Additive Manufacturing Technology
《增材制造技术》(双语)

MACH502201
Spring II 2020

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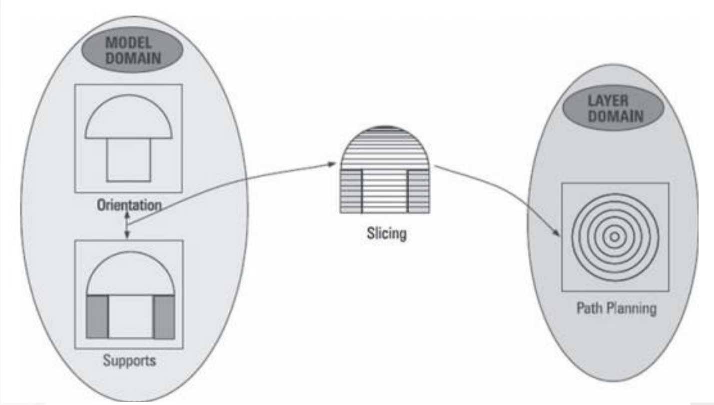
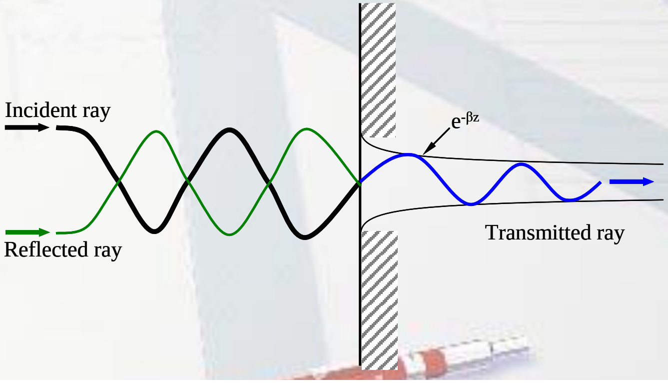
Fundamental process-Review

Steps for the AM process

- Designing/Modeling
  - CAD software
  - STL or AMF file
- Adding support
- Slicing
- Layer-by-layer
  - Material depositing
  - Joining
  - Process optimization
- Cleanup
- Post treatment



Geometric model data preparation



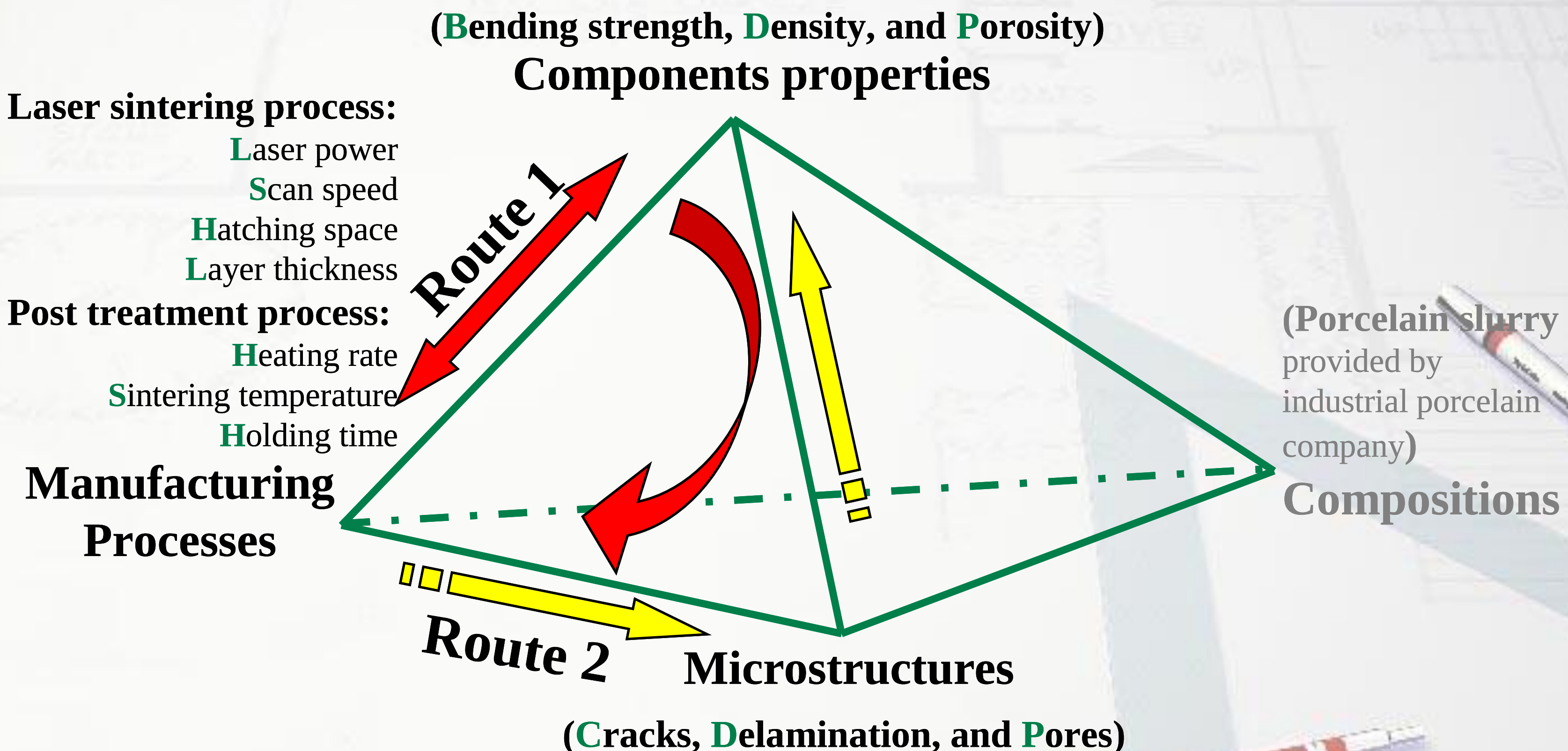
Interaction between energy and materials

Lecture 05
Process optimization

- Methods for process parameter optimization
  - An example for PBF process optimization
    - Simulations & Experiments
- New strategies for high efficiency processes

Process parameters optimization

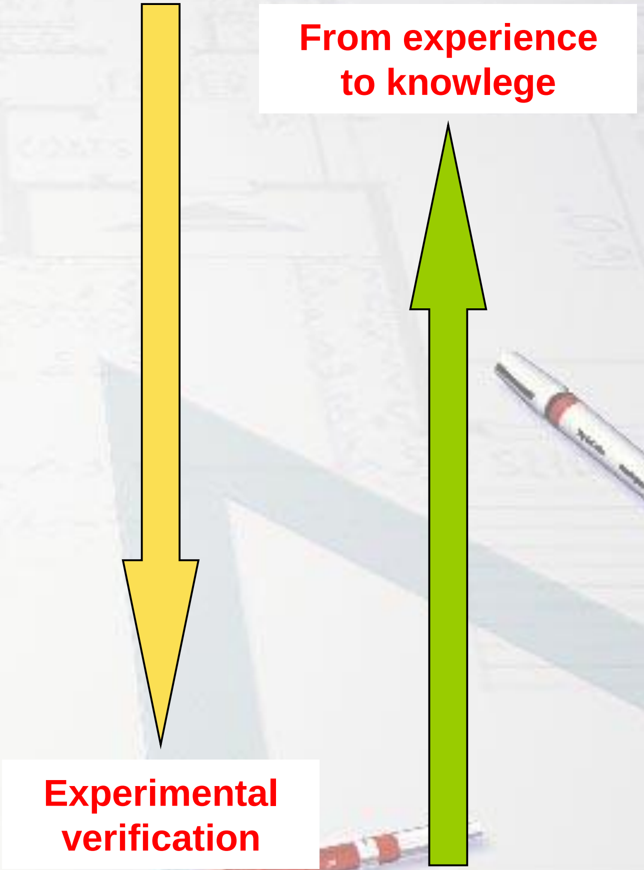
Parameters matrix in powder bed fusion (SLS/M) process



Process parameters optimization

Methods for process optimization

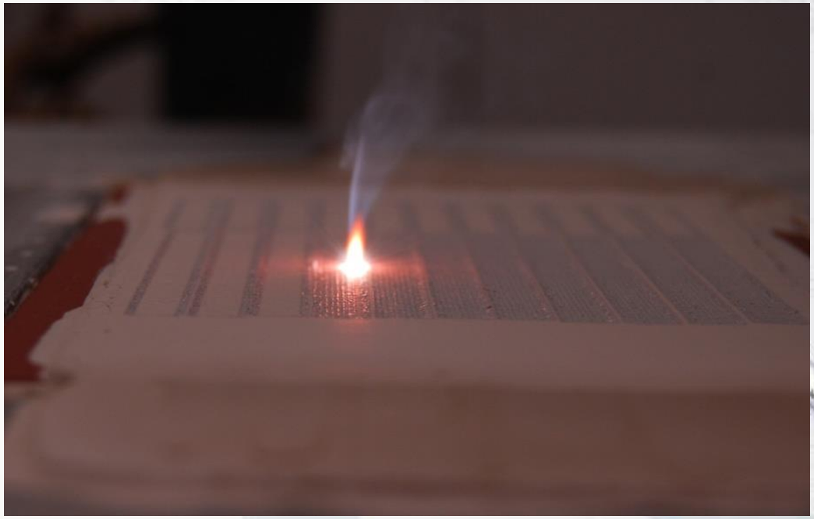
- Theoretical Analysis
  - Qualitative analysis
  - Instructive
    - optical system, interaction between material and energy
- Simulation
  - Simulating the real situation
  - Regularity analysis
    - temperature, stress
- Experiments
  - Quantitative analysis
  - Real situation
    - microstructure, mechanial perperties, accuracy



Mathematic modeling of PBF process is very difficult, numerical simulation is usually used.

What can we get by simulation?

