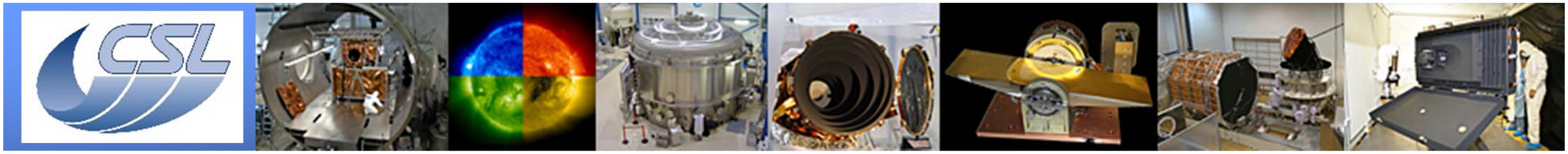


"Additive Layer Manufacturing for Space Instrumentation and subsystems"

Pierre Rochus

Professor at University of Liège

Scientific Director at Centre Spatial de Liège

Invited Professor at KUL (Leuven)

☎+32 4 382 46 07 - ✉ prochus@ulg.ac.be

With a contribution of Jean-Yves Plesseria CSL, SIRRIS, ESA, TAS, AlmaSpace, Xiao HU (EMAC Student) and J Oger (PhD student)

Many thanks to Professor Xiaozhou Yu for his invitation

Outline of the presentation

- Space instrumentation and Space Environmental optical testing activities at CSL
- Dreams, a priori expectations and space specificities
- Advanced Manufacturing Techniques considered in our studies
- First realizations 10 years ago
- More concrete and more recent examples
- Conclusions and future activities

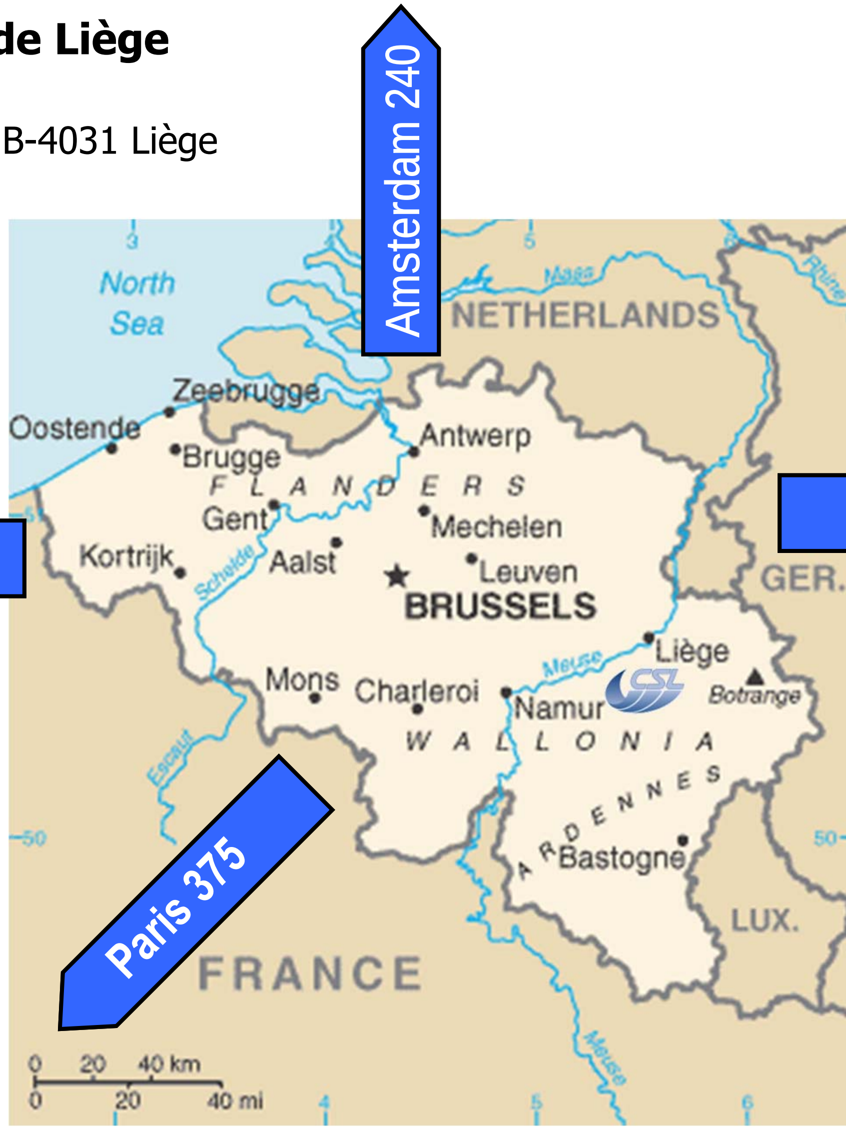
Outline of the presentation 1

- **Space instrumentation and Space Environmental testing activities at CSL**
- **Dreams, a priori expectations and space specificities**
- **Advanced Manufacturing Techniques considered in our studies**
- **First steps realizations years ago**
- **More concrete and more recent examples**
- **Conclusions and future activities**

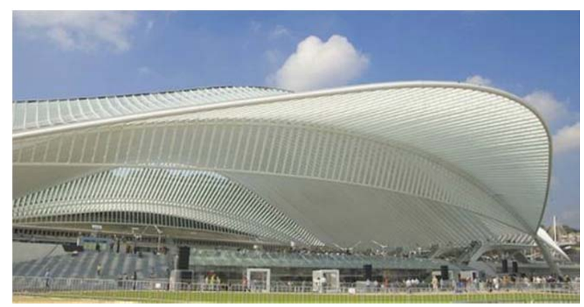
Location

Centre Spatial de Liège
Liege Science Park
Avenue du Pré-Aily, B-4031 Liège
Belgium
+32 4 382 46 00

GPS:
N 50.5980
E 5.5660



We're located 6 km south of the city centre of Liege, next to the University Campus



Liege « Space Pole »

Introducing CSL

- **<u>C</u>entre <u>S</u>patial de <u>L</u>iège**
- **R&D Organisation (non-profit), University of Liege**
- **Active in space instruments engineering and testing since the 60's**
- **ESA-recognised test centre**
- **ESA-C-o-Excellence in Optics**
- **Develops Space & Earth Science Instruments or subsystems**
- **Payroll ~95 FTEs**
- **Turnover ~11.5 M€ (2013)**
- **More… http://www.csl.ulg.ac.be/**

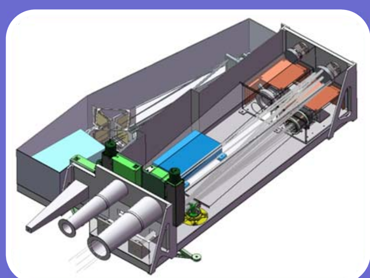
CSL main entrance

Planck spacecraft entering CSL vacuum chamber

Products & Services: 3 Business Lines

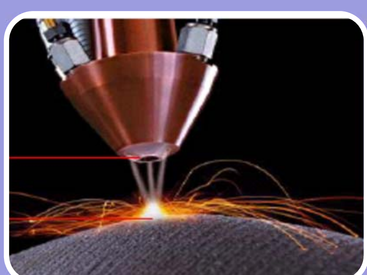
Testing (Resp. Christophe Grodent)

- Environmental test services (thermal-vacuum, vibration…)
- Development of test systems (thermal systems…)
- Rare & complex test equipment



Space Systems (Resp. Etienne Renotte)

- Space mission studies
- Space instrument, payload elements
- Technology development for space applications
- Ground calibration, ground support equipment



Technological Partnering (Resp. Jean-Hervé Lecat)

- R&D support, expertise to industry
- Technology upgrade or validation (TRL raising)
- Technology transfer and services
- Customized training

Space Systems Projects

Science
- TD1, GIOTTO, HST, SOHO, XMM, INTEGRAL, CoRoT, PROBA-2, Herschel, JWST…
- S1 (CHEOPS); M1 (SolO); M2 (Euclid); M3 (EChO/Plato); L1 (JUICE(MAJIS/UVS)/Athena)…
- MoO (Proba-3, ICON…)

Exploration
- ExoMars/TGO 2016 (NOMAD)
- LaRa, Lunar Lander Mars lander

Earth Observation
- VEGETATION, ENVISAT, METOP, Sentinel-2, Sentinel-3, Sentinel-4, MTG…
- (SAOCOM/TreeVol), PROBA-V, PROBA-V Successor

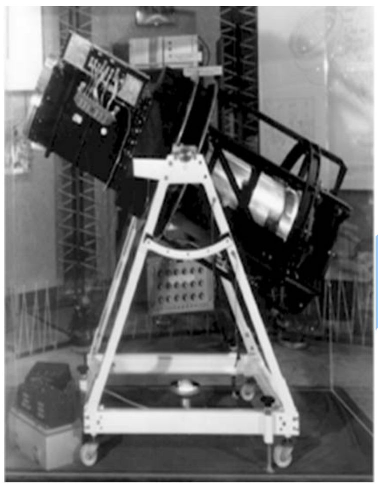
SSA (Space Weather)
- IMAGE, STEREO, ICON (with NASA)
- KuaFu (with China)
- ESIO

