Additive Manufacturing

S. Kenzari, D. Bonina, J-M. Dubois, V. Fournée

IJL – Institut Jean Lamour – UMR 7198
Matériaux-Métallurgie-Nanosciences-Plasmas-Surfaces

Parc de Saurupt, 54011 Nancy, France

samuel.kenzari@ijl.nancy-universite.fr

Outline

- **Additive Manufacturing:**
  Selective laser Sintering process (SLS)
- **Materials for SLS**
  Indirect fabrication or direct fabrication
- **CMAs as alternative materials**
- **Perspectives**

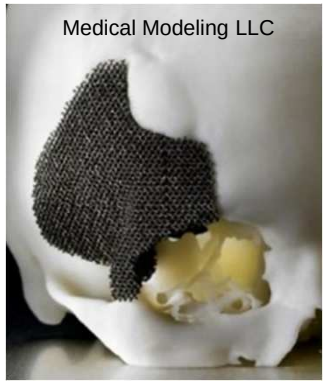
Additive Manufacturing

➢ Automatic **freeform fabrication** of physical **objects** (metals, plastics or composite materials) using **additive manufacturing technology**

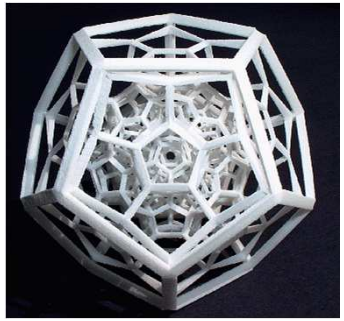
Additive Manufacturing

- Automatic **freeform fabrication** of physical **objects** (metals, plastics or composite materials) using **additive manufacturing technology**

- **Examples of freeform parts**



Ti-based implant



Polyamide

Bulatov's collection

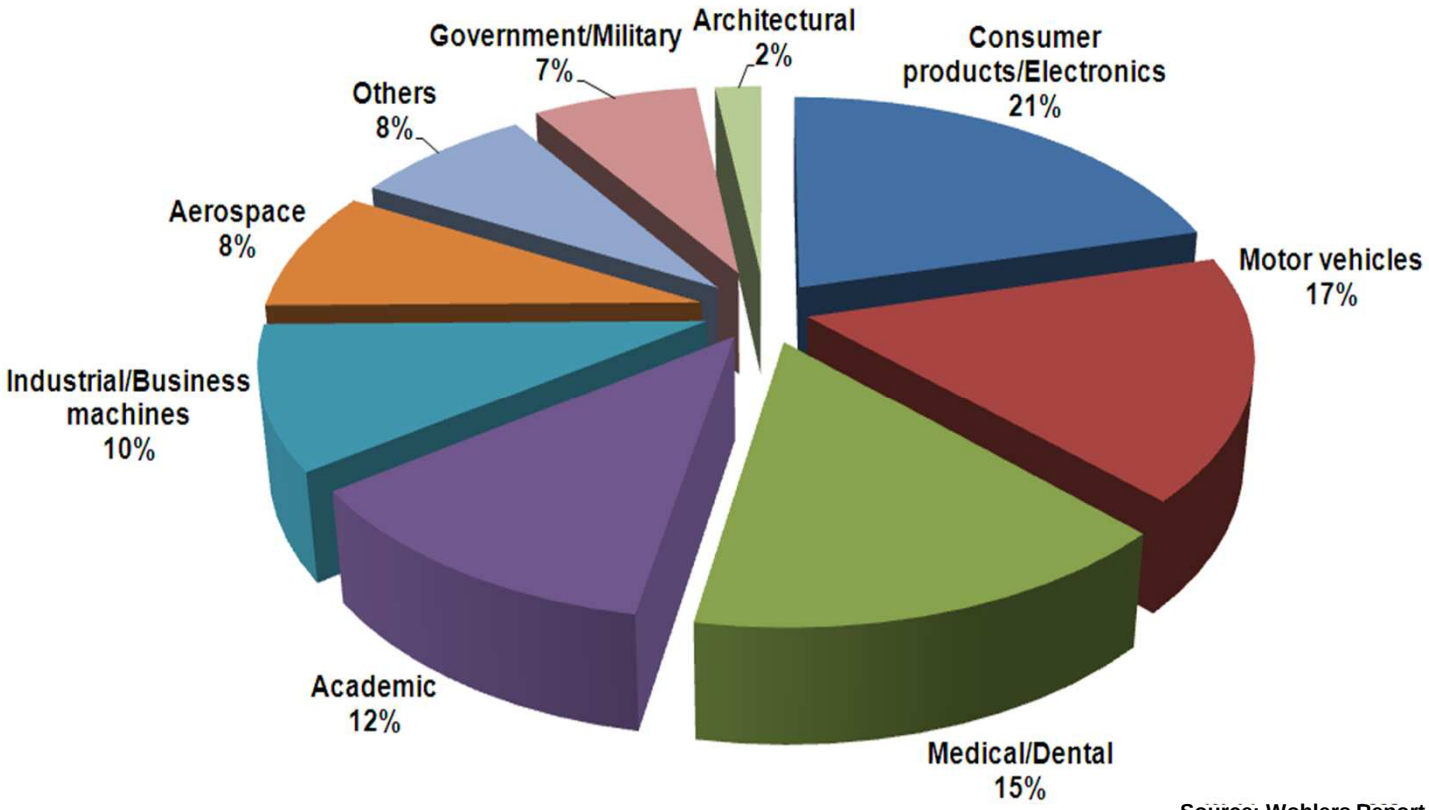
Steel/bronze composite

knee implant (CoCr alloy)

Polyamide based composite

Additive Manufacturing

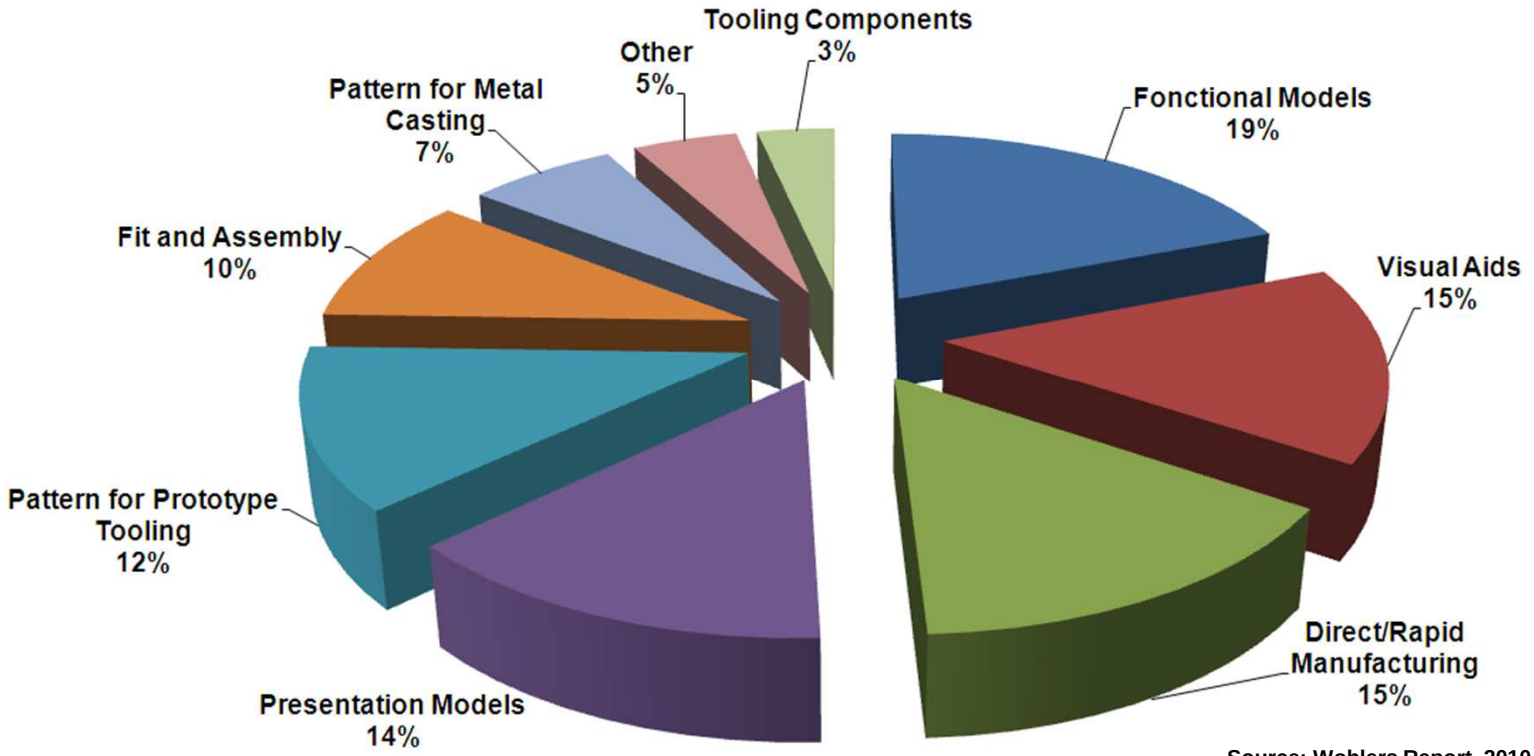
- Automatic **freeform fabrication** of physical **objects** (metals, plastics or composite materials) using **additive manufacturing technology**
- **Additive manufacturing worldwide by activities:**



Source: Wohlers Report 2010

Additive Manufacturing

- Automatic **freeform fabrication** of physical **objects** (metals, plastics or composite materials) using **additive manufacturing technology**
- **Additive manufacturing worldwide by activities:**
- **Additive manufacturing worldwide by utilizations:**

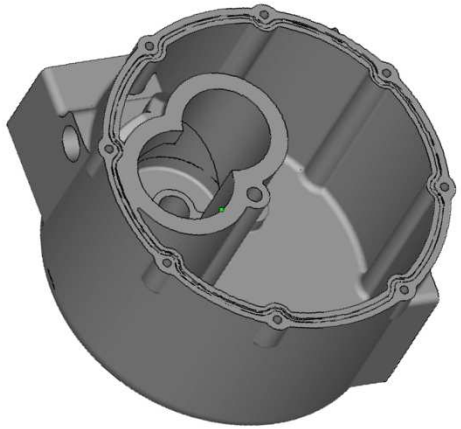


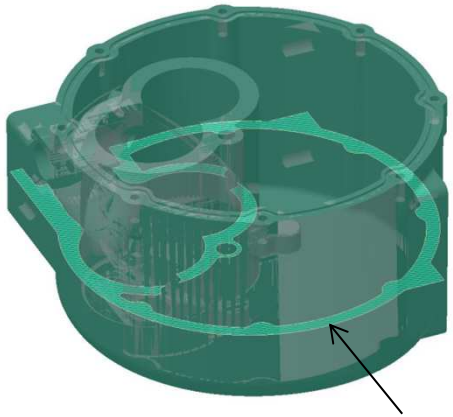
Source: Wohlers Report 2010

Selective Laser Sintering (SLS)

- **Powder based method**
- **Fabrication of freeform shaped parts**

3D CAD model (STL file format)



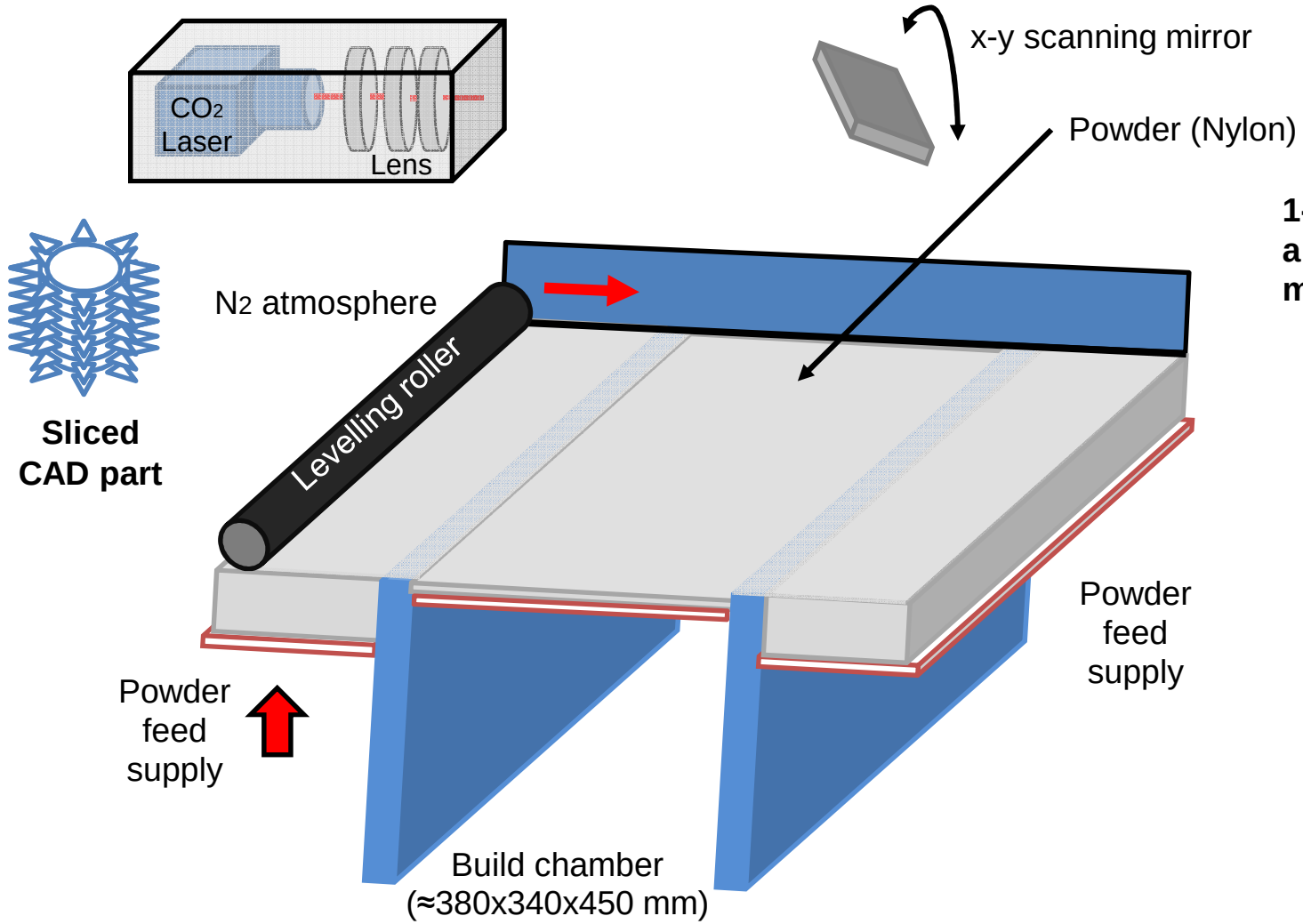


Cross-section

Selective laser sintered part (SLS part)

