Different types of material forming processes

By ablation

Sculpture

By deformation

Pottery

By addition

Building

Rapid Manufacturing / Additive processes

?

Eastern Macedonia and Thrace Institute of Technology

3D Printing

Principle : using a printhead.

Advantage :

- Can be used in engineering and design depts, in drawing offices, at home

Drawback :

- Fragile parts

Applications :

- Prototyping, design office

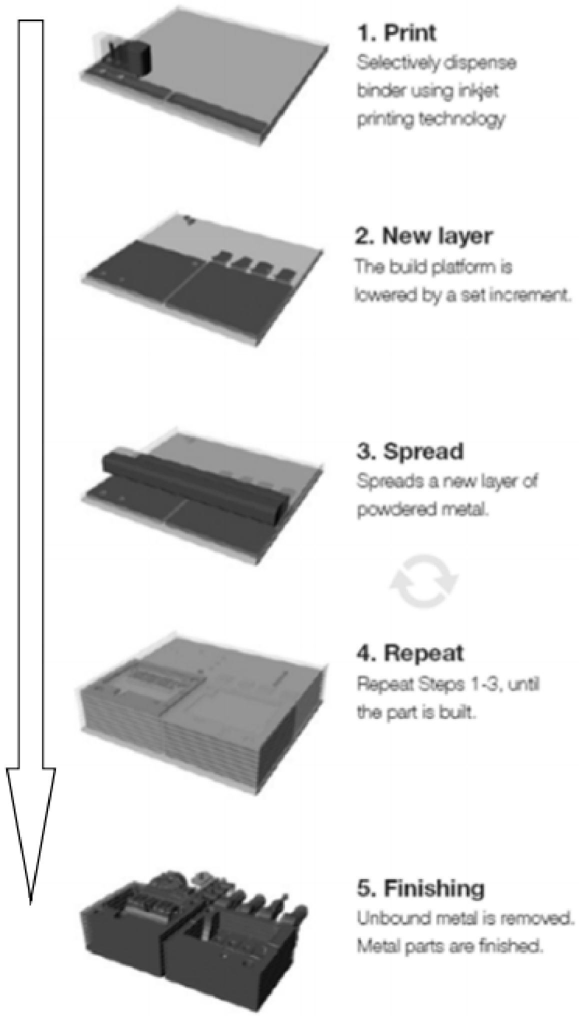
Materials :

- Light sensitive resins, epoxy
- Polymer melt
- Polymer binder on polymer, metal, sand, ceramic powders.

Some machine manufacturers :

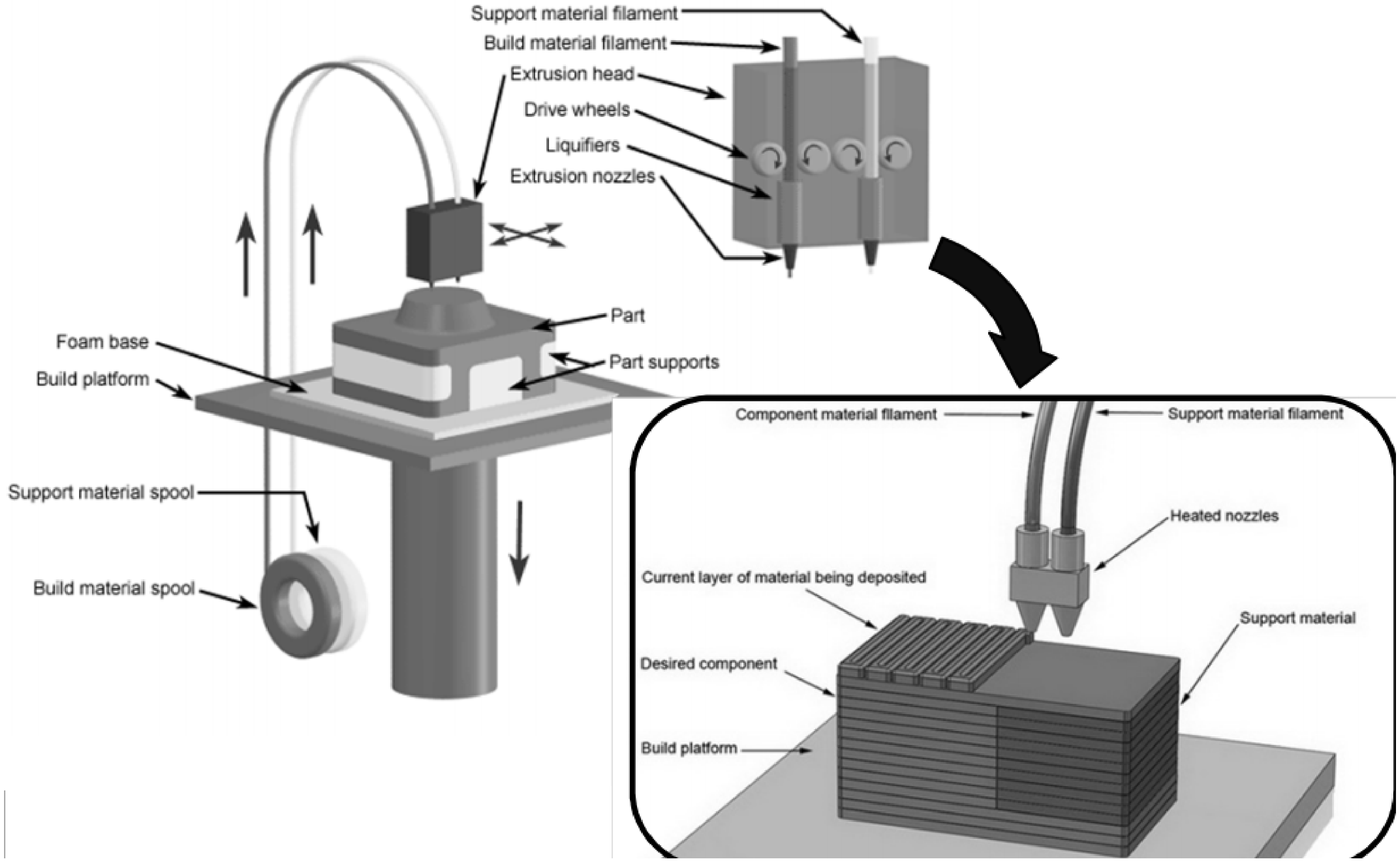
- Molten polymer thread: Stratasys
- Light sensitive systems : Objet
- Powder + binder system : Prometal.

Dimensions : up to 4 x 2 x 1 metres (Voxeljet, binder jetting)



EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

FUSED DEPOSITION MODELING (FDM)



Examples Fused Deposition Modelling (FDM)

Stratasys

EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

FUSED DEPOSITION MODELING (FDM)

Advantages :
- **Functional and flexible models.**
- **Soluble supports**
- **Simple system, possibility of desktop use.**
- **Non-toxic materials**

Machine manufacturer : Stratasys, USA

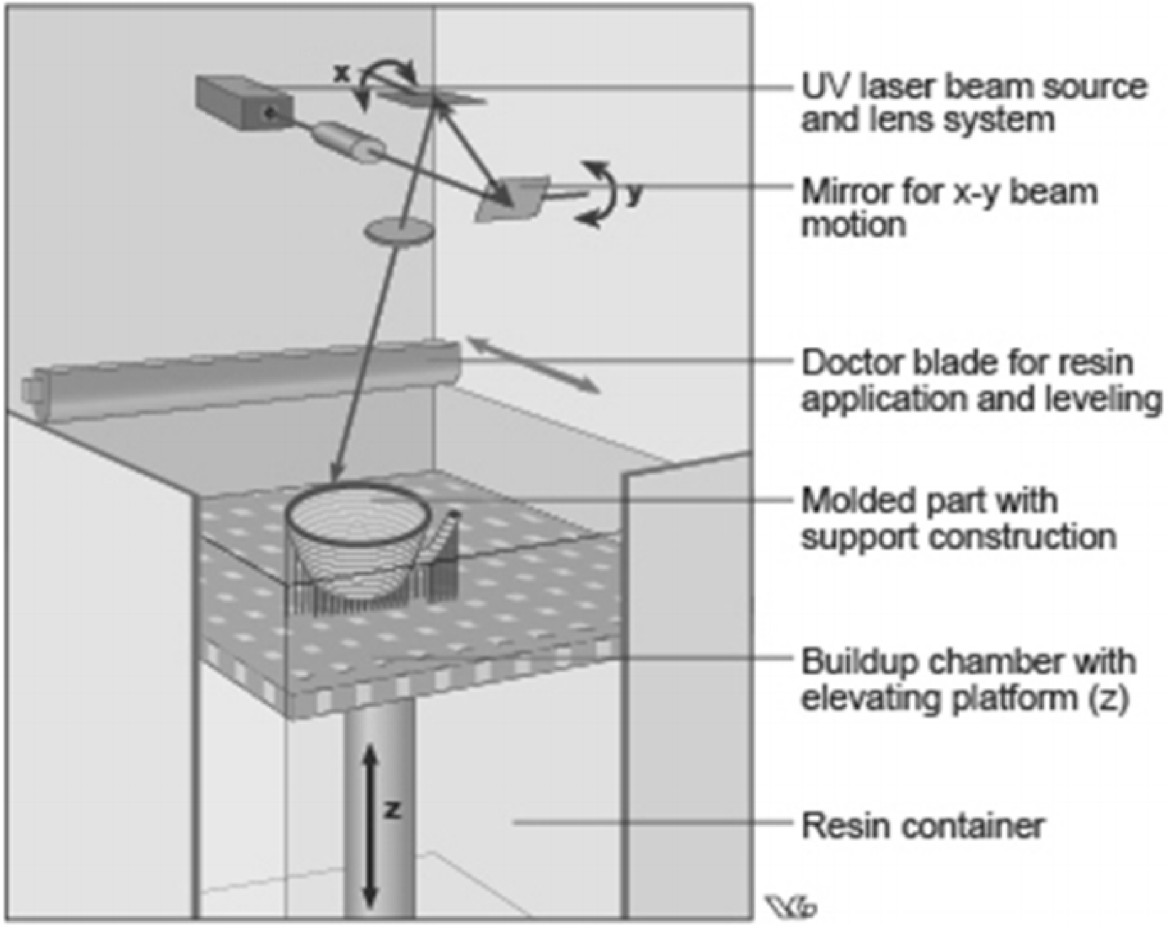
- Materials :
  - **ABS**
  - **Polycarbonate**
  - **PC-ABS**
  - **Elastomer**