Manned Space Flights
- RAMSES/SBS (IML2)
- COLUMBUS FSL VMU

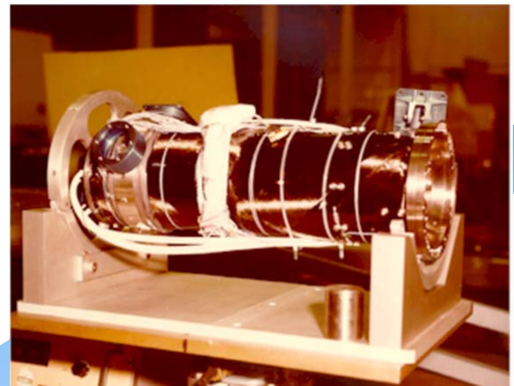
+ Technologies…..
Interest in Advanced Manufacturing Methods

Space Instruments

1967-1972 : Design, manufacture and calibration of the S2/S68 experiment aboard the TD1 satellite for a sky survey in the ultraviolet

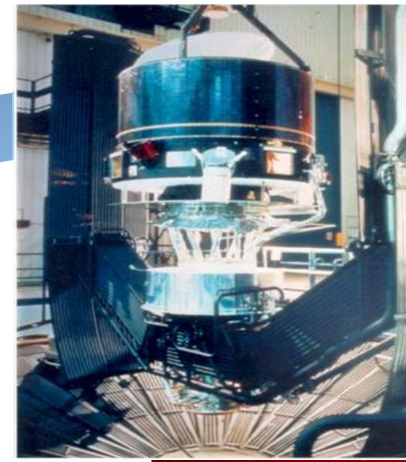


1978-1988 : HUBBLE Space Telescope



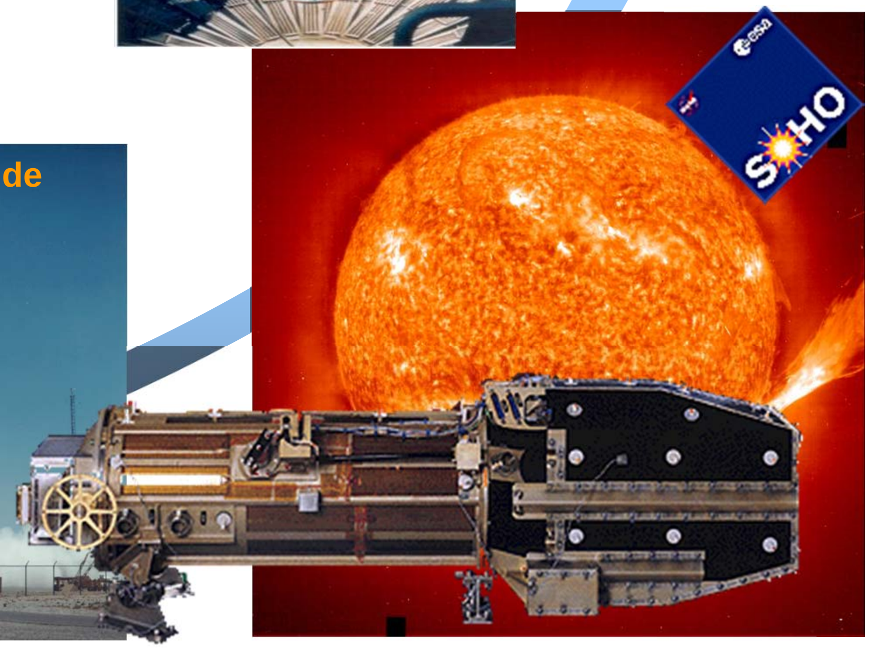
Qualification et calibration of the Photon Detector Assembly of the Faint Object Camera

1982-1985 : development of the Halley multicolour camera on the ESA Giotto satellite



1988-1995

SOHO-EIT



11 in space in

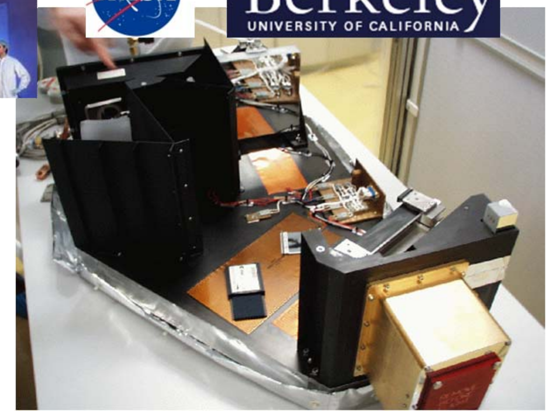
L1, L2, LEO, HEO, EPO, SO

2 delivered 5 in preparation to go to SSO

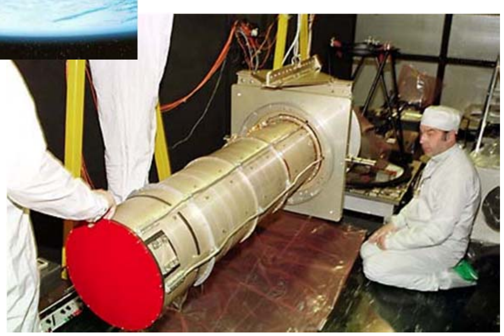
Past Projects (1/2)

SOHO/EIT (1995)

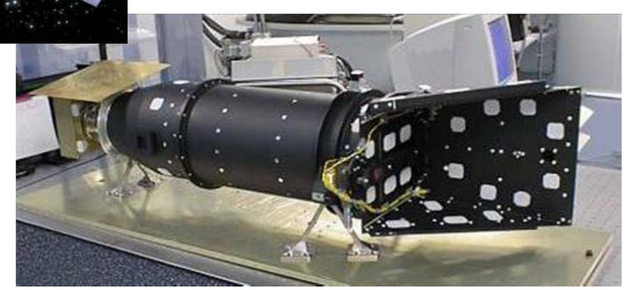
IMAGE/FUV-SI (2000)



XMM/OM (1999)

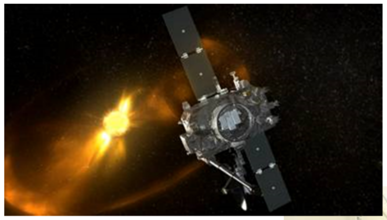


INTEGRAL/OMC (2002)



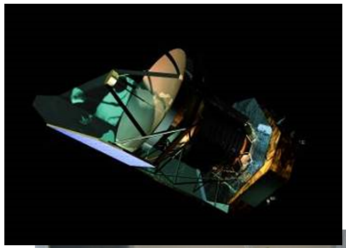
10

Past Projects (2/2)

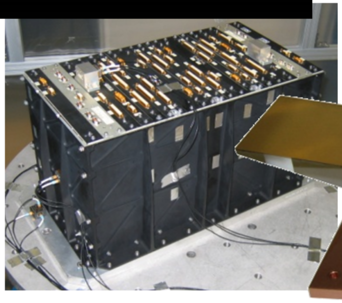


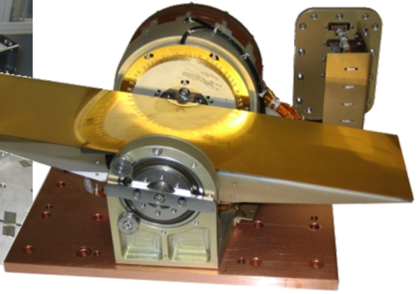
STEREO/HI (2006)

CoRoT (2006)

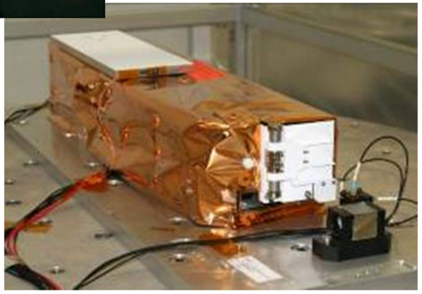


Herschel/PACS (2009)





PROBA-2/SWAP & LYRA (2009)



JUNO/UVS (2011)

11 instruments in space

Participation to ESA Science Missions

Mission	Launch	H/W	Tests	Mission	Launch	H/W	Tests
TD_1 A *Giotto* Hipparcos *HST (NASA)*	1974 1985 1989 1990	X X X	X X X X	GAIA	2013	-	X
SOHO	1995	X	-	LISA-Pathfinder	2014	-	-
CASSINI-H. (NASA)	1997	-	-	*ASTRO-H (JAXA)*	2014	-	-
XMM	1999	X	X	BEPI-COLOMBO	2015	-	X
IMAGE (NASA)	2000	X	-	*MICROSCOPE (CNES)*	2016	-	-
CLUSTER	2000	-	-	SOL. ORBITER (M1)	2017	X	-
INTEGRAL	2002	X	-	CHEOPS (S1)	2017	X	?
MARS-EXPR.	2003	-	-	*JWST (NASA)*	2018	X	X
ROSETTA	2004	-	-	*Solar Probe+ (NASA)*	2018	X	-
VENUS-EXPR.	2005	-	-	EUCLID (M2)	2020	X	X
HINODE (JAXA)	2006	-	-	JUICE (L1)	2022	X	?
COROT (CNES)	2006	X	X	*SPICA (JAXA)*	2022	X	?
STEREO (NASA)	2006	X	-	PLATO… (M3)	2024	?	?
HERSCHEL	2009	X	X	??? (L2/L3) ATHENA	(Call for ideas)		
PLANCK	2009	-	X	??? (M4)	(Call in 2014)		
PROBA-2	2009	X	-	??? (S2)	(Call in 2015)		
JUNO (NASA)	2011	X	-	PROBA-3		X	