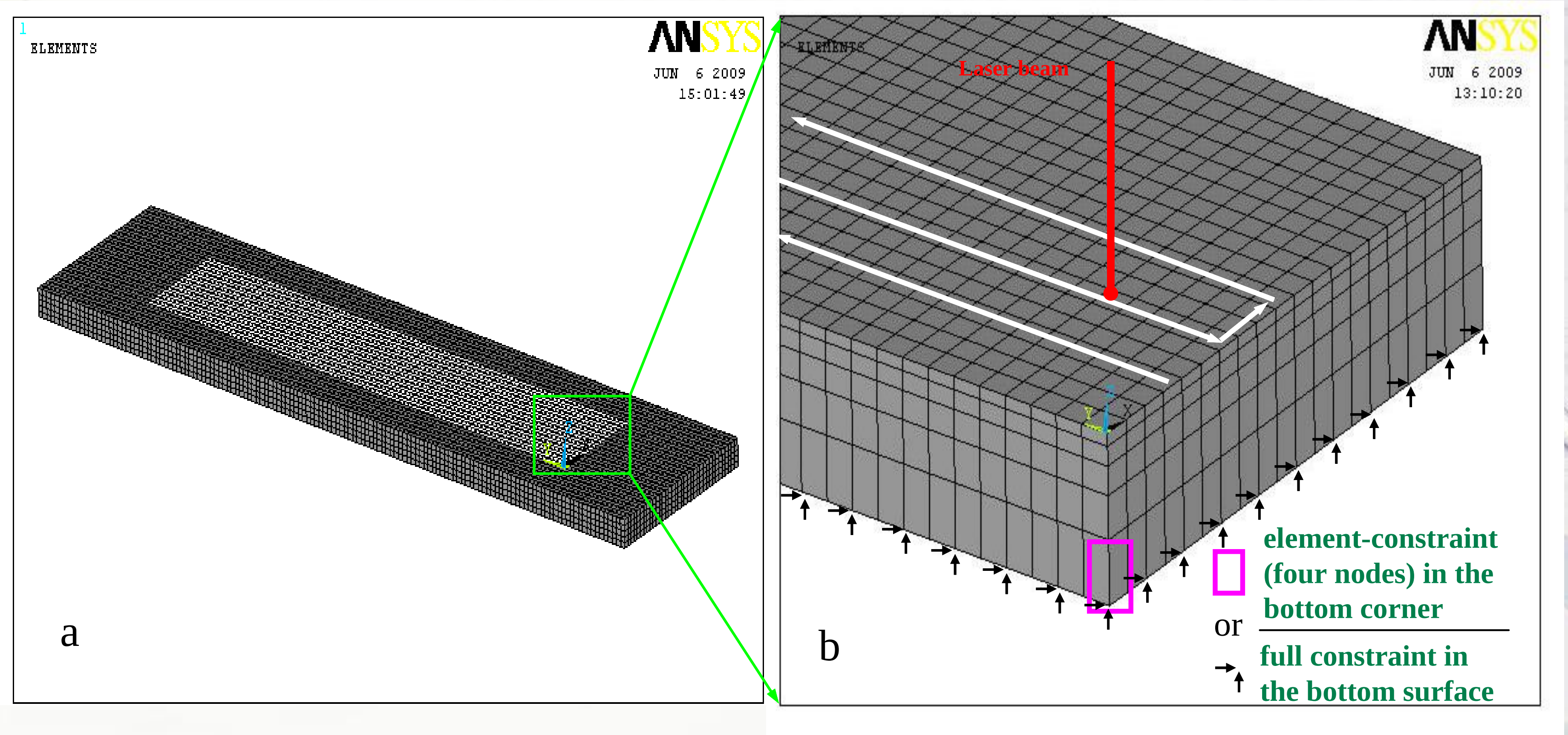
- Temperature
  - Predicting penetration depth（HAZ）
- Stress history and residual stress
  - Predicting cracking, distortion, and delamination
- Parameter optimization
  - Reducing the time-consuming experiments



Simulation of PBF process

Finite element model

Laser scanning style



Simulation of PBF process

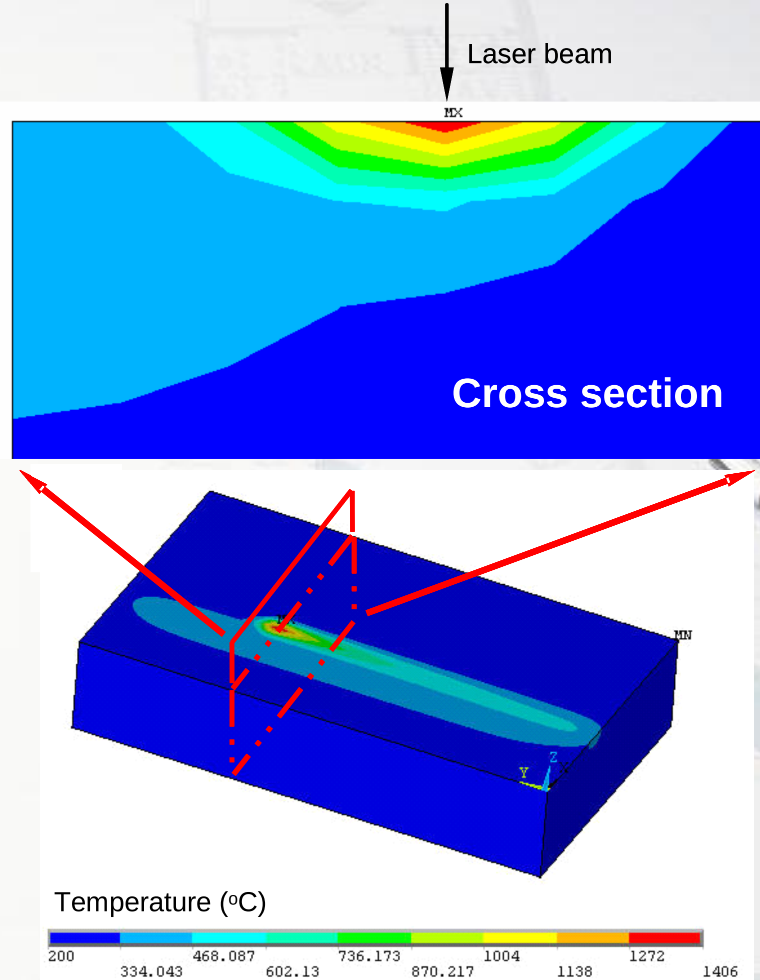
Parameters for the simulation

RUN	Factors			LaserED (J/cm^2)
	Laser power (watt)	Scan speed (mm/s)	Hatch spacing (mm)	
R1	40	85	0.3	78.43
R2	40	100	0.45	66.67
R3	40	150	0.6	44.44
R4	50	85	0.45	98.04
R5	50	100	0.6	83.33
R6	50	150	0.3	55.56
R7	60	85	0.6	117.65
R8	60	100	0.3	100
R9	60	150	0.45	66.67

Simulation of PBF process

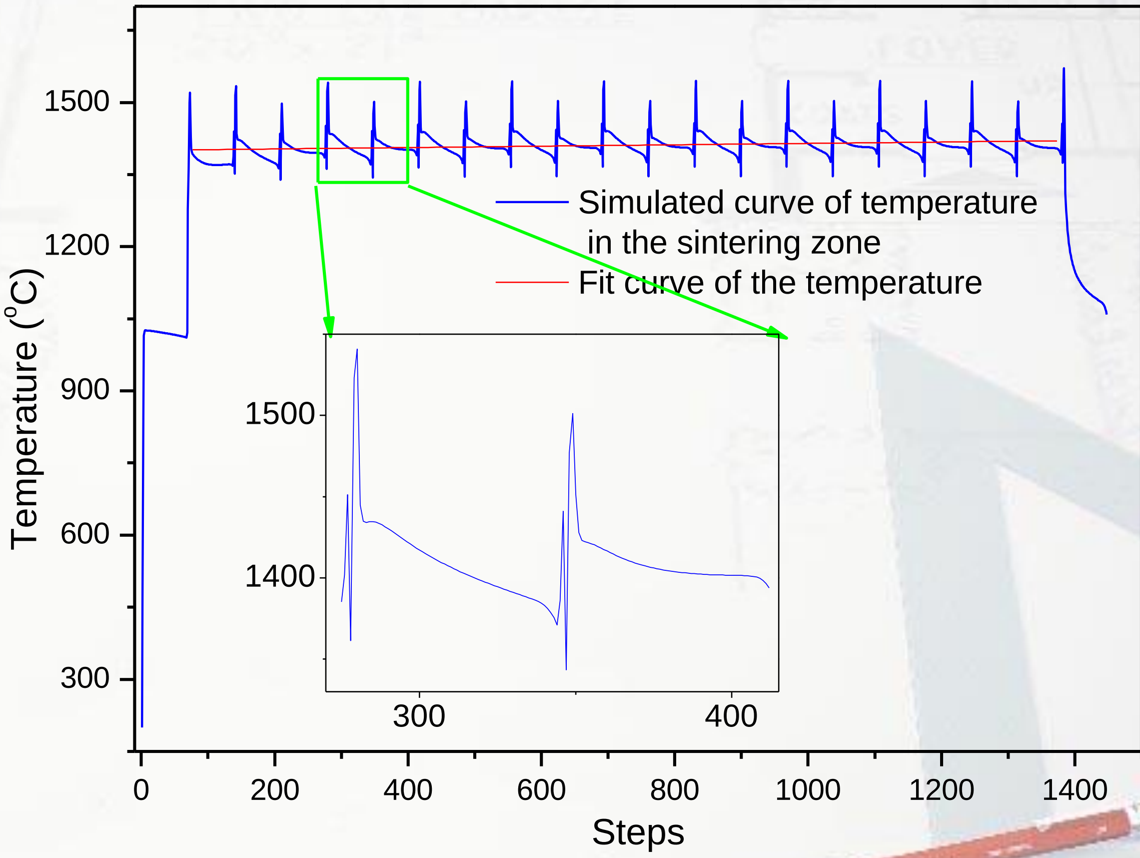
Transient temperature

Simulated temperature distribution in the cross section of the laser sintering model