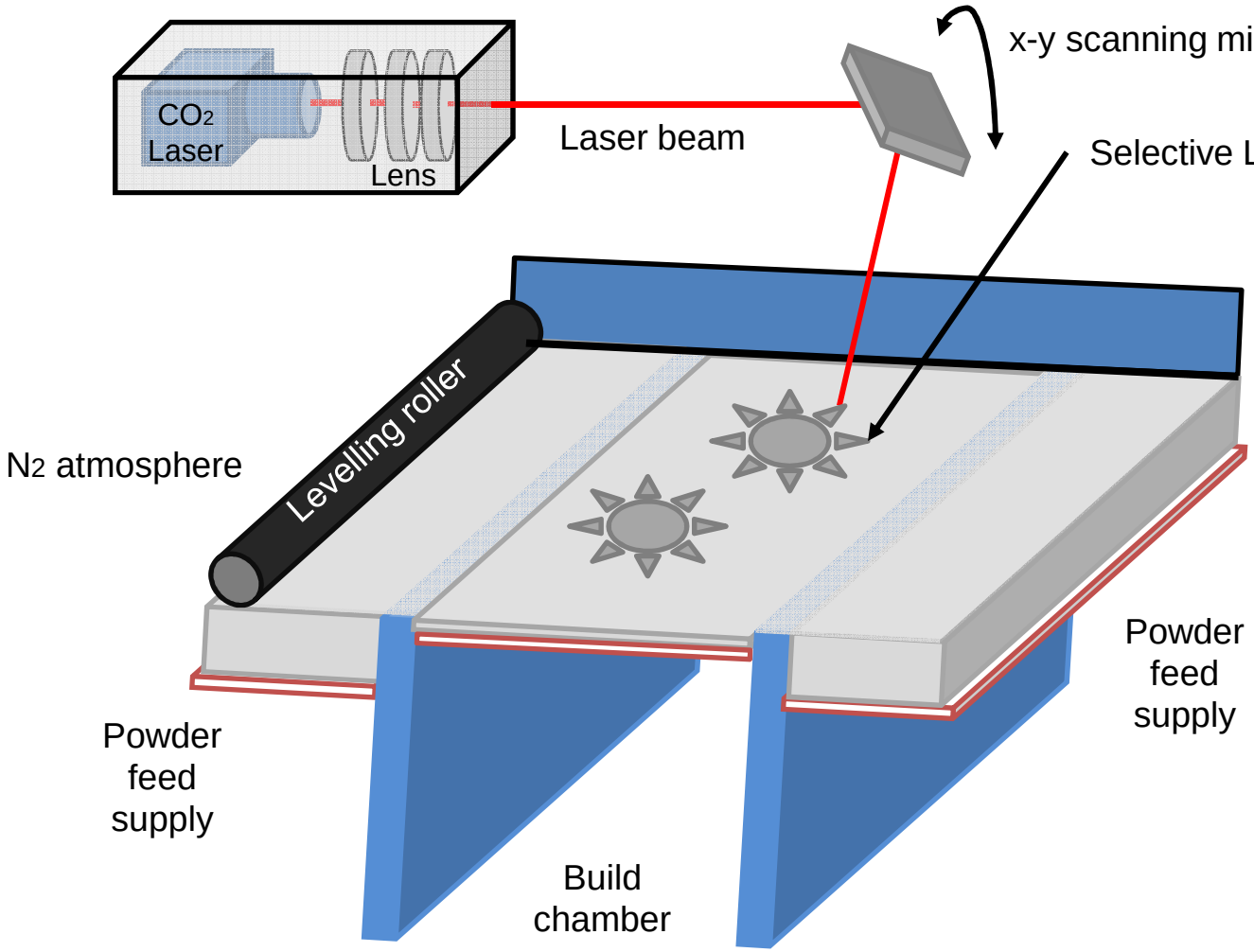
- **Additive layer manufacturing process**

SLS: How does it work ?
Layer by layer manufacturing



1- Powders are heated a few °C below its first melting point (175°C)

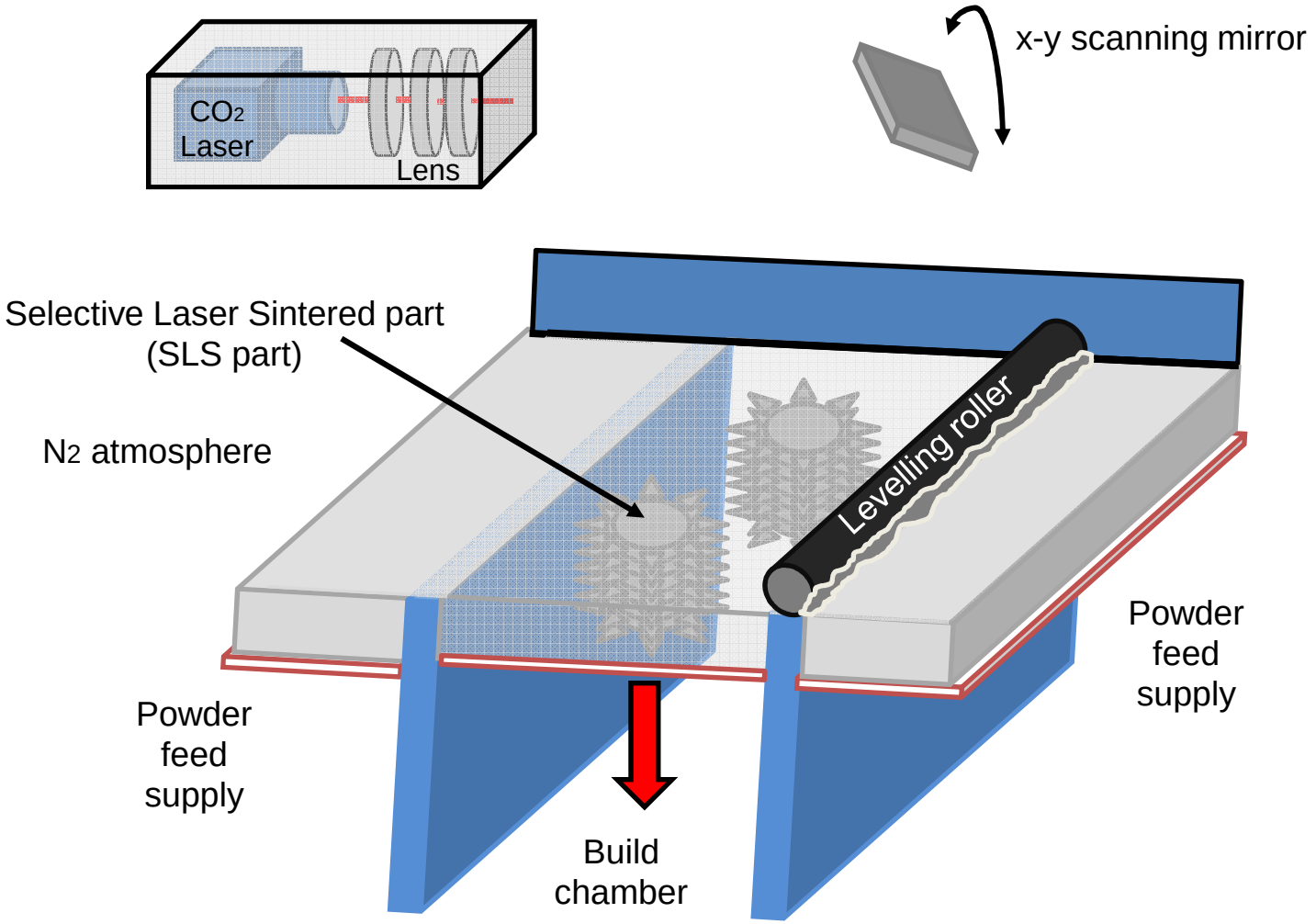
SLS: How does it work ?
Layer by layer manufacturing



1- Powders are heated a few °C below its first melting point

2- Laser brings just enough energy to melt the nylon

SLS: How does it work ?
Layer by layer manufacturing

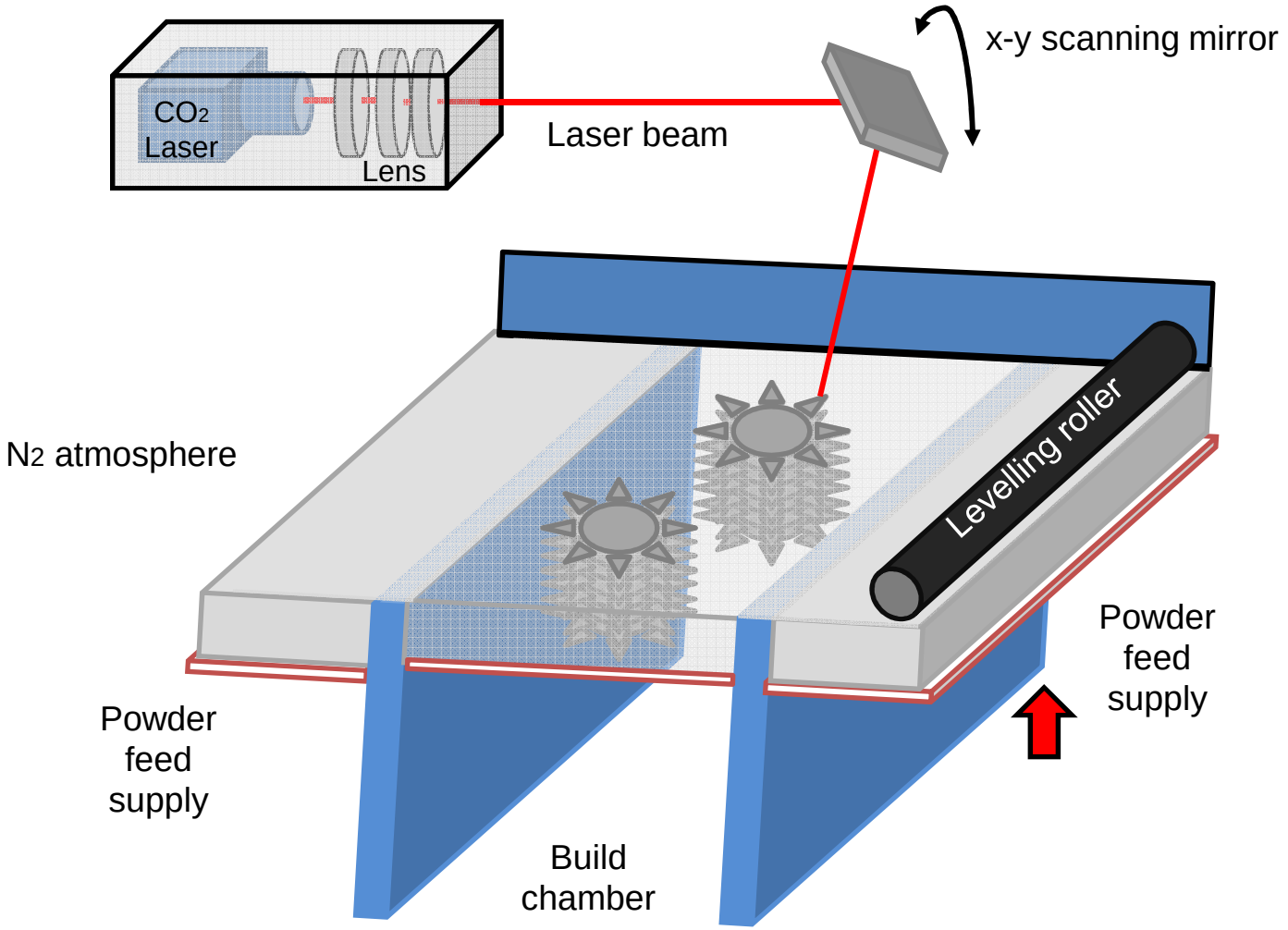


1- Powders are heated a few °C below its first melting point

2- Laser brings just enough energy to melt the nylon

3- Build chamber is lowered and a new layer powders is leveled

SLS: How does it work ?
Layer by layer manufacturing

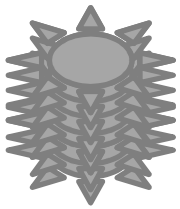


1- Powders are heated a few °C below its first melting point

2- Laser brings just enough energy to melt the nylon

3- Build chamber is lowered and a new layer of powders is leveled

4- Similar steps are repeated



SLS Part

Materials for SLS

Indirect fabrication

Metal parts

Several steps are necessary

Direct fabrication

Polymer matrix composites

Parts can be used directly

Materials for SLS

Indirect fabrication

Metal parts

Several steps are necessary

- Steel / bronze composite

Direct fabrication

Polymer matrix composites

Parts can be used directly

Materials for SLS

Indirect fabrication

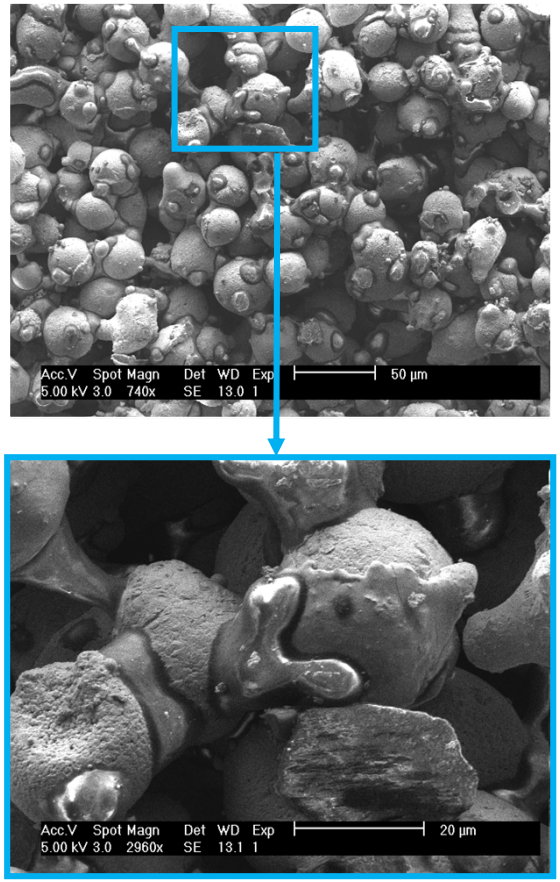
Metal parts

Several steps are necessary

- Steel / bronze composite

1- **SLS** of steel + 10 vol.% nylon powders (preform)
- Nylon acts as binder
- Preform has ≈ 40 vol.% of porosities
- Preform is handleable