ICON NASA

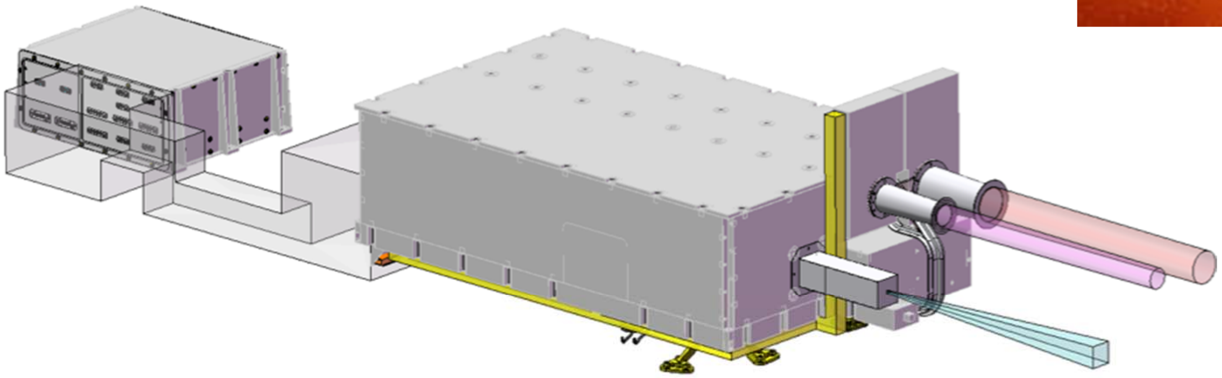
www.esa.int/ESA/Our_Missions

Participation to ESA Science Missions


planck
Launched: 2009
Mapping the cosmic microwave background
CSL
smos
Launched: 2009
Measuring soil moisture and ocean salinity
atu
Launched: 2008, 2011, 2012
Space truck for ISS resupply
columbus
Launched: 2008
Europe's ISS research laboratory
metop series
Launched: 2006, 2012
Polar meteorological services
cryosat
Launched: 2005 (failed), 2010
Measuring polar-ice thickness
venus express
Launched: 2005
Europe's first Venus orbiter
giove-a & b
Launched: 2005, 2008
Technology demonstration for Galileo
sloshsat
Launched: 2005
Investigating fuel sloshing effects
rosetta
Launched: 2004
Deep space comet rendezvous mission
mars express
Launched: 2003
Europe's first Red Planet orbiter
smart-1
Launched: 2003
Experimental Moon mission
envisat
Launched: 2002
10-instrument environmental satellite
CSL
integral
Launched: 2002
Gamma-ray astronomy
CSL
msg series
Launched: 2002, 2005, 2012
Second-generation European meteorology satellites
CSL
artemis
Launched: 2001
Technology demonstration for telecommunications
proba series
Launched: 2001, 2009, 2013
Technology demonstration microsatellites
CSL
xmm-newton
Launched: 1999
X-ray astronomy
CSL
ard
Launched: 1998
First European experimental reentry vehicle
huygens
Launched: 1997
Surface probe of Saturn's moon Titan
cluster
Launched: 1996 (failed), 2000
Space plasma physics in 3D
iso
Launched: 1995
Infrared astronomy
CSL
soho
Launched: 1995
Continuous observation of the Sun
CSL
eureca
Launched: 1992
Reusable free-flying microgravity testbed


ers-1 & -2
Launched: 1991, 1995
Radar-based Earth observation
hubble space telescope
Launched: 1990
ESA contributed solar arrays and Faint Object Camera
CSL
ulysses
Launched: 1990
Charting space above and below the Sun's poles
hipparcos
Launched: 1989
Mapping the positions of more than 100 000 stars
CSL
olympus
Launched: 1989
Technology demonstration for telecommunications
giotto
Launched: 1985
Intercepting Comet Halley and Comet Grigg–Skjellerup
CSL
exosat
Launched: 1983
X-ray astronomy
ecs series
Launched: 1983, 1984, 1985, 1987, 1988
Operational European telecommunications satellites
spacelab
First launched: 1983
Laboratory module for NASA's Space Shuttle; 22 launches
marecs series
Launched: 1981, 1982 (failed), 1984
Maritime telecommunications satellites
ariane
First launch: 1979
Commercial launcher securing Europe's non -dependent space access
iue
Launched: 1978
Ultraviolet astronomy
isee-2
Launched: 1977
Charting Sun–Earth relations and magnetic field
geos-1 & -2
Launched: 1977, 1978
Probing dynamics of Earth's magnetic field, waves and particles
meteosat series
Launched: 1977, 1981, 1988, 1989, 1991, 1993, 1997, 2002
Europe's weather satellites for daily forecasting
CSL
ots-1 & -2
Launched: 1977 (failed), 1978
Demonstrating technologies for telecommunications
cos-b
Launched: 1975
Gamma-ray astronomy
td-1
Launched: 1972
UV, X-ray and gamma -ray astronomy
CSL
esro series
Launched: 1967 (failed), 1968, 1969, 1972
Scientific exploration of space's particle and radiation environment
heos-1 & -2
Launched: 1968 & 1972
Probing Earth's magnetic field and the interplanetary medium