Simulation of PBF process

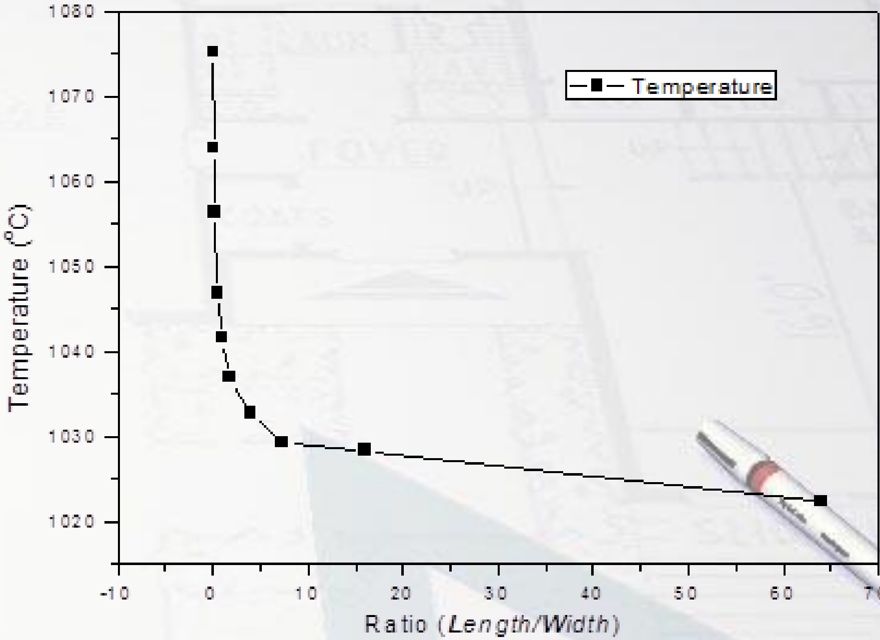
Temperature curve

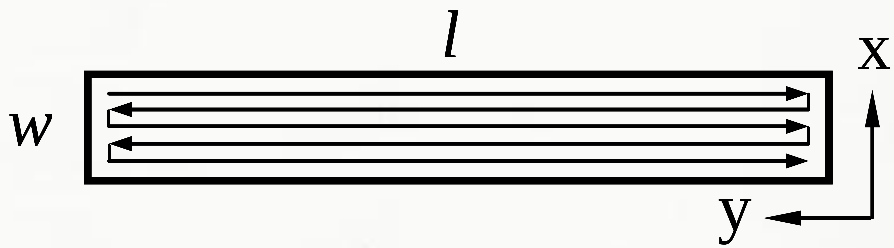


Simulation of PBF process

Scan patterns

- Long raster pattern
- Short raster pattern
- Average sintering temperature vs. ratio

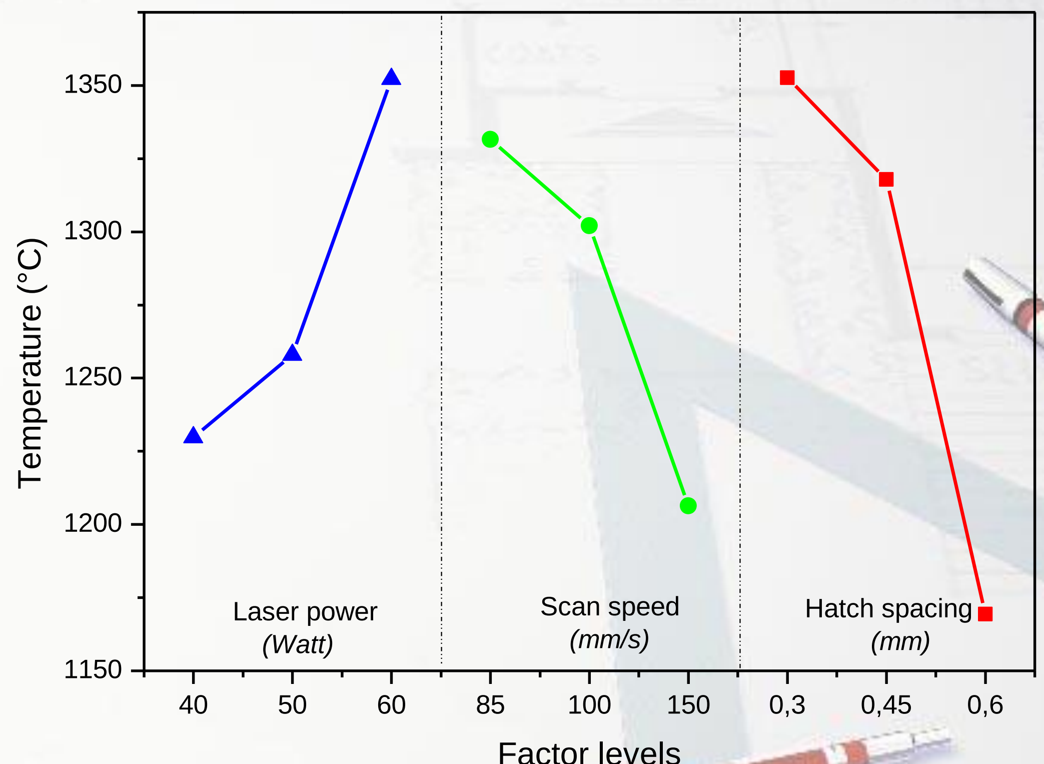




Simulation of PBF process

Influence of laser parameters on temperature

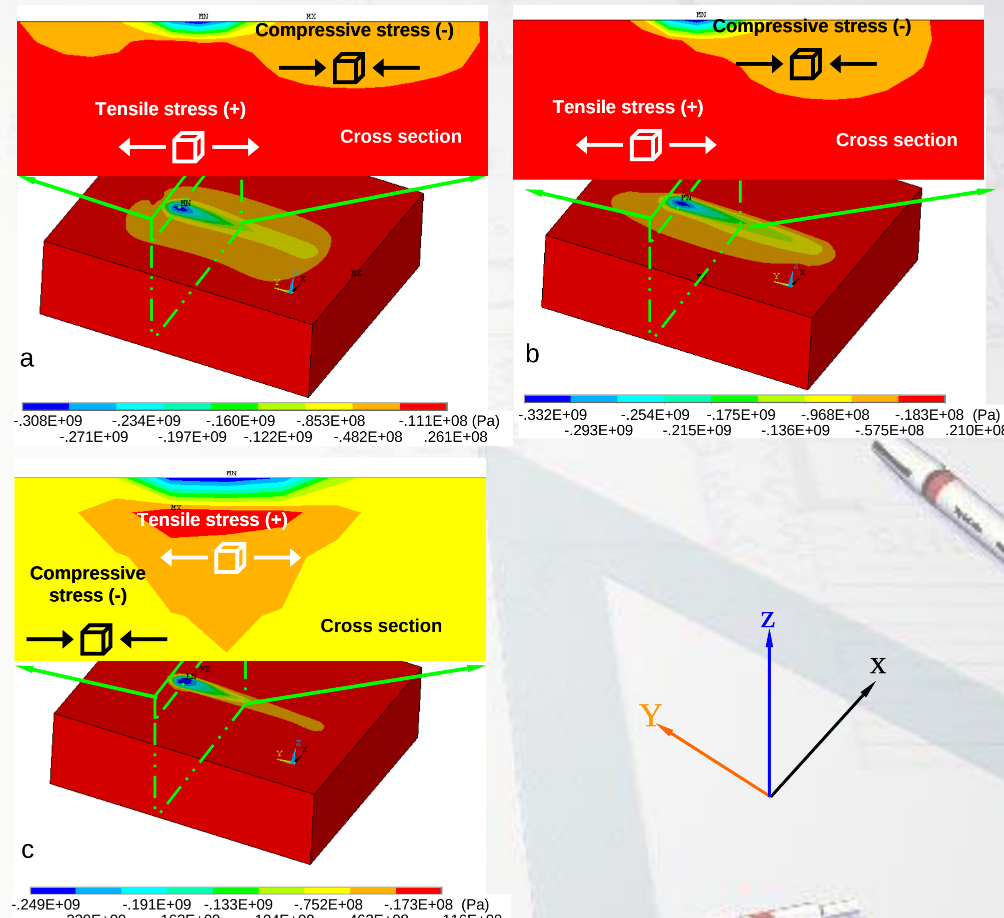
- Laser power
- Scanning speed
- Hatch spacing



Simulation of PBF process

Transient stresses

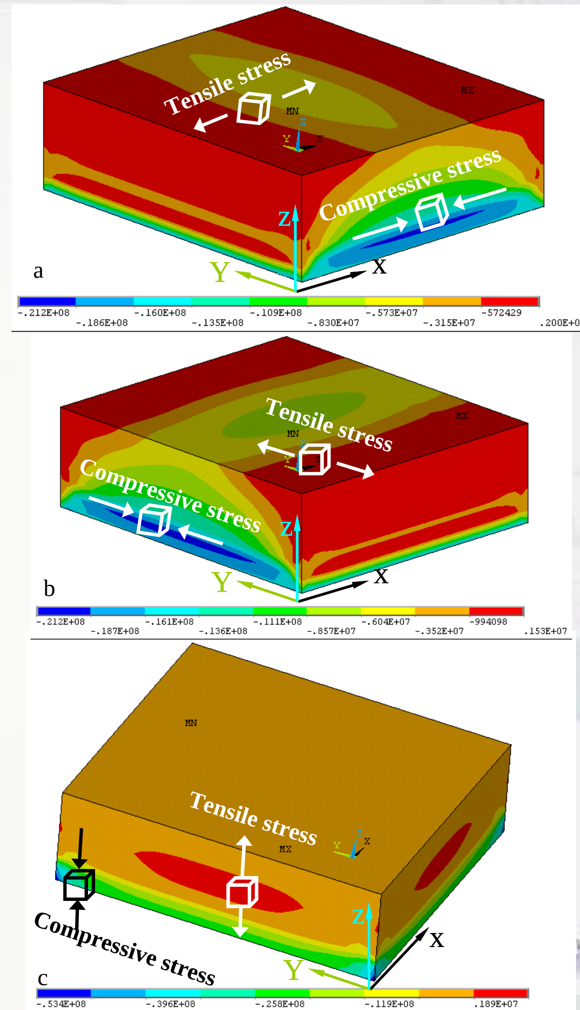
- Compressive stress
- Tensile stress



Simulation of PBF process

Residual stress

- Surface area
    - Tensile stress
- Bottom area
    - Compressive stress
- Multi-layer
    - Converse stress states
    - Delamination



