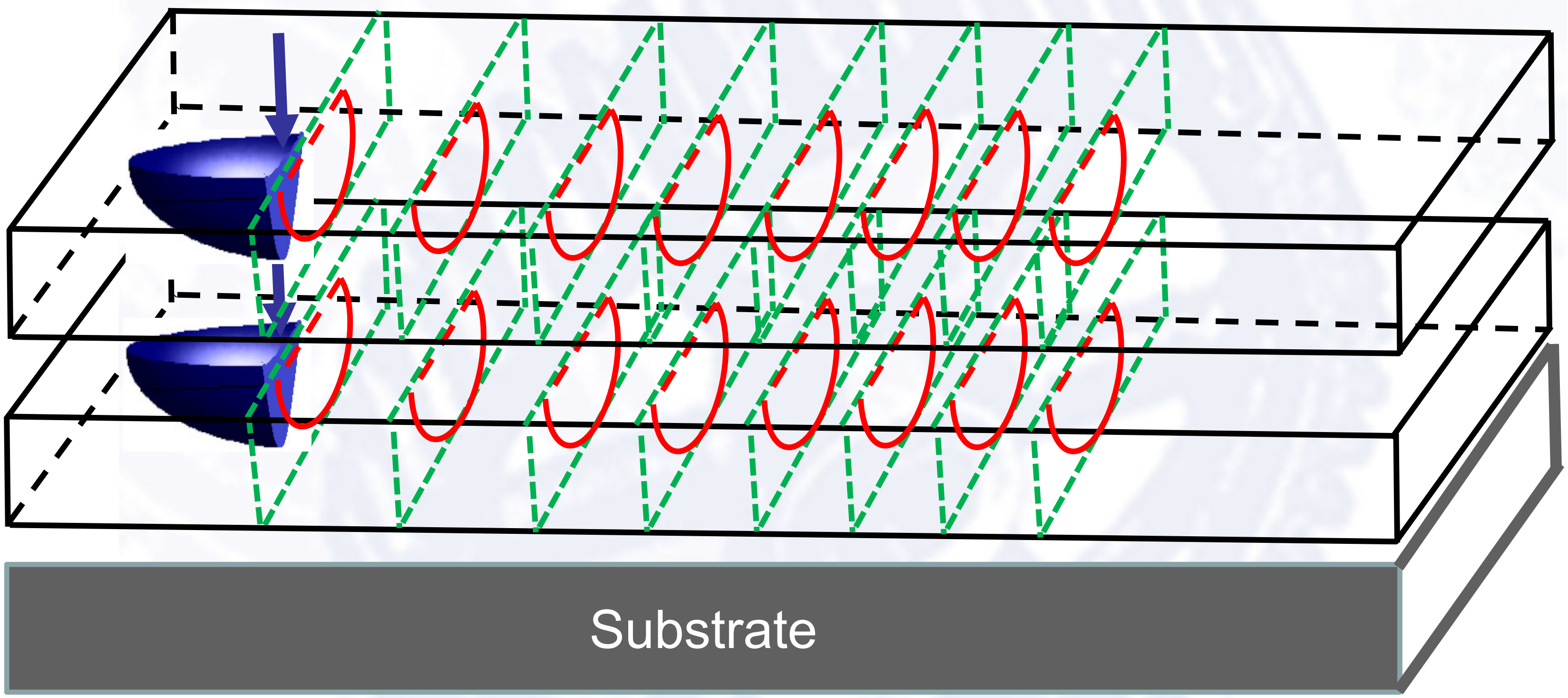


Ti64, Laser Power 100W, Scan Speed 0.01 m/s with various layers (single layer thickness 0.05 mm)