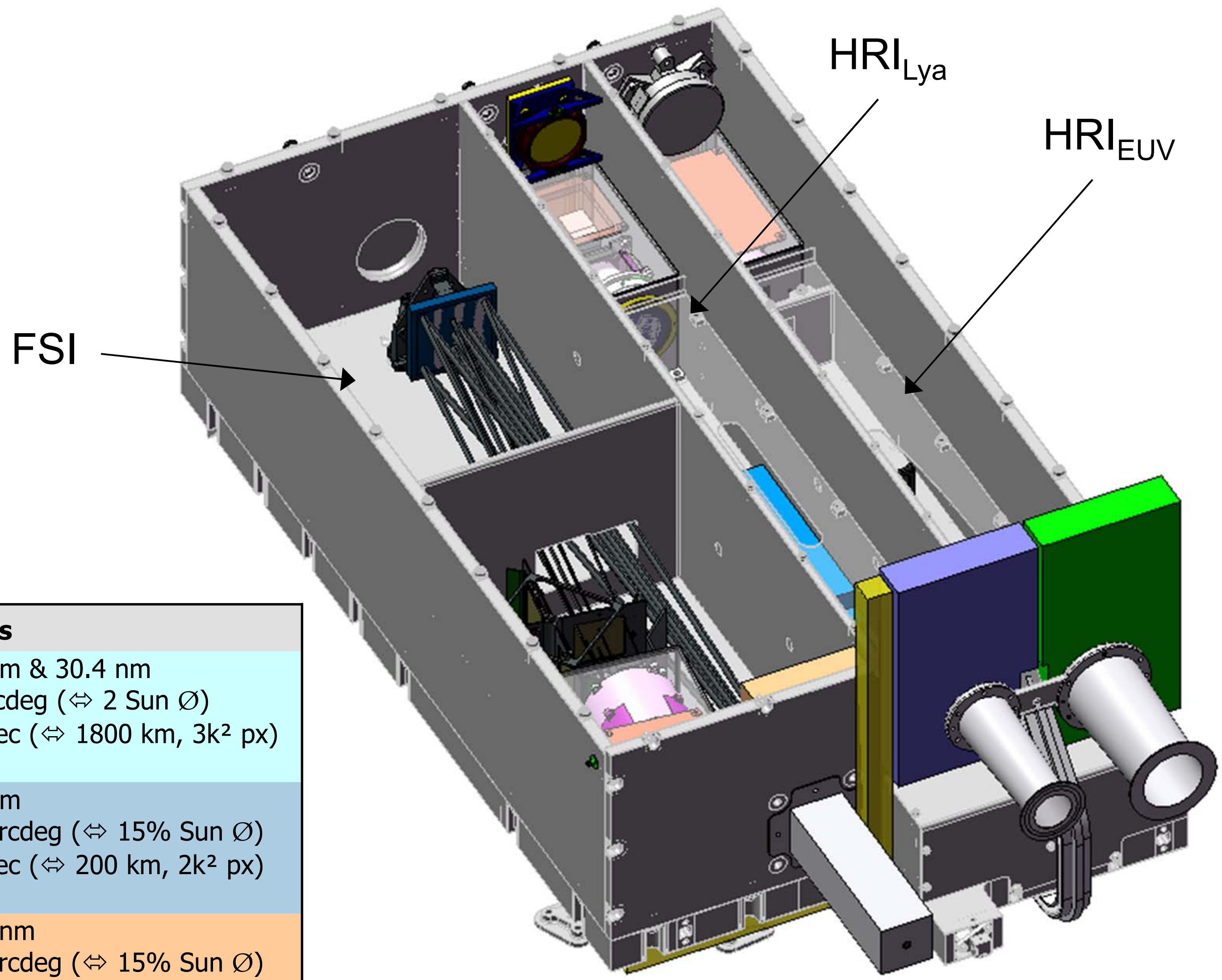
EUV Imager (EUI) on board Solar Orbiter



EUI overview

OBS

- **3 telescopes**
- **4 channels**



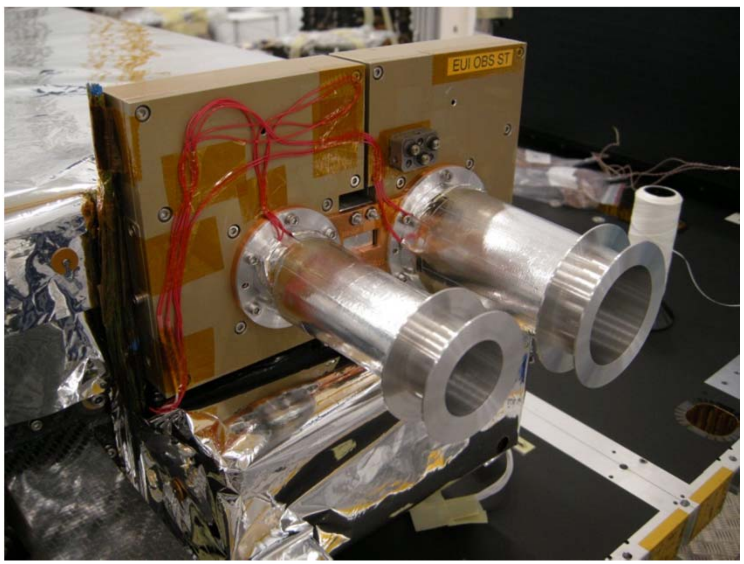
Channel	Parameter	Values
FSI	Passbands	17.4 nm & 30.4 nm
	FOV	3.8 arcdeg (⇔ 2 Sun Ø)
	Resolution (2 px)	9 arcsec (⇔ 1800 km, $3k^2$ px)
	Cadence	600 s
HRI_{EUV}	Passbands	17.4 nm
	FOV	0.28 arcdeg (⇔ 15% Sun Ø)
	Resolution (2 px)	1 arcsec (⇔ 200 km, $2k^2$ px)
	Cadence	≥ 1 s
HRI_{Lya}	Passband	121.6 nm
	FOV	0.28 arcdeg (⇔ 15% Sun Ø)
	Resolution (2 px)	1 arcsec (⇔ 200 km, $2k^2$ px)
	Cadence	≤ 1 s

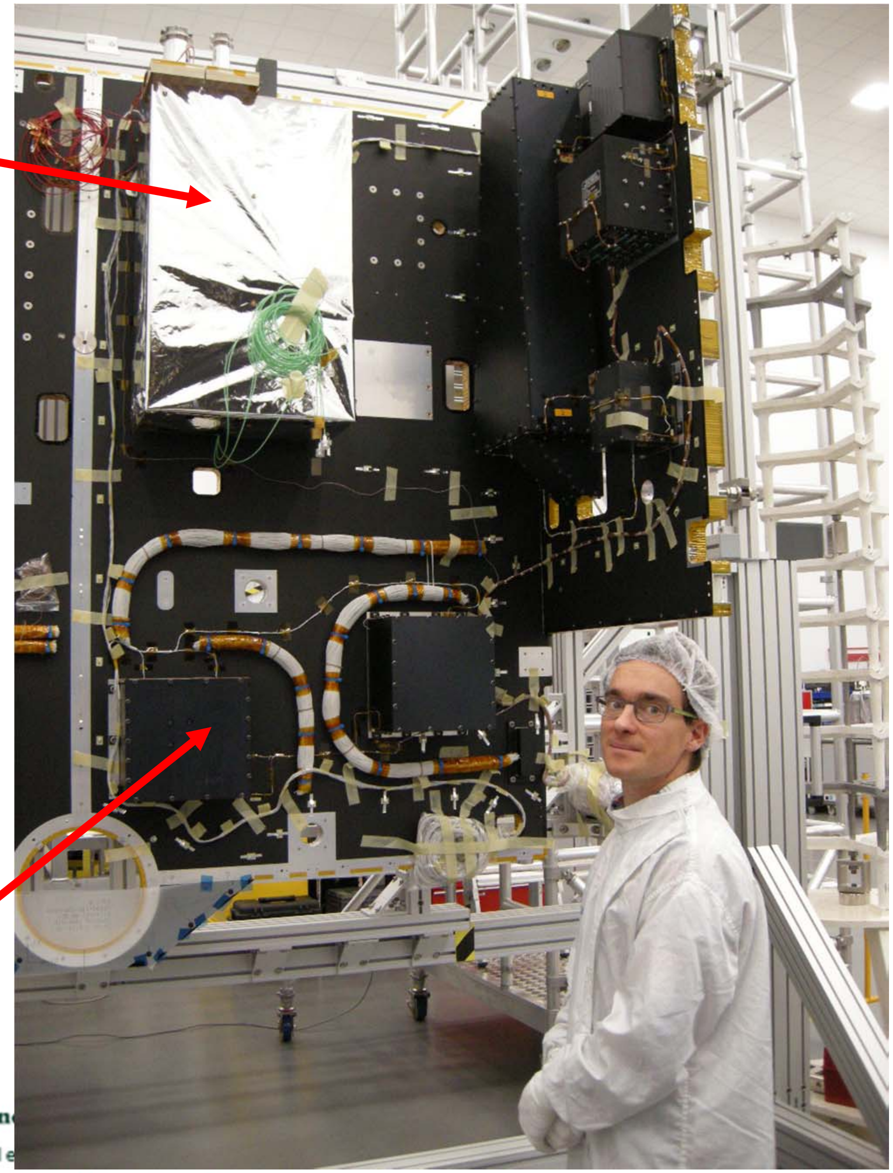
(at perihelion)

S/C STM

OBS STM

Second accelerometer on OBS STM

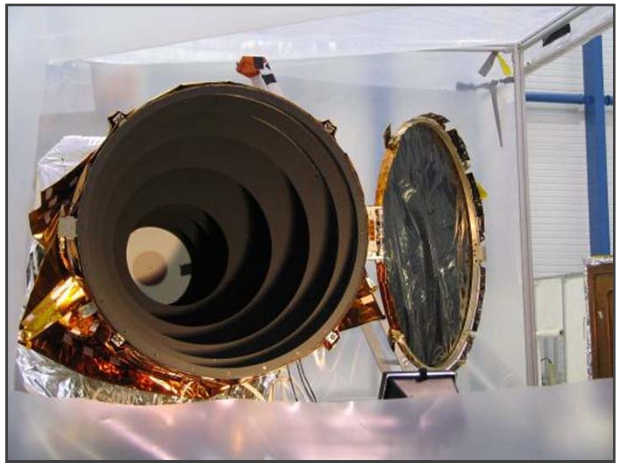




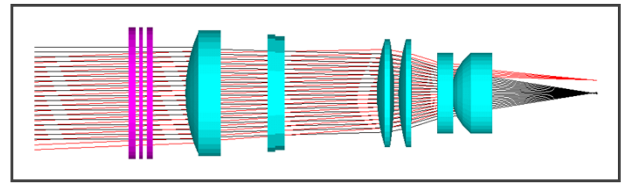
CEB MTD

Optical Systems

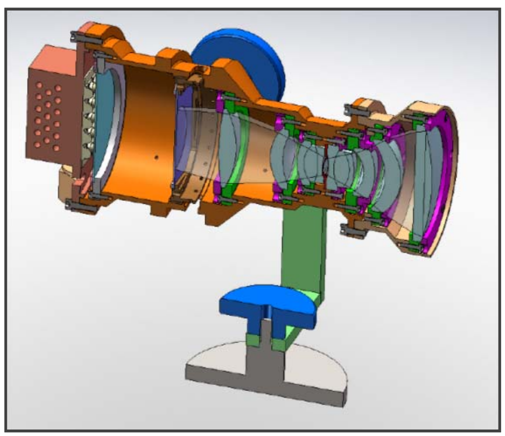
Optics & coatings

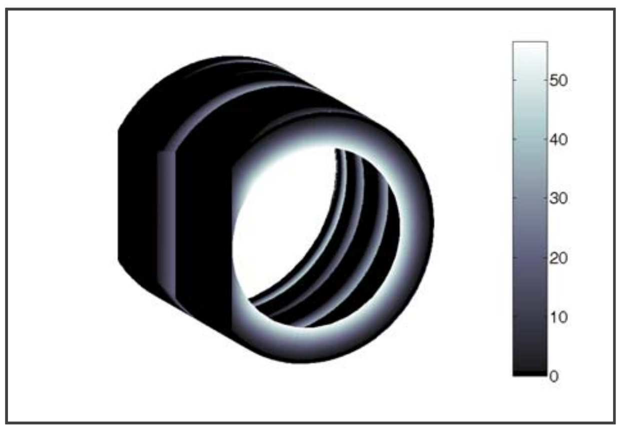


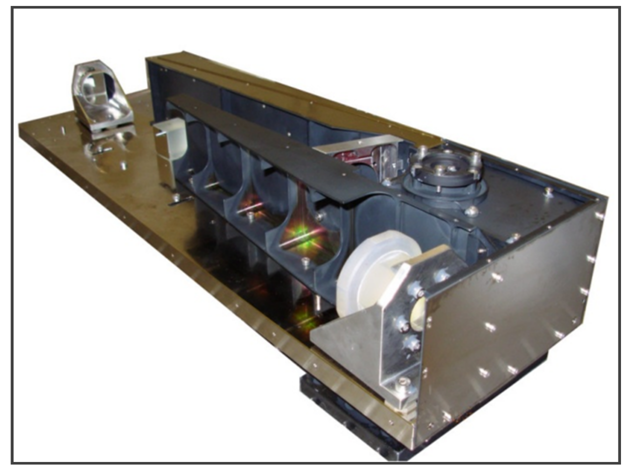
Baffle design &
stray-light analyses



Ray-tracing

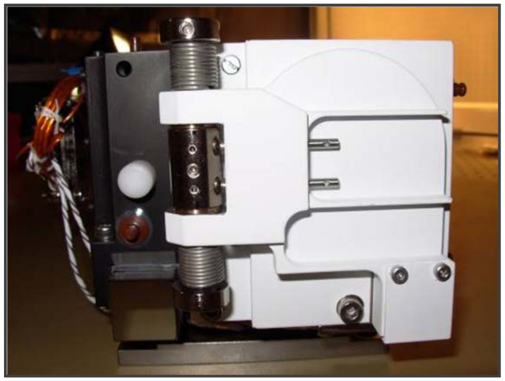




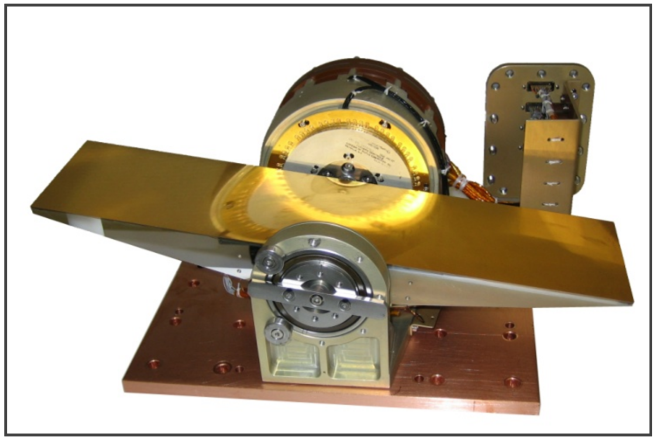


Complete optical instruments
or sub-assemblies

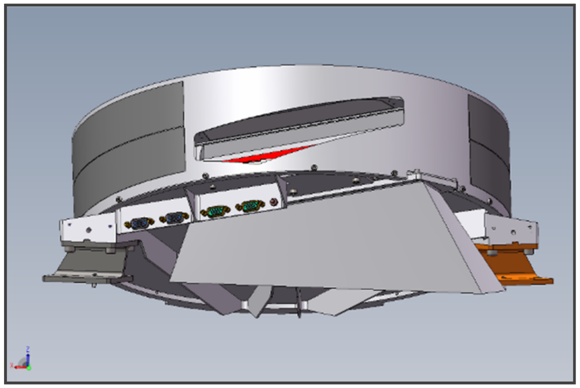
Mechanisms



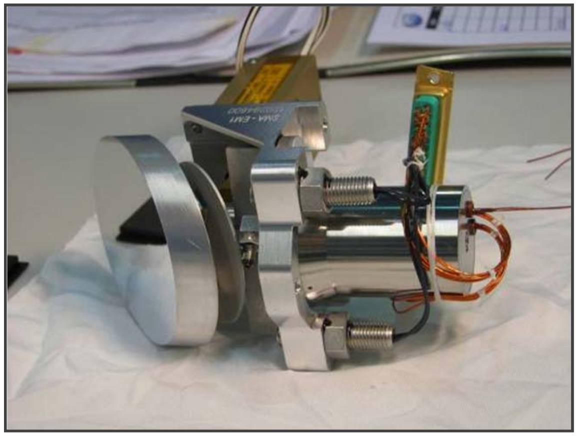
Cover mechanisms



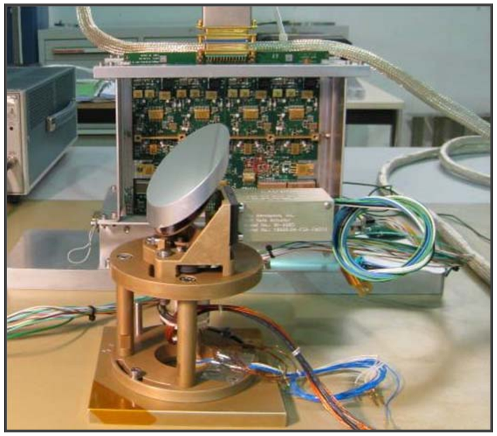
Positioning mechanisms operating in extreme environment (4K)

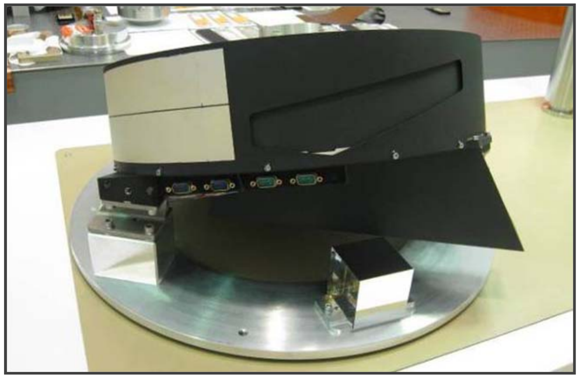


Wheel mechanism

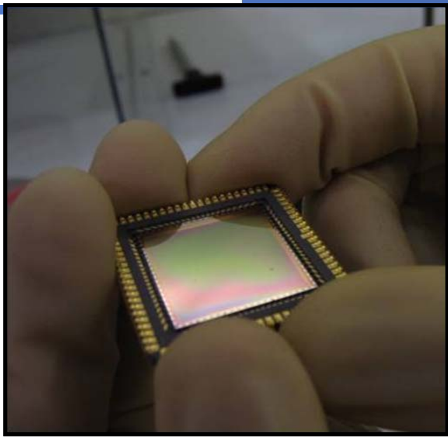


Scan mirror



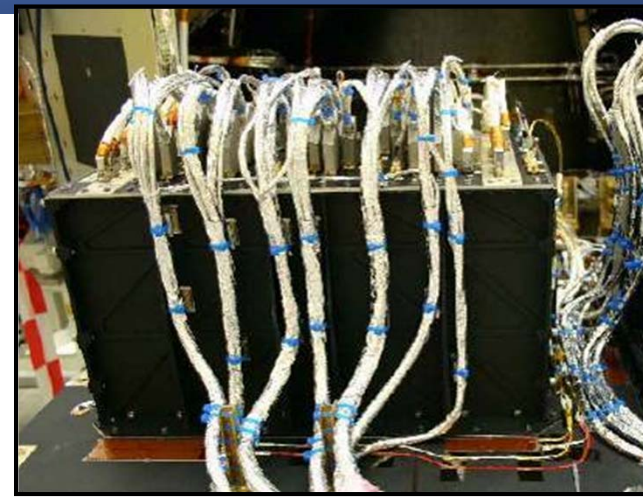


Electronics



Detectors

Processor & software



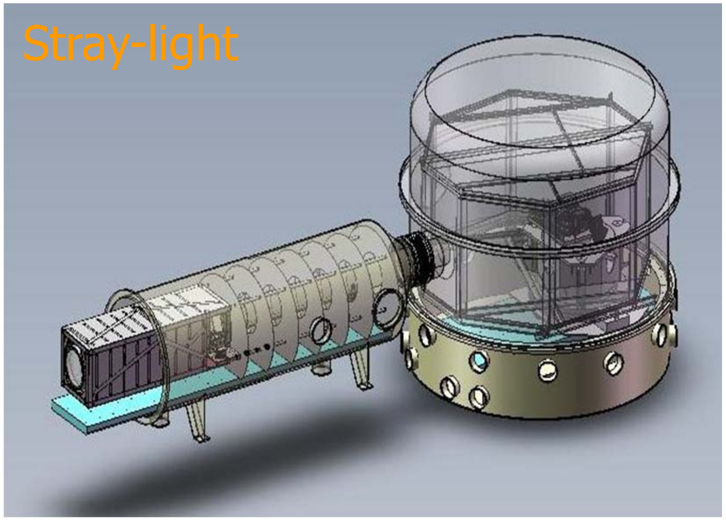
Detector controllers

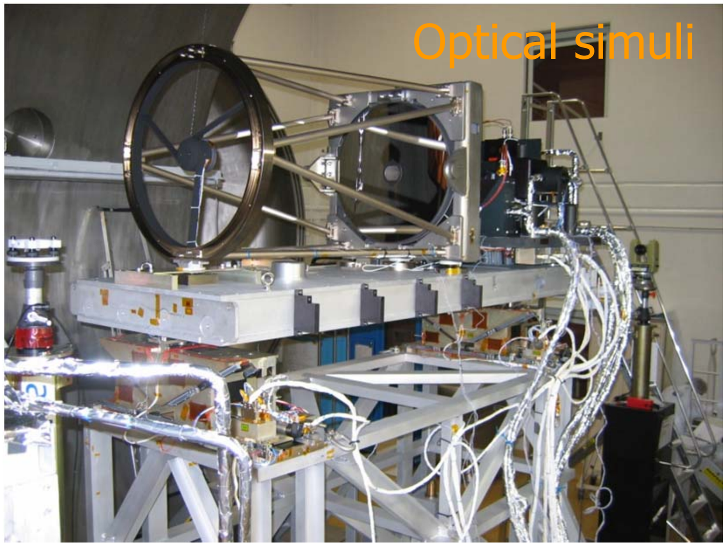
Power conditioning

EGSE

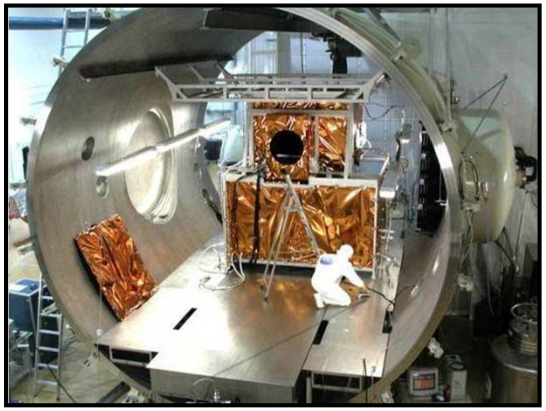
Mechanism controllers

GSE & Calibration Facilities





AIV, Testing Facilities



1,000-m² integration clean rooms (ISO-7 / ISO-5)

Cryogenics (LN_2 & LHe)

Th. Vac. chambers from ∅1.5-m… up to ∅6.5-m

Shakers (90 kN – 200 kN)

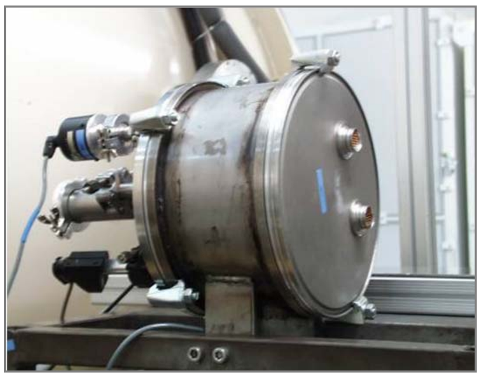
Vacuum Environment

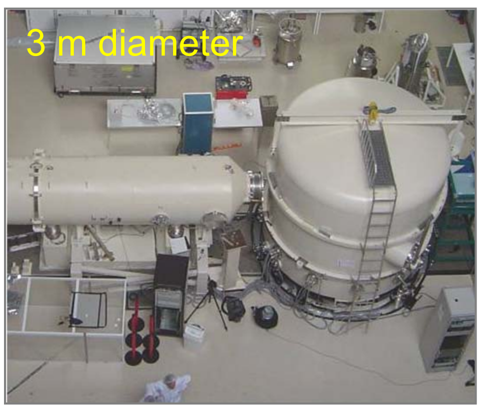
✓ CSL houses chambers with extended vacuum capabilities and with 0.25-m to 6.5-m diameter

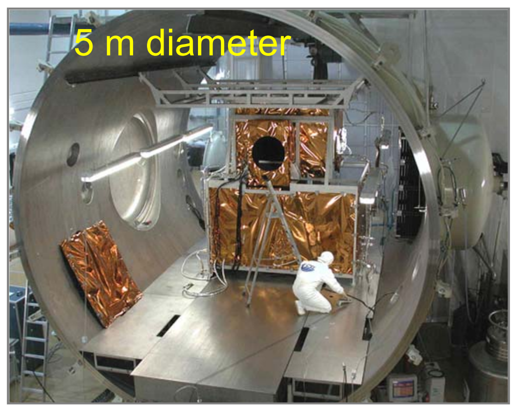
✓ The chambers are equipped with primary and turbo pumping system

✓ Cryogenic pumping available as well

✓ Most of the chambers are equipped with optical bench laying on seismic device allowing ground vibration decoupling







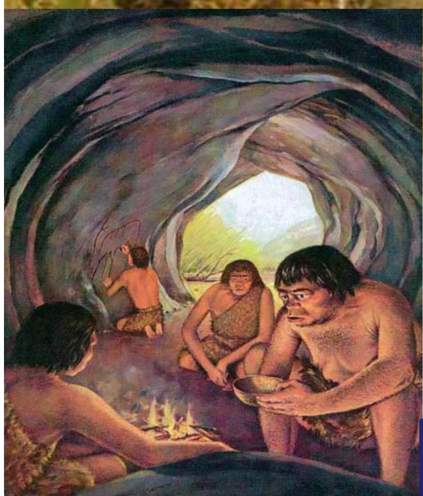
Motivations and Objectives of the ALM project

- **Why this project ?**
  - Several Additive Layer Manufacturing **technologies matured to a level compatible with space** applications
  - They are well suited to
    - Space flight hardware since they are applicable to **unique parts or small series**
    - Unique GSE→ **complex test Ground Support Equipment's**.
  - Nevertheless there is a need to better understand **their optimal implementation within design and manufacturing chain**
    - Design for manufacture and assembly typically means that **designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs.**
  - **Compatibility with Space environment**
  - Additive Manufacturing: **Making Imagination the Major Limitation**
- **Background of the project**
  - SIRRIS is highly implied in additive manufacturing techniques for several years
  - SIRRIS and CSL participated in a similar project with KULeuven in 2003 (with Belgian funding)
    - *"New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation"* P. Rochus (CSL), J.-Y. Plesseria (CSL), J.-P. Kruth (KUL), M. VanElsen (KUL), T. Dormal (CRIF), R. Carrus (CRIF), IAC-06-C2.8.05, International Astronautical Congress, Valencia, 2006 and Acta Astronautica 61 (2007) 352 – 359
  - TAS-F and ALMASpace are closely following all advanced technologies in order to improve the performances of their instruments and increase the fly-to-buy ratio of their development

Outline of the presentation 2

- Space instrumentation and Space Environmental testing activities at CSL
- **Dreams, a priori expectations and space specificities**
- Advanced Manufacturing Techniques considered in our studies
- First steps realizations years ago
- More concrete and more recent examples
- Conclusions and future activities

From Rapid Prototyping to Rapid Tooling and Direct Manufacturing.



Disruptive technologies

Classical manufacturing | **Direct manufacturing (ALM)**

Soustractive | **Additive**

Manufacturing

General Status of ALM

Additives manufacturing technologies using metals are now able to produce **functional, complex and optimized parts**, which make them attractive for the **aerospace sector**.

The **geometrical complexity** achievable with those technologies gives a lot of possibilities for designers to make part

- more efficient
- lighter,
- less energy/material consuming,
- internal cavities/channels capabilities,

Making Imagination the Major Limitation

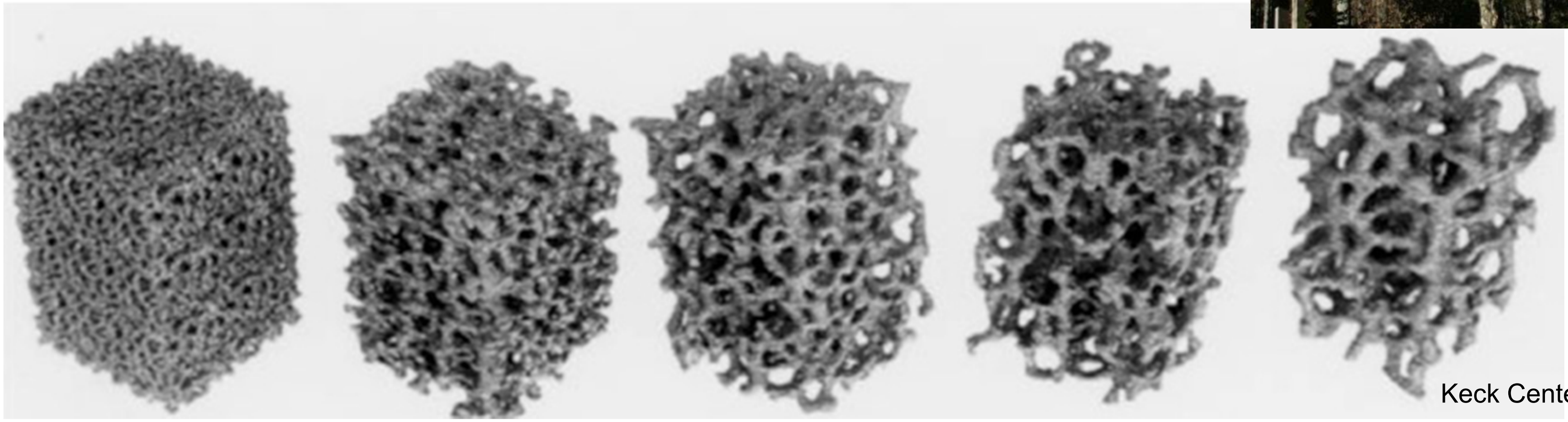
There are a lot of advantages by using those AM machines and the part produced can be really competitive compared to traditional technologies like machining, injection or foundry.

Some comparative studies have already shown valuable gain in mass, manufacturing time and environmental aspect regarding energy consumption reduction.

Why Use AM?

1. Reduce Cost.

2. Fabricate structures that would otherwise be impossible prohibitively expensive to build (see reduce cost).
   - Complex geometries
   - Multi-material structures
   - Fully encapsulated devices
3. Possibilty of a High Surface to Volume ratio (without being at nanoscale), like the leaves of a tree



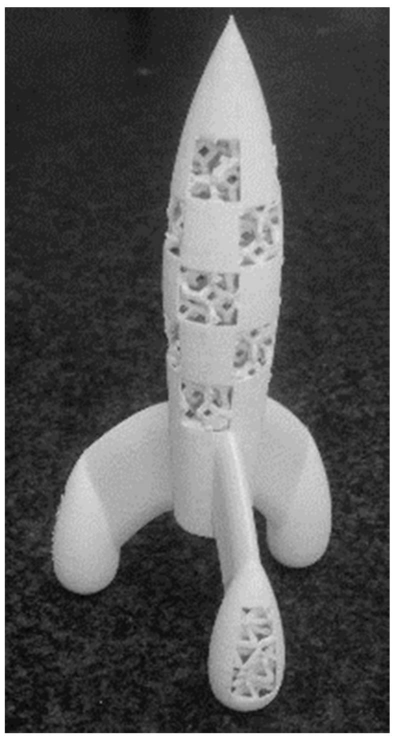
Keck Center

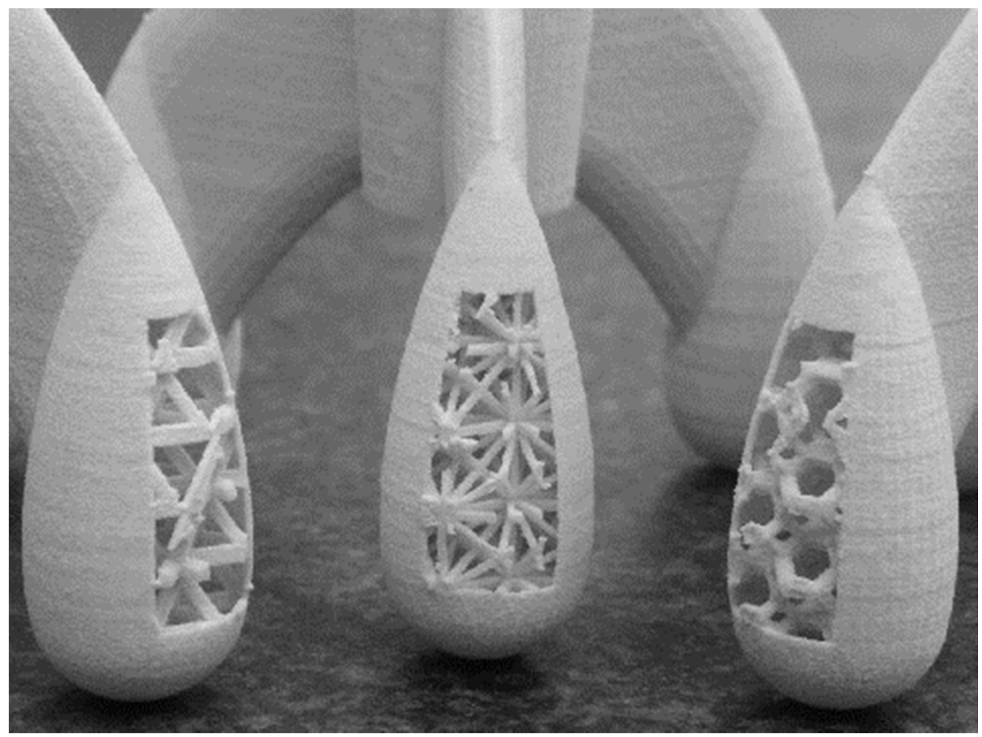
Metal Foam produced through Electron Beam Melting

Designing for RP/RM

Plain volumes

- **Full density volume something to avoid : heavier, longer to manufacture and overheating can occur due to the several passes of the laser in close locations.**
- **Plain volume converted in hollow structure.**
- **Some analyses have been performed in the frame of the project to even optimise this hollow structure as would be done for a 2D honeycomb panel.**

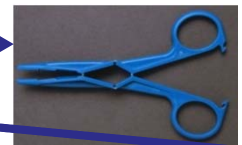




Possibilities

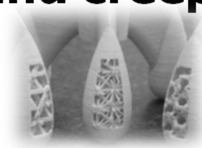
- **Reduce the number of parts**
- **Integrated functions (hinges, snap-fit's, springs)**

- **Compliant mechanisms**



- **Internal channels**

- **Lightweight parts (topology optimization)**
- **Bi-materials**
- **Variable density (graded or controlled porosity)**
- **Functionality graded material (optomechanics, 3 differents Ti alloys with 3 specific functions: impact resistance, fatigue and creep)**
- **Internal structures for**
  - maximum weight reduction with minimal strength reduction
  - local variation of lattice types --> graded porosity, **intended anisotropy**, ...
  - shock damping, vibration reduction



- **Integrated electrical circuit**
- **New technologies available soon : Laser Induced Forward Transfer (LIFT), Two-photon polymerization, the femtosecond (10-15 sec) laser systems**

AM shows very attractive qualities

- Decrease of the parts weight through optimized design. This "topological optimization", performed with special software, like **Samcef, SolidThinking or 3-matics**, leads to quite **"organic" geometries that are therefore not achievable using traditional machining**;
- Thanks to layer-by-layer manufacturing, geometry complexity is no more a real obstacle and lattices**, mesostructures or hollow parts** can be produced;
- **The time to market may be reduced up to 75%** depending on the traditional technique used ;
- **Product improvement through design iteration** becomes possible. For instance, **some components of the Mars Rover test vehicles are the result of 70 parts/trials made by additive manufacturing;**
- Lockheed Martin's demonstrated production **wastes reduction down to 10-30%** thanks to AM;
- Part simplification can be achieved at low cost and the assembly effort can be reduced. GE made fuel **nozzle simplification from an assembly of 20 parts to only one**;
- Last but not least, it will **possible to produce part where it is needed**. NASA planned to install AM device in the ISS and architects Fosters and Partners have designed buildings to be made by AM on the Moon.

Space telescopes trends

- **The next generation of space telescopes will require structures and reflectors with large dimensions and high surface figure quality. → difficult to build and test**
- **Weight issues are forcing the struc... and reflectors to b... ...upportive technologies ... materials.**

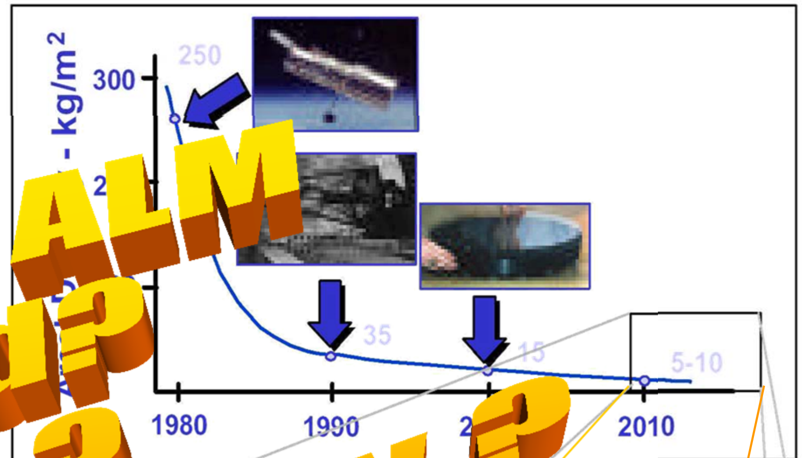
A dream by ALM on ground? in space ? under microgravity ?

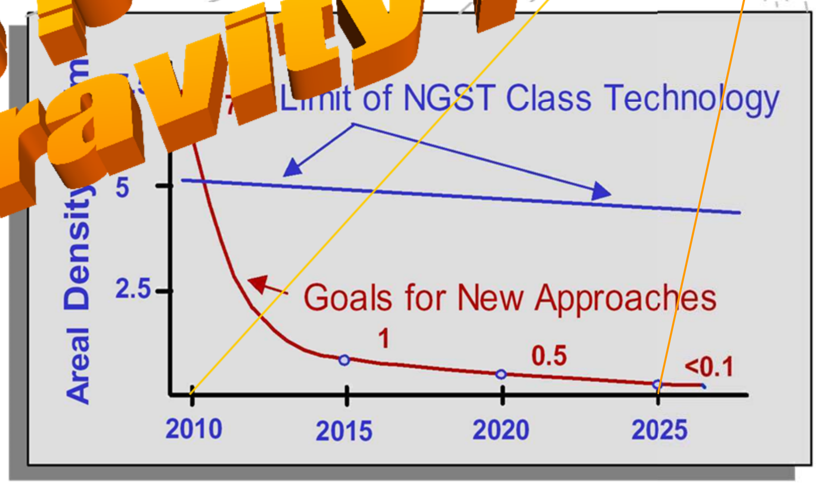
<u>**Light Weight mirrors**</u>

HST 250 kg/m²,
HERSCHEL : 21 kg/m²,
JWST 15 to 5 kg/m²
and one day 1kg/m² ?

H... would ... 1.5 to ... of 300 ... traditional technology

- 3 D Printing
- Variable porosit...
- Variable ...
- FGM
- Ionic polishing

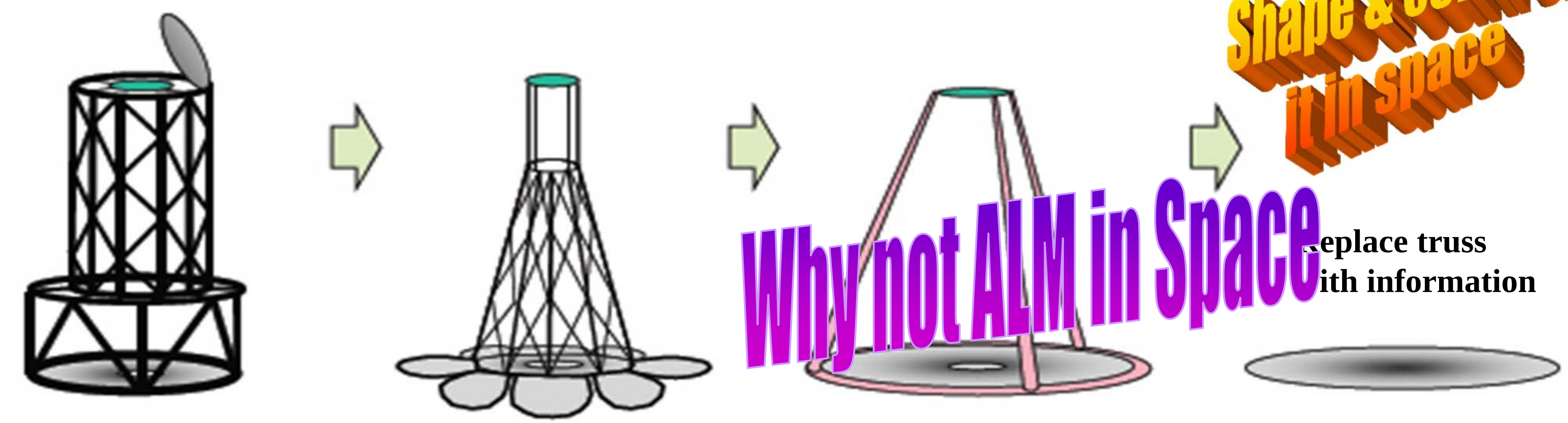




Optics Innovations are Required

EVOLUTION OF OPTICAL SPACE TELESCOPES

Shape & control it in space



Hubble Design (unitary)	JWST Design (deployable)	Inflatable design (concept)	Bekey Concept (no structure)
2,000 kg/sq.m	40 kg/sq.m	≈ 10 kg/sq.m	0.53 kg/sq.m

Comparative total weight of a hypothetical 25 m. diameter telescope

980,000 kg	20,000 kg	5,000 kg	260 kg

Current Application Fields for Direct Manufacturing

- **Aerospace Industry**
- Armament Industry
- Automotive Industry
- Dental Industry
- Electronics Industry
- Furniture Industry
- Implants and Prosthetics Industry
- Jewelry Industry
- Specialty Food Industry
- Sports Industry
- Surgical Devices and Aids Industry
- Textiles Industry
- Tool and Mold Making Industry
- Toys and Collectibles Industry
- Food Industry

The aerospace industry requires parts that are lightweight, strong as well as geometrically complex; they are manufactured in relatively small quantities.

- Systems of Nanospacecrafts
- Space qualification
- OGSE, MGSE, TGSE

Main bottlenecks in the space field

Lack of cases studies which validate the technologies, the **"poor" accuracy** and **repeatability of the processes** which often **need post-machining** and the **"new but unknown"** aspect of these technologies compare to the well-known and experienced conventional machining.

These challenges have to be faced to drive wider adoption of AM in the space field.

However, some conferences about precision in the AM field are now held.

The main problem with space is that **1,5 kg of payload in space costs about 7600€ (and even more for GEO)**. Thanks to AM, it becomes possible to **dramatically reduce weight of parts by an optimized design.**

Special software (like SAMCEF) can perform **"topological optimization"**. That means **"remove a desired quantity of material of a part but maximize its rigidity in a given stressed state".**

But usually, the geometries suggested by this kind of processing are quite "organic" or really complex to manufacture with traditional machining. There are a lot of voids inside (= lot of scraps, accessibility problems,...) and long delivery time due to the complexity.

ALM could be the solution and reduce costs and improve performance of space sensors and systems.

A Comprehensive analysis of the effects of the **space environment on AM materials** and practices must be carried out before the full potential of AM can be realized.

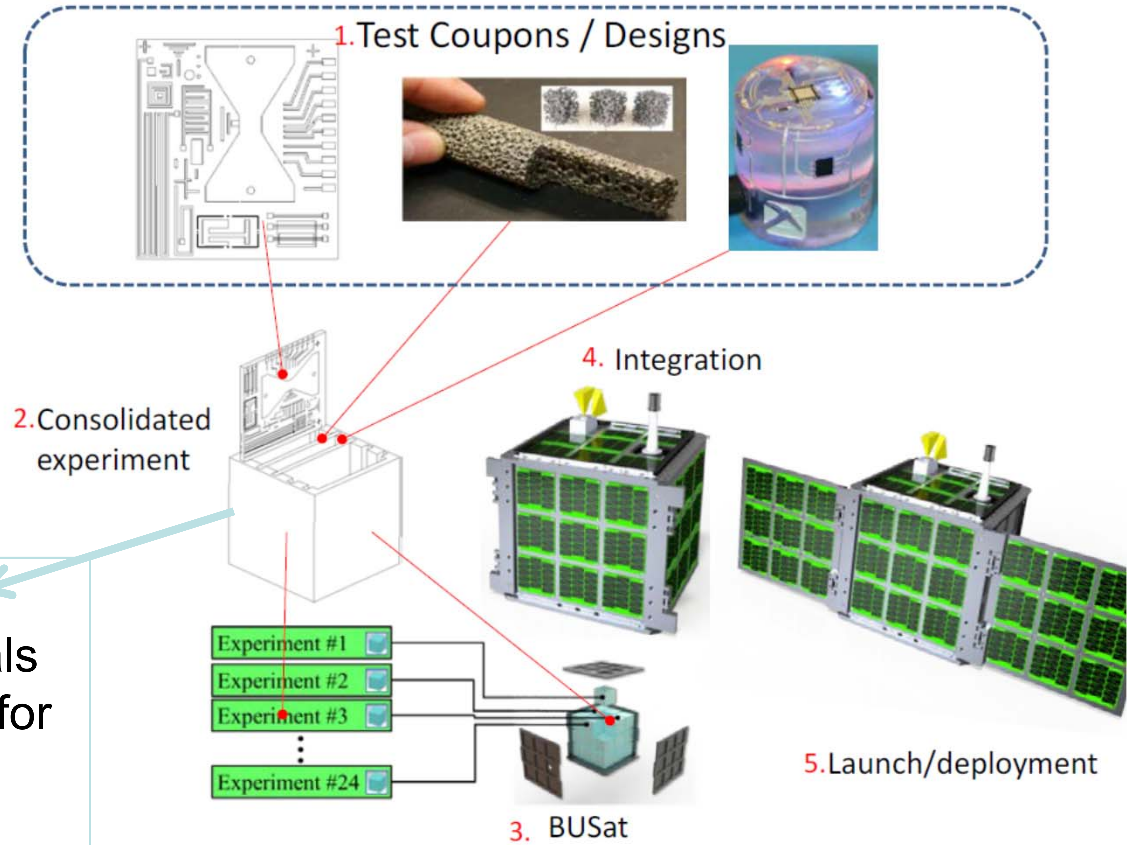
These topics were addressed in our case studies.

AM Materials Testing

- A database of material properties and fabrication procedures is required before AM can be efficiently used in space.

- **Ground testing**
  - Outgassing
  - Environmental evaluation
  - Electrical evaluation
  - Mechanical testing
  - Radiation testing
  - Reliability testing

Flight Testing



Reference database of:

- Space compatible AM materials
- Guidelines and best practices for manufacturing

Space requirements (1)

Space instrument particularities:

- ***Number of pieces**: space hardware generally implies only **a few prototypes and a few parts**. With classical manufacturing or with casting, this imply development of the tools and the procedures only for some pieces causing high cost.*
- ***Complexity**: **the fight for weight** that occurs in space often leads **to parts having a lot of functions in a small volume**. This causes the manufacturing to be very complex. **Most of the time, the manufacturability is a constraint for the design of a piece.***
- ***Need for good knowledge and predictability**: **confidence in the final result predictability and repeatability** is required for space where high reliability is necessary.*
- ***Time constraints and flexibility**: schedule are generally very tight and **time between prototype qualification and flight hardware is generally small.** It is often necessary to apply small modifications to a design and using classical processes, this can lead to the need of redesigning and/or remanufacturing of manufacturing tooling.*