Process parameters optimization

Experimental investigation

Factors	Level 1	Level 2	Level 3
Laser power (Watt)	40	50	60
Scan speed (mm/s)	85	100	150
Hatch spacing (mm)	0.3	0.45	0.6

RUN	Factors			LaserED (J/cm^2)
	Laser power (watt)	Scan speed (mm/s)	Hatching space (mm)	
R1	40	85	0.3	78.43
R2	40	100	0.45	66.67
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R6	50	150	0.3	55.56
R7	60	85	0.6	117.65
R8	60	100	0.3	100.00
R9	60	150	0.45	66.67

Experimental designs

- Laser sintering process
  - Laser power (W)
  - Scan speed (mm/s)
  - Hatch spacing (mm)
- Post treatment process

Average laser energy density:

$$LaserED = \frac{P}{D \times V} (J/cm^2)$$

P: laser power (CO_2 laser, max 100 W)
D: diameter of the laser beam (0.6mm)
V: laser scan speed

Orthogonal experiments

Process parameters optimization

Experimental investigation

Factors	Level 1	Level 2	Level 3
Heating rate (°C/min)	10	15	20
Sintering temperature (°C)	1225	1275	1325
Holding time (min)	10	60	120

RUN	Factors		
	Heating rate (°C/min)	Sintering temp. (°C)	Holding time (min)
R1	10	1225	10
R2	10	1275	60
R3	10	1325	120
R4	15	1225	60
R5	15	1275	120
R6	15	1325	10
R7	20	1225	120
R8	20	1275	10
R9	20	1325	60

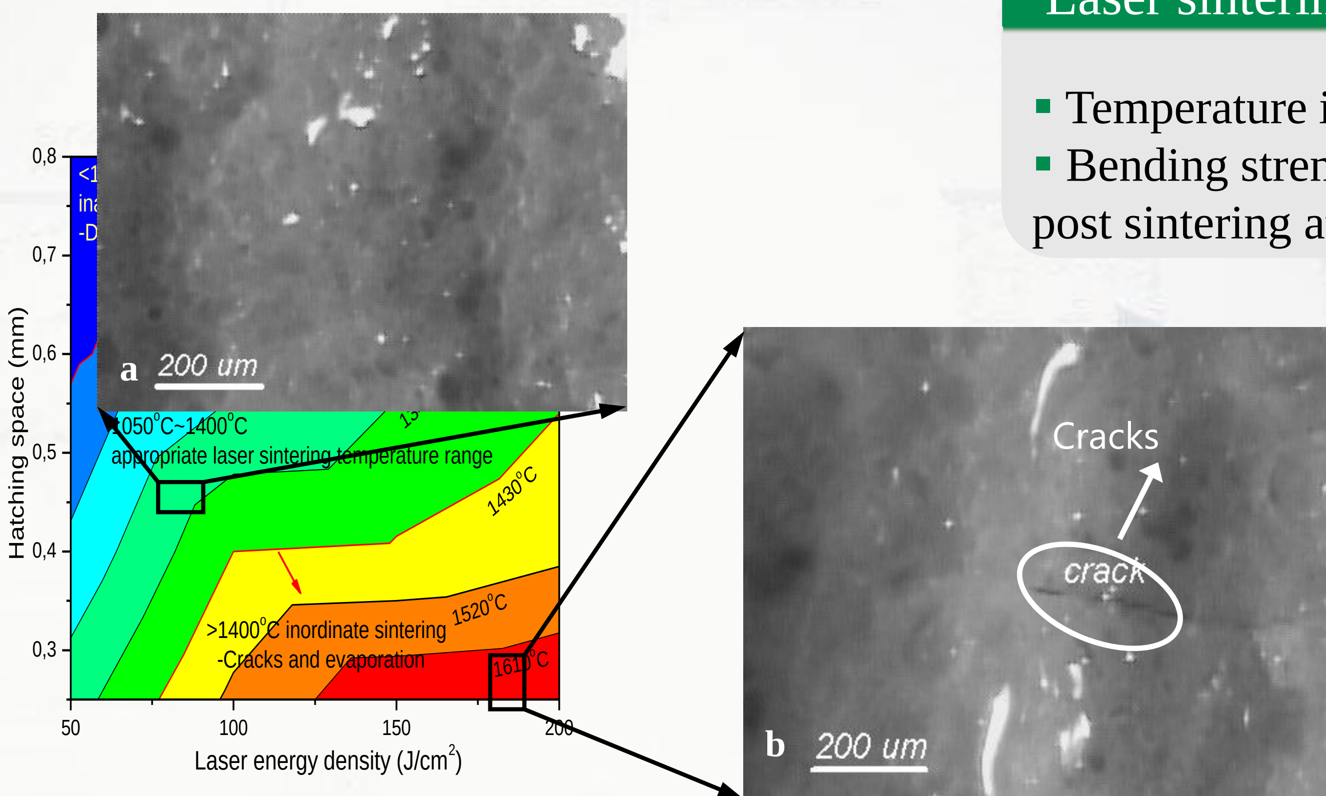
Experimental designs

- Laser sintering process
- Post sintering process
  - Heating rate (°C/min)
  - Sintering temperature (°C)
  - Holding time (min)