Validation with
various process parameters

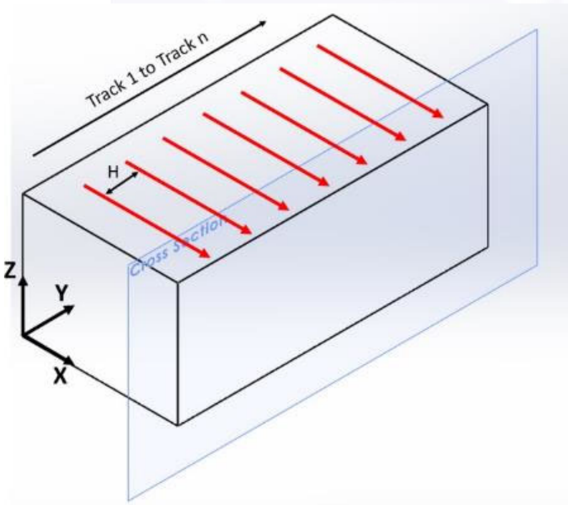


Moving-Heat-Source Transverse Area Analysis



Part Porosity Prediction by Transverse Area Analysis

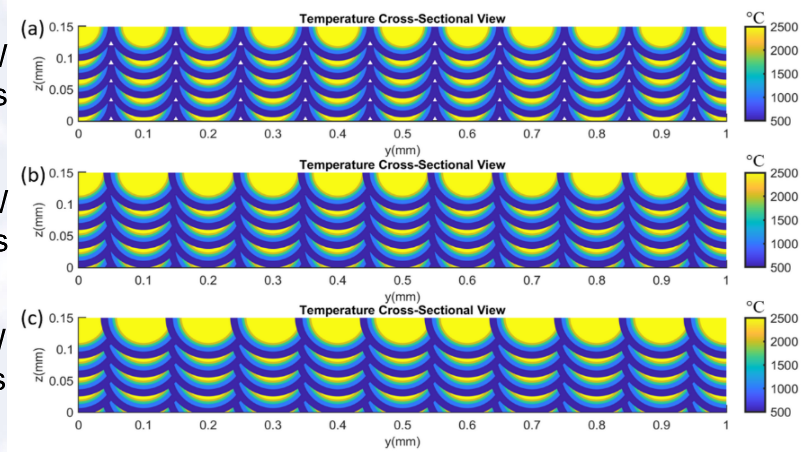
Liang



100W 750mm/s

150W 750mm/s

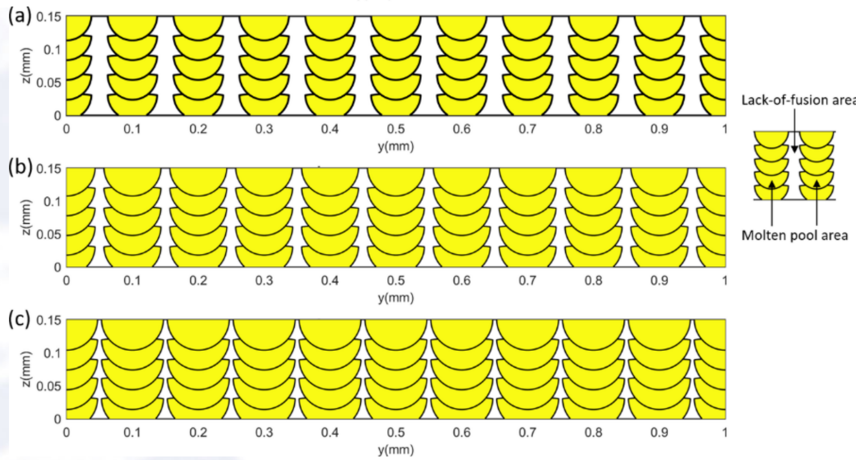
195W 750mm/s



100W 750mm/s

150W 750mm/s

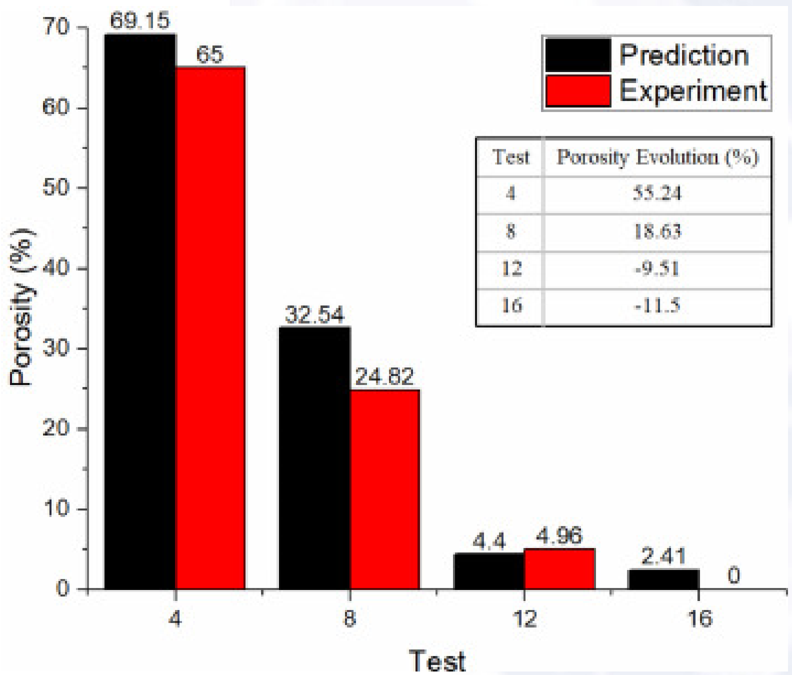
195W 750mm/s



Model	Computational Time	Area Size	Computing Power
Current Model	26 seconds	5 layer with 11 tracks per layer	2.8 GHz
Finite Element Analysis	5 hours	5 layer with 5 tracks per layer	3.4 GHz

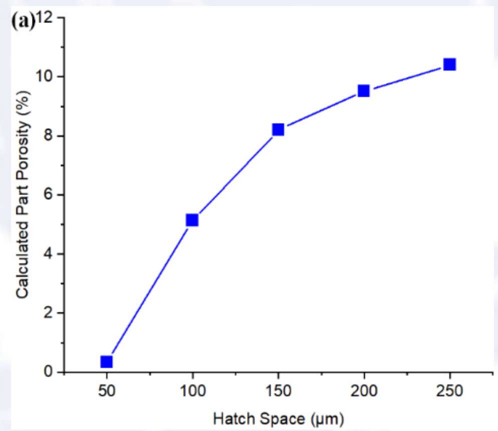
Experimental Validation of Part Porosity Prediction

Experimental Validation

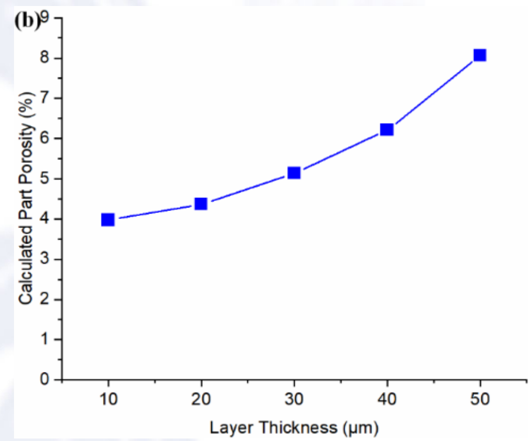


Test	Porosity Evolution (%)
4	55.24
8	18.63
12	-9.51
16	-11.5

Sensitivity Analysis PBMAM of Ti6Al4V



P = 100 W,
V = 750 mm/s,
LT = 30 μm

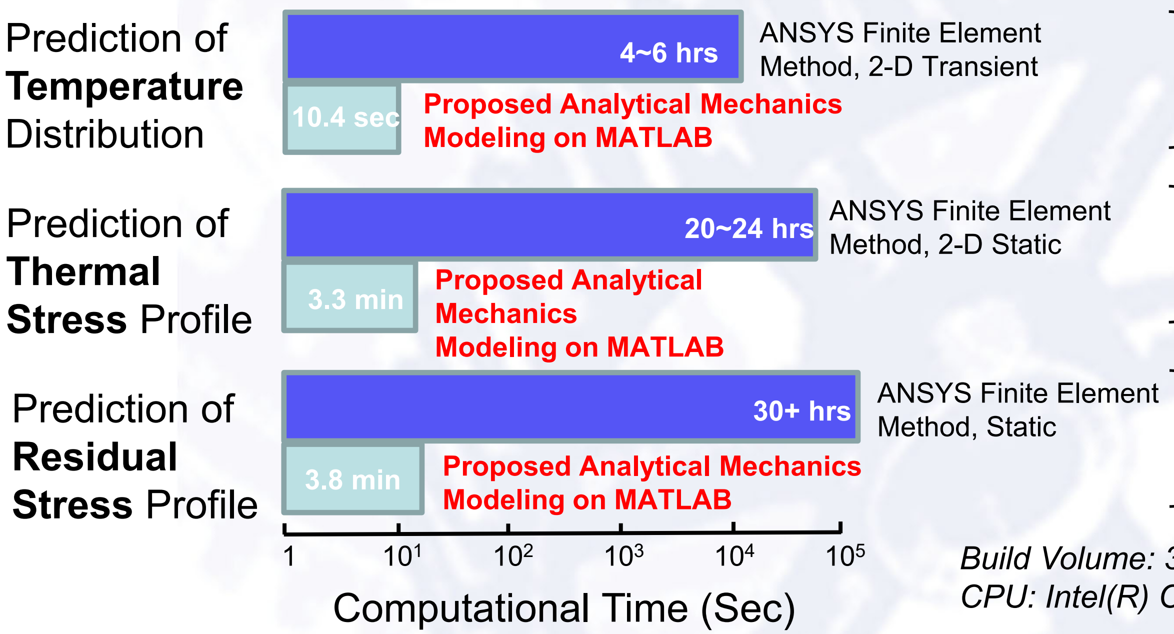


P = 100 W,
V = 750 mm/s,
H = 100 μm

Non-linear sensitivity as caused by the geometry of molten pool cross-section and the range of process parameter variation.

Computational Speed Advantages – GT Lab

Liang



Analytical Computation is **2,000** times faster than FEM

Analytical Computation is **450** times faster than FEM

Analytical Computation is **500** times faster than FEM

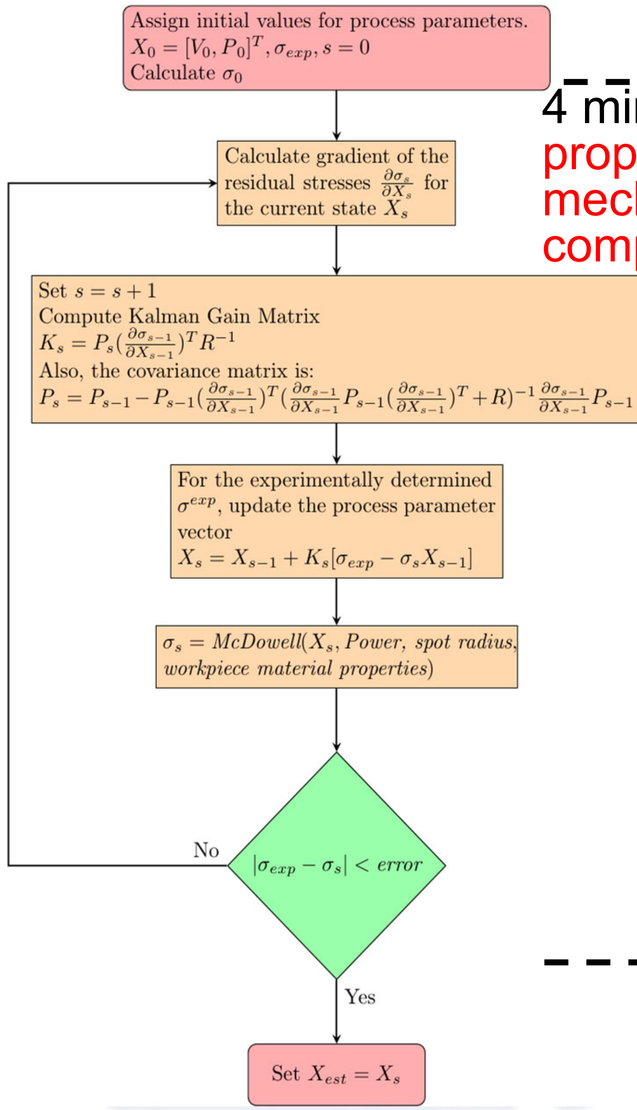
*Build Volume: 30 mm*10mm*

CPU: Intel(R) Core i5-2500 CPU @3.3 GHz, RAM: 4GB

Process Planning Enabled by Speed Advantages

Liang

Design of process parameters to achieve desirable AM temperature, thermal stress, and residual stress