2- **Infiltration of bronze** in the porous steel preform
- Tm bronze < Tm steel

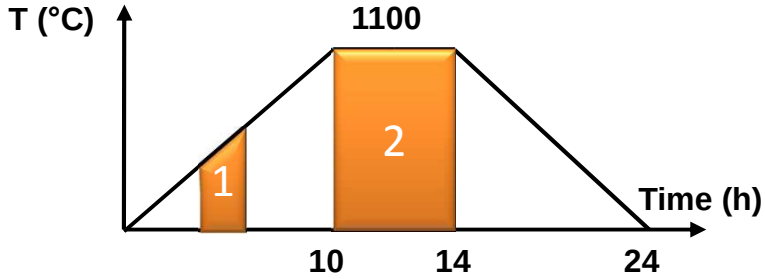


Typical SEM images of SLS preform

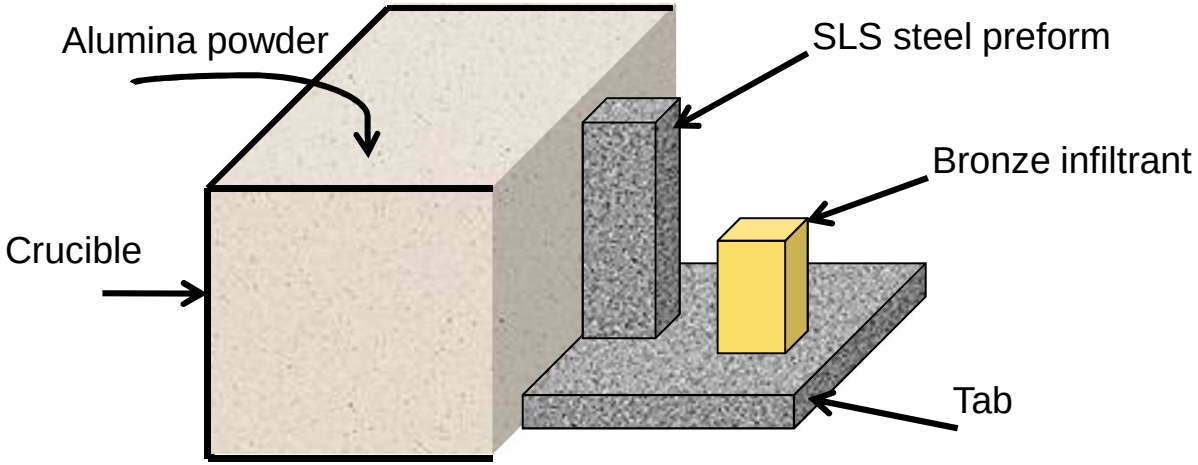
Infiltration

Indirect fabrication

Steel / bronze composite

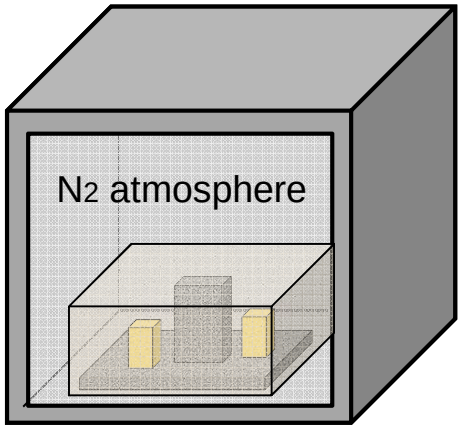


Preparation



Thermal cycle

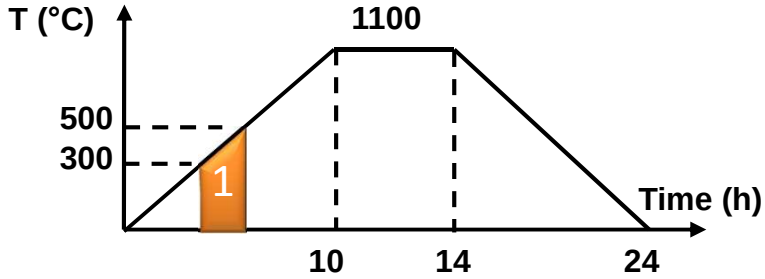
1. Debinding
2. Infiltration



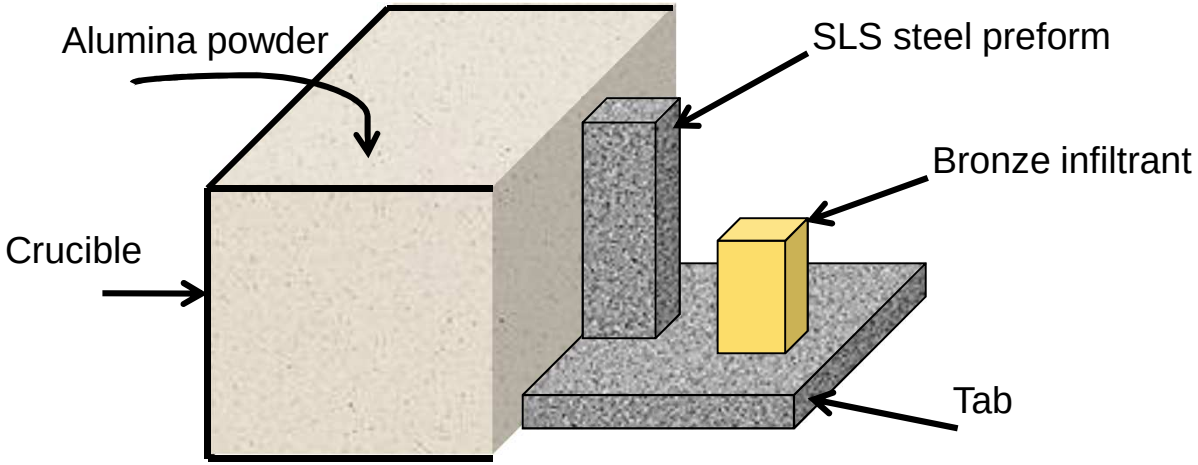
Infiltration

Indirect fabrication

Steel / bronze composite

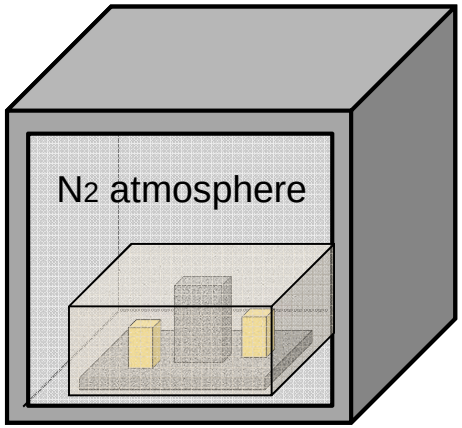


Preparation



Thermal cycle

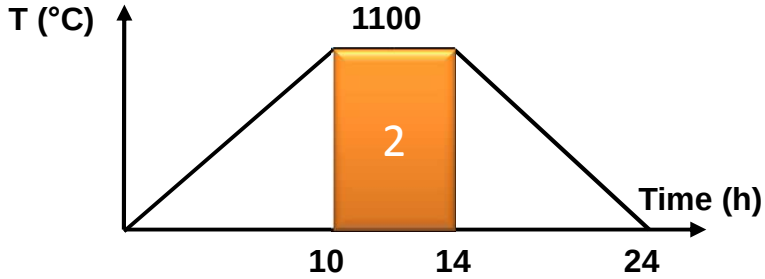
1. Debinding
2. Infiltration



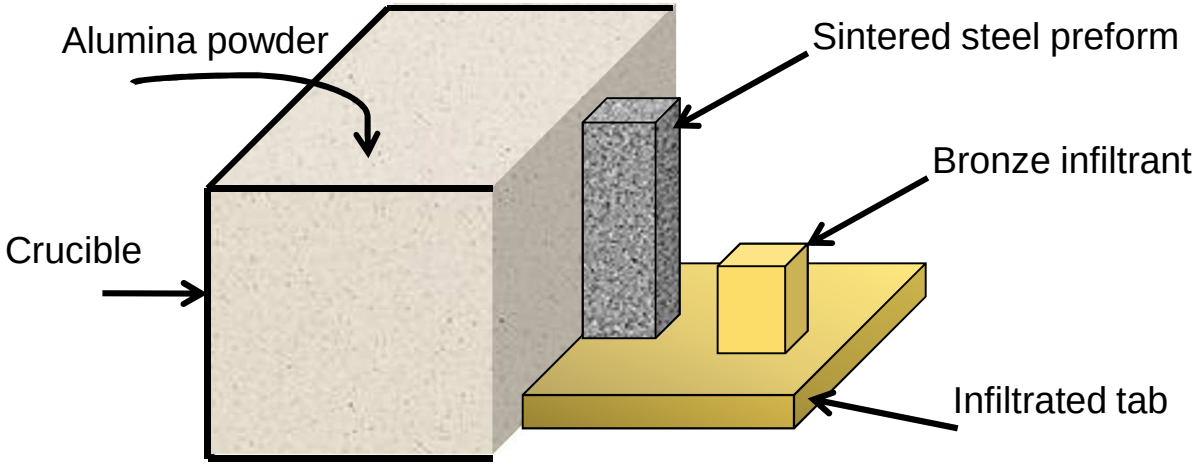
Infiltration

Indirect fabrication

Steel / bronze composite

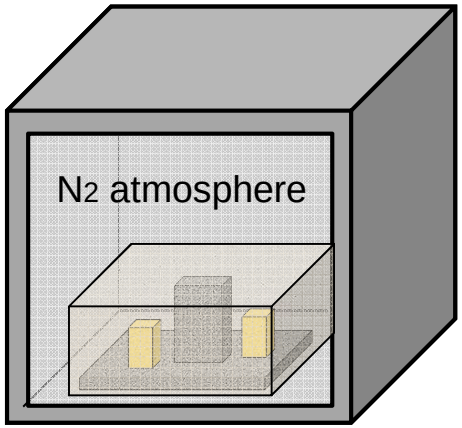


Preparation



Thermal cycle

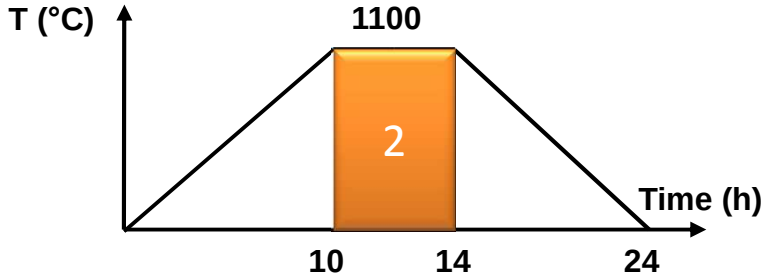
1. Debinding
2. Infiltration



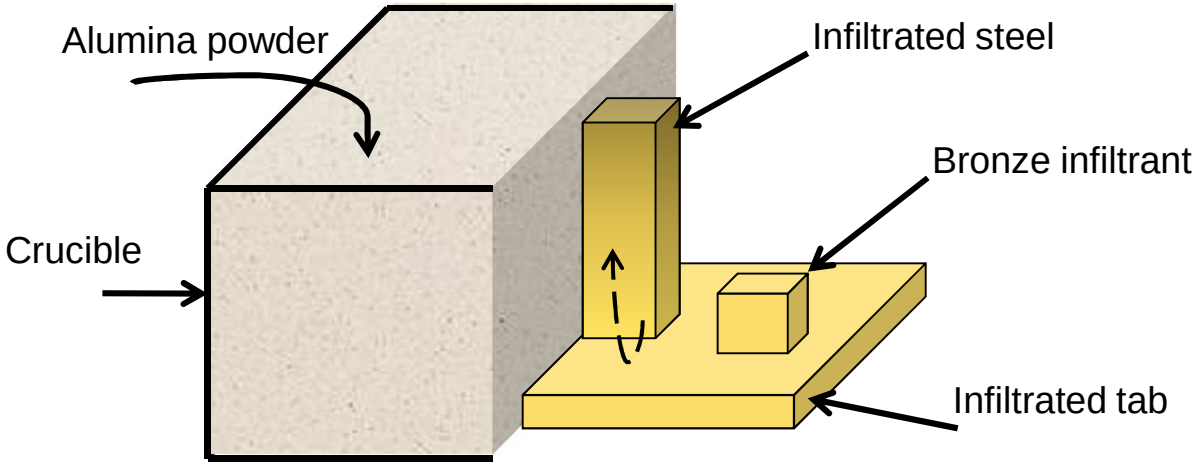
Infiltration

Indirect fabrication

Steel / bronze composite

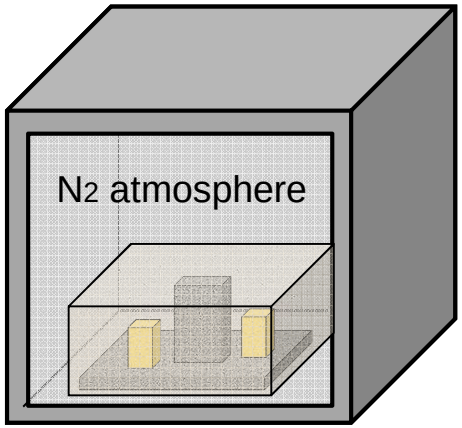


Preparation



Thermal cycle

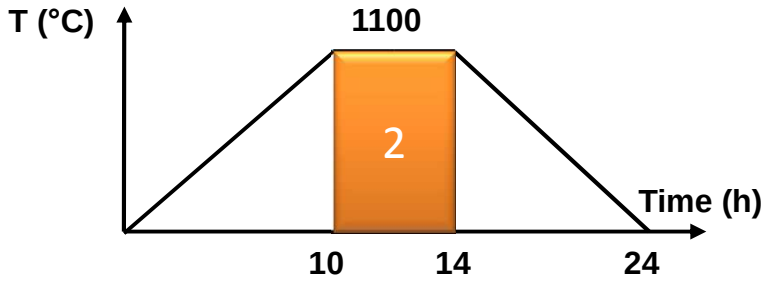
1. Debinding
2. Infiltration



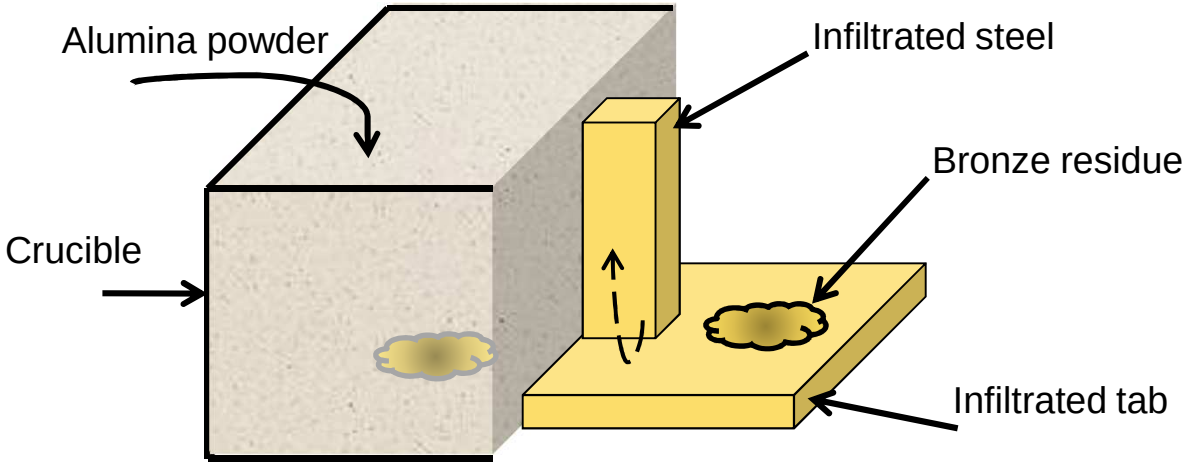
Infiltration

Indirect fabrication

Steel / bronze composite

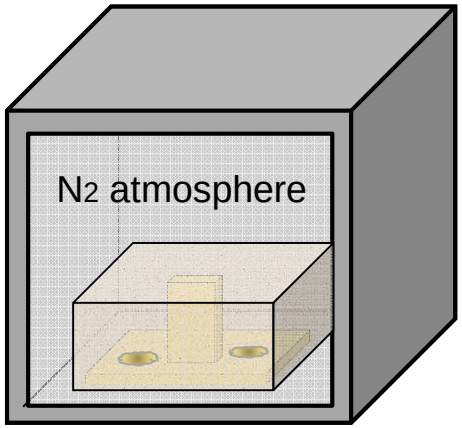


Preparation



Thermal cycle

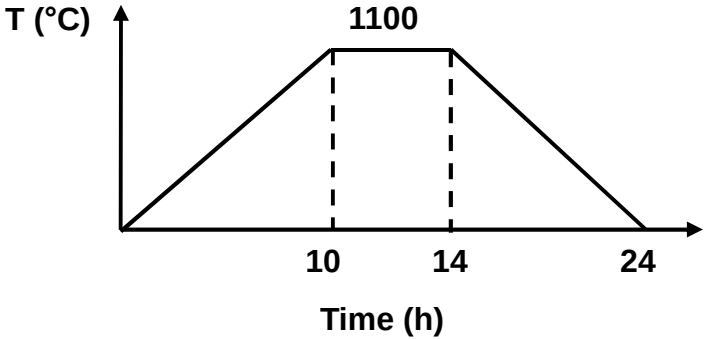
1. Debinding
2. Infiltration

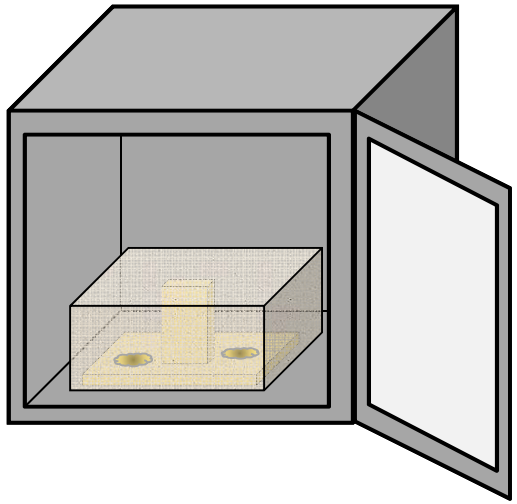


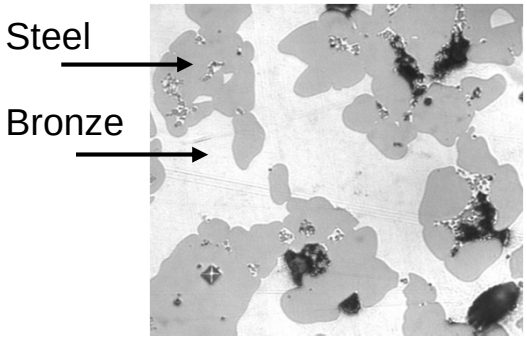
Infiltration

Indirect fabrication

Steel / bronze composite







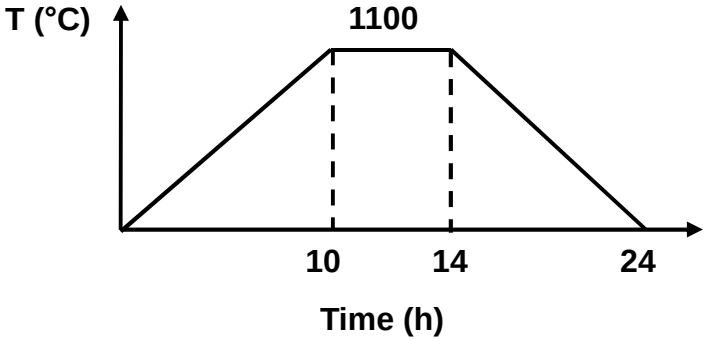
Properties:

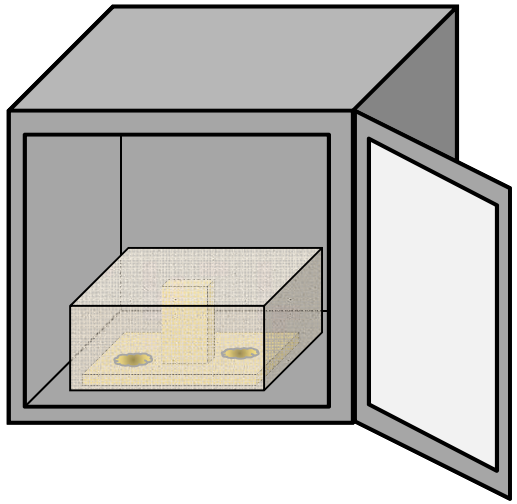
Density ≈ 8 g/cm³
Porosities ≈ 5 vol.%
Hardness ≈ 200 Hv
Fracture strain ≈ 3-5 %

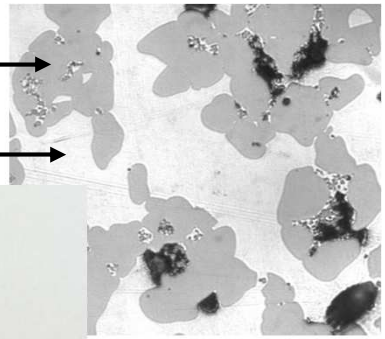
Infiltration

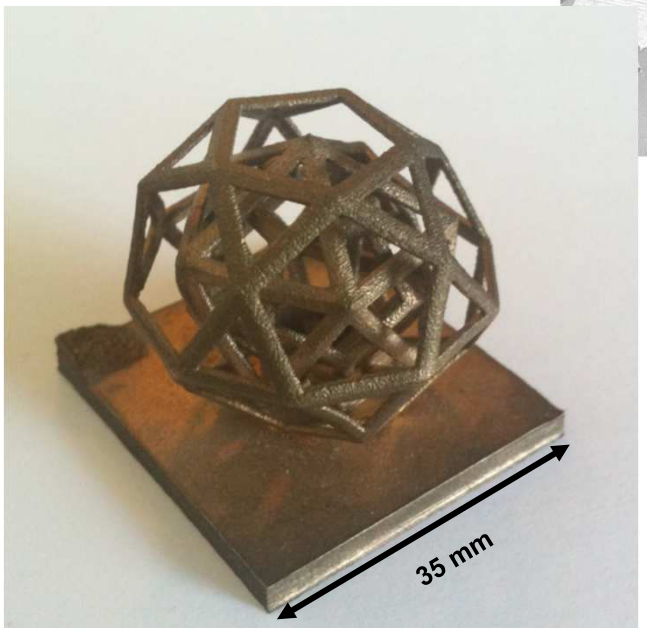
Indirect fabrication

Steel / bronze composite

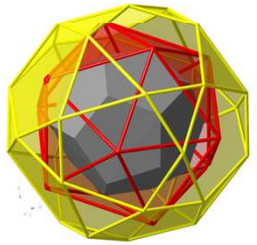








Steel/Bronze part



model

Towards light-weight materials: Al-based materials

Light-weight materials: Al-based materials