Orthogonal experiments

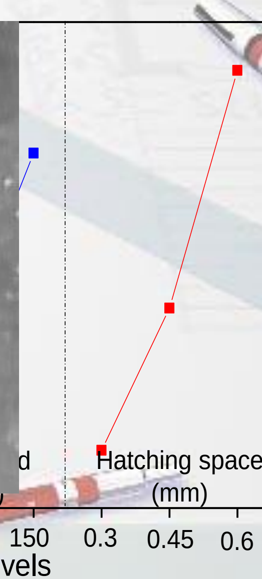
Process parameters optimization

Experimental investigation



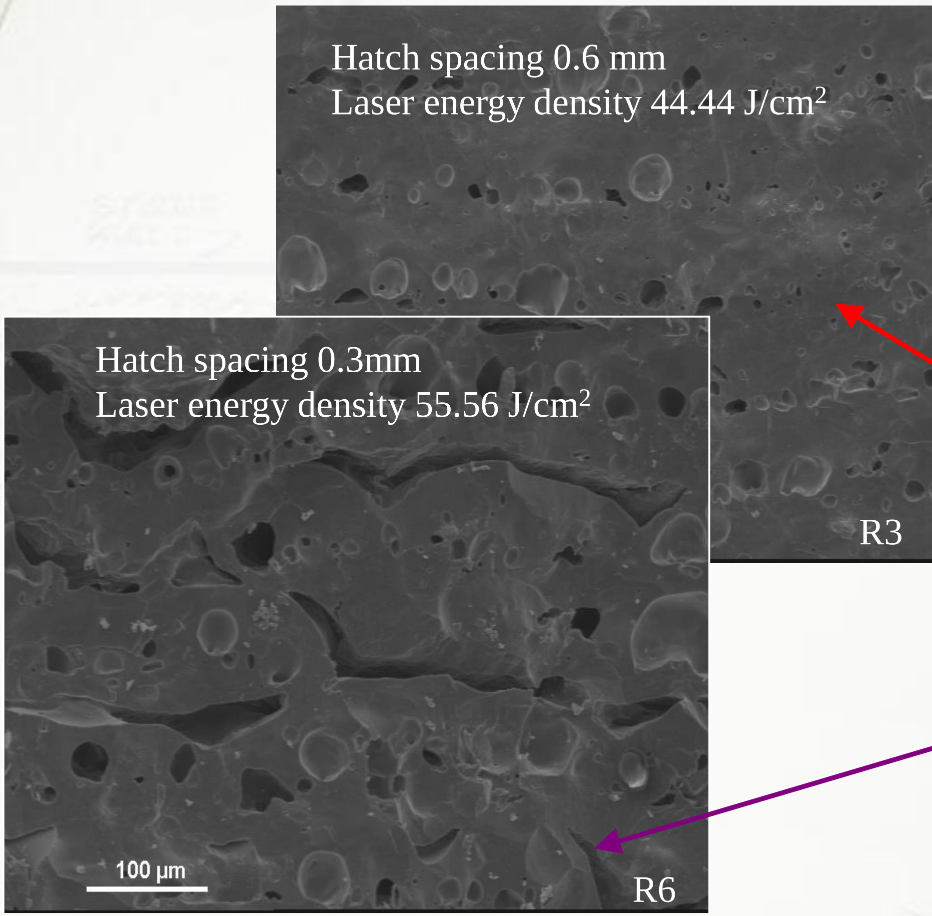
Laser sintering process

- Temperature in HAZ
- Bending strength after post sintering at 1425^{o}C



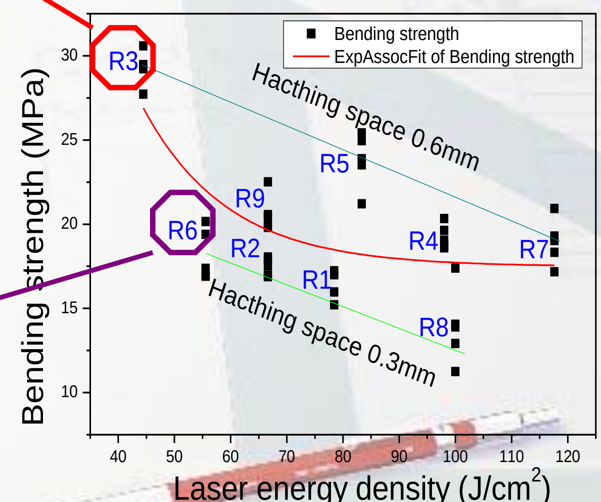
Process parameters optimization

Experimental investigation



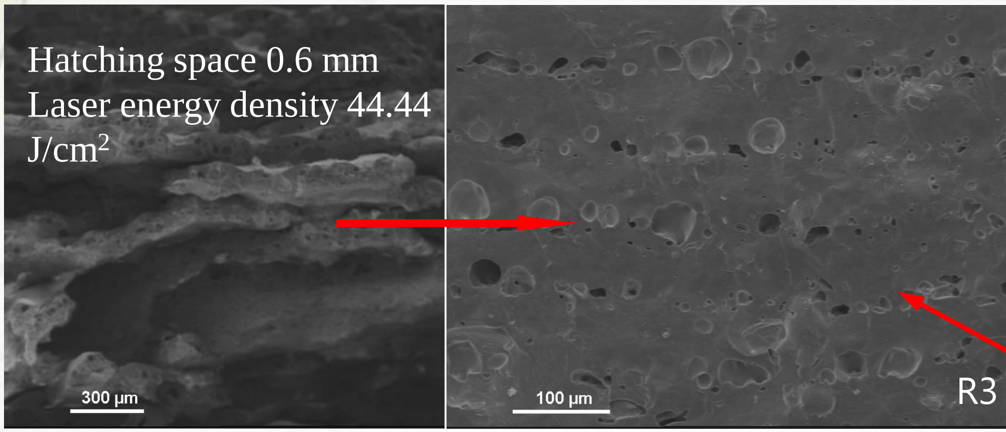
Laser sintering process

- Bending strength after post sintering at 1425°C
- Microstructure

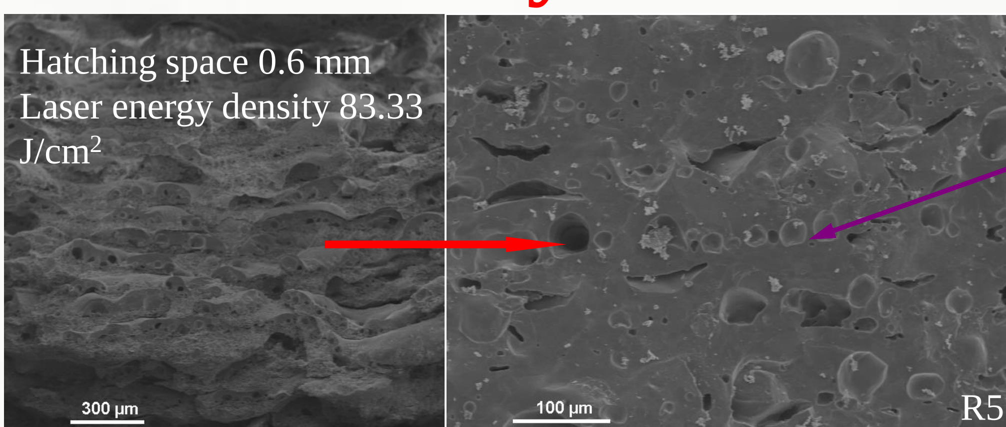


Process parameters optimization

Experimental investigation

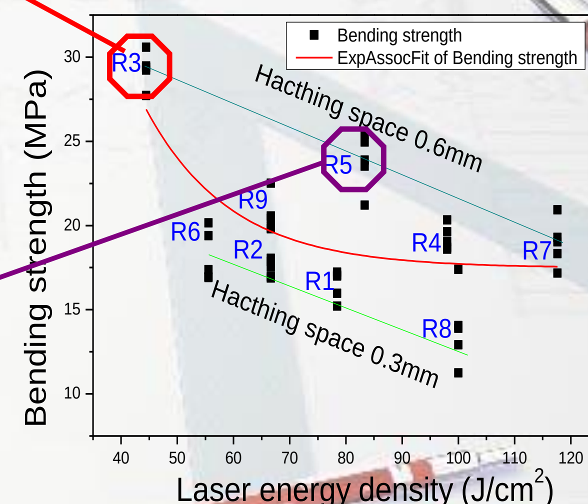


Laser sintered **Why ?** Post sintered



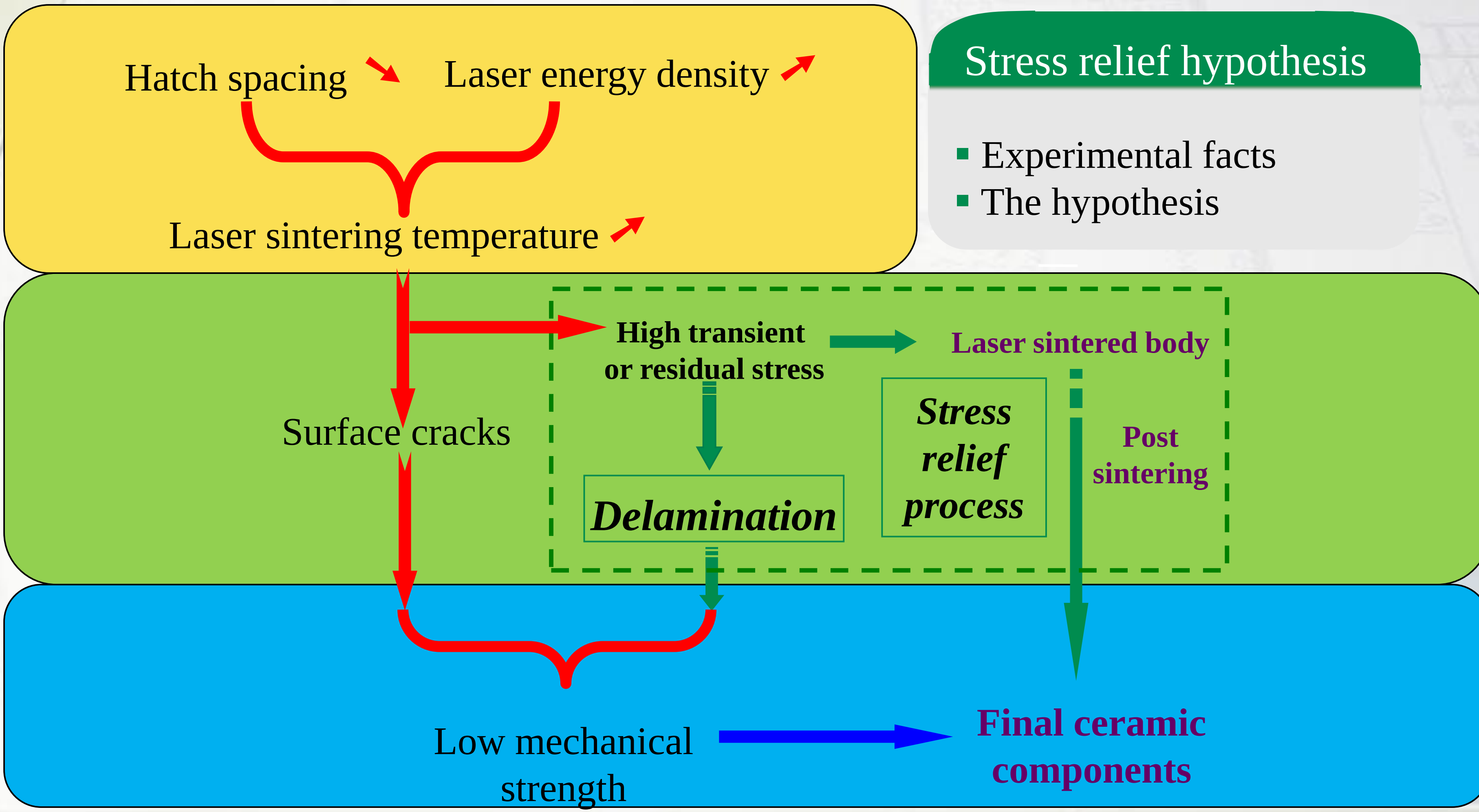
Laser sintering process

- Bending strength after post sintering at 1425^{o}C
- Microstructure



Process parameters optimization

Experimental investigation



Stress relief hypothesis

- Experimental facts
- The hypothesis

Process parameters optimization

Theoretical analysis

Stress relief mechanism

- Interpretation of stress relief hypothesis

Steady-state creep by Power law equation *

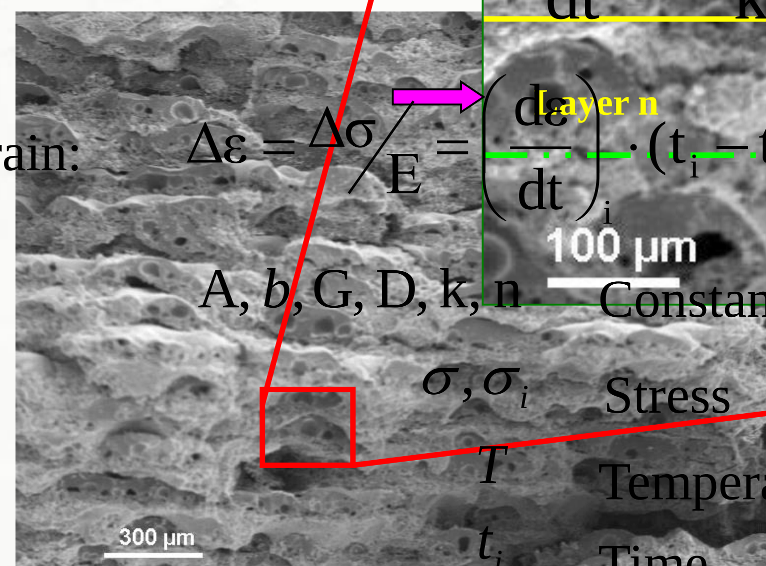
Steady-state creep rate:

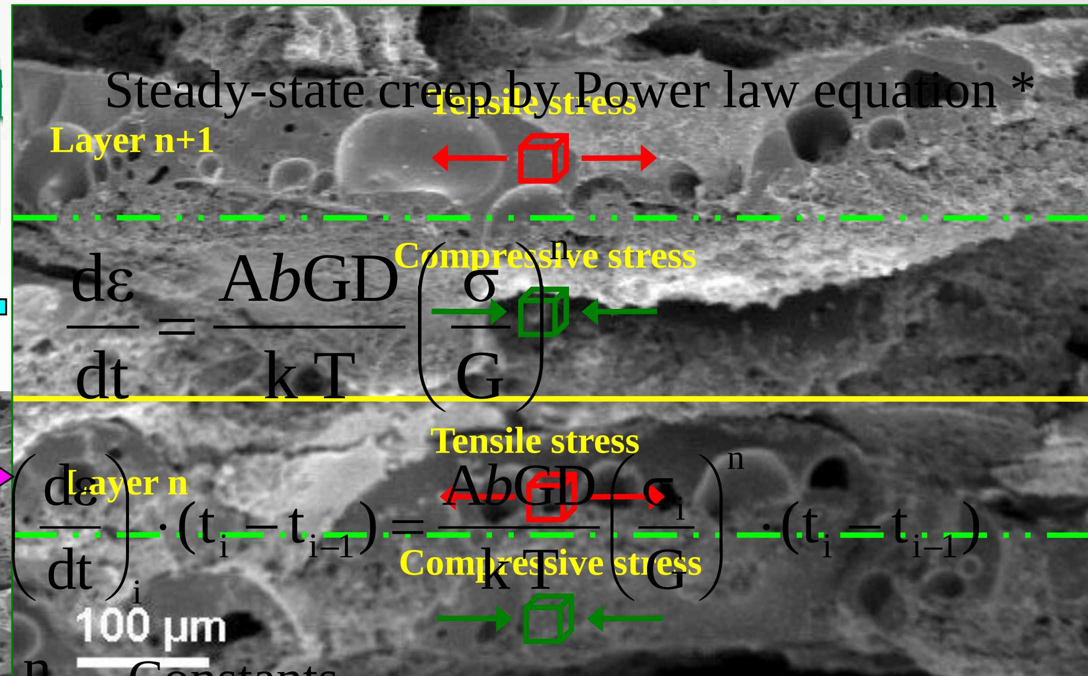
$$\frac{d\varepsilon}{dt} = \frac{AbGD}{kT}\left(\frac{\sigma}{G}\right)^n$$

Strain:

$$\Delta\varepsilon = \Delta\sigma / E = \left(\frac{d\varepsilon}{dt}\right)_i \cdot (t_i - t_{i-1}) = \frac{AbGD}{kT}\left(\frac{\sigma_i}{G}\right)^n \cdot (t_i - t_{i-1})$$

A, *b*, G, D, k, n	Constants
σ, σ_i	Stress
T	Temperature
t_i	Time





Different creep directions will cause delamination between adjacent layers during post treatment process.

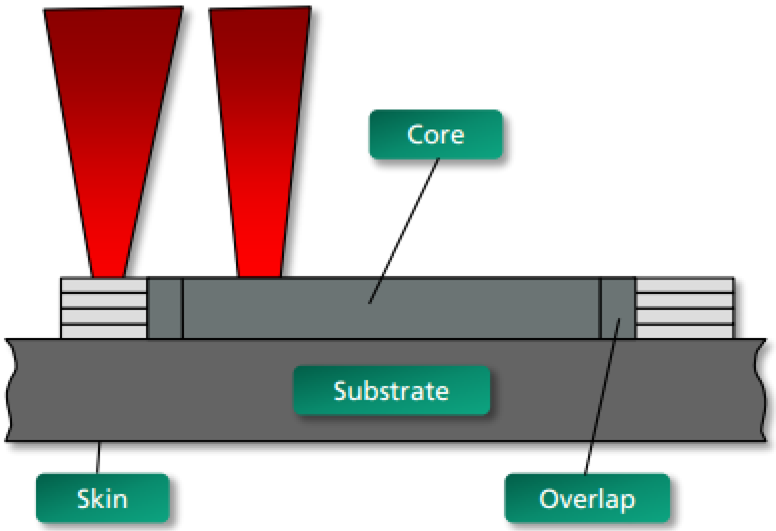
* *J.B. Wachtman, Mechanical properties of ceramics, New York, John Wiley & Sons; 1996, pp. 311*

New strategies for high efficiency process

Skin-core method for powder bed fusion

High surface quality and productivity

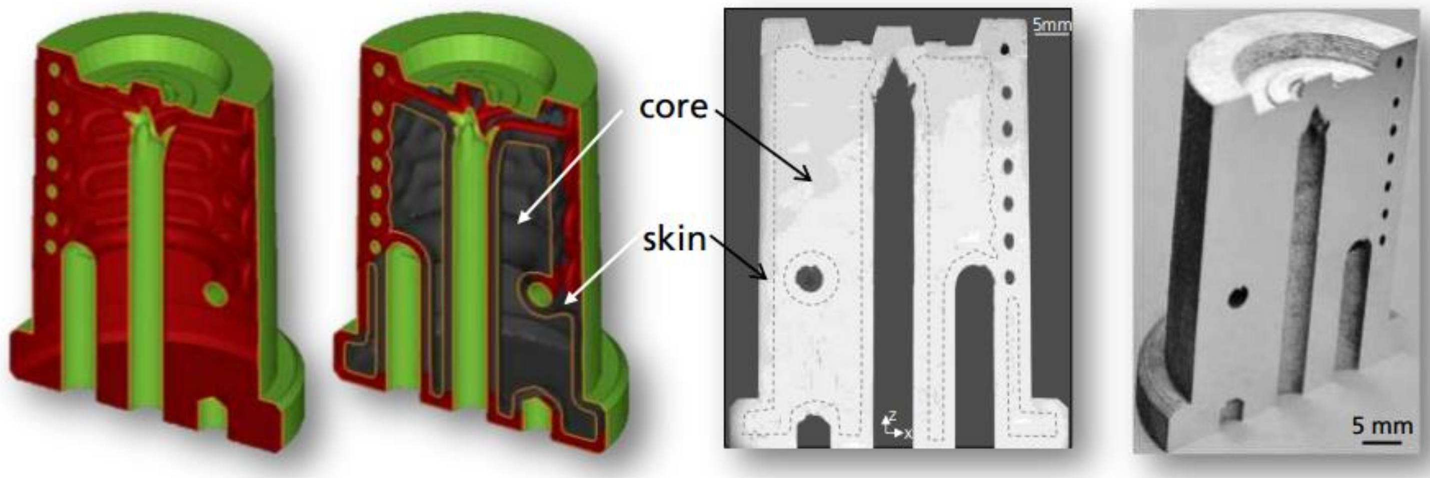
- Skin processing by small beam diameter
  - Maintaining detail resolution and surface quality
- Core processing by larger beam diameter
  - Increasing process related build-up rate
  - Decreasing primary processing time
  - Metallurgical bonding between skin and core by using overlap



New strategies
for high efficiency process

Increasing the Process Productivity with HP-SLM

HP-SLM Demonstrator Steel



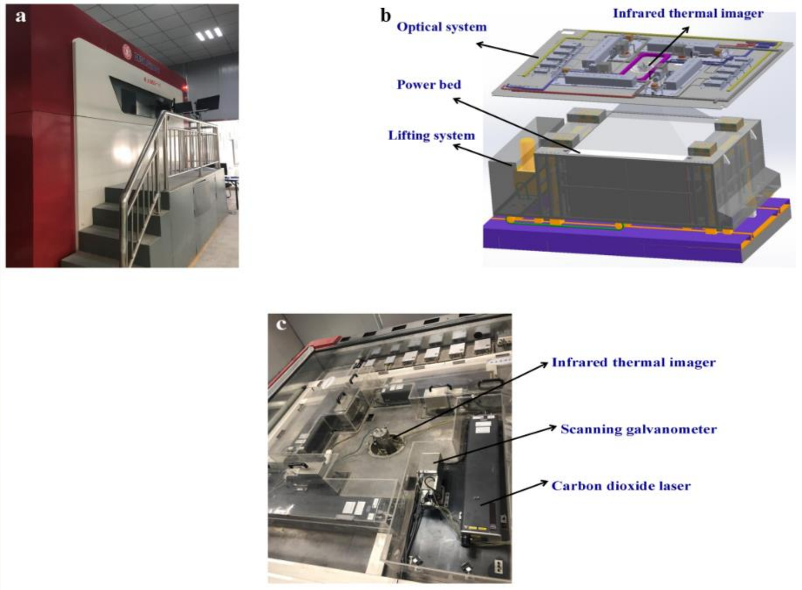
Theoretical build-up rate:	Skin:	Core:	Overall:
SLM (200 W)			≈3 mm^3/s
High Power SLM	8 mm^3/s	16,8 mm^3	12 mm^3/s

x 4

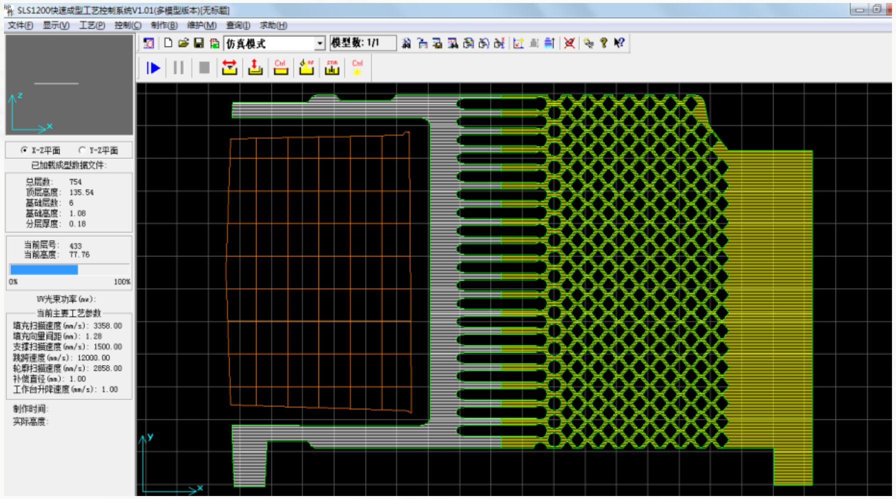
New strategies for high efficiency process