Drawbacks :
- Extrudable materials only
- Layer thickness (0.2 mm mini) and wall thickness (0.3 mm mini)
- Precision : +/- 0.15 mm

EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

BINDER JETTING ON A POWDER

STEREOLITHOGRAPHY (SLA)

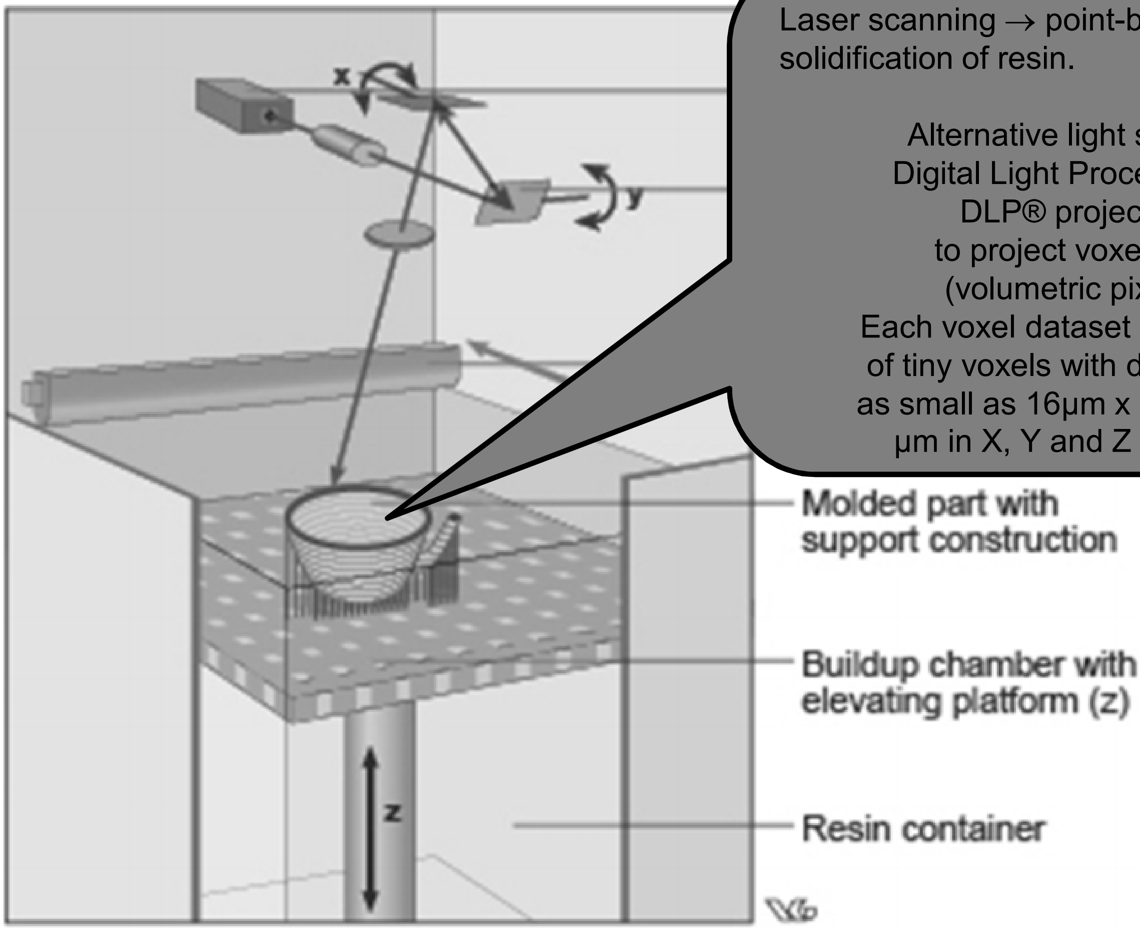


EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

STEREOLITHOGRAPHY (SLA)

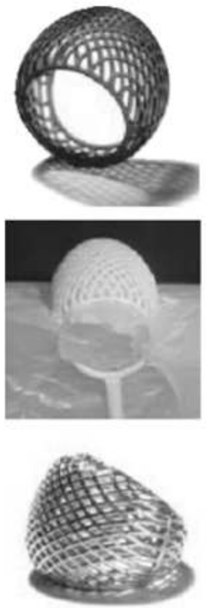
Laser scanning → point-by point solidification of resin.

Alternative light source :
Digital Light Processing or
DLP® projectors
to project voxel data
(volumetric pixels).
Each voxel dataset is made up
of tiny voxels with dimensions
as small as 16μm x 16 μm x 15
μm in X, Y and Z direction



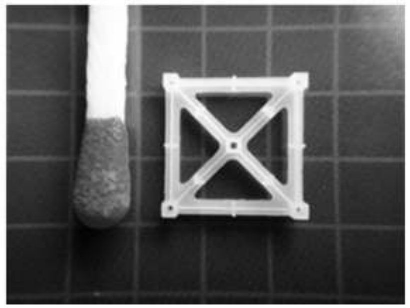
STEREOLITHOGRAPHY (SLA)

3D Systems



Envisiontec

Objet

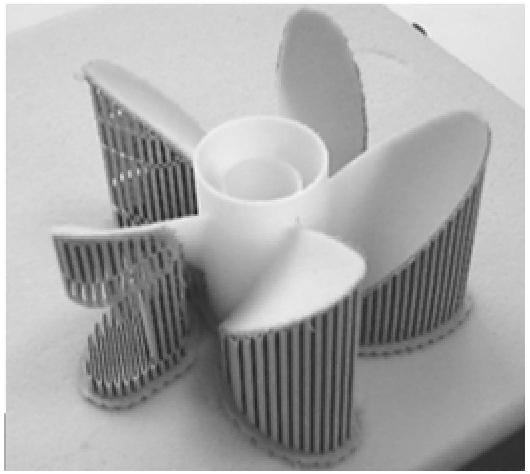


Examples of models for investment (« waste wax ») casting

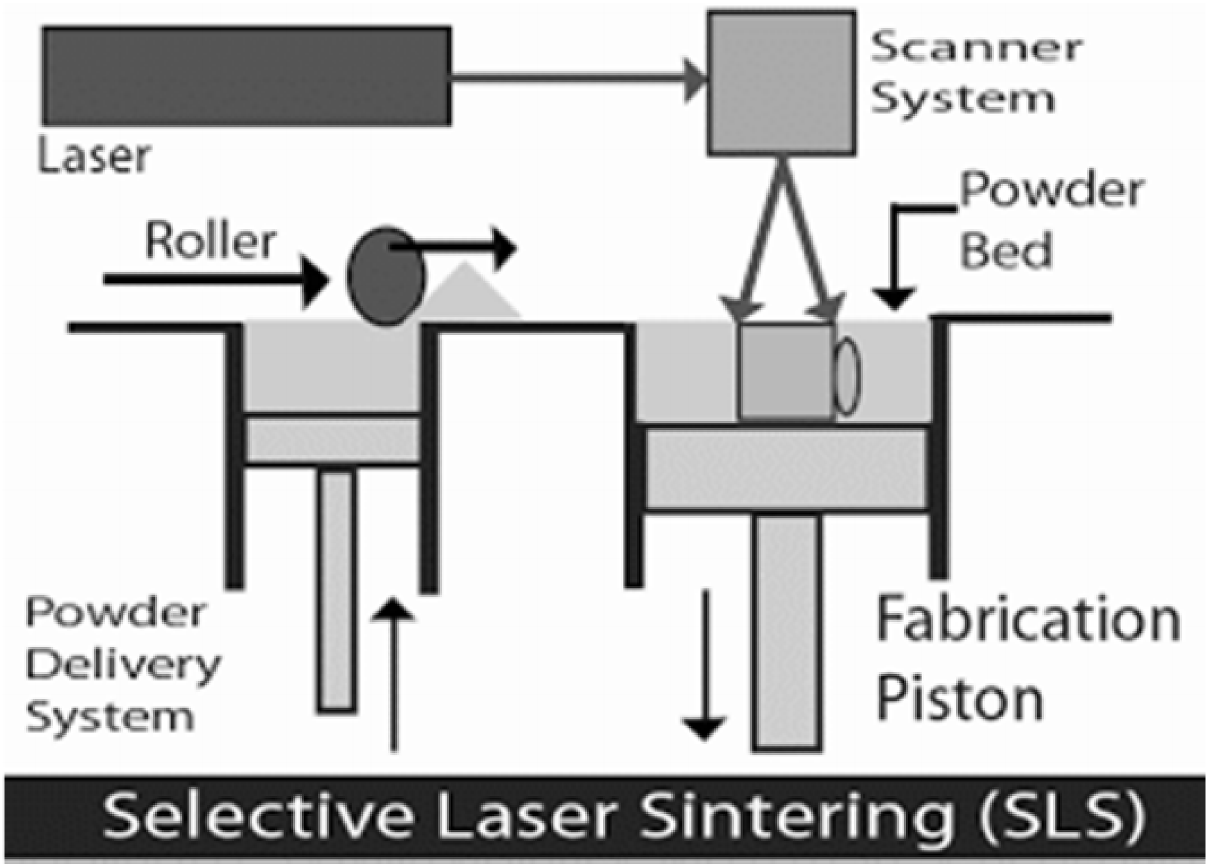
Eastern Macedonia and Thrace Institute of Technology

STEREOLITHOGRAPHY

- Materials :
  - light-sensitive epoxy resins .
  - UV-curable flexible or high-T°resins…
- Advantages :
  - + Surface aspect, precision (esp. DLP systems)
  - + Well-known, mature technology
  - + Large volume machines
  - + …
- Drawbacks :
  - Only light-sensitive resins
  - Supports necessary
  - Quite fragile parts, UV-sensitive
  - Uncontrolled shrinkage

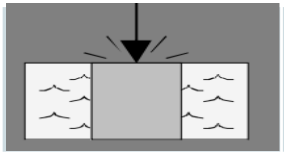
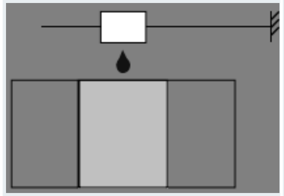
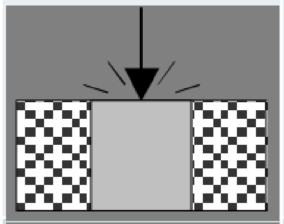
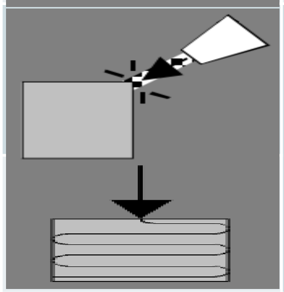