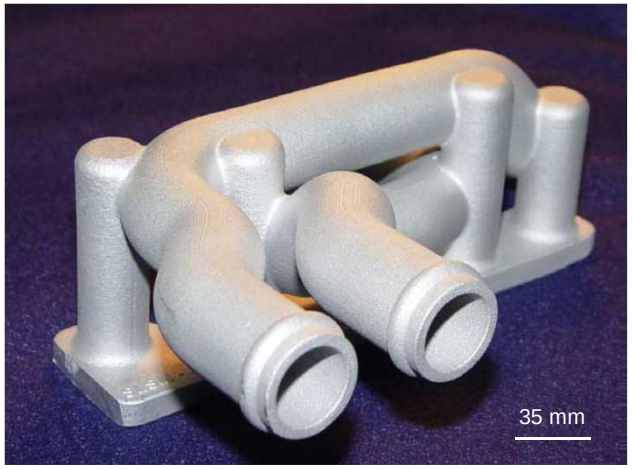
Al_1 / Al_2 composite

1- SLS of Al_1 + 10 vol.% nylon powders

2- Nitridation of Al_1 preform

3- Infiltration of Al_2 in the porous Al-AlN preform
- Tm Al_2 infiltrant < Tm Al_1 preform

≈ 2.7 g/cm³



T.B. Sercombe and G.B. Schaffer, *Science* **301** (2003)

Steel / bronze composite

1- SLS of steel + 10 vol.% nylon powders (preform)
- Nylon acts as binder
- Preform has ≈ 40 vol.% of porosities
- Preform is handleable

2- Infiltration of bronze in the porous steel preform
- Tm bronze < Tm steel

≈ 8 g/cm³

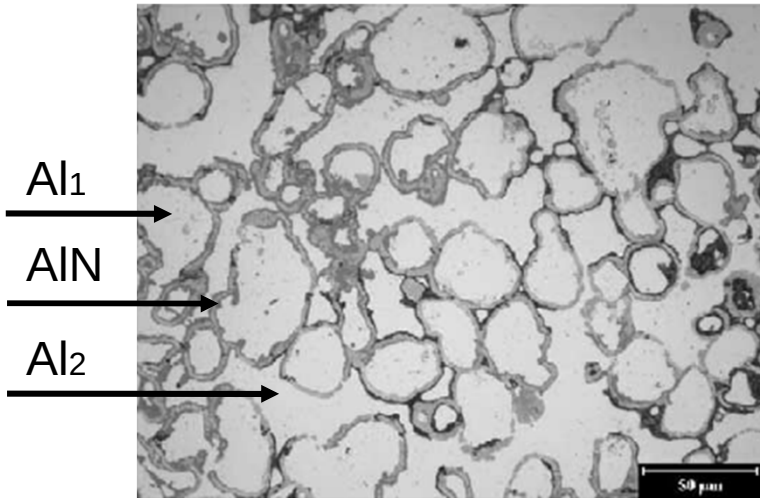
Light-weight materials: Al-based materials

Al_1 / Al_2 composite

1- **SLS of Al_1** + 10 vol.% nylon powders

2- **Nitridation** of Al_1 preform

3- **Infiltration of Al_2** in the porous Al-AlN preform
- Tm Al_2 infiltrant < Tm Al_1 preform



T.B. Sercombe and G.B. Schaffer
Acta Mater. **52** (10), (2004)

Nitridation is essential to achieve a successful infiltration of Al_1 by Al_2

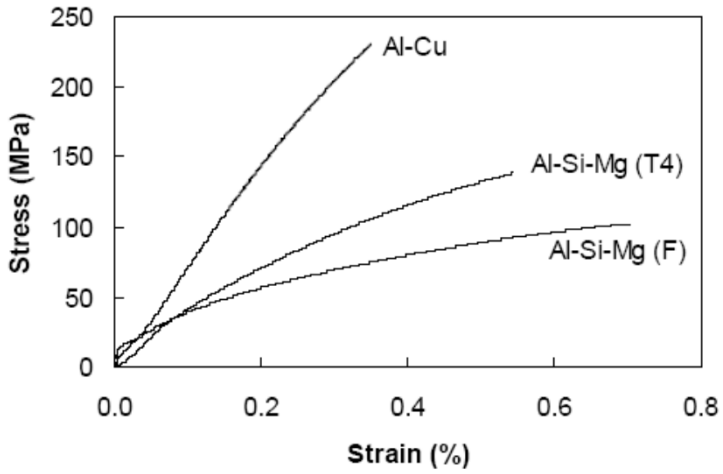
Light-weight materials: Al-based materials

Al_1 / Al_2 composite

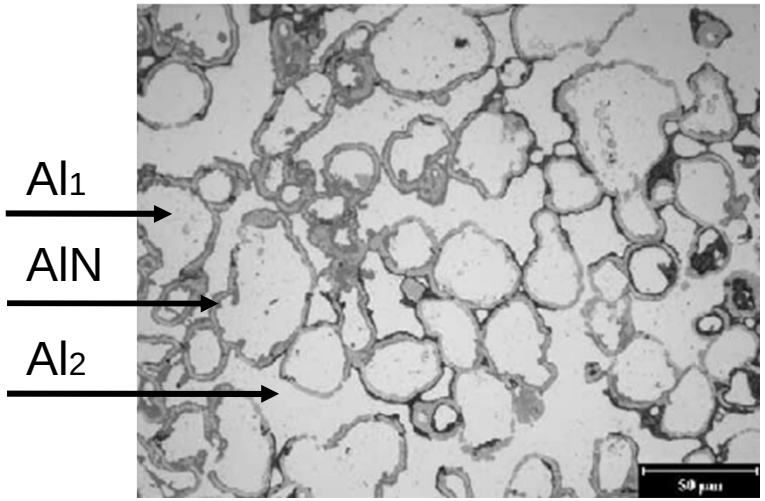
1- SLS of Al_1 + 10 vol.% nylon powders

2- Nitridation of Al_1 preform

3- Infiltration of Al_2 in the porous Al-AlN preform
- Tm Al_2 infiltrant < Tm Al_1 preform



T.B. Sercombe and G.B. Schaffer, *Science* **301** (2003)



T.B. Sercombe and G.B. Schaffer
Acta Mater. **52** (10), (2004)

Nitridation embrittles Al_1/Al_2 interface

Fracture strain < 1%

CMAs as alternative materials

Al_1 / Al_2 composite

Al-based CMA / Al composite

1- **SLS of Al_1** + 10 vol.% nylon powders

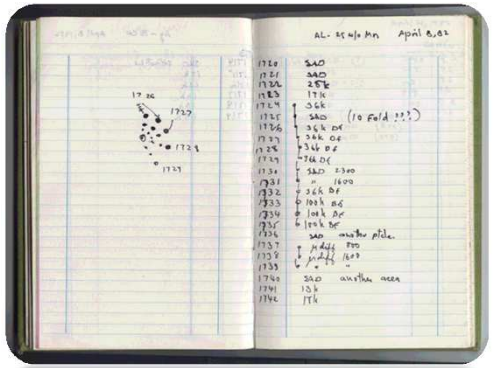
2- **Nitridation** of Al_1 preform

3- **Infiltration of Al_2** in the porous Al-AlN preform
- Tm Al_2 infiltrant < Tm Al_1 preform

Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (°C)
Al alloys	≈ 70	50 - 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 - 200**	**600 - 900**	**4 - 5**	**800 - 900**
Steel	≈ 200	300 - 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