4 minutes by proposed mechanics computation

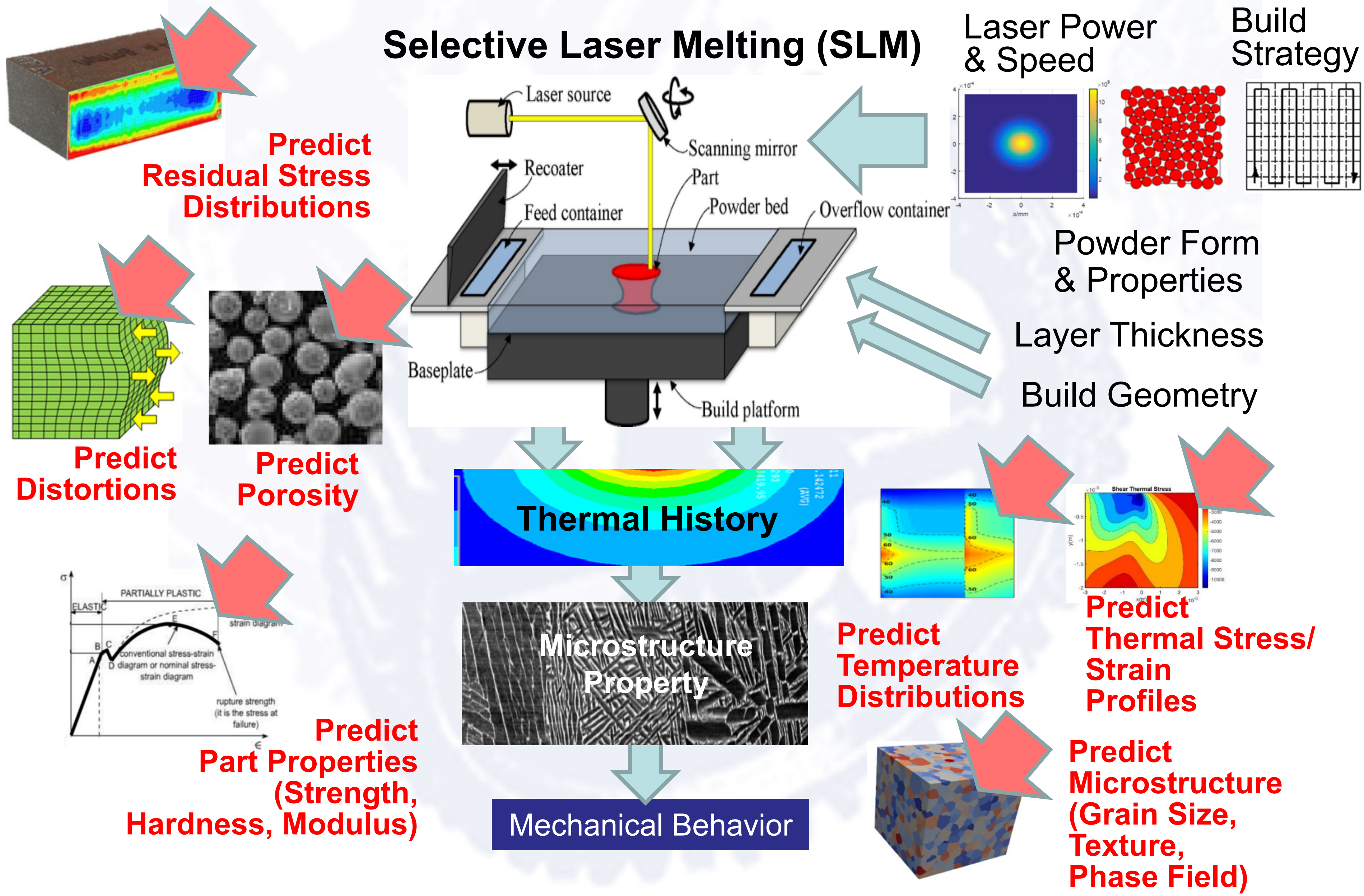
30 hours by ANSYS

Proposed Mechanics computation is **10,000** times faster than FEM (20+ iterations):

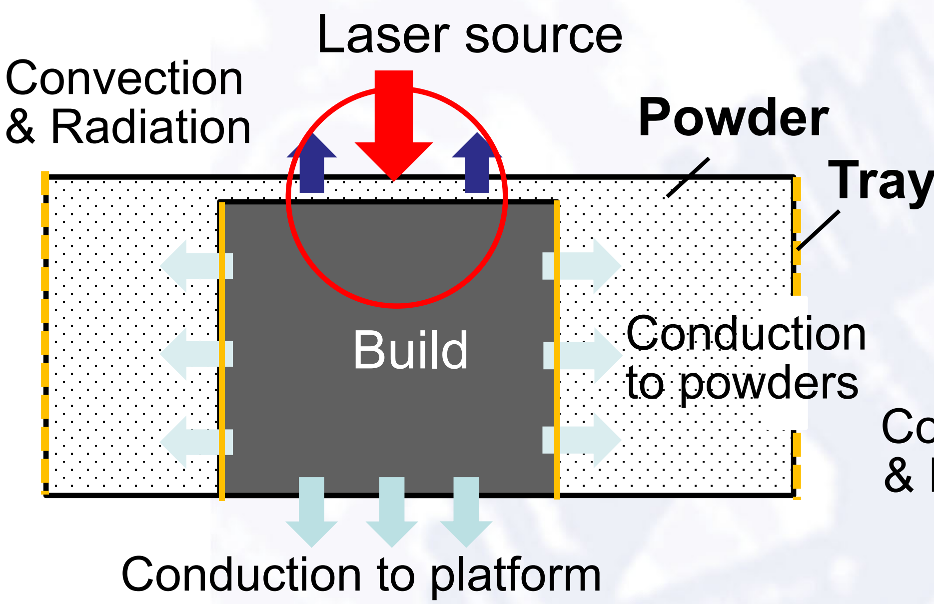
80 mins by mechanics
600+ hours by ANSYS