LASER SINTERING



Selective Laser Melting: equivalent of SLS for metal powders

Classification of additive processes

Materials to be transformed	Principles of transformation	Technologies	Acronyms	Pictures	Main groups
Photo-Sensitive resin	Photo Polymerizatio n	Laser of UV flashing	SLA STL DLP		Stereo lithography
		Printhead	Polyjet		3D printing
Powder: polymeric, metal, ceramic, sand	Binding	Printhead	3DP		
	Sintering/ fusion	Laser, IR flashing, or electron beam	SLS SLM DMLS EBM SMS		Laser Sintering /Melting
		Projection	DMD		Deposition
Polymer filament	Liquid State "welding"	Deposition	FDM		

Product Development: Context and Stakes

Industrial targets:

- Reduction of marketing times
- Decrease of costs
- Quality control(and standards)

Trends:

- Evolution towards small / medium size series, ma
customization, increased complexity
- Product lifetime
- Delocalization of large series manufacturing, of mouldmaking industry…
- Need for flexibility and reactivity of productio

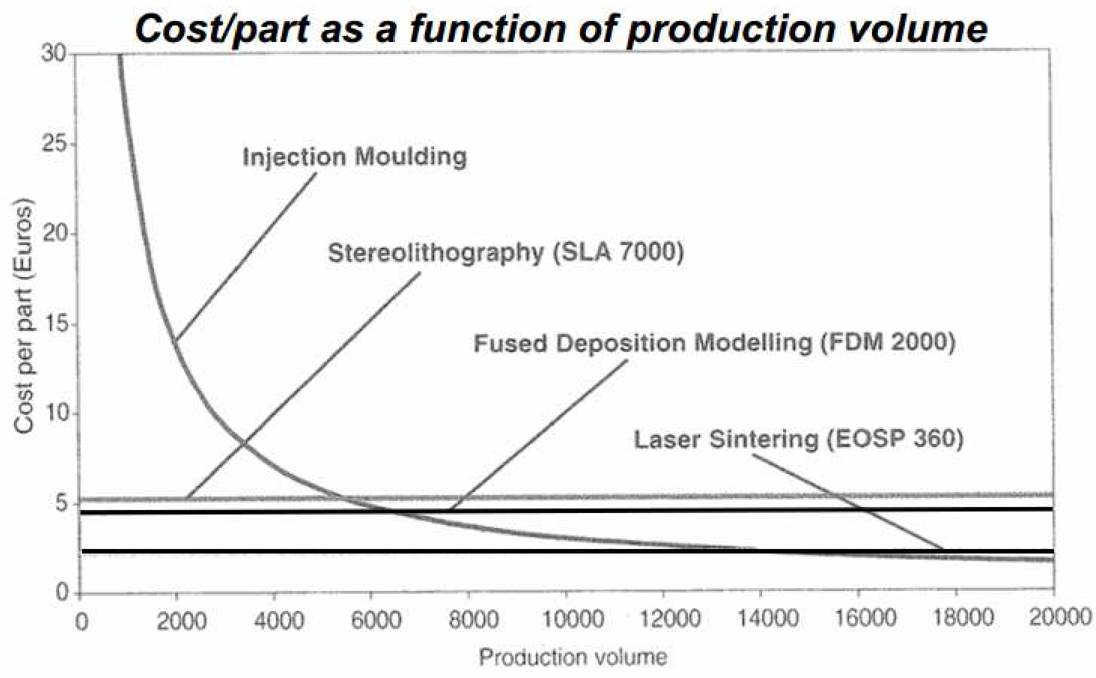
Important economical stakes

COMPARISON OF COSTS

- ⊕ **of Development**
- ✓ **Independent on part complexity**
- ✓ **Fast**
- ✓ **No specific tooling**

BUT:

- ✓ **Limited choice of materials**
- ✓ **Materials cost**
- ✓ **Production time**
- ✓ **…**



SLS : on the way to industrial production

Main current materials available :
Polyamide 11 or 12 : plain, filled : glass beads,
aluminium, carbon, and/or flame retardant
Polystyrene
PEEK (specific machine, 1 in Germany)

Main machine manufacturers :
EOS GmbH, 3D Systems.

Dimensions : 700 X 380 X 600

Laser Sintering

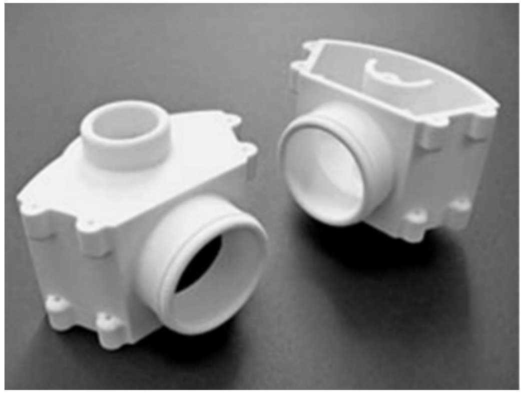
principle:
- Powder preheating below melting T°
- Spreading of powder layer
- Scanning with CO_2 laser (infra-red),
- Particles fusion and « sintering »
- Build tank going down by a layer thickness
- Next layer…

Advantages:
- Self-supporting powder
- Great freedom of shapes,
- Possible assembling and functional systems

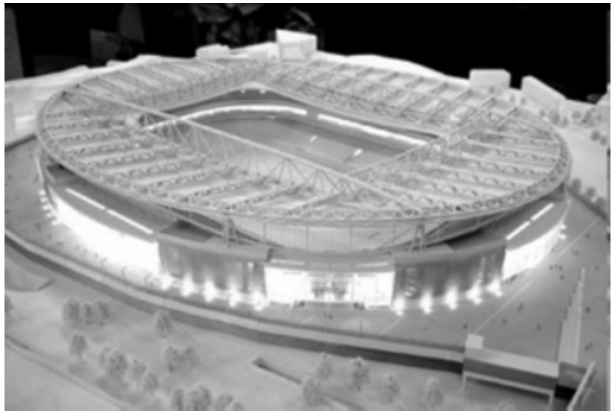
Drawbacks:
- Few commercial materials available
- Anisotropy of parts.
- Limited part size

Application field:
- Prototyping, direct part manufacturing, rapid manufacturing.

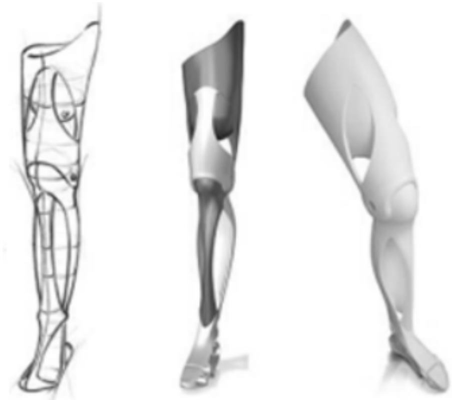
Laser Sintering Polymer



Helicopter part



Models



Prosthetics

Centrifug
e

Development of Additive Manufacturing

FDM machines at the production facility of RedEye on Demand, a business unit of Stratasys in Eden Prairie, Minnesota

EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

ADDITIVE MANUFACTURING PROCESSES FOR POLYMERIC MATERIALS FORMING

Part 2 : Selective sintering processes for polymer powders

- Analysis of SLS physical mechanisms
- Introducing SMS

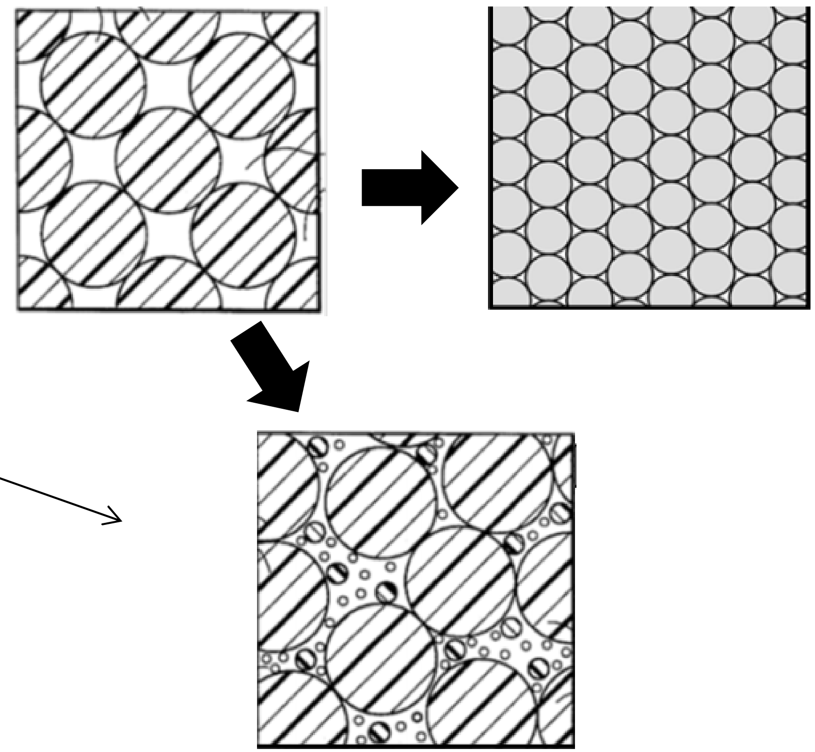
IDENTIFICATION OF THE KEY MATERIALS PARAMETERS

Prior to sintering, 2 conditions are very important for the process:

Powder **flowability**
Powder **bed density**

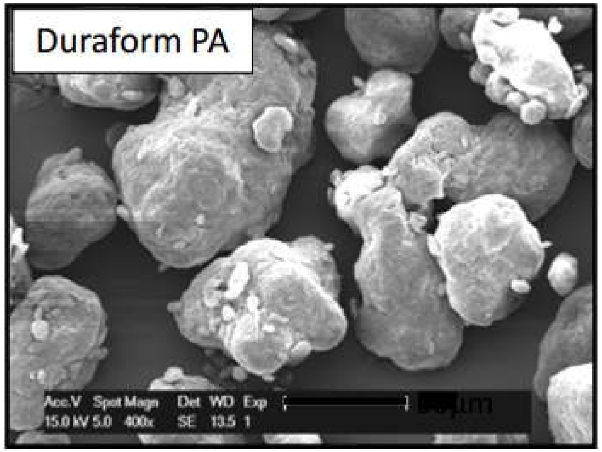
Main influent parameters

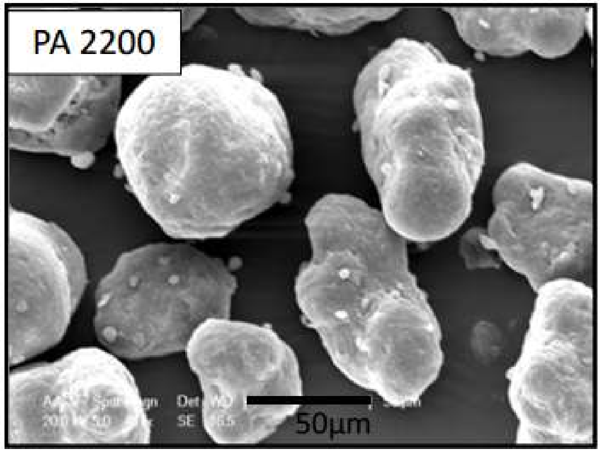
- Particle size
- Size distribution
- Sphericity



Eastern Macedonia and Thrace Institute of Technology

DIFFERENT POWDER MORPHOLOGIES





Main influent parameters

- Particle size
- Size distribution
- Sphericity

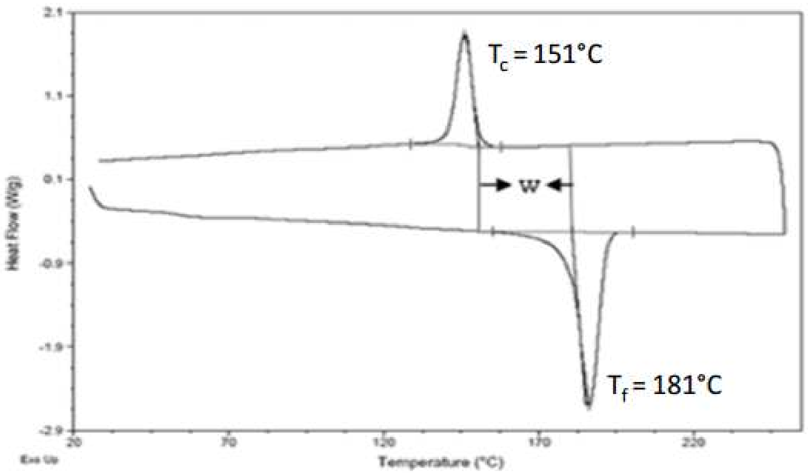
All of them need SiO_2 as flowability agent (< 1 wt%)

IDENTIFICATION OF THE KEY MATERIALS PARAMETERS

Sintering of semi-crystalline polymers

- *Warpage due to shinkage throughout the crystallization is a key issue*
  ➡ *Re-crystallization must be controlled*

Powder bed T° maintained in the ***processing window w : T_m - T_c***



➡ Part warpage(“curling”) avoided

Polyamide 12 mostly used thanks to very wide w range

MOST INFLUENT PROCESS PARAMETERS

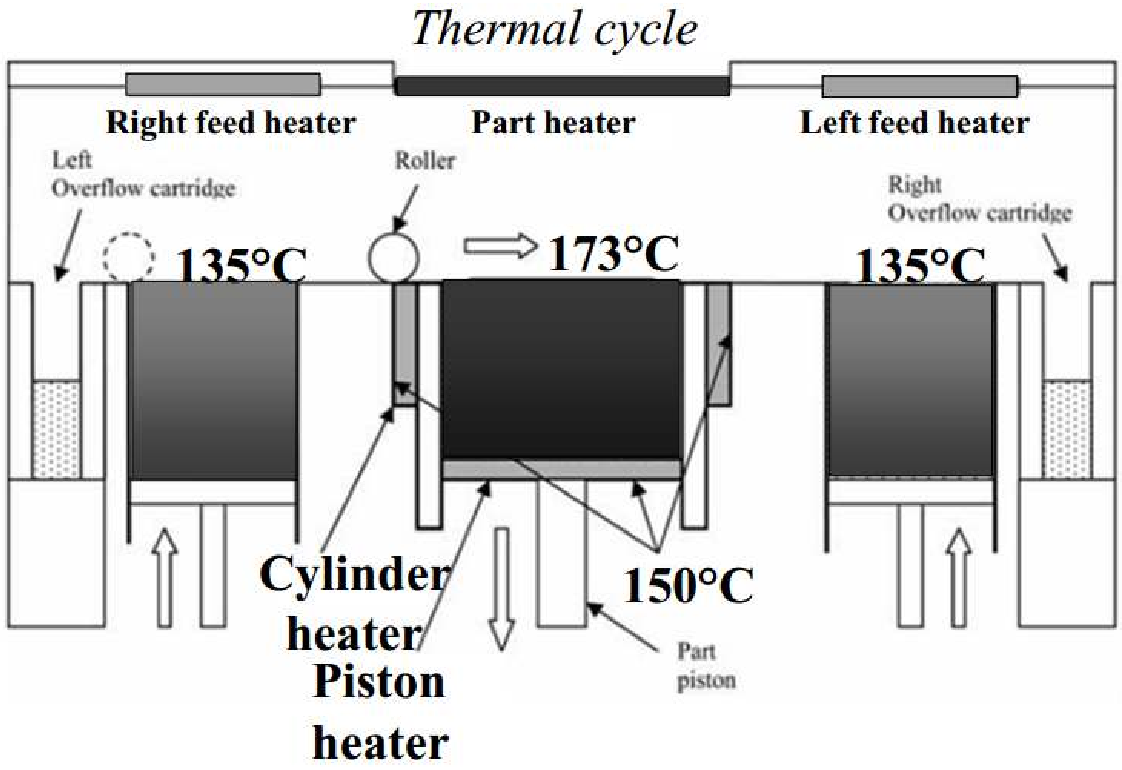
- *Process conditions of first order influence are :*

➡ *The heat provided to the powder during the whole fabrication cycle*

➡ *The energy provided to the polymer material by the laser*

EASTERN MACEDONIA AND THRACE INSTITUTE OF TECHNOLOGY

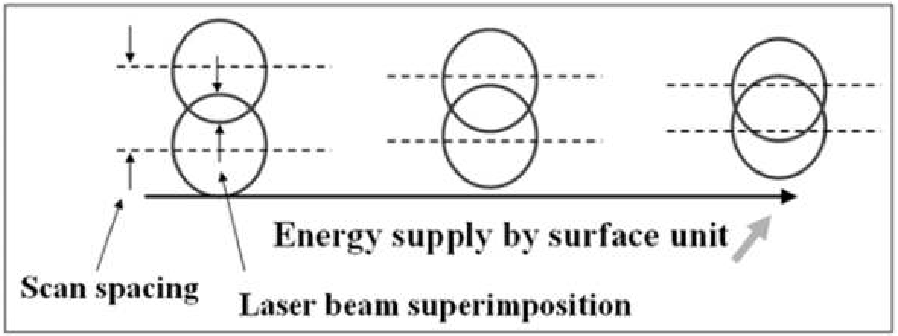
PROCESS PARAMETERS

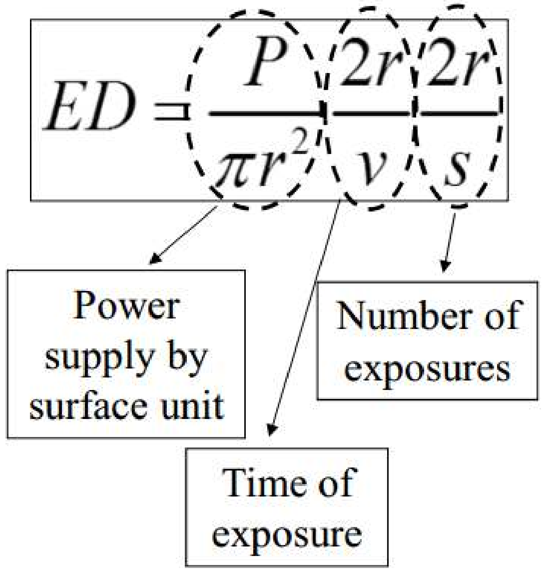


- **Different temperatures of preheating**

PROCESS PARAMETERS

Energy Density ED : a single parameter





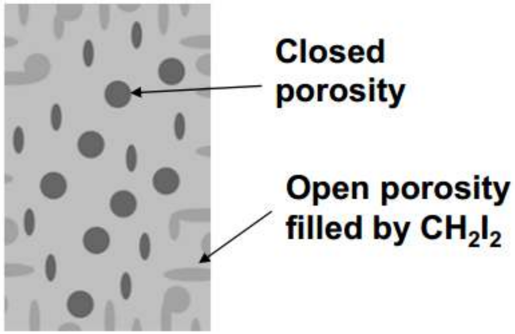
$$ED = \frac{P}{\pi r^2}\,\frac{2r}{v}\,\frac{2r}{s}$$

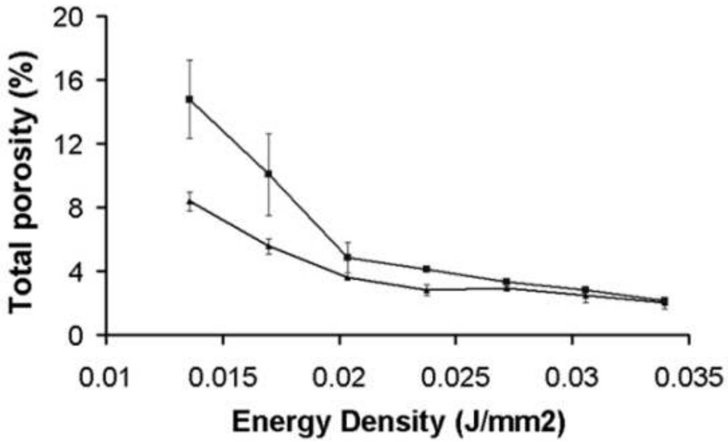
The energy supply depends on the:

- Scan spacing (S) via laser beam superimposition
- Laser beam celerity (v)
- Laser radius (r)
- Laser power (P)

CHARACTERIZATION OF MICROSTRUCTURE
1. POROSITY

- By application of Archimedes' principle on samples infiltrated with CH_2I_2
  → Calculation of open and closed porosities



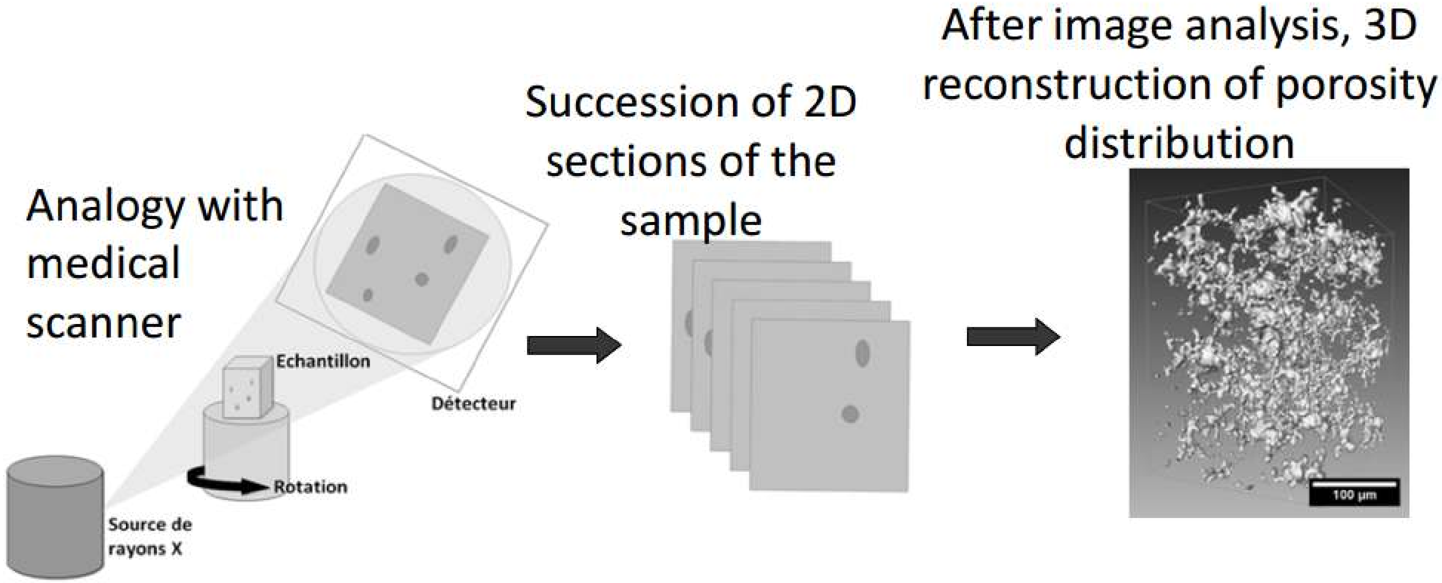


Evolution of the global porosity (vs. ED):

- Porosity decreases when ED increases
- Porosity reaches a minimum value about 2%

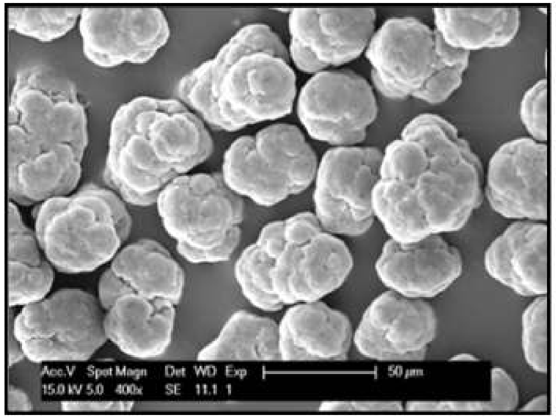
ENHANCED CHARACTERIZATION OF POROUS MICROSTRUCTUE

- By 3D X-Ray tomography



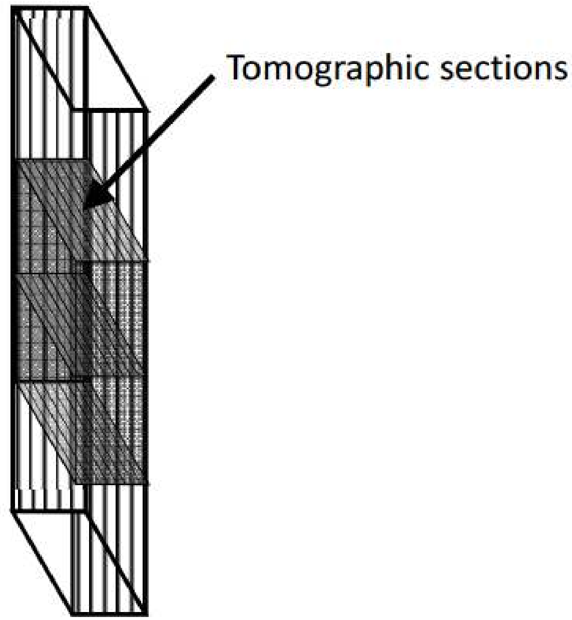
➡ Computation of closed porosity fraction, information on size and spatial distribution of pores

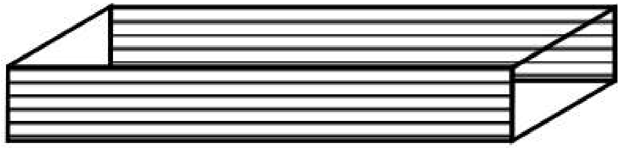
Eastern Macedonia and Thrace
Institute of Technology



Example for Innov PA powder

Characterization of porosity by Xray tomography





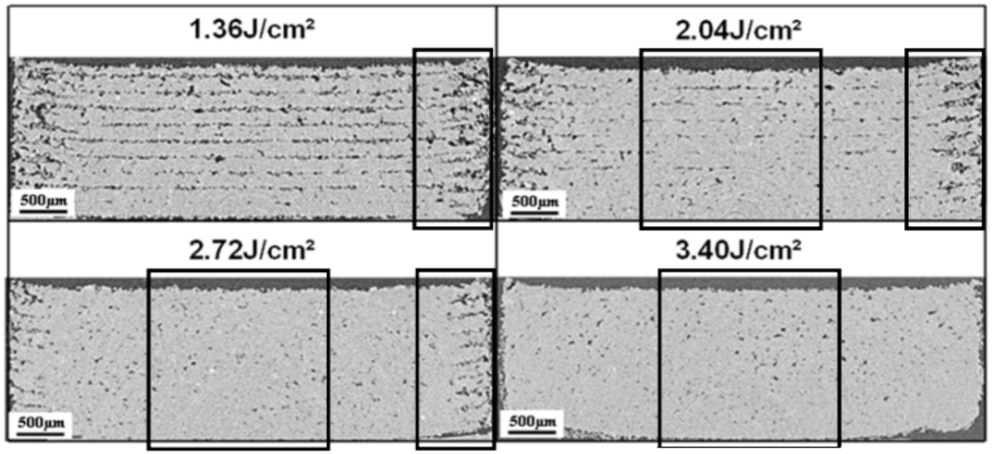
Position of the part in the build tank

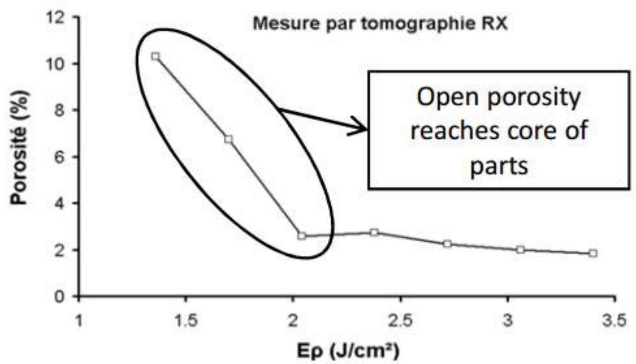
Position of the part during analysis

EASTERN MACEDONIA AND THRACE
INSTITUTE OF TECHNOLOGY

INFLUENCE OF ENERGY DENSITY ED ON POROSITY

<u>Example for Innov PA powder</u>

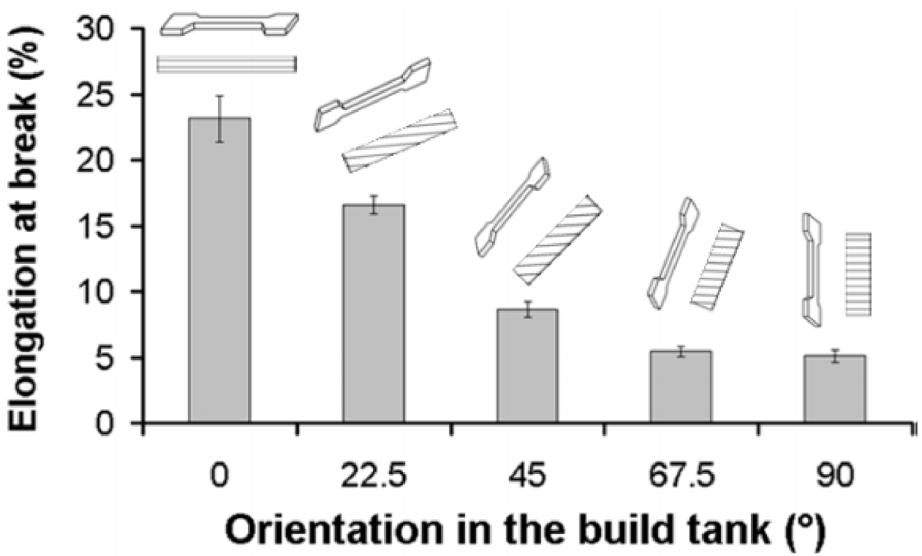




- LOW ED: bad welding between layers
- Observation of the 2 types of porosity: open and closed