CMAs as alternative materials

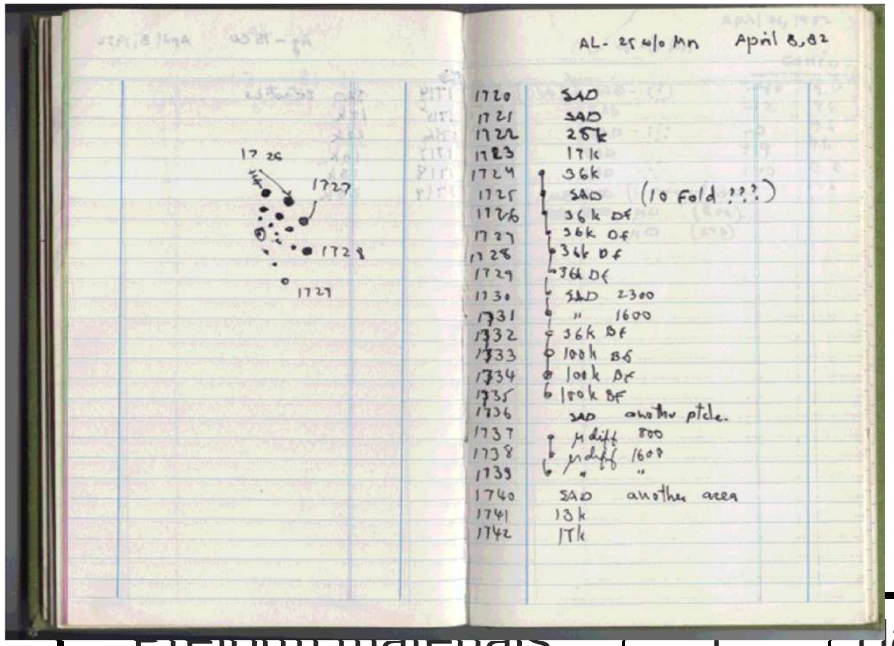


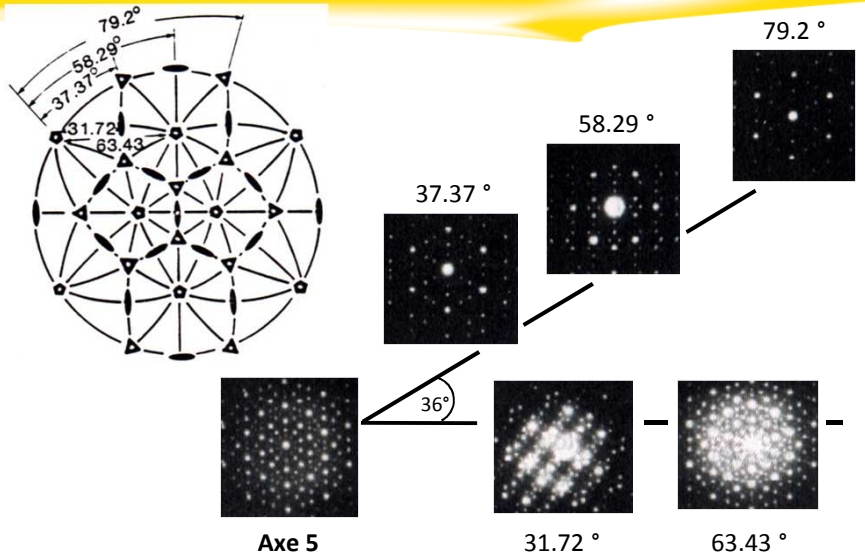
D. Shechtman et al.
Phys. Rev. Lett. **53**, 1951, 1984

Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (℃)
Al alloys	≈ 70	50 - 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 - 200**	**600 - 900**	**4 - 5**	**800 - 900**
Steel	≈ 200	300 - 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

CMAs as alternative materials



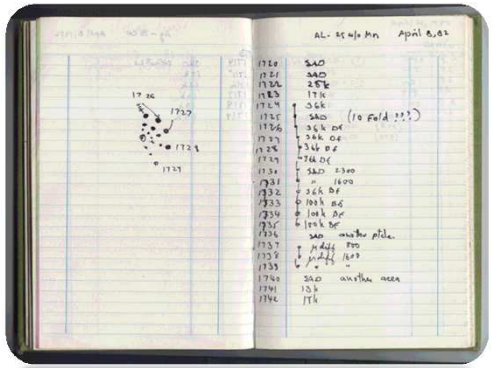


D. Shechtman et al.,*Phys. Rev. Lett.* **53**, 1951, 1984

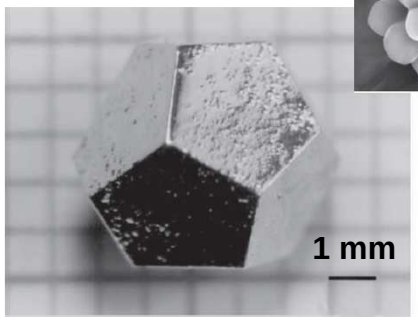
Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (℃)
Al alloys	≈ 70	50 – 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 – 200**	**600 – 900**	**4 – 5**	**800 - 900**
Steel	≈ 200	300 – 1000	7.8	> 1300

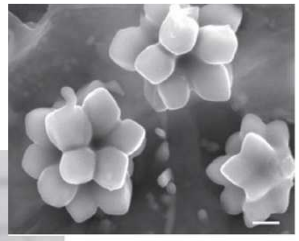
AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

CMAs as alternative materials

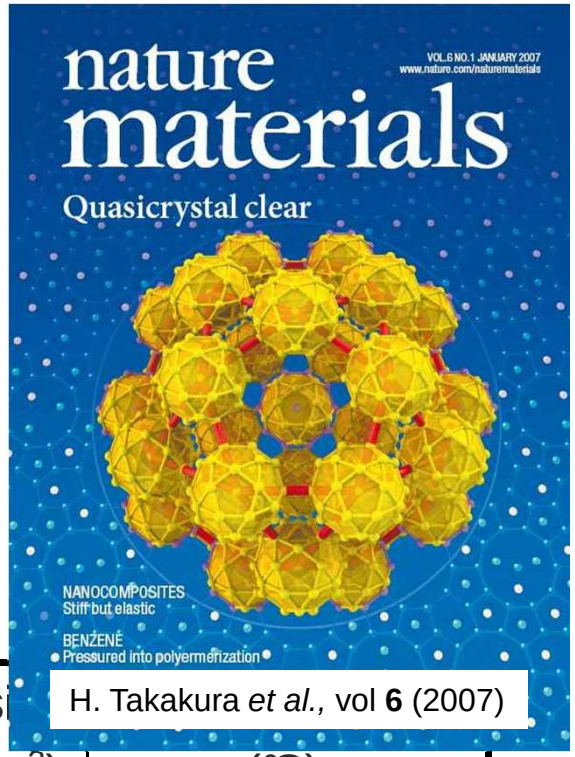


D. Shechtman *et al.*,
Phys. Rev. Lett. **53**, 1951, 1984





E. Abe *et al.*, *nature materials* **3**, 2004

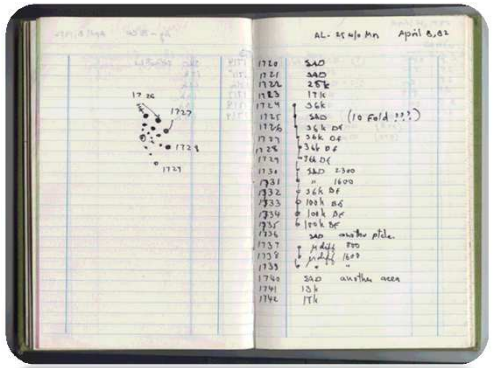


H. Takakura *et al.*, vol **6** (2007)

Preform materials	E (Gpa)	Hardness (Hv)	Densi ($g.cm^{-3}$)	(°C)
Al alloys	≈ 70	50 – 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 – 200**	**600 – 900**	**4 – 5**	**800 - 900**
Steel	≈ 200	300 – 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

CMAs as alternative materials

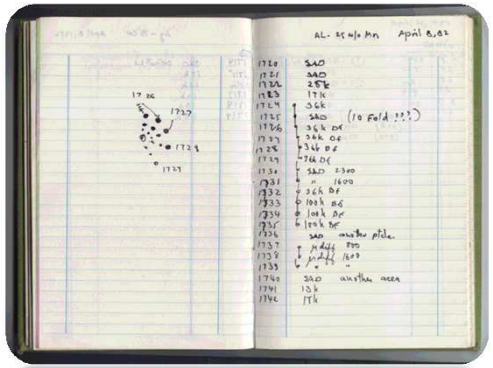


D. Shechtman *et al.*,
Phys. Rev. Lett. **53**, 1951, 1984

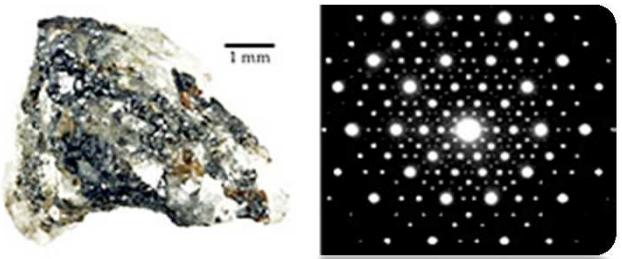
Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (℃)
Al alloys	≈ 70	50 – 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 – 200**	**600 – 900**	**4 – 5**	**800 - 900**
Steel	≈ 200	300 – 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

CMAs as alternative materials



D. Shechtman *et al.*,
Phys. Rev. Lett. **53**, 1951, 1984

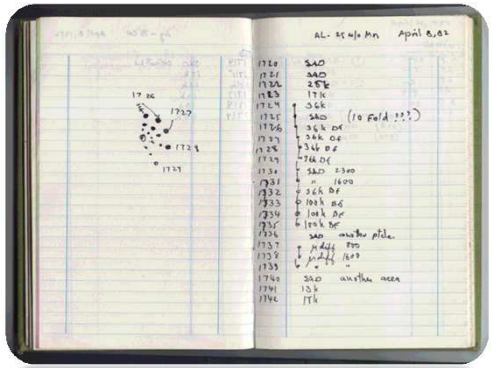


L. Bindi *et al.*, *Science* **324**, 1306, 2009

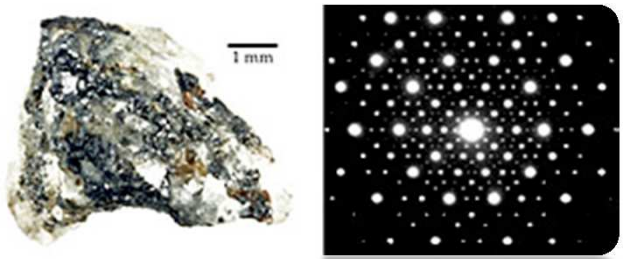
Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (℃)
Al alloys	≈ 70	50 – 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 – 200**	**600 – 900**	**4 – 5**	**800 - 900**
Steel	≈ 200	300 – 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

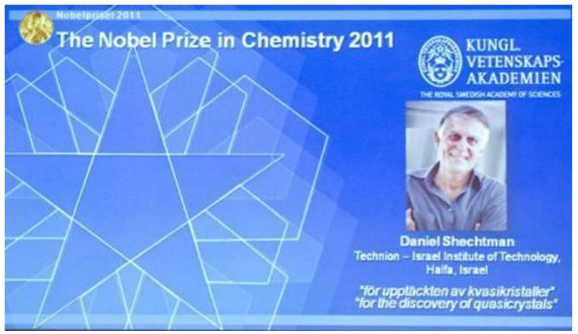
CMAs as alternative materials



D. Shechtman *et al.*,
Phys. Rev. Lett. **53**, 1951, 1984



L. Bindi *et al.*, *Science* **324**, 1306, 2009



Preform materials	E (Gpa)	Hardness (Hv)	Density ($g.cm^{-3}$)	Thermal stability (℃)
Al alloys	≈ 70	50 – 320	2.7	550 - 660
CMA - AlCuFe(X)	**160 – 200**	**600 – 900**	**4 – 5**	**800 - 900**
Steel	≈ 200	300 – 1000	7.8	> 1300

AlCuFe(X) => *i*-AlCuFeB ; O-AlCuFeCr

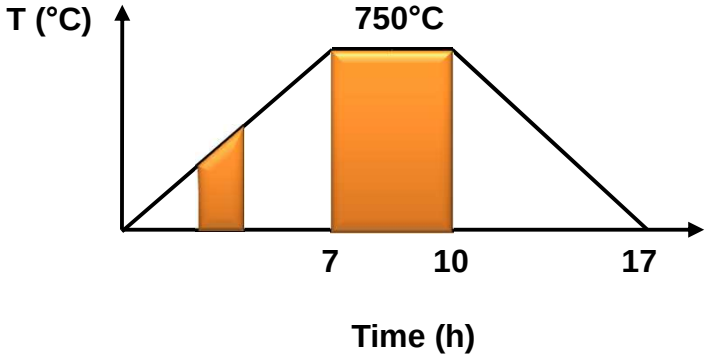
CMAs as alternative materials

Al-based CMA / Al composite

1- SLS of Al-based CMA + 10 vol.% nylon powders

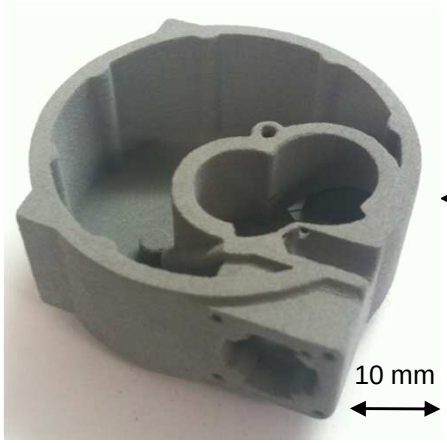
~~**2-** Nitridation of CMA preform~~

3- Infiltration of Al in the porous CMA preform
- Tm Al infiltrant < Tm CMA preform