Georgia Tech Precision Manufacturing Lab Research Goals

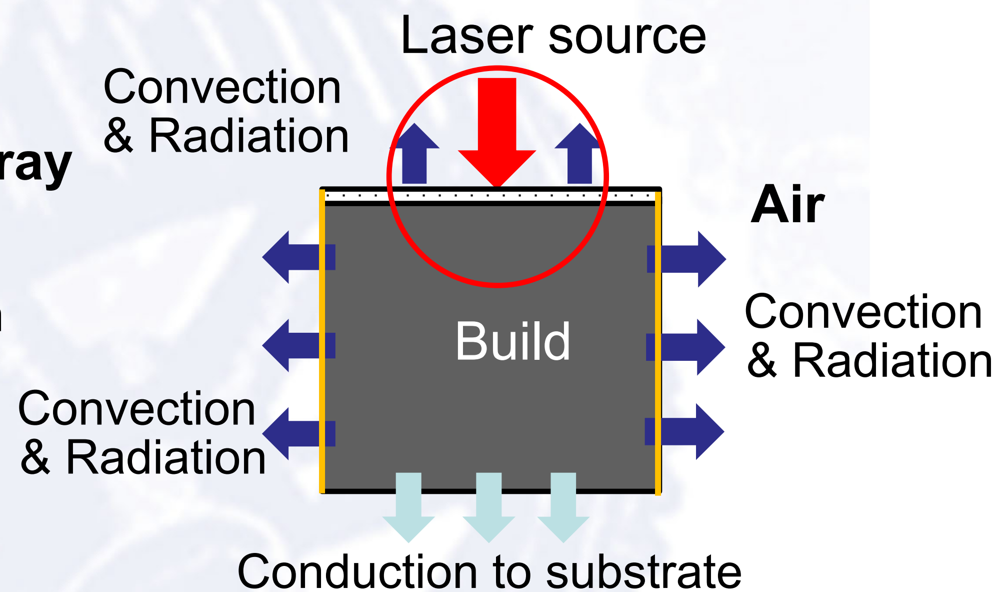
Liang

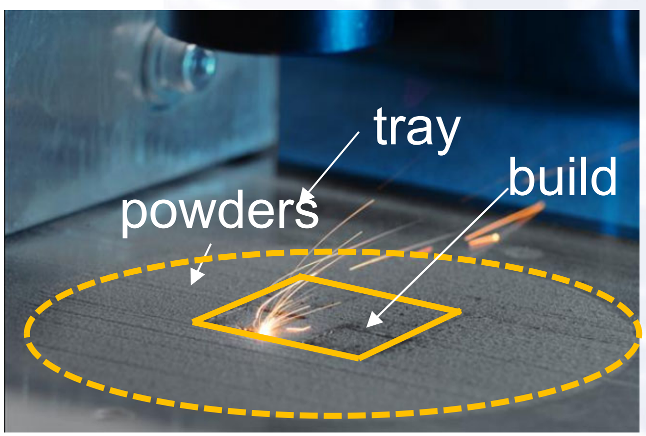


Powder Bed

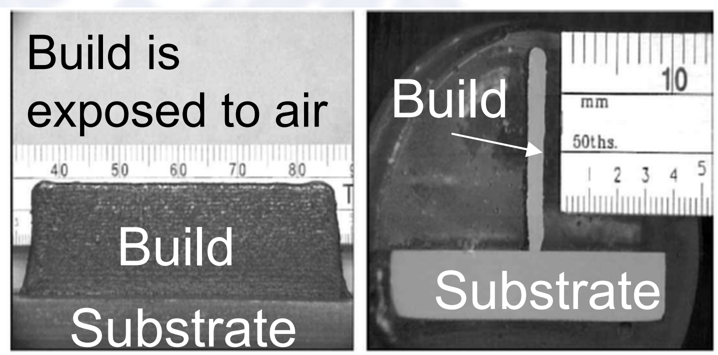


Powder Feed



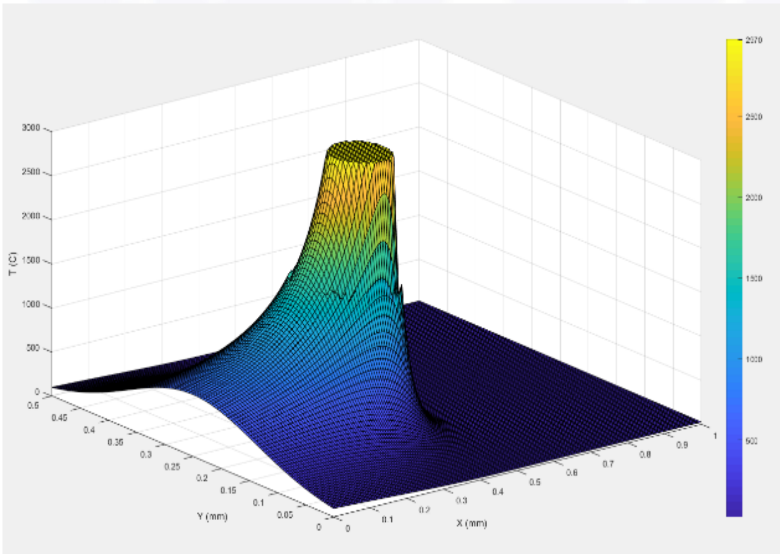


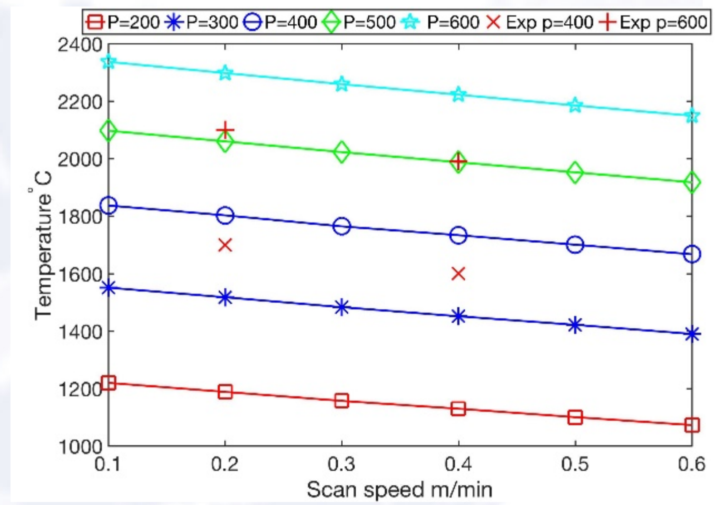
Build is embedded inside powder

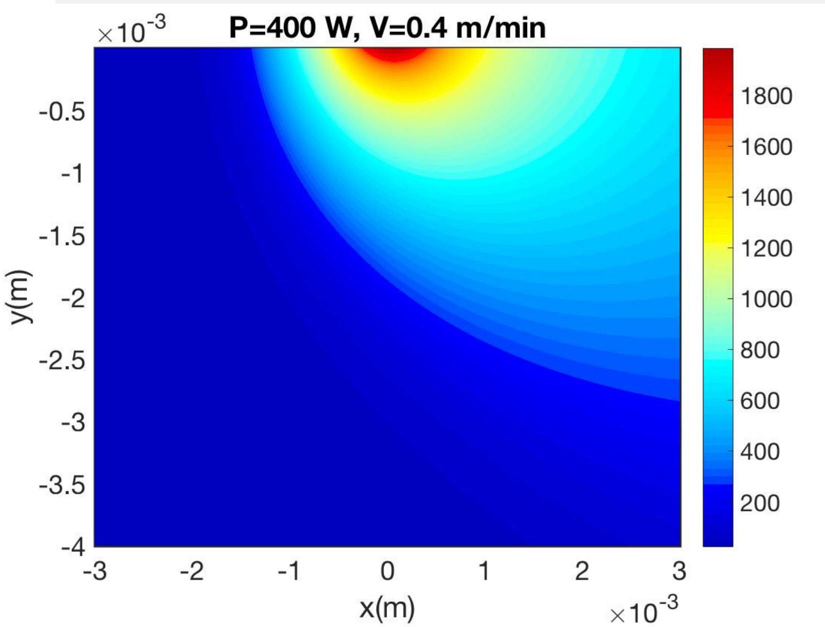


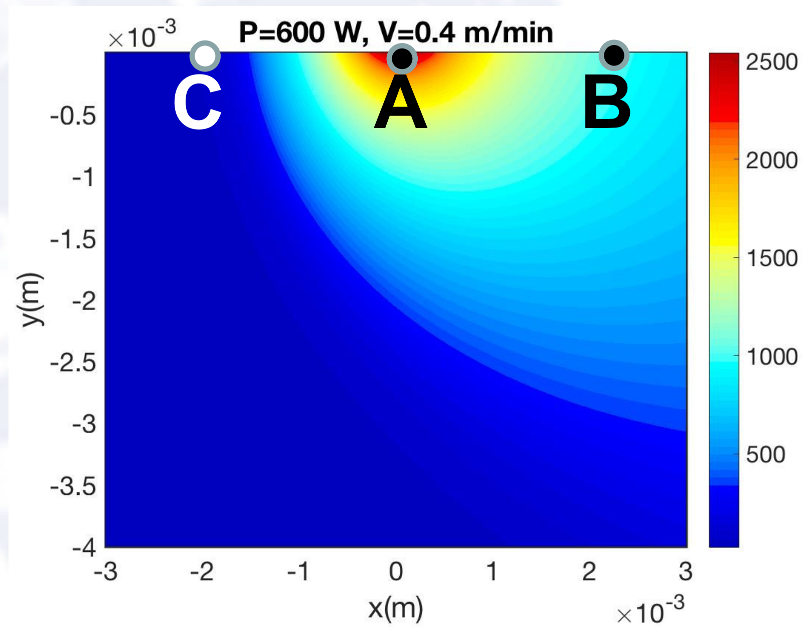
Temperature Profile by 3-D Moving Heat Source Analysis (Ti-6Al-4V) – GT Lab