INTERPRETATION OF PART ANISOTROPY

InnovPA parts, ED $=0.024\ J/mm^2$



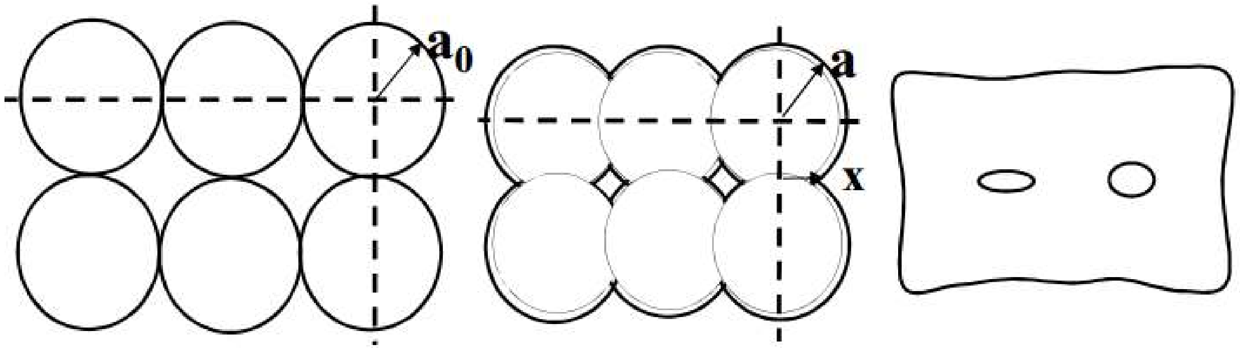
- Porosity is concentrated at the interface between successive layers
- This is mostly noticeable at low ED, but still present at high ED

➡ **Mechanical properties are anisotropic**

DENSIFICATION PARAMETERS

During sintering 2 stages occur : Coalescence and melt densification

- Evolution of the particles during coalescence : Frenkel's model



$$\frac{x}{a} = \left(\frac{3}{2}\frac{\Gamma t}{\eta a}\right)^{1/2}$$

With η : viscosity
Γ : surface tension

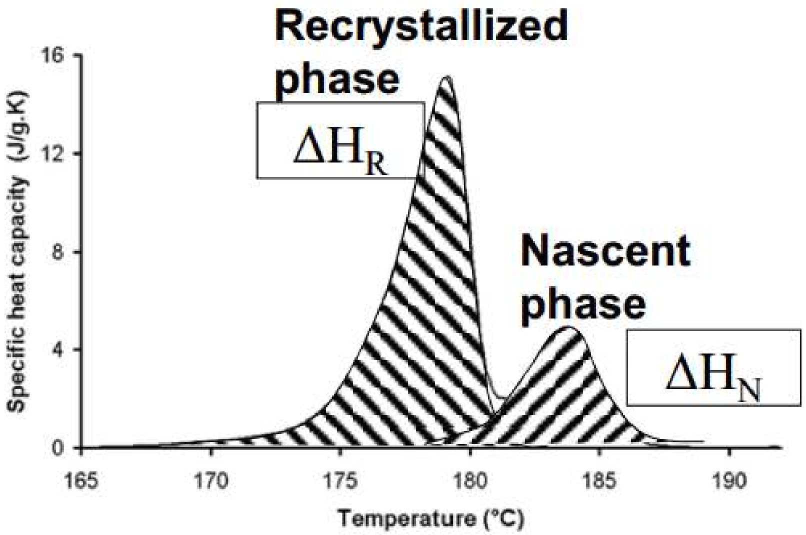
- Melt densification is due to diffusion/dissolution ofgases from pores

➡ **Final microstructure is governed by:**

- ❑ Granular characteristics which impact powder bed density
- ❑ Melt viscosity
- ❑ Crystallization temperature (and build tank T°during proce ss)

CHARACTERIZATION OF MICROSTRUCTURE – 2) CRYSTAL WEIGHT FRACTION AND RECRYSTALLIZED PHASE

DSC shows the presence of both recrystallized and nascent fractions



Recrystallised fraction (fr) can be calculated by a deconvolution method:

Source: D. Jauffres et al, Polymer 48, 6375-6383, 2007

$$fr = \frac{\Delta H_R X_{CN}}{\Delta H_R X_{CN} + \Delta H_N X_{CR}}$$

With ΔH_R: recrystallized phase enthalpy of fusion

ΔH_N: nascent phase enthalpy

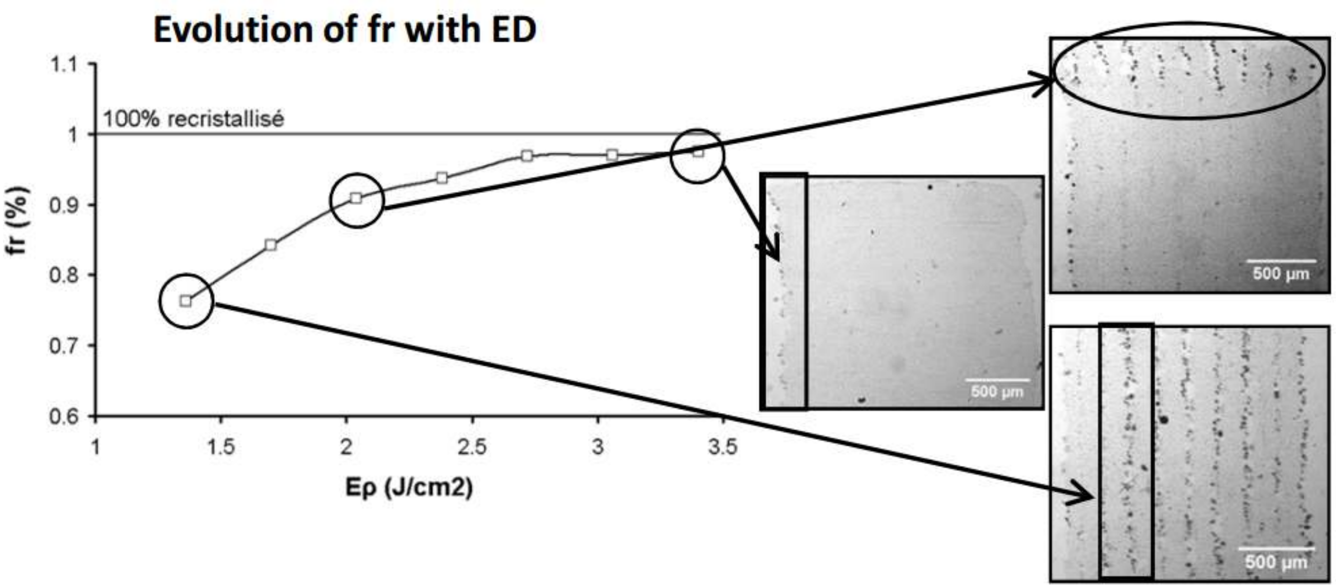
X_{CN}: nascent crystal weight fraction (50%)

X_{CR}: recrystallized phase crystal weight fraction (30%)

Objective:

measure the evolution of fr and Xc with ED

INFLUENCE OF THE ENERGY PROVIDED BY THE LASER ON PARTICLE MELTING AND CONSOLIDATION



- Strong increase of f_r up to $\approx 2.5\ J/cm^2$ then stabilizes
- Occurrence of nascent particles between successive layers
- From ED $\approx 2\ J/cm^2$, no more nascent particles in the core of parts, but still present at the surface

INFLUENCE OF THE PROCESSING WINDOW

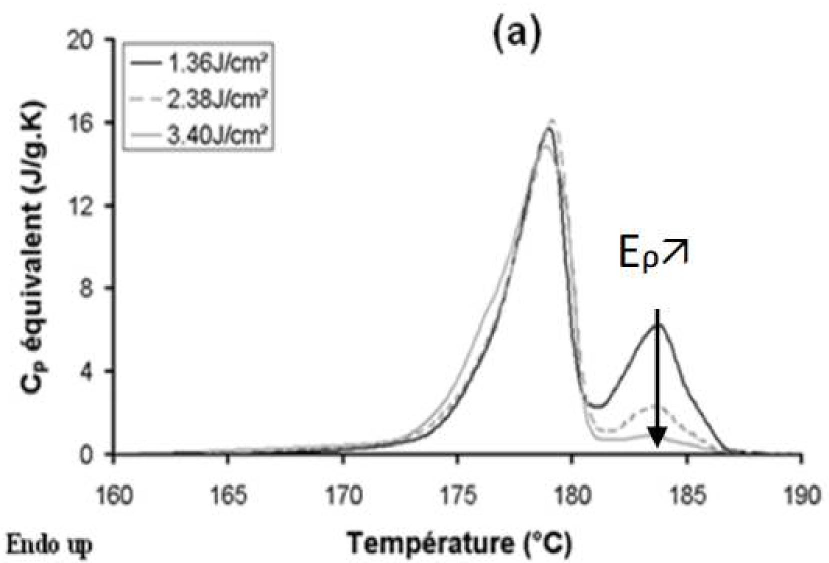
Comparison between InnovPA and DuraformPA

Build tank $T^o = 150^oC$
Crystallization T^o measured by DSC at $10^0C/min$:
Innov PA $Tc = 151^oC$ / Duraform PA $Tc = 147^oC$

Crystalline fraction measured by DSC:

► X_c ↓ when ED ↗

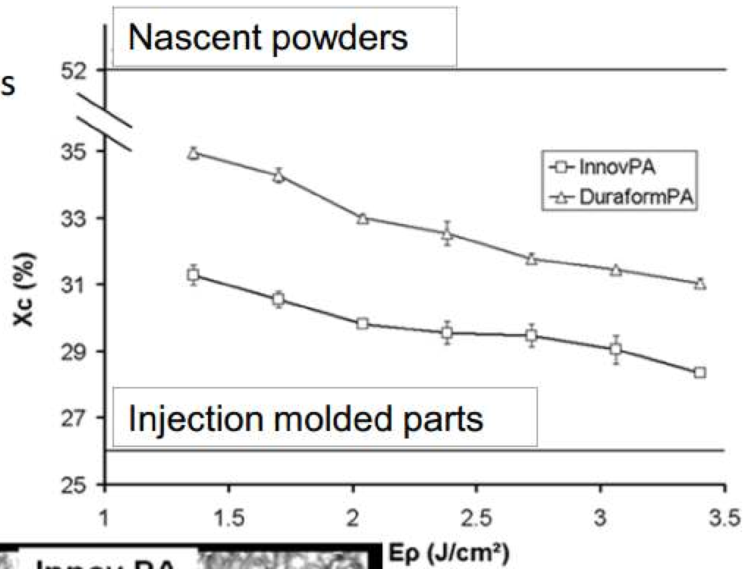
because more nascent polymer is melted



Comparison between InnovPA and DuraformPA

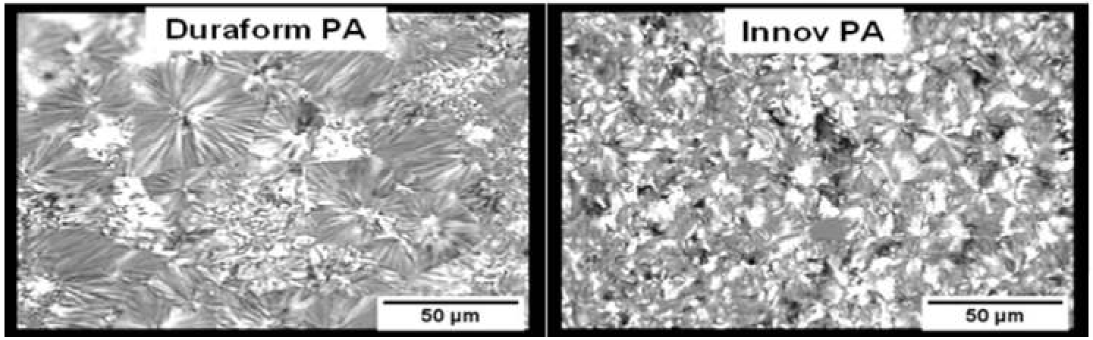
Build tank $T^o = 150^oC$
Crystallization T^o measured by DSC at $10^0C/min$:
Innov PA $Tc = 151^oC$ / Duraform PA $Tc = 147^oC$

▶ X_c lower for Innov PA samples



lower T_c for Duraform PA

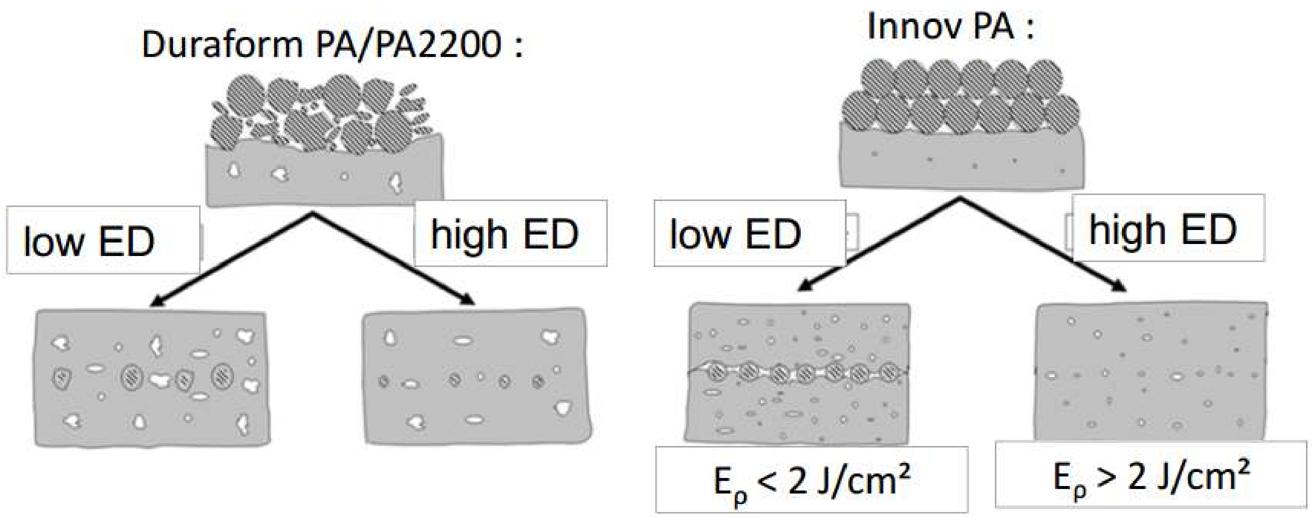
→ slower crystallization, larger crystalline ratio



Eastern Macedonia and Thrace Institute of Technology

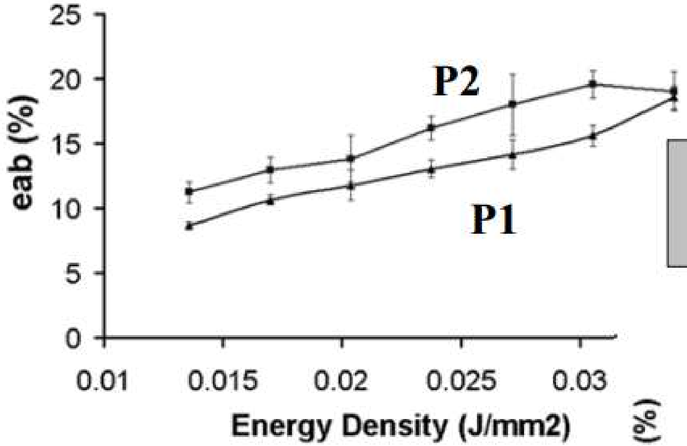
CONCLUSION ON FORMATION OF POROUS AND CRYSTALLINE MICROSTRUCTURE

- Powder bed density (granulometry and morphology of powders)
  ➡ strong impact on porosity formation
- Time spent in molten state (also depends on T° of build tank)
  ➡ strong influence on porosity and on final crystalline microstructure



Porosity can be also influenced by viscosity (coalescence)

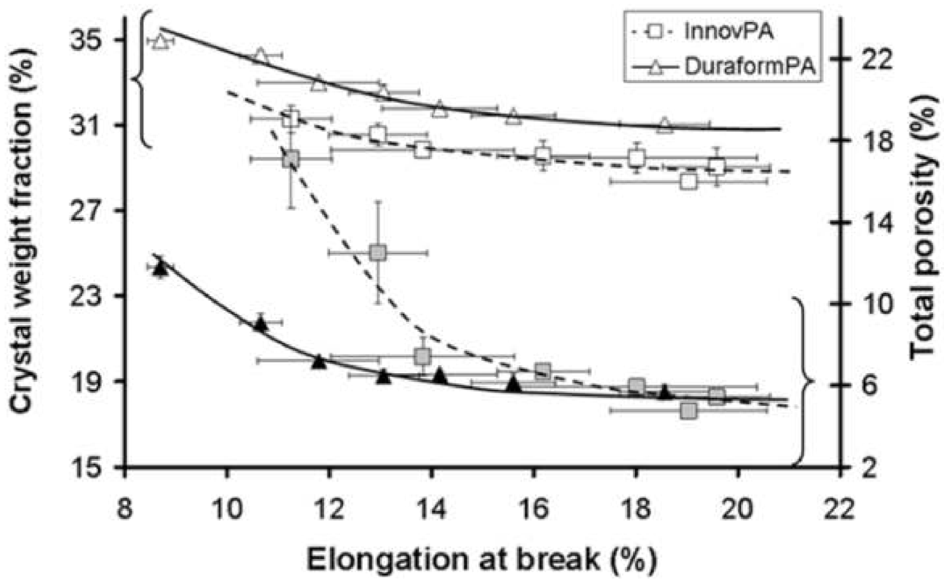
RELATIONS BETWEEN MECHANICAL PROPERTIES (TENSILE) AND MICROSTRUCTURE



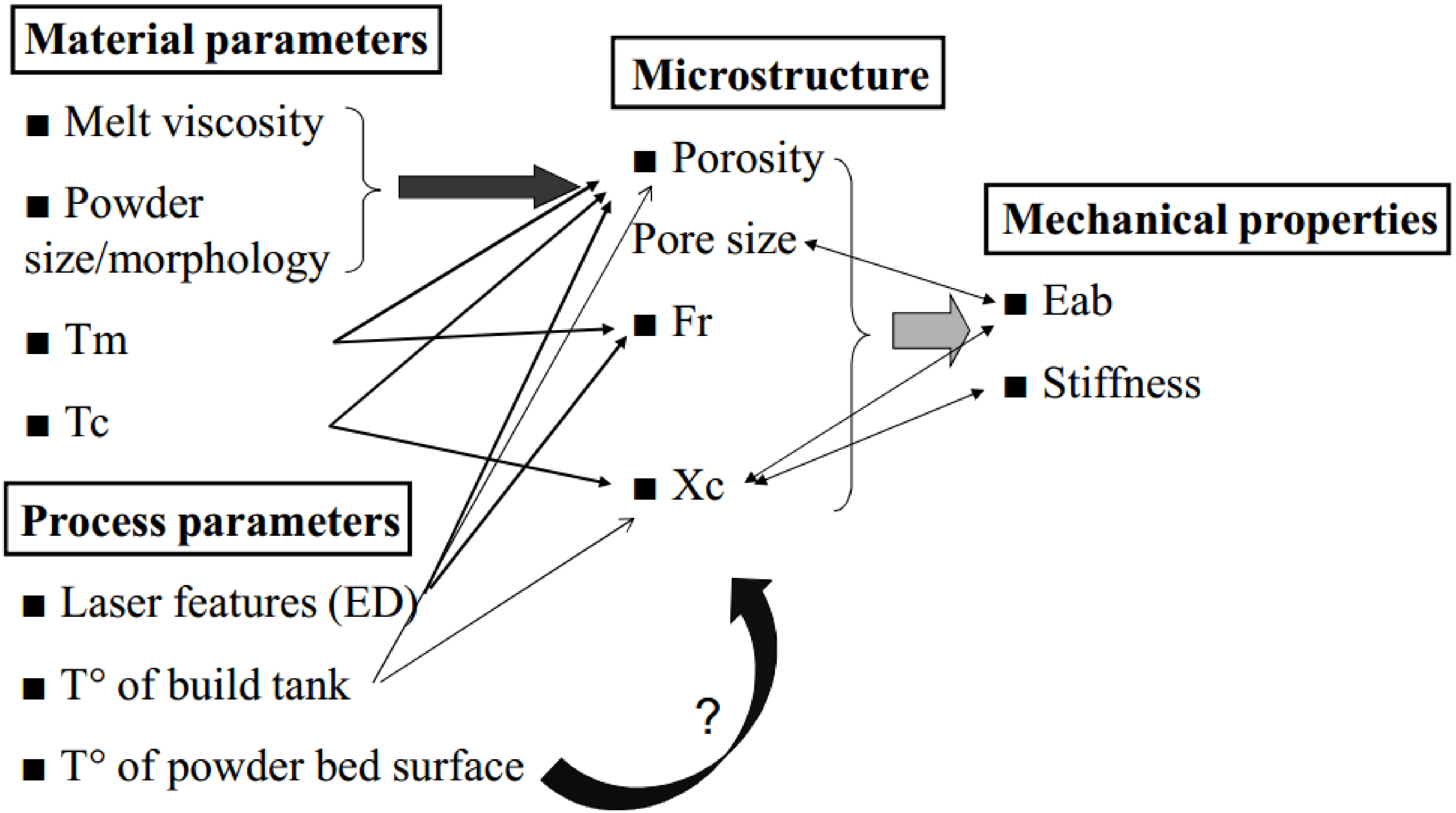
General trend : when ED ↗ , ductility ↗ because Xc ↘