Nitridation is avoided by using vacuum or Argon

CMAs as alternative materials



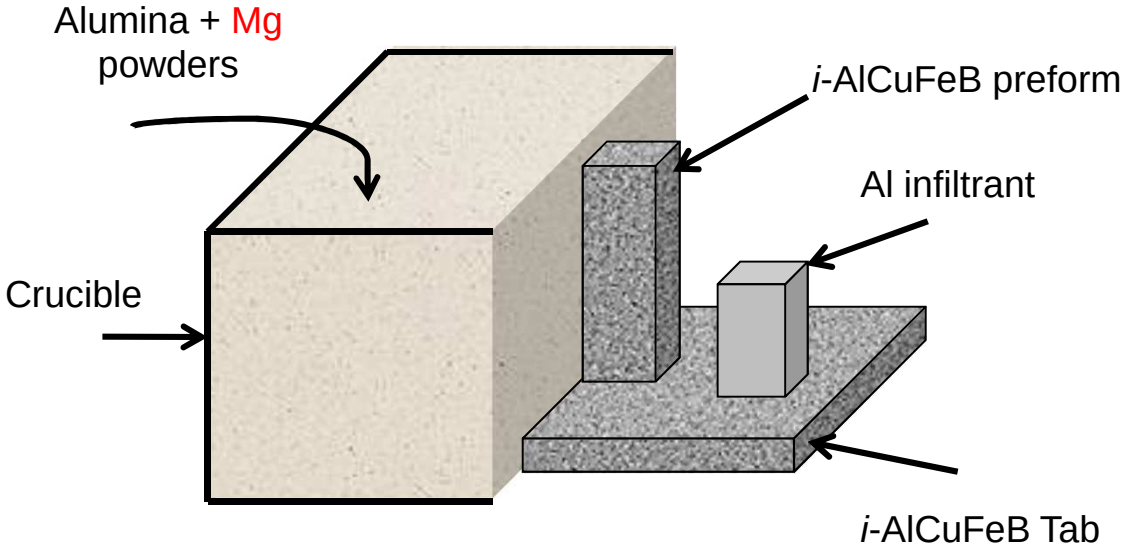
Quasicrystalline Preform

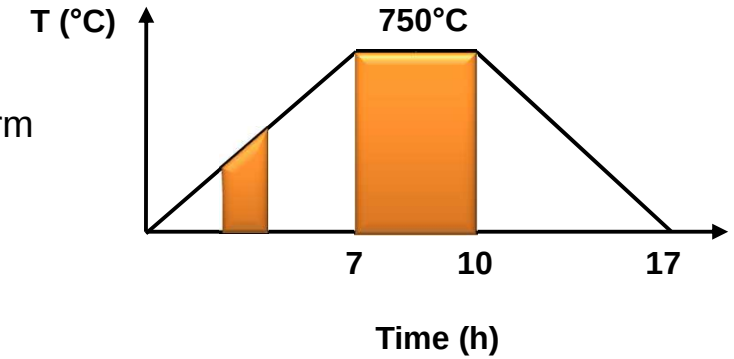
Al-based CMA / Al composite

1- SLS of Al-based CMA + 10 vol.% nylon powders

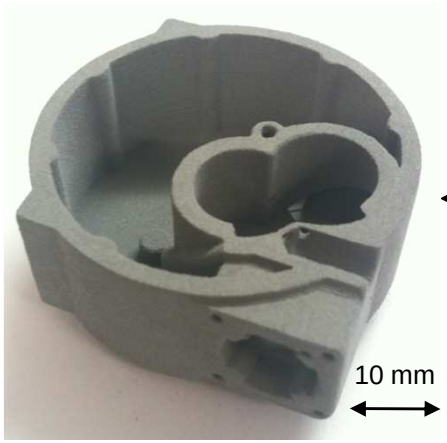
~~**2-** Nitridation of CMA preform~~

3- Infiltration of Al in the porous CMA preform
- Tm Al infiltrant < Tm CMA preform





CMAs as alternative materials

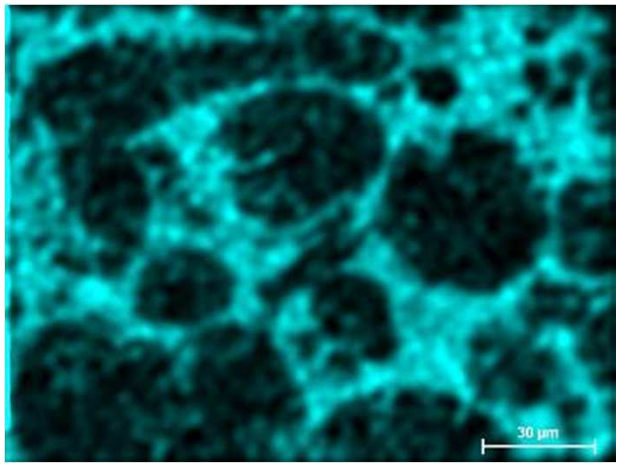


Quasicrystalline Preform

Al-based CMA / Al composite

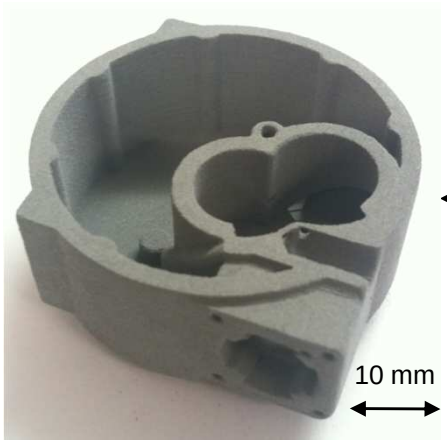
1- SLS of Al-based CMA + 10 vol.% nylon powders

2- Infiltration of Al in the porous CMA preform
- Tm Al 1050 < Tm *i*-AlCuFeB



EDS map of Mg in the infiltrated part

CMAs as alternative materials

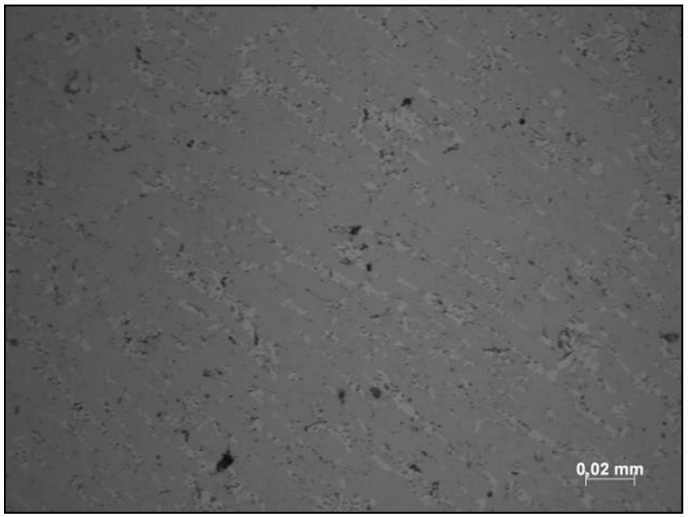


Quasicrystalline Preform

Al-based CMA / Al composite

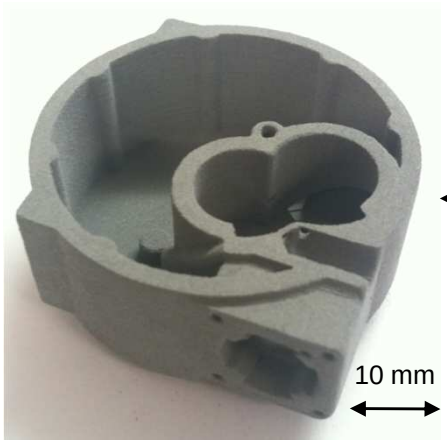
1- SLS of Al-based CMA + 10 vol.% nylon powders

2- Infiltration of Al in the porous CMA preform
- Tm Al 1050 < Tm *i*-AlCuFeB



Preform is fully infiltrated by aluminium

CMAs as alternative materials



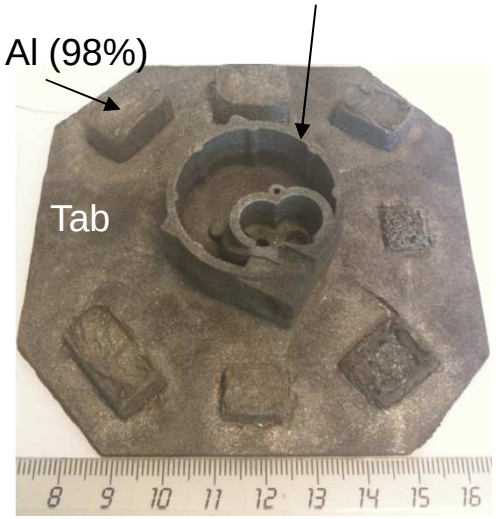
Quasicrystalline Preform

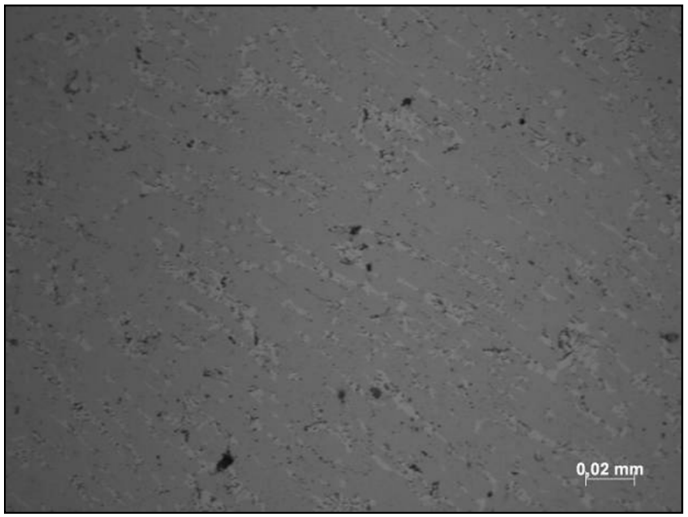
Al-based CMA / Al composite

1- SLS of Al-based CMA + 10 vol.% nylon powders

2- Infiltration of Al in the porous CMA preform
- Tm Al 1050 < Tm *i*-AlCuFeB

i-AlCuFeB infiltrated by aluminium alloy (98%)



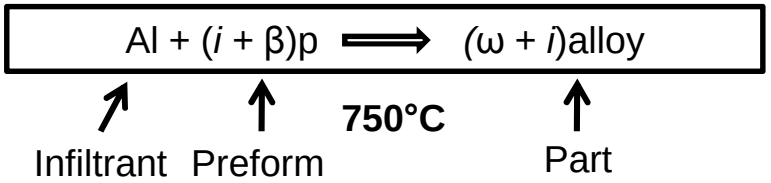


Preform is fully infiltrated by aluminium

CMAs as alternative materials

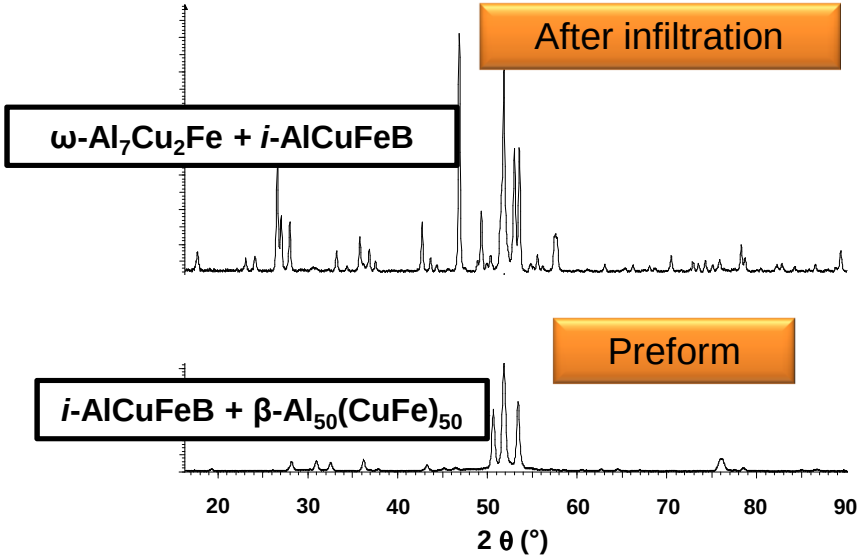
Al-based CMA / Al composite

i-AlCuFeB infiltrated by aluminium alloy (98%)



1- SLS of Al-based CMA + 10 vol.% nylon powders

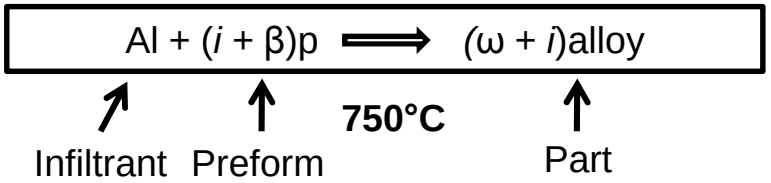
2- Infiltration of Al in the porous CMA preform
- Tm Al 1050 < Tm *i*-AlCuFeB



λCoKα$_1$ = 1.788965 Å

CMAs as alternative materials

i-AlCuFeB infiltrated by aluminium alloy (98%)



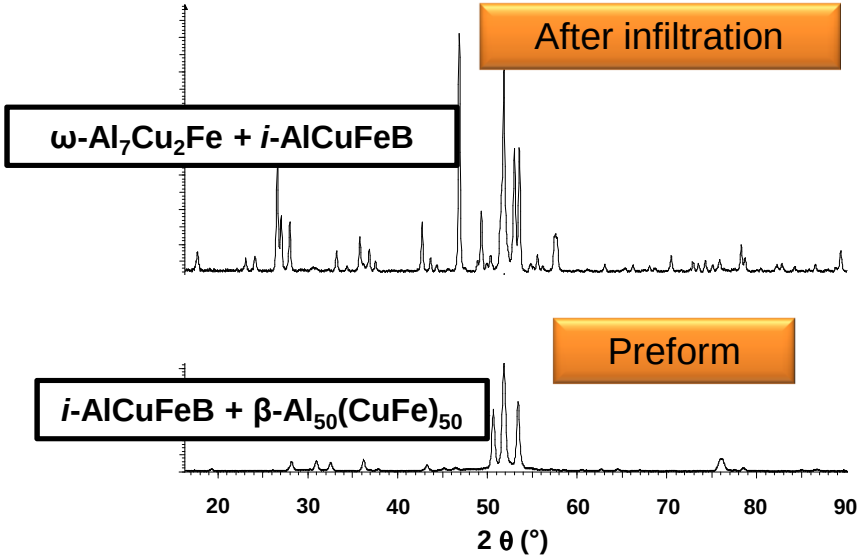
Properties:

Density ≈ 4 g/cm³
Porosities < 5 vol.%
Hardness: 350 – 400 Hv

Al-based CMA / Al composite

1- SLS of Al-based CMA + 10 vol.% nylon powders

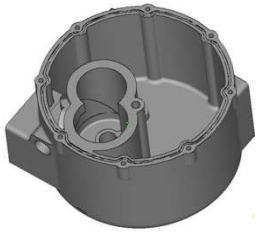
2- Infiltration of Al in the porous CMA preform
- Tm Al 1050 < Tm *i*-AlCuFeB

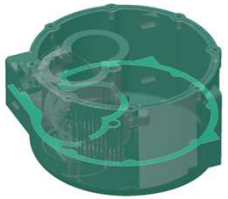


$\lambda CoK\alpha_1$ = 1.788965 Å

Conclusions - Perspectives

➢ Preforms can be produced by SLS from quasicrystalline + nylon powders and infiltrated by commercial aluminium alloys (Al 98%, AlSi)





➢ This work shows a new application of CMAs and extends the SLS process towards a new class of light-weight materials

➢ What is the maximum part size?
➢ What are mechanical properties?

Materials for SLS

Direct fabrication

FOC
FREEDOM OF CREATION

EOS
e-Manufacturing Solutions

Parts can be used directly

- Polyamide (nylon)
- Polyamide based composites
  Nylon+glass fiber, Carbon fiber, Al...