Liang



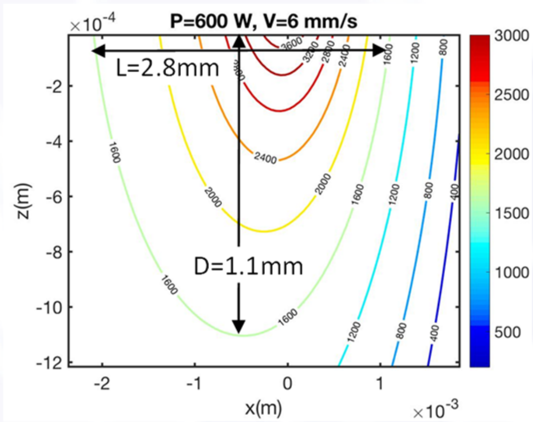


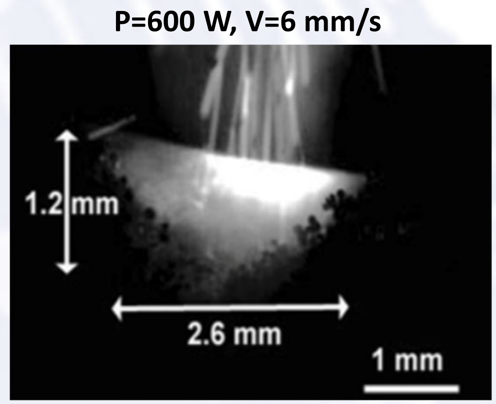




Computational Accuracy Advantages – GT Lab

Liang



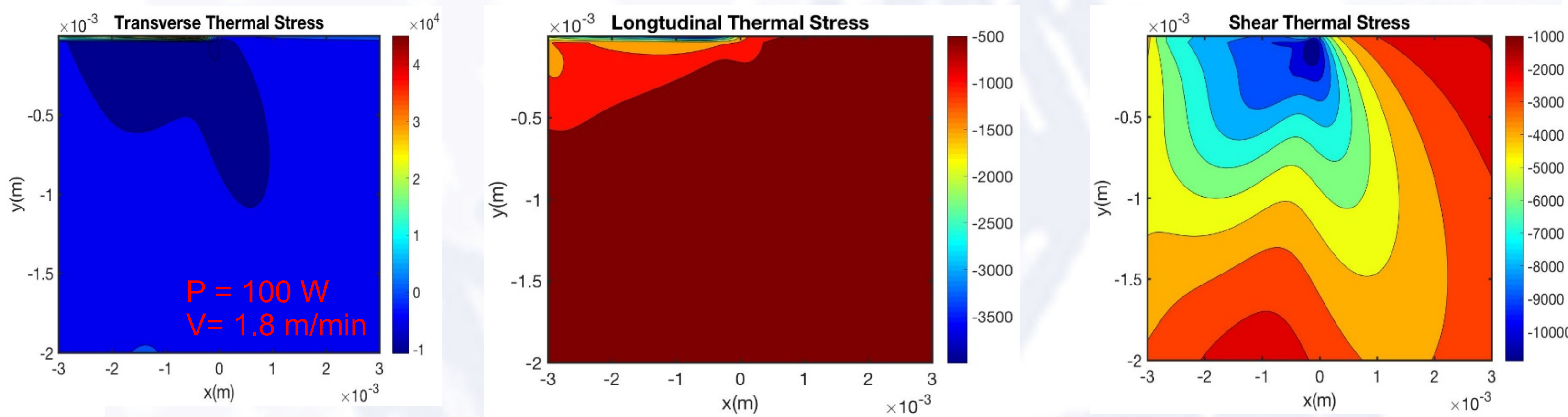


Melt Pool: Analytically Predicted *Experimentally Measured*

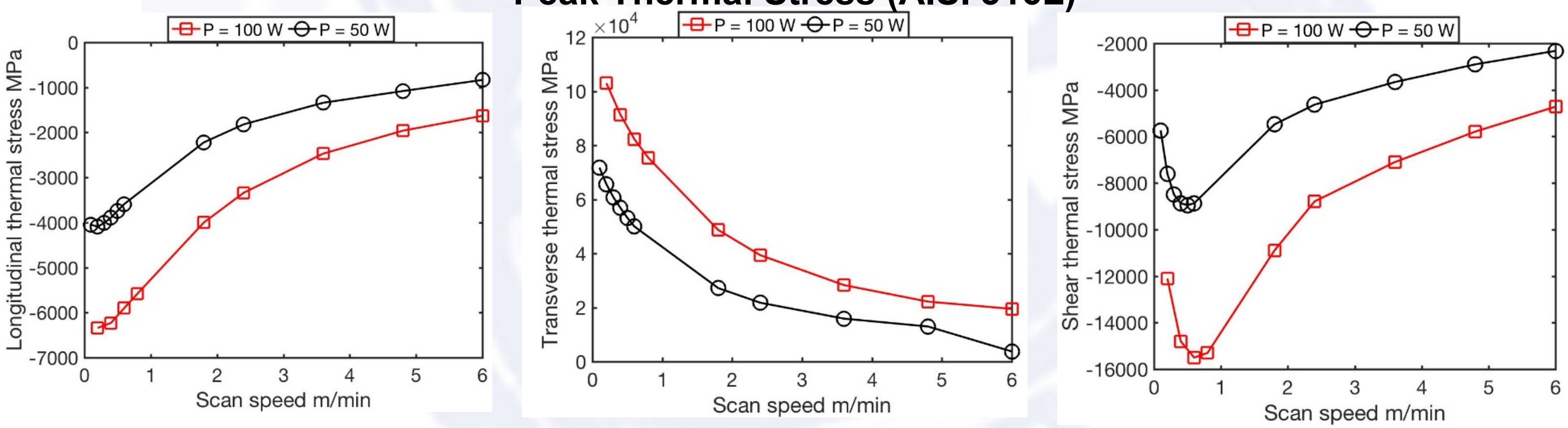
P (W)	V (mm/s)	Melt pool length (mm) Model	Melt pool length (mm) Experimental	Melt pool depth (mm) Model	Melt pool depth (mm) Experimental	Error in length	Error in depth
600	6	2.80	2.60	1.10	1.20	**7.6%**	**2.0%**
360	100	-	-	0.29	0.30	-	**3.4%**
300	100	-	-	0.26	0.27	-	**3.7%**
240	100	-	-	0.22	0.20	-	**1.0%**