But relations are more complex

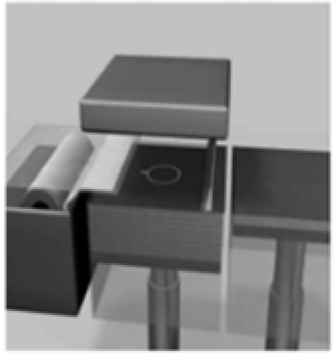
Elongation at break is one of the most critical features of sintered polymer parts



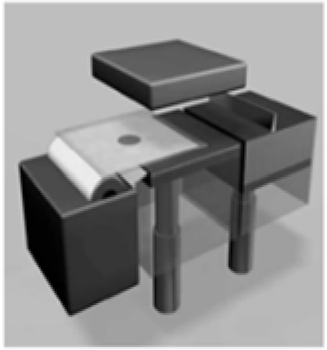
CONCLUSION


Material parameters
■ Melt viscosity
■ Powder size/morphology
■ Tm
■ Tc
Process parameters
■ Laser features (ED)
■ T° of build tank
■ T° of powder bed surface
Microstructure
■ Porosity
Pore size
■ Fr
■ Xc
?
Mechanical properties
■ Eab
■ Stiffness

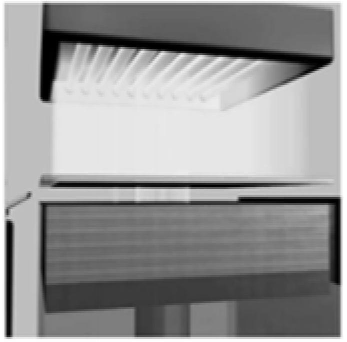
SMS – Selective Mask Sintering by IR flashing



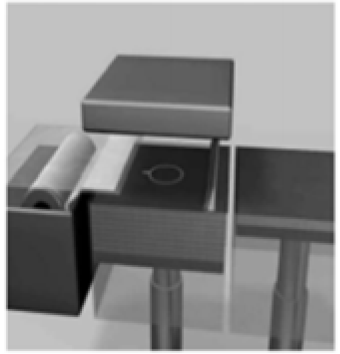
powder spreading



printing



flashing

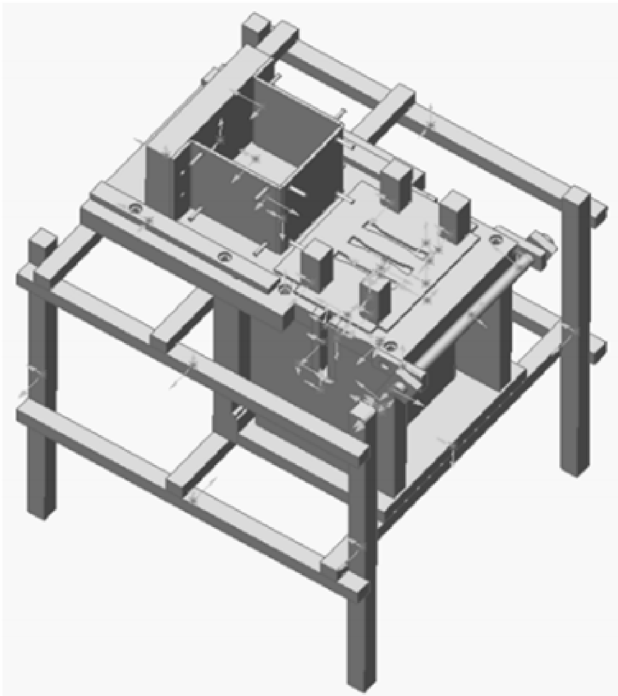


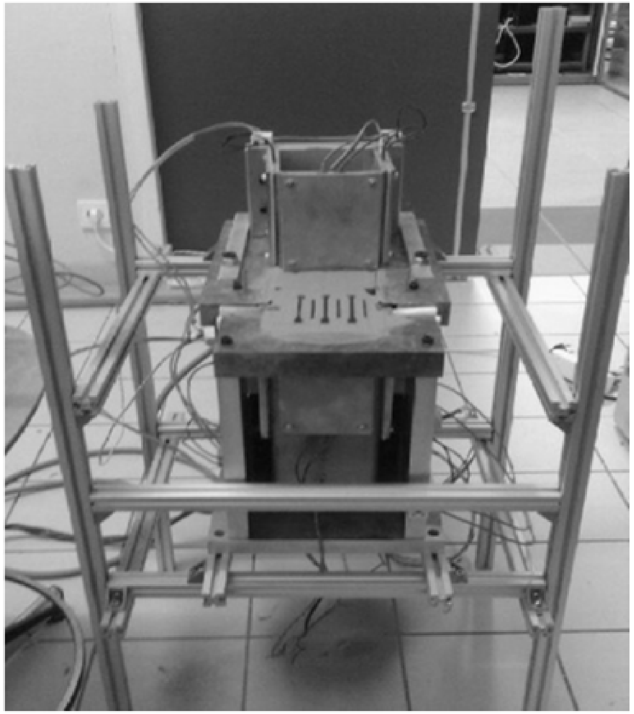
repeat cycle

Principles of sintering by IR flashing through a mask
Patent owned by Sintermask GmbH, Parsberg, Germany

- Each section (slice) is sintered as a whole by IR flashing through a mask which is regenerated for each layer
- Potentially faster than SLS
- Size part less limited
- Present technological issue : mask generation
- Process still in development

SMS-IR flashing :
Lab-built prototype machine at INSA



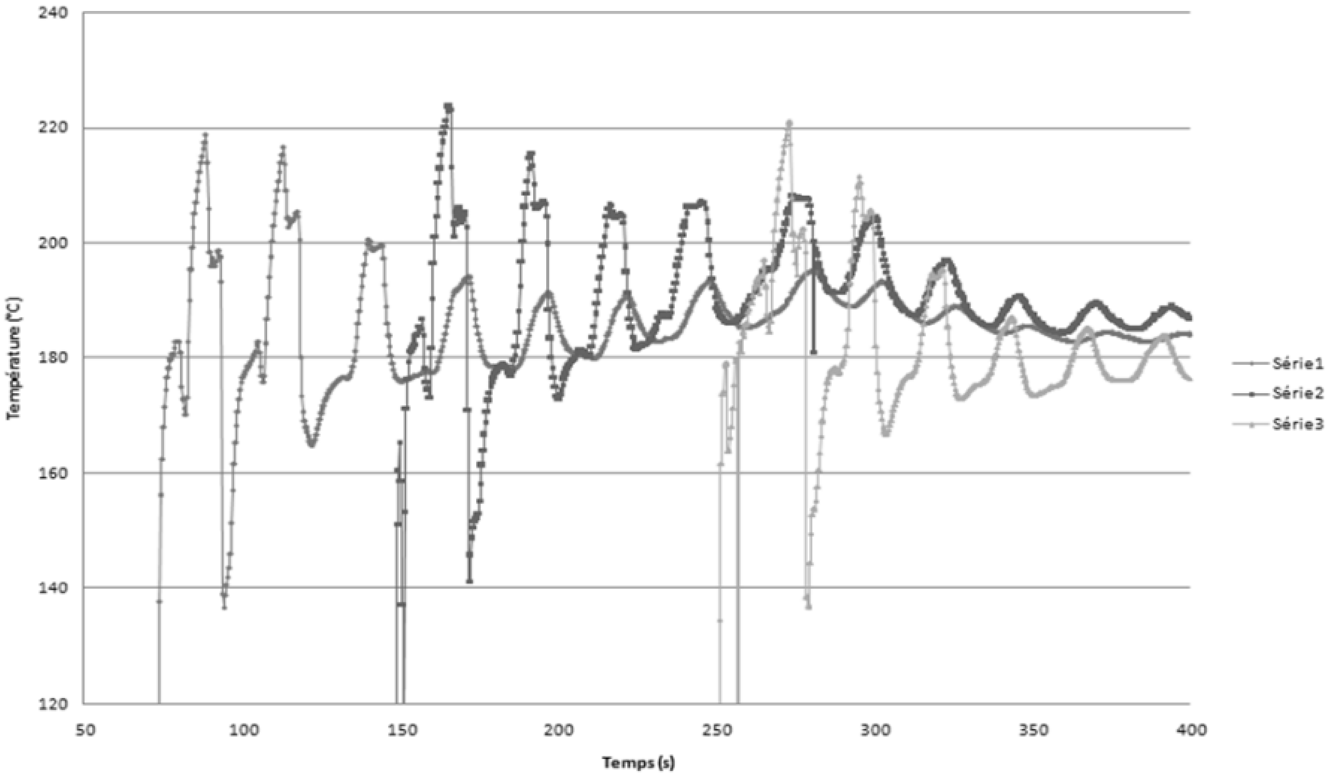


- Manually operated, but automatization in project
- Can be equipped with thermocouples for T° monitoring during sintering

EASTERN MACEDONIA AND THRACE INSTITUTE OF TECHNOLOGY

Temperature monitoring in lab-IR machine (here 3 thermocouples inserted)

Comparison with numerical simulation



Some features of polymer sintering processes

A few orders of magnitude :

Maximum build velocities : SLS : ~ 25 mm/h (small area)
IR-SMS : 35 mm/h , 10 to 20 s / layer, 5s target

Cooling time ~ fabrication time
Nb of powder re-uses : ~ 7 times, mixed with « fresher »powder (e.g. 50% from feed tanks, 50% from build tank, or 75% used + 25% fresh)

Layer thickness : ~ 100 µm
Minimum wall thickness : ~ 300 – 500 µm

Diameter of laser beam : 250 µm

Material cost : 50 - 150 Euros/kg