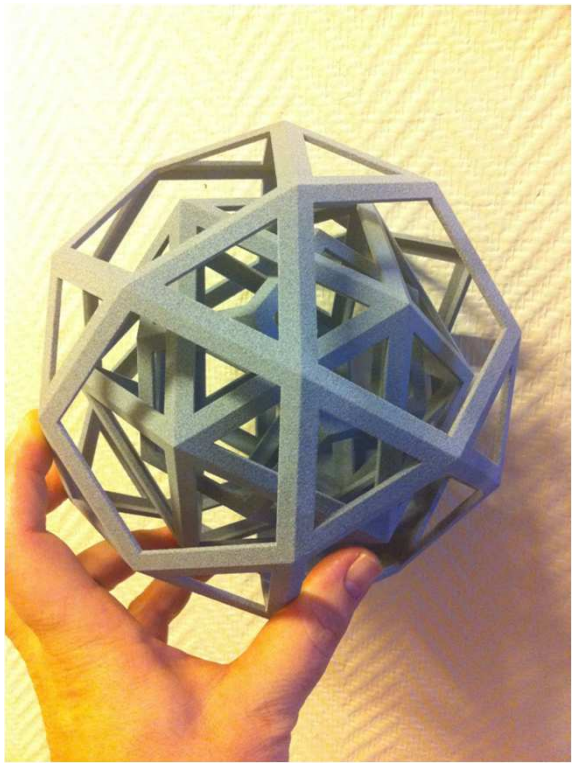
3D SYSTEMS

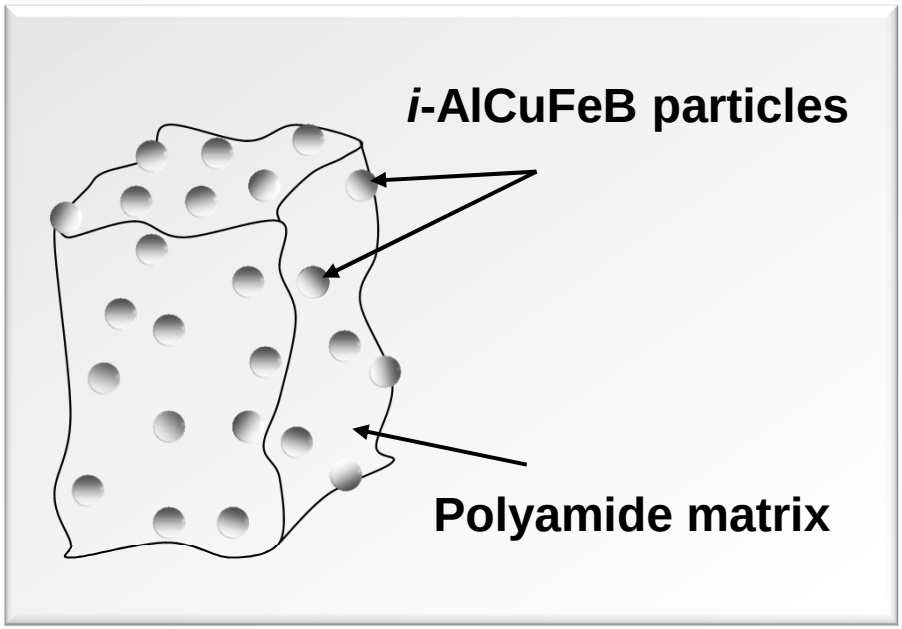
Polyamide+Al

Materials for SLS

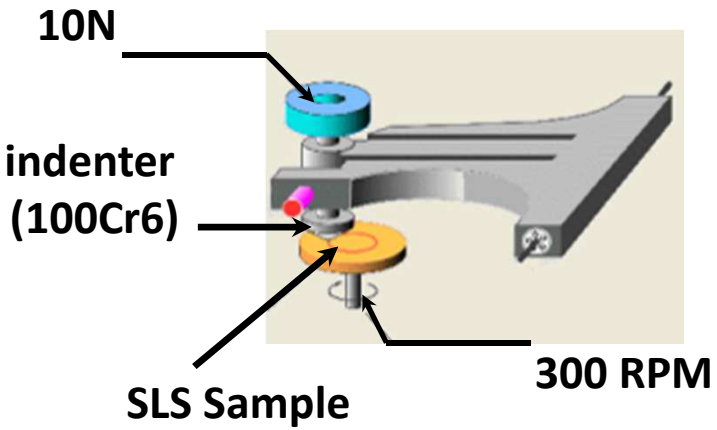
Direct fabrication

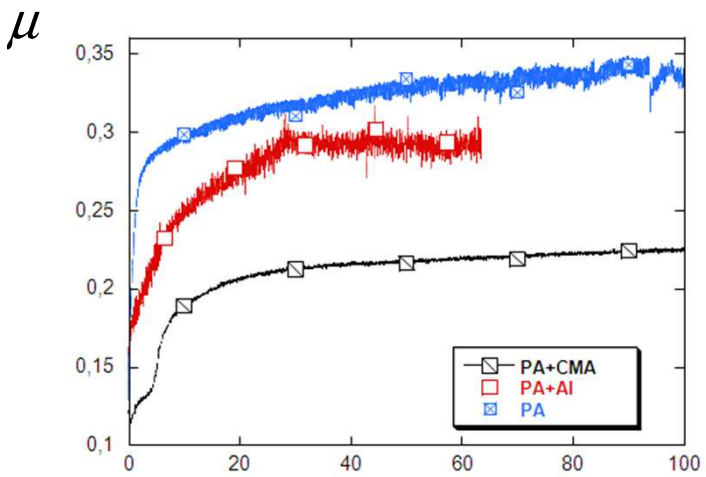
Polymer matrix composites

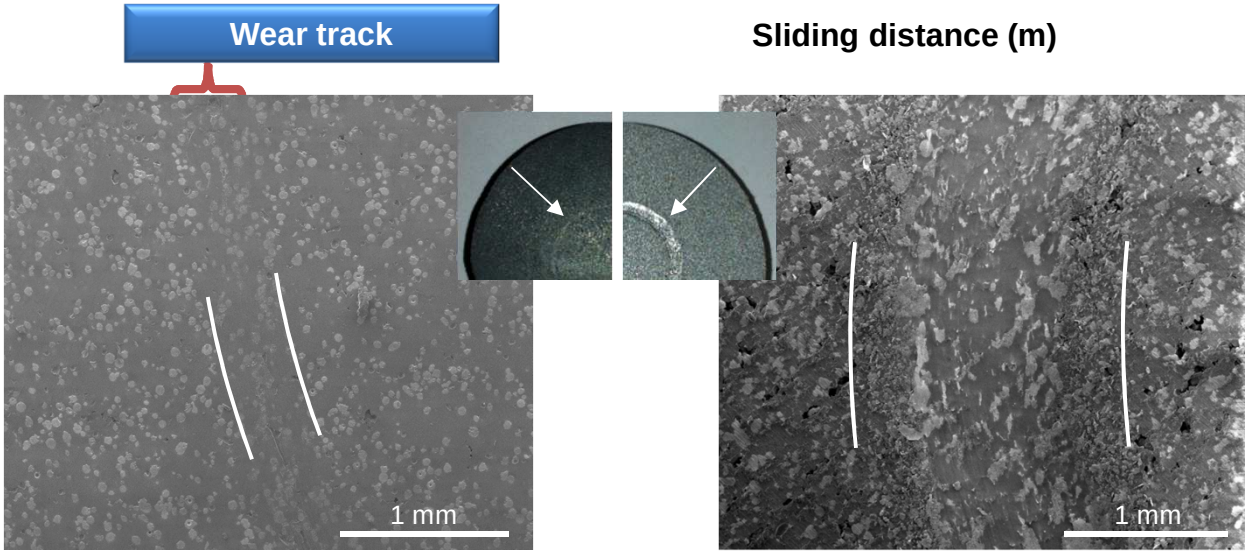




Friction and Wear



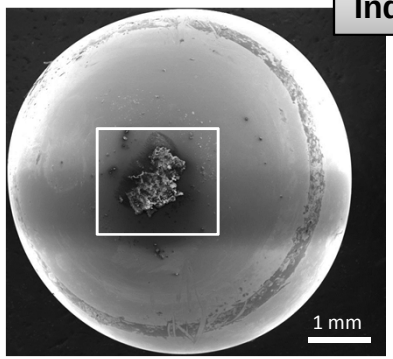


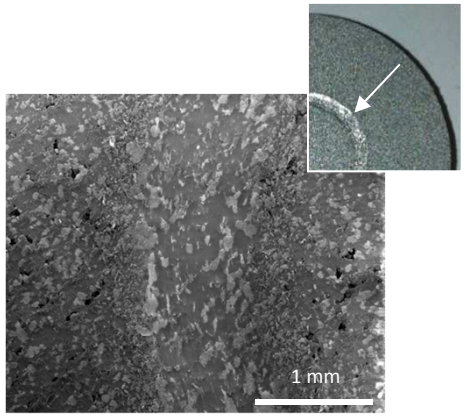


PA+CMA, after 100 m

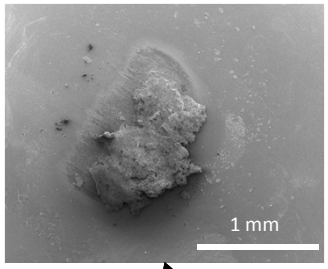
PA+Al, after 60 m

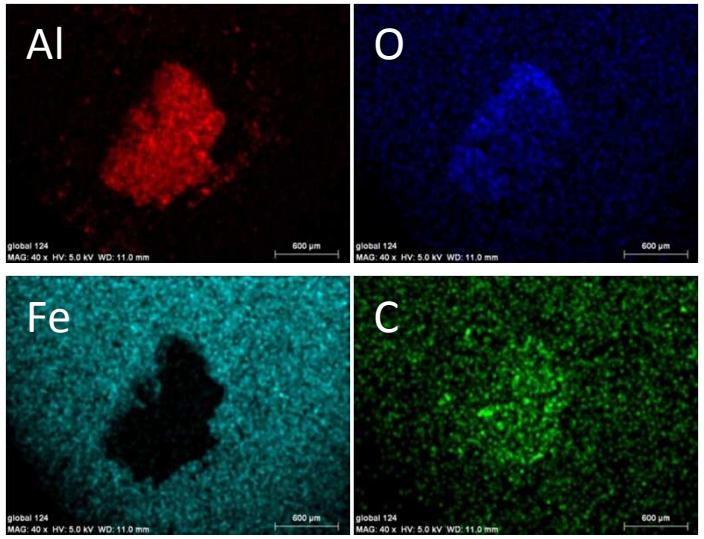
Friction and Wear





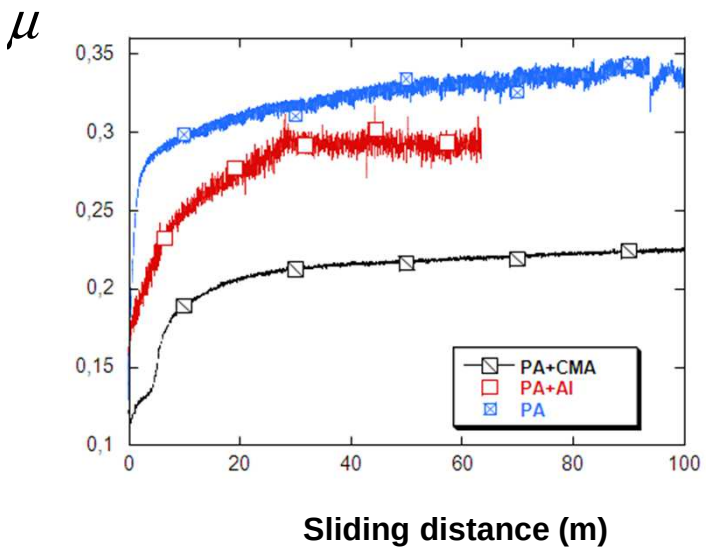
SLS (PA+Al)
after 60 m



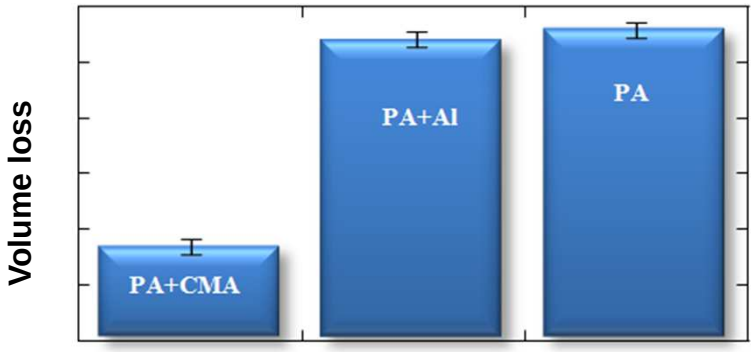


Transfered material after 60 m of sliding → Al oxides

Friction and Wear



Reduction of the volume loss by about 70%



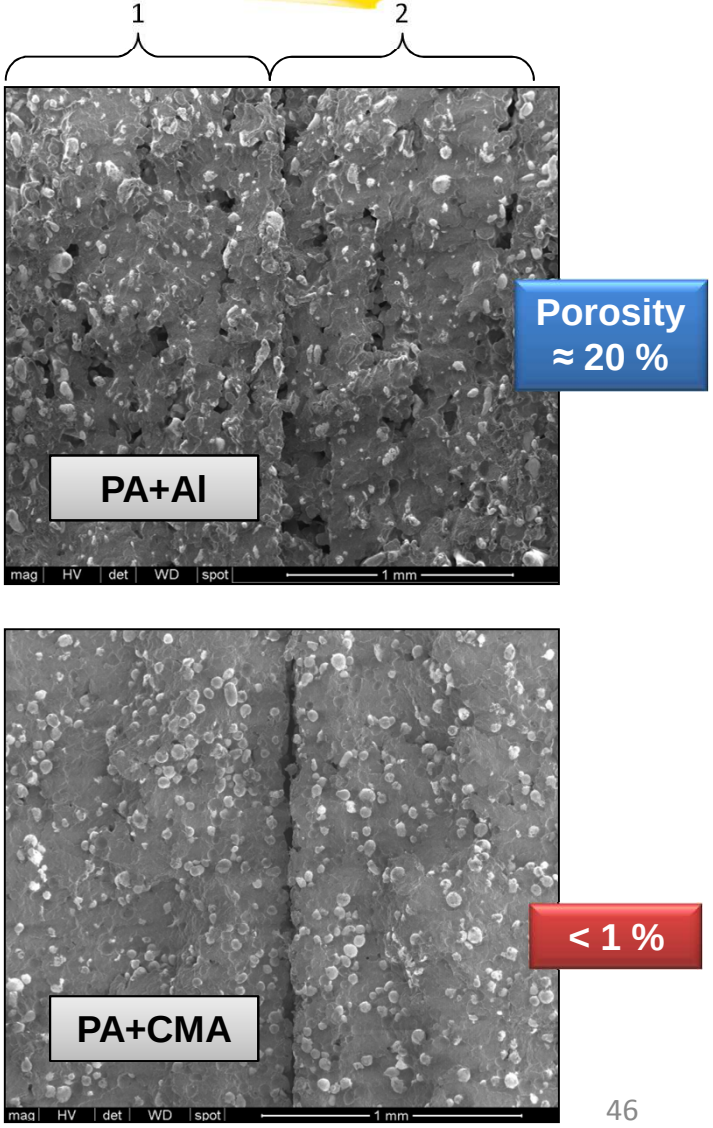
Density

SLS (PA+Al)