Four-laser selective laser sintering

- Four optical systems
- Model Segmentation algorithm
- Synchronous control



Scheme for the equipment



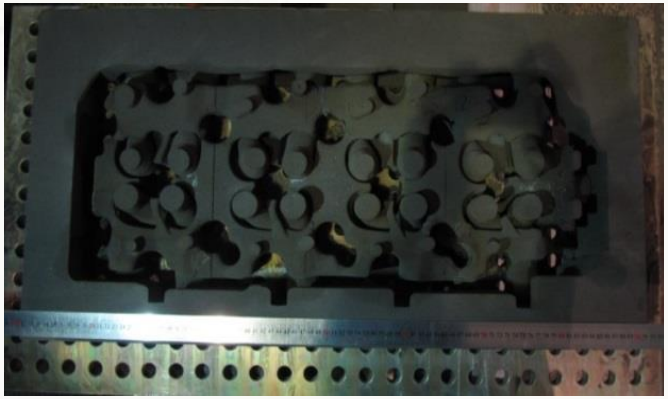
Synchronous control processing

New strategies for high efficiency process

For-laser selective laser sintering

- Machine characteristics
  - 4 X 200W CO_2 laser
  - Size:2000×2000×1000mm
  - Efficiency: 7000 cm^3/h
- Foundry sand mould

Sintering room / pre-heating

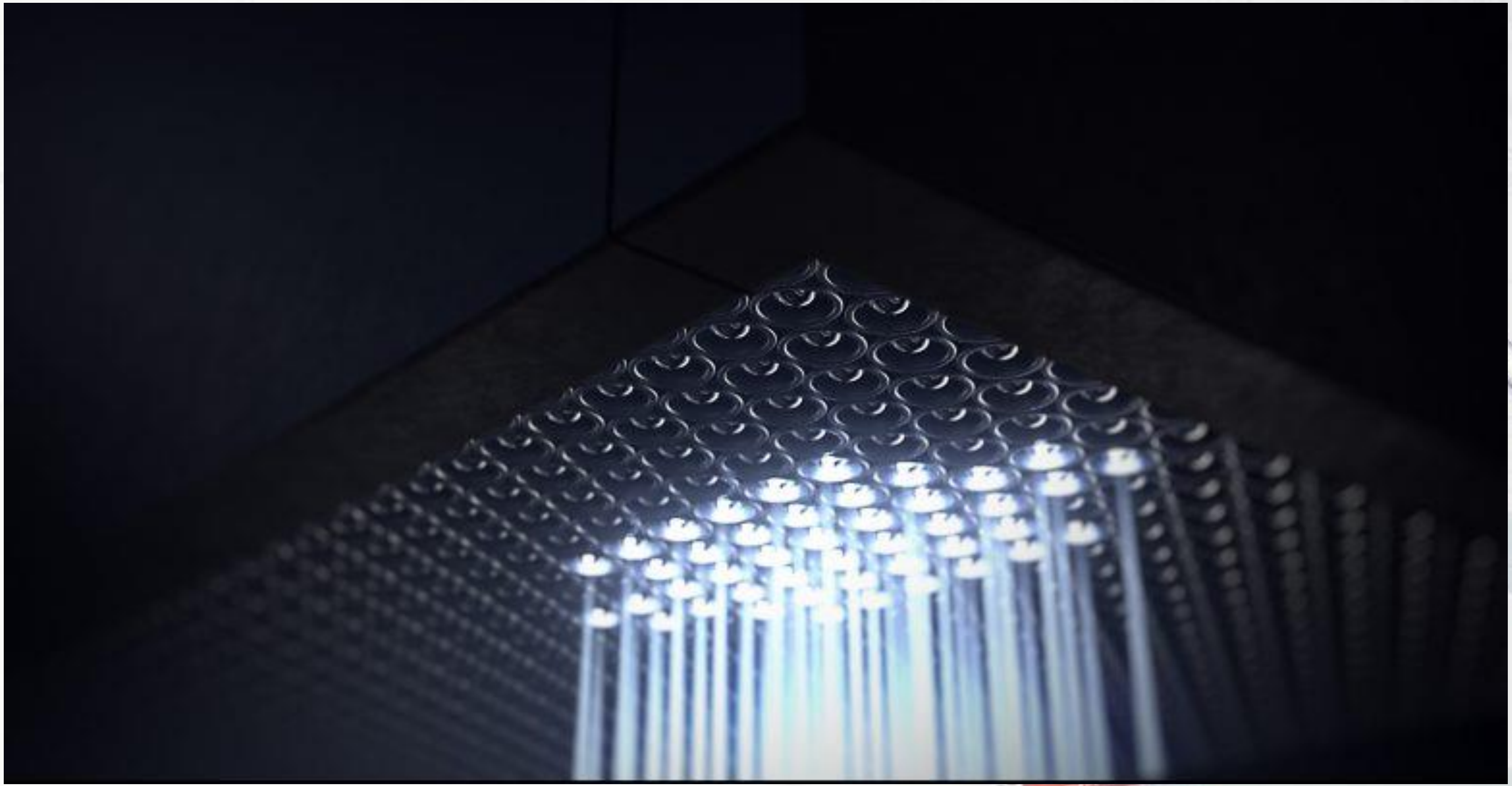


Cylinder cover sand mould

Complicated part sand mould

New strategies for high efficiency process

- **LaserProFusion-EOS, Germany**
  - **10 times faster using one million diode lasers**

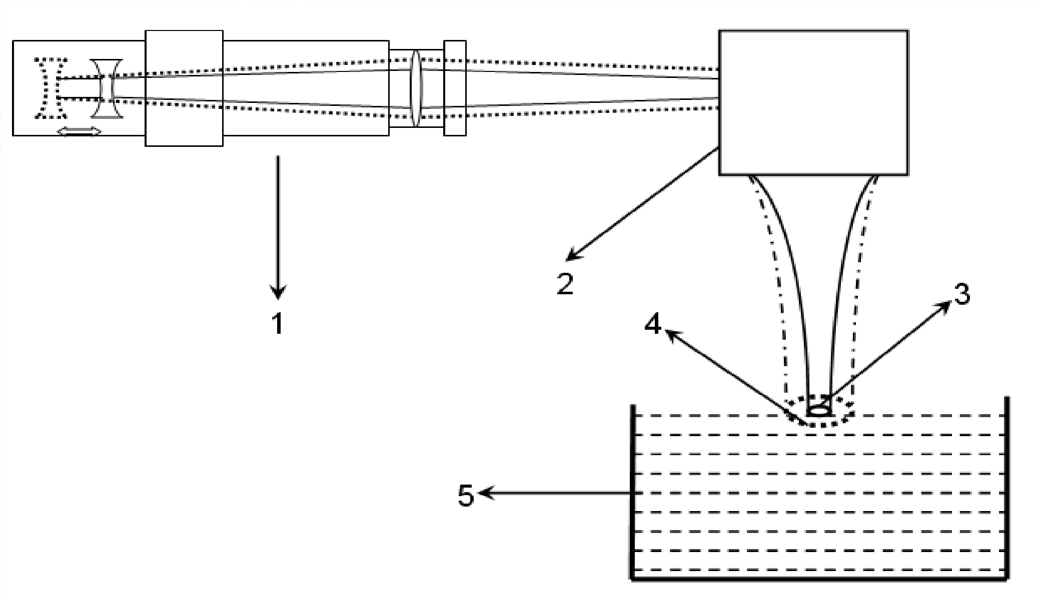


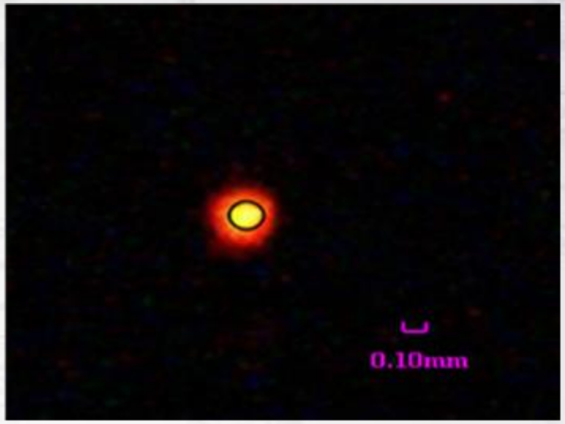
https://www.eos.info/systems_solutions/plastic/laserprofusion

New strategies for high efficiency process

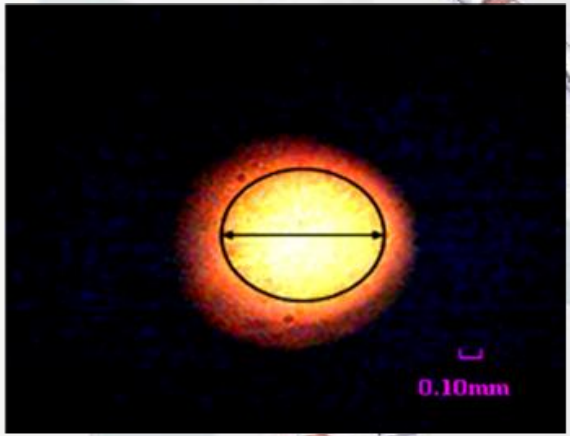
High-efficiency Stereolithography

- Dynamic focusing lens
- Variable laser beam waist
  - Contour-focused laser spot
  - Hatch- defocused laser spot





Focused beam waist



Defocused beam waist

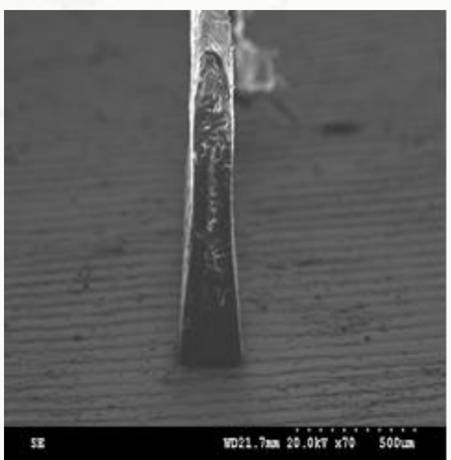
Rapid Prototyping J.17/6 (2011) 441–450

New strategies for high efficiency process

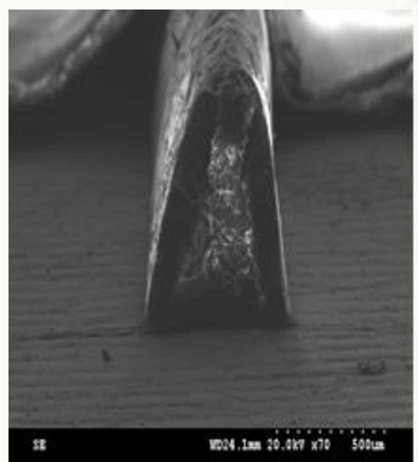
High-efficiency Stereolithography

- Using self-adaptive laser power
- Fabrication efficiency improved up to 38.1%

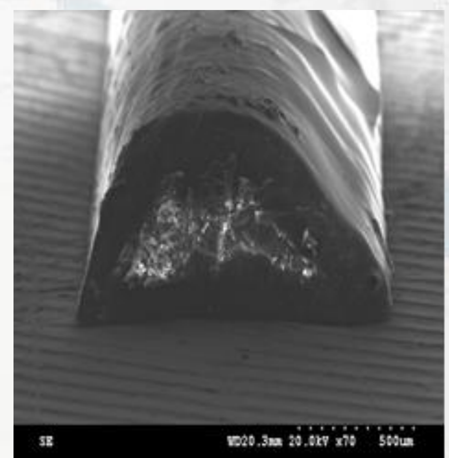
Fabricated part



0.16mm



0.36mm

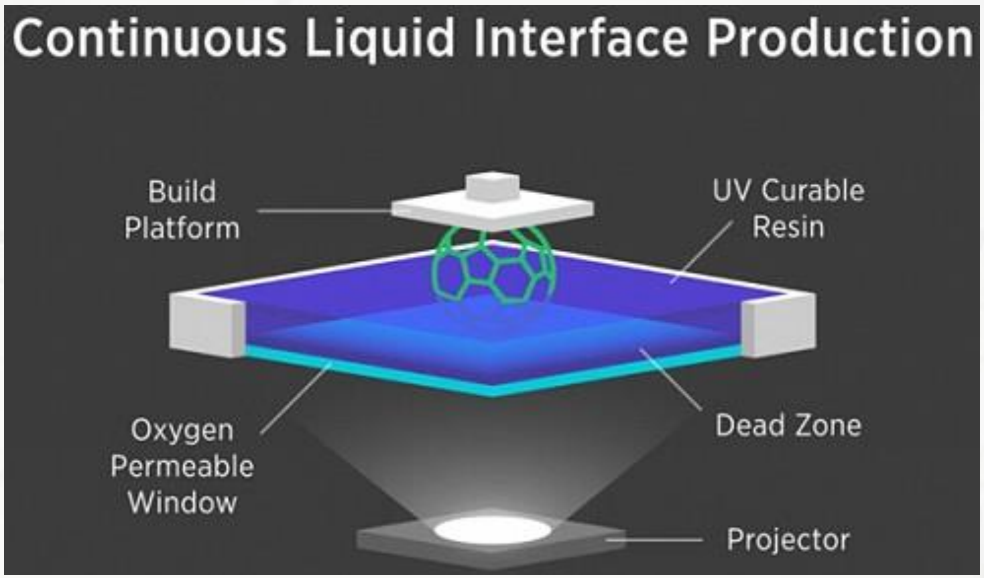


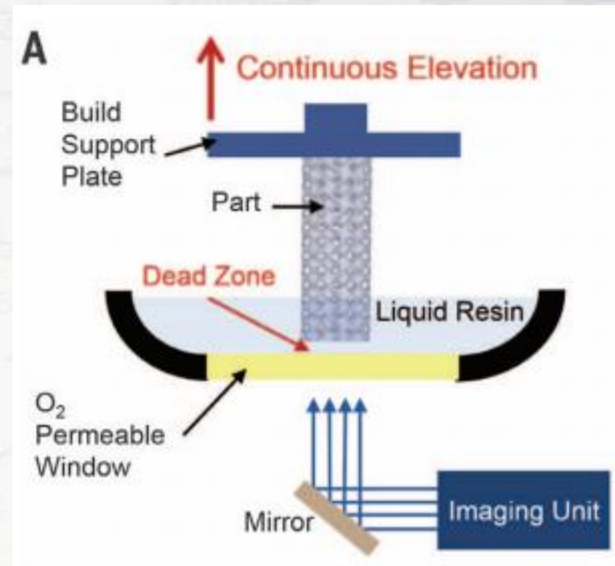
0.8mm

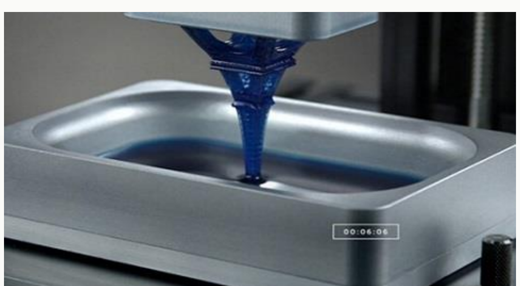
Laser spot size

New strategies
for high efficiency process

Continuous Liquid Interface Production







“drawn out of the resin at rates of hundreds of millimeters per hour”

Science, 20 MARCH 2015 • VOL 347 ISSUE 6228

New strategies for high efficiency process

Volumetric additive manufacturing via tomographic reconstruction

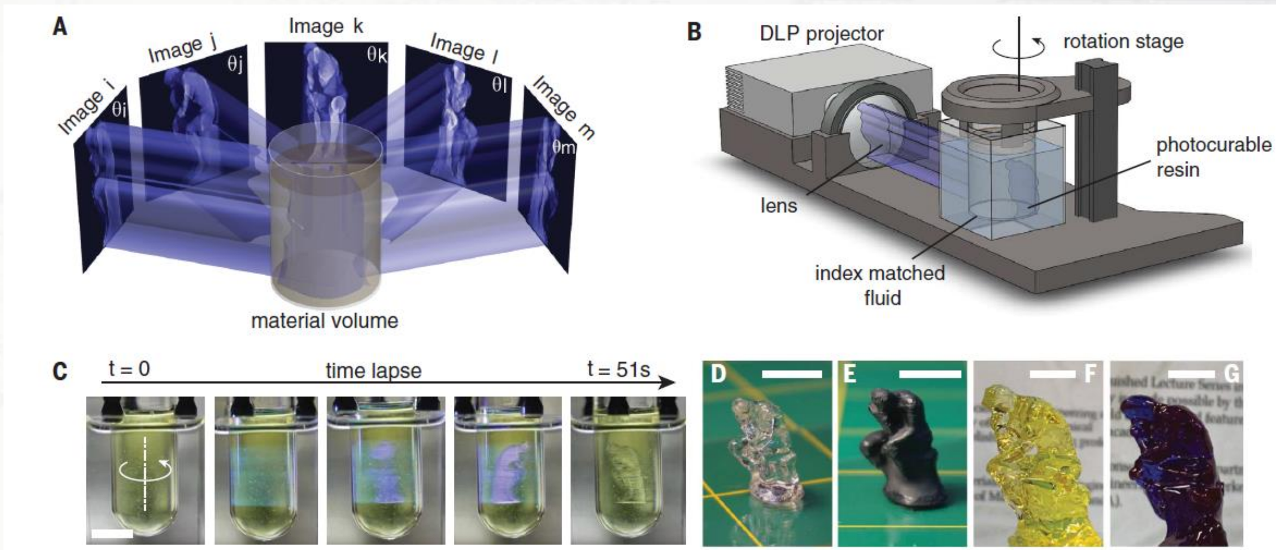


Fig. 1. CAL volumetric fabrication. (**A**) Underlying concept: Patterned illumination from many directions delivers a computed 3D exposure dose to a photoresponsive material. (**B**) Schematic of the CAL system used in this work. DLP projector, digital light processor–based projector. (**C**) Sequential view of the build volume during a CAL print. A 3D geometry is formed in the material in less than 1 min. (**D**) The 3D part shown in (C) after rinsing away uncured material. (**E**) The part from (D), painted for clarity. (**F**) A larger (40-mm-tall) version of the same geometry. (**G**) Opaque version of the geometry in (F), using crystal violet dye in the resin. Scale bars: 10 mm.

"printing times of 30 to 120 seconds for diverse centimeter-scale objects"

Computed axial lithography (CAL)

Kelly et al., Science 363, 1075–1079 (2019) 8 March 2019

- Project research
  - Using AM process and equipment to solve a practical problem
  - *采用增材制造技术解决工程实际问题，包括问题提出、分析、解决方案、实施、评估等环节内容*
    - **Grasp the basic design method of three-dimensional parts;**
    - **Master the data processing flow of the additive manufacturing process;**
    - **Ability to operate additive manufacturing equipment skillfully.**

    - **You can fabricate your design during the experiments from next week!**

Questions and Answers ?