Thermal Stress Distributions (AISI 316L) – GT Lab

Liang

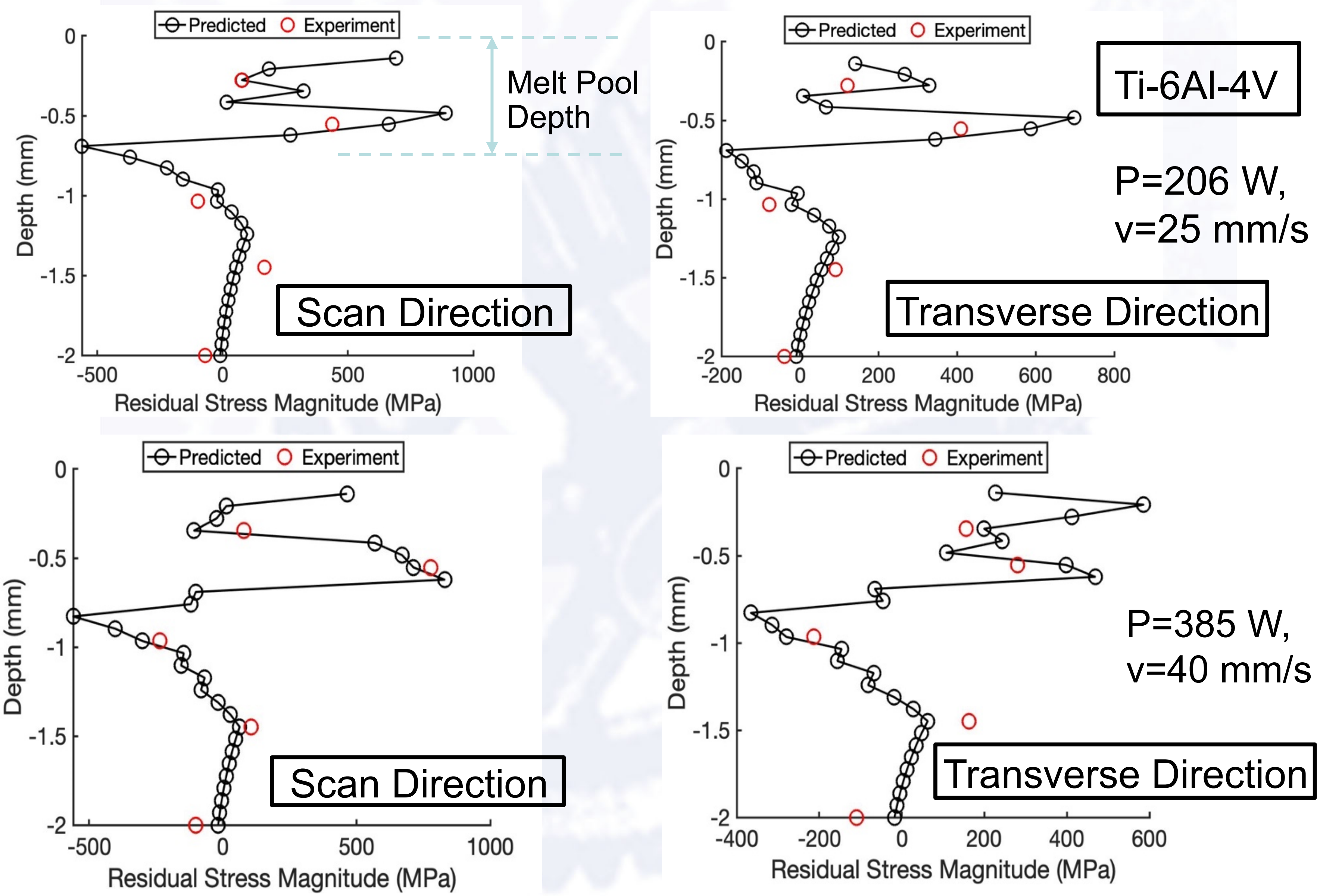


Peak Thermal Stress (AISI 316L)



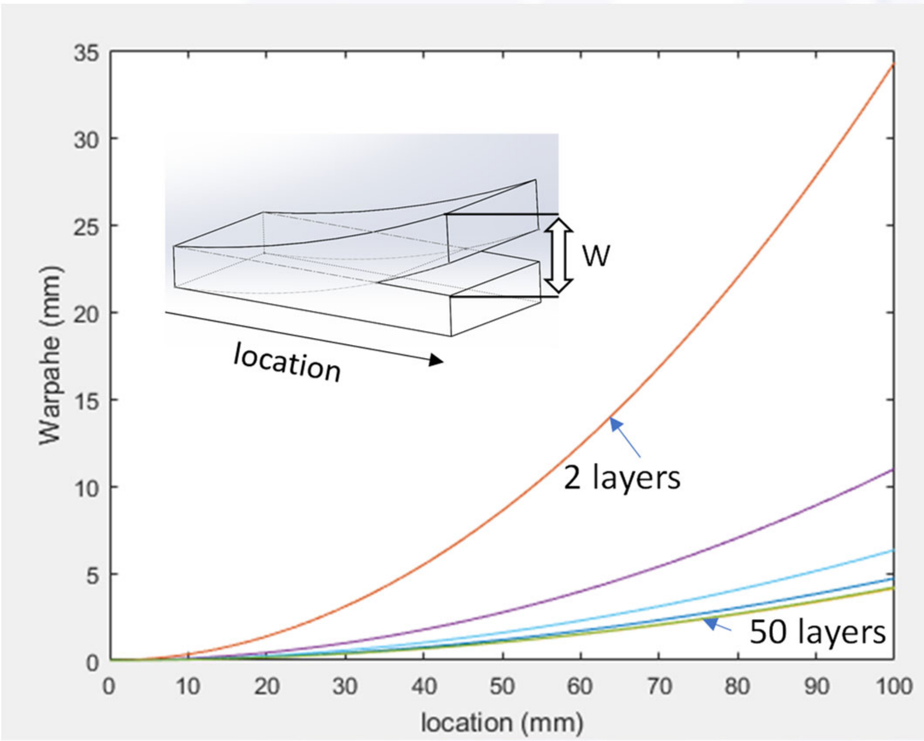
Post-Printing Residual Stress Profiles – GT Lab

Liang



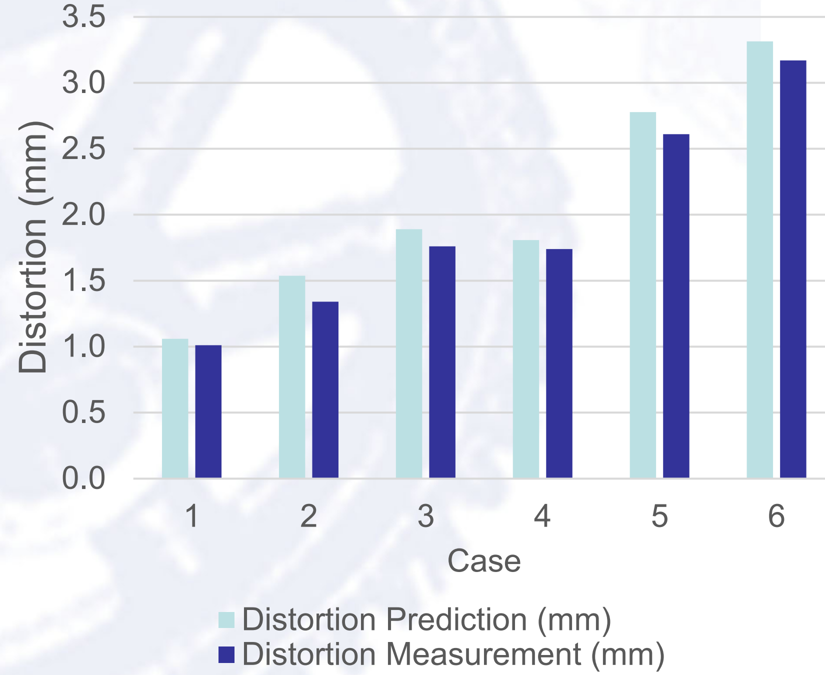
Distortion with Various Build Layers – GT Lab

Liang

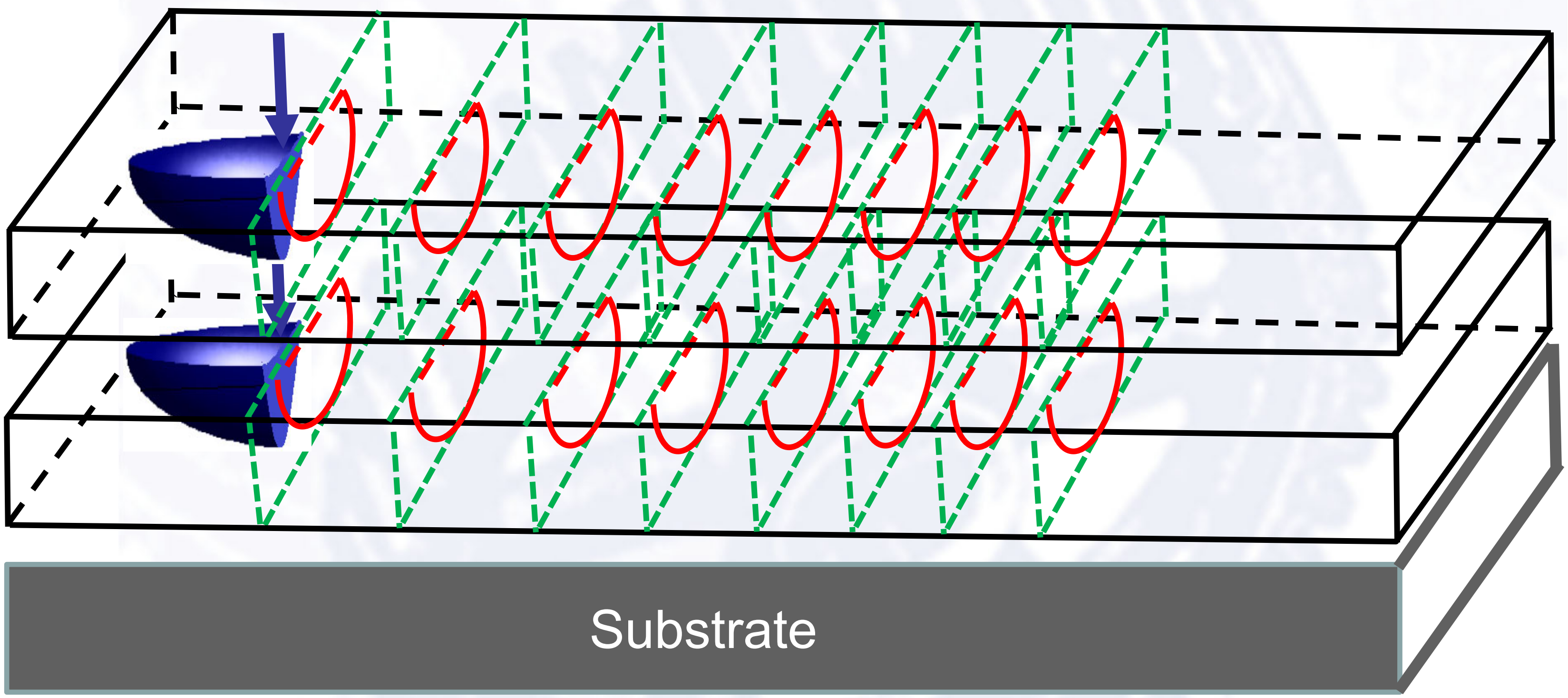


Ti64, Laser Power 100W, Scan Speed 0.01 m/s with various layers (single layer thickness 0.05 mm)

Validation with
various process parameters

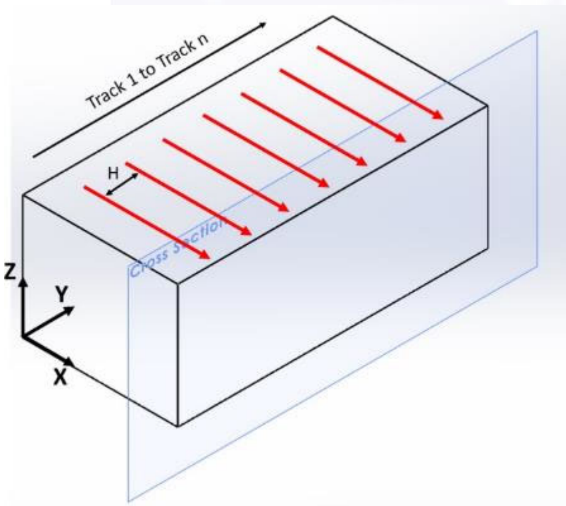


Moving-Heat-Source Transverse Area Analysis



Part Porosity Prediction by Transverse Area Analysis

Liang

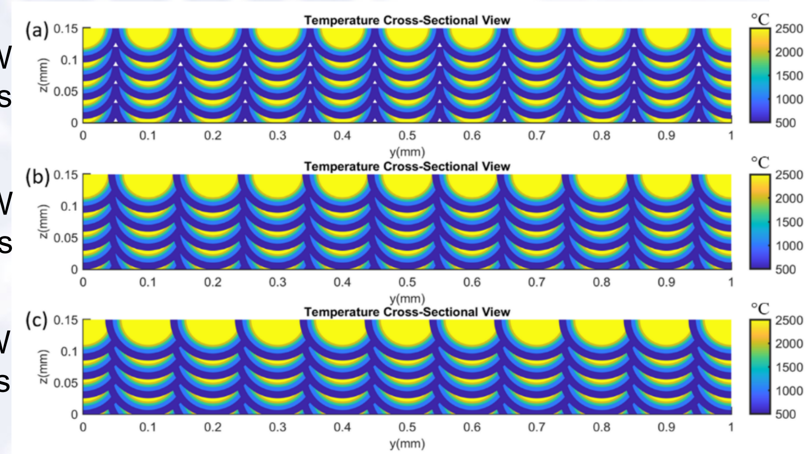


Model	Computational Time	Area Size	Computing Power
Current Model	26 seconds	5 layer with 11 tracks per layer	2.8 GHz
Finite Element Analysis	5 hours	5 layer with 5 tracks per layer	3.4 GHz

100W 750mm/s

150W 750mm/s

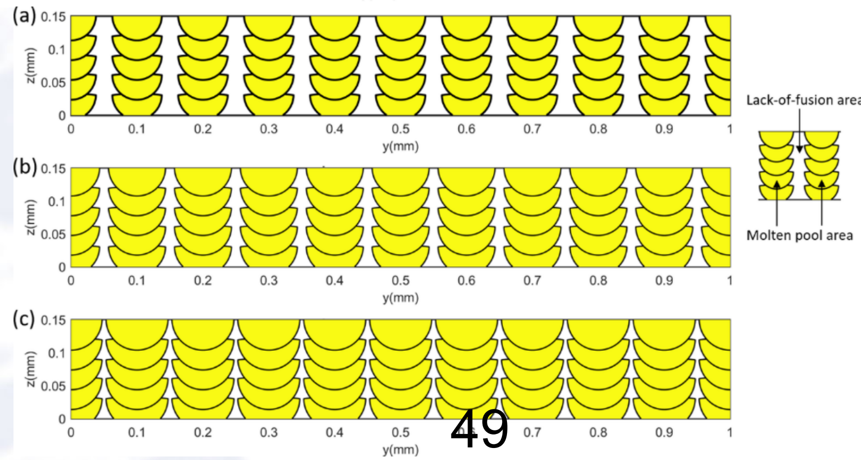
195W 750mm/s



100W 750mm/s

150W 750mm/s

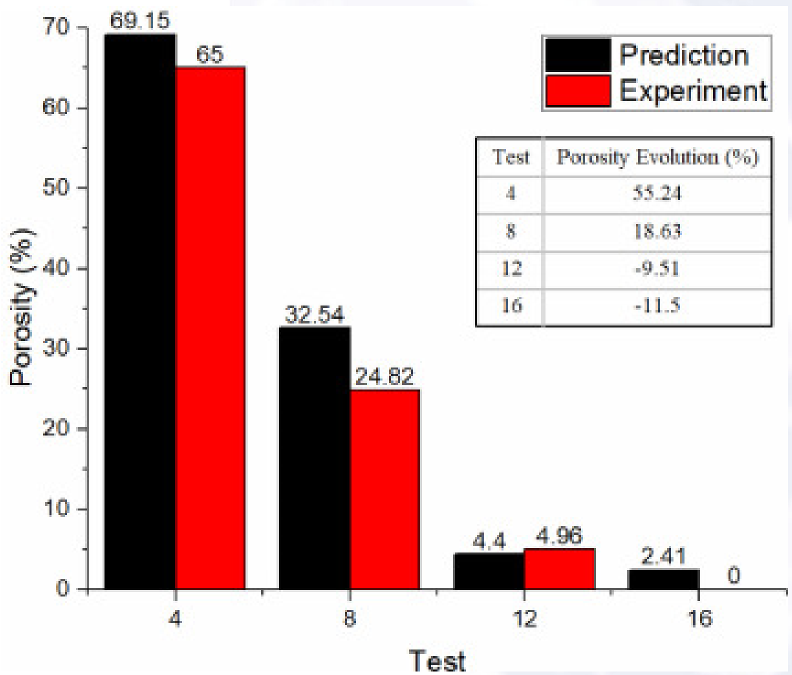
195W 750mm/s



Experimental Validation of Part Porosity Prediction

Liang

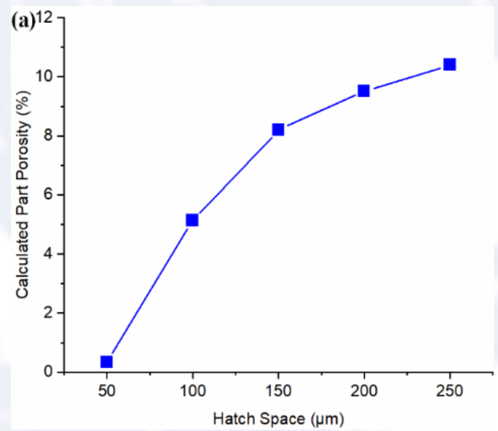
Experimental Validation



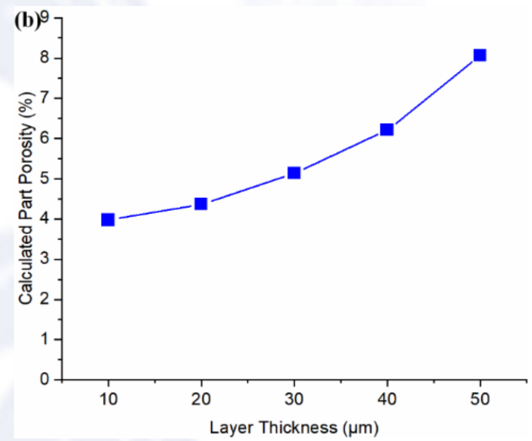
Test	Porosity Evolution (%)
4	55.24
8	18.63
12	-9.51
16	-11.5

Sensitivity Analysis

PBMAM of Ti6Al4V



P = 100 W,
V = 750 mm/s,
LT = 30 μm

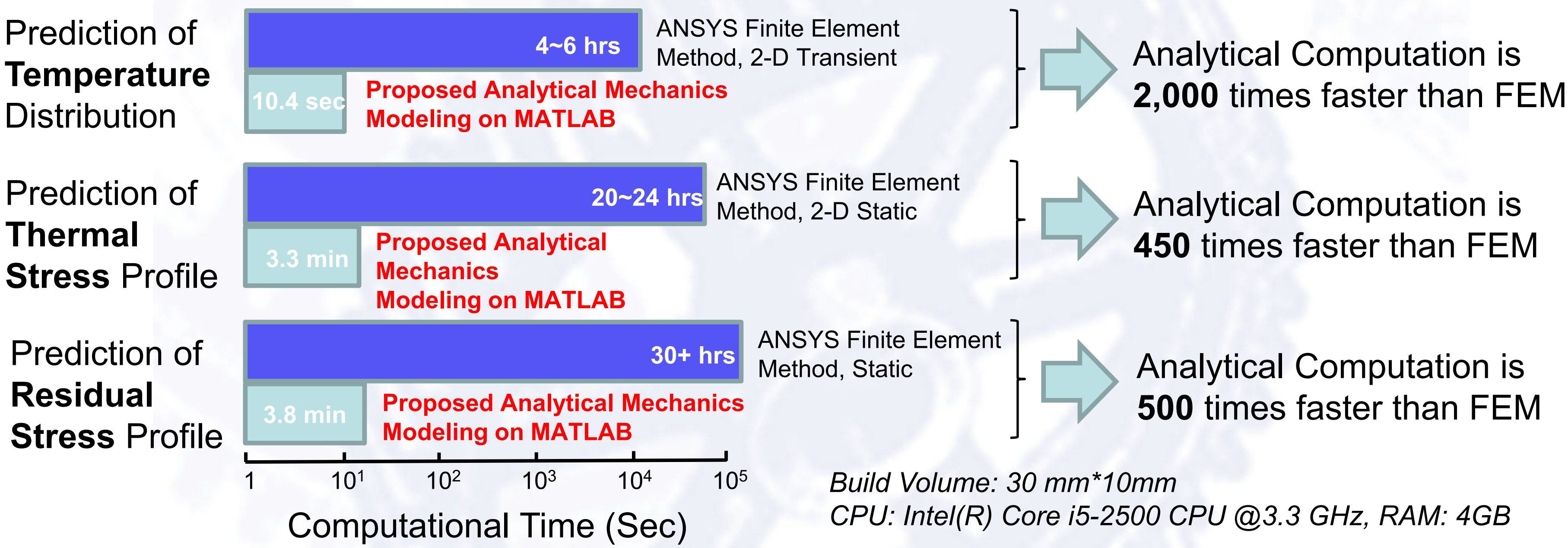


P = 100 W,
V = 750 mm/s,
H = 100 μm

Non-linear sensitivity as caused by the geometry of molten pool cross-section and the range of process parameter variation.

Computational Speed Advantages – GT Lab

Liang



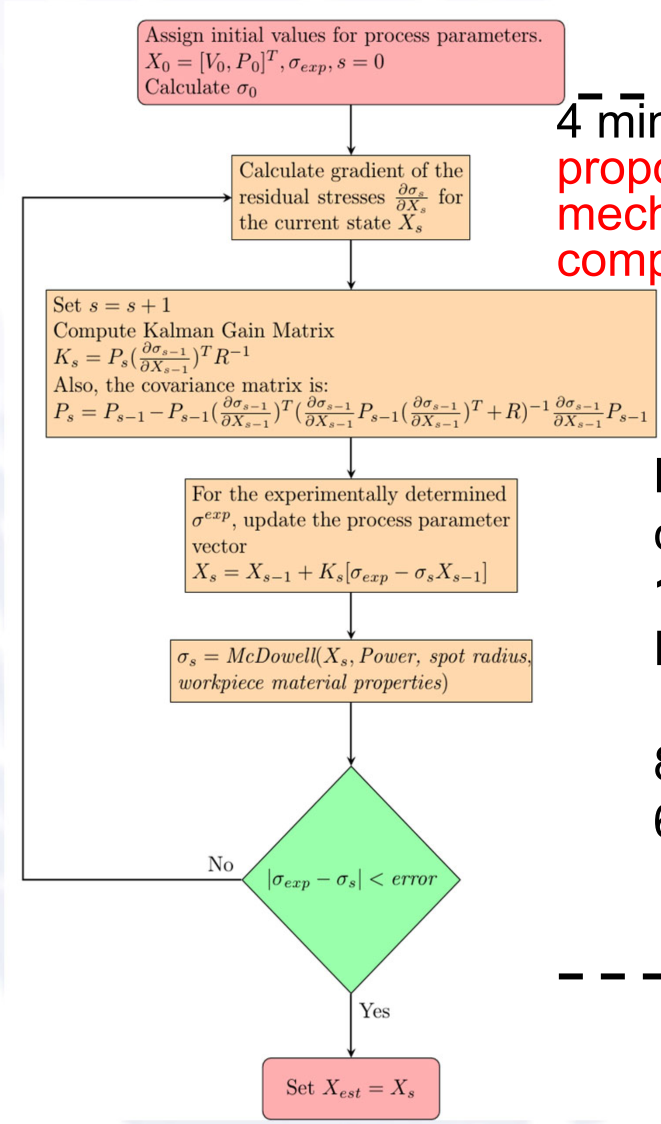
*Build Volume: 30 mm*10mm*

CPU: Intel(R) Core i5-2500 CPU @3.3 GHz, RAM: 4GB

Process Planning Enabled by Speed Advantages

Liang

Design of process parameters to achieve desirable AM temperature, thermal stress, and residual stress



4 minutes by proposed mechanics computation

30 hours by ANSYS

Proposed Mechanics computation is **10,000** times faster than FEM (20+ iterations):

80 mins by mechanics
600+ hours by ANSYS