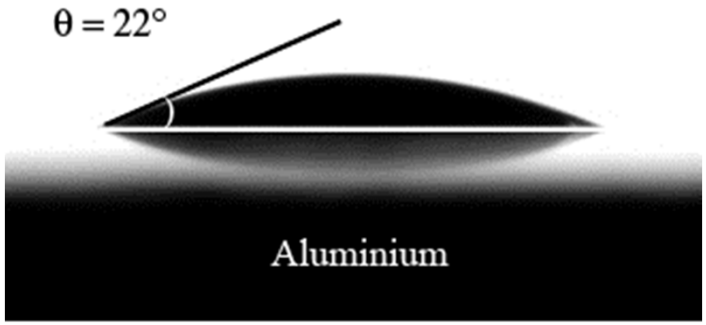
SLS (PA+AlCuFeB)

Tensile strength (35±5 MPa)

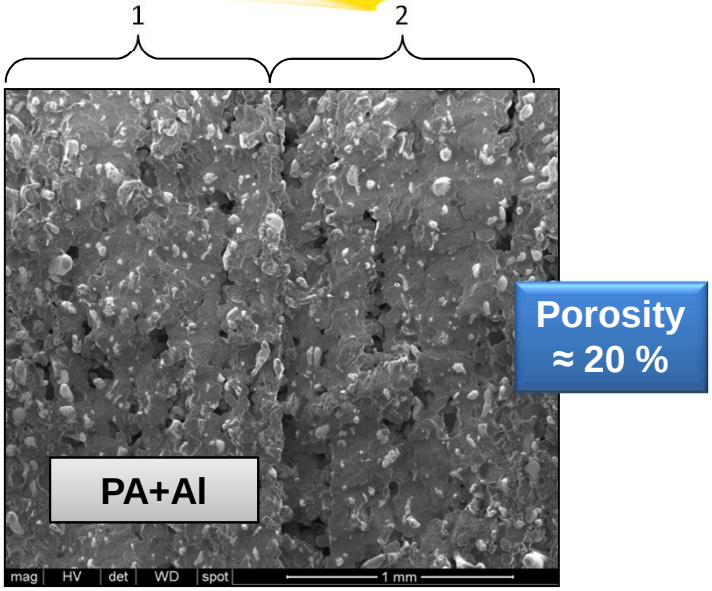
Elongation at break (2%±1)

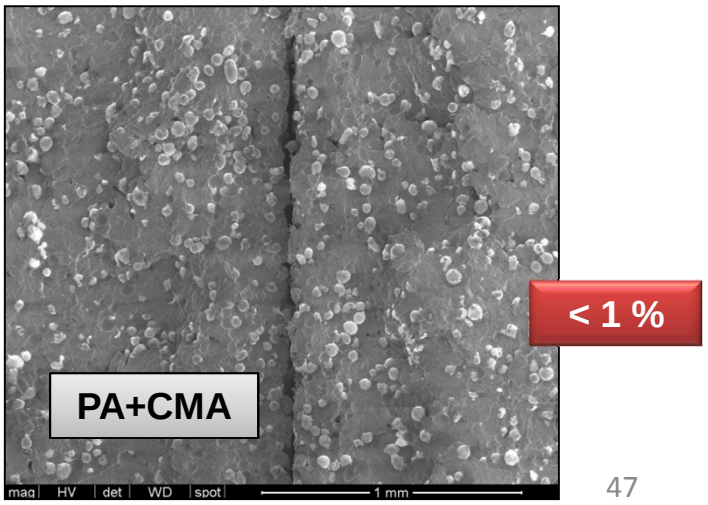


Density

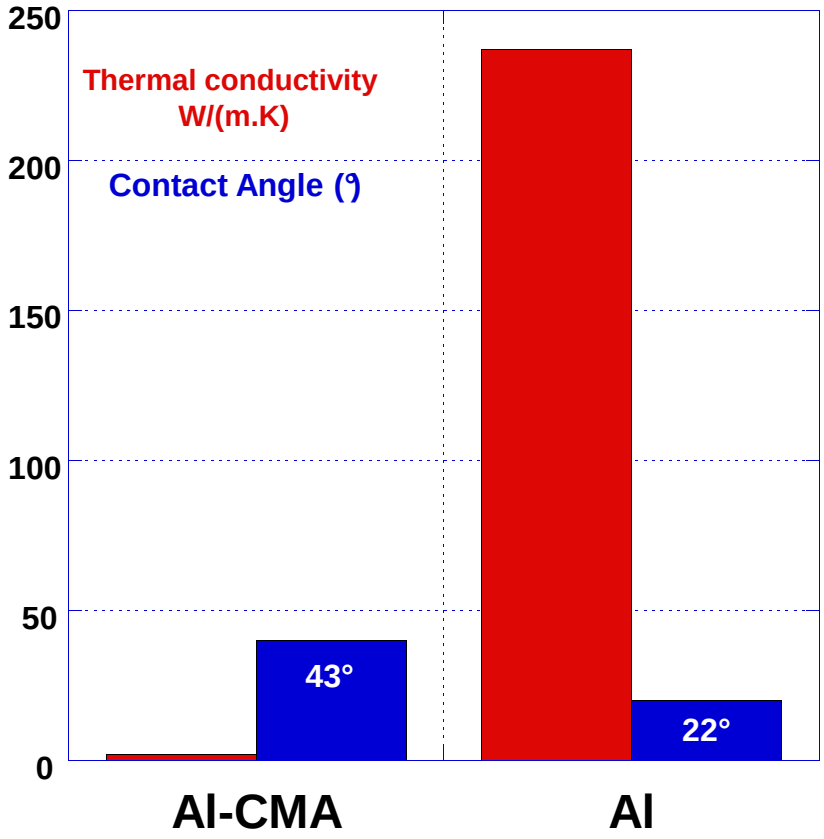

θ = 22°
Aluminium

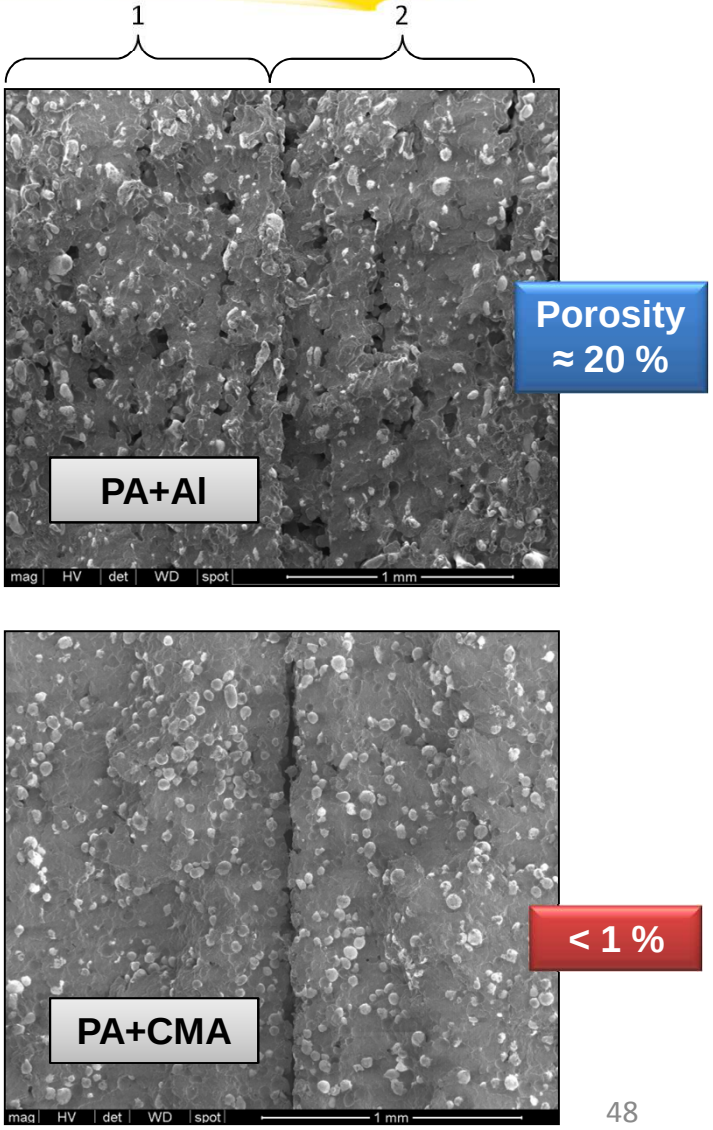

θ = 43°
AlCuFeB


1
2
PA+Al
Porosity
≈ 20 %
mag HV det WD spot 1 mm

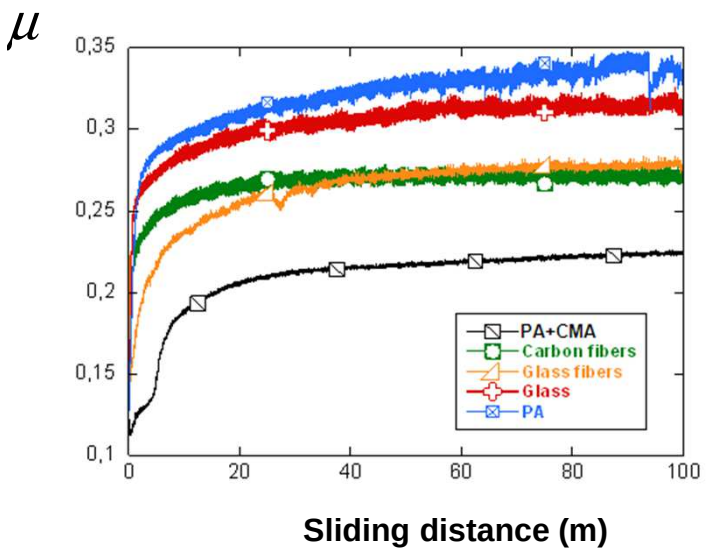

PA+CMA
< 1 %
mag HV det WD spot 1 mm

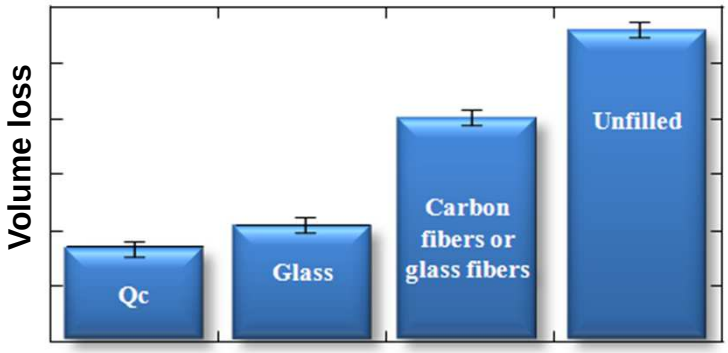
Density


250
200
150
100
50
0
Thermal conductivity W/(m.K)
Contact Angle (°)
43°
22°
Al-CMA
Al


1
2
PA+Al
Porosity ≈ 20 %
mag HV det WD spot 1 mm
PA+CMA
< 1 %
mag HV det WD spot 1 mm

Friction and Wear



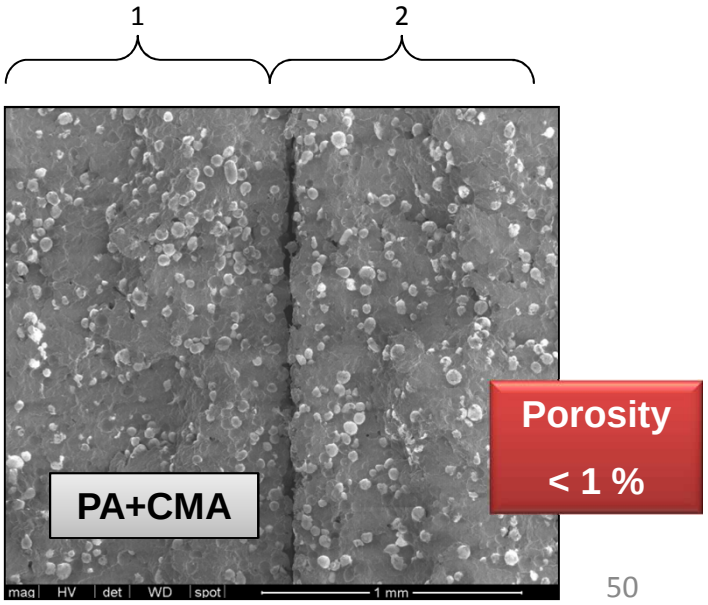


Leak-tight part

(PA+CMA) intake manifold

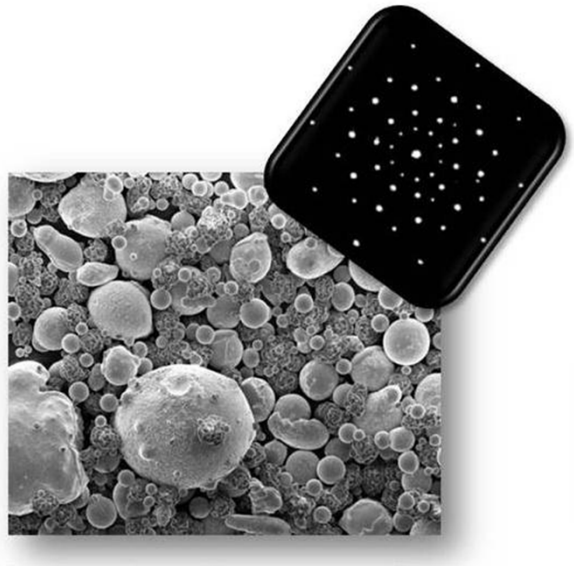
Leak tests :
High air pressure and water pressure (up to 7 bars)

No post-impregnation of resin



Conclusions

- Quasicrystal-polymer composite was adapted and commercialized for applications in Selective laser sintering process

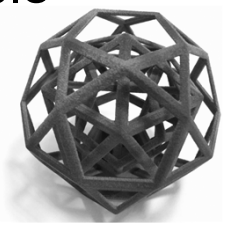


Composite polymer powders with CMA particles

Selective Laser Sintering

Functional part

-This new light-weight composite extends the materials choice compatible with the SLS process and offers improved functional properties



Additive Manufacturing

S. Kenzari, D. Bonina, J-M. Dubois, V. Fournée

IJL – Institut Jean Lamour – UMR 7198
Matériaux-Métallurgie-Nanosciences-Plasmas-Surfaces

Parc de Saurupt, 54011 Nancy, France

samuel.kenzari@ijl.nancy-universite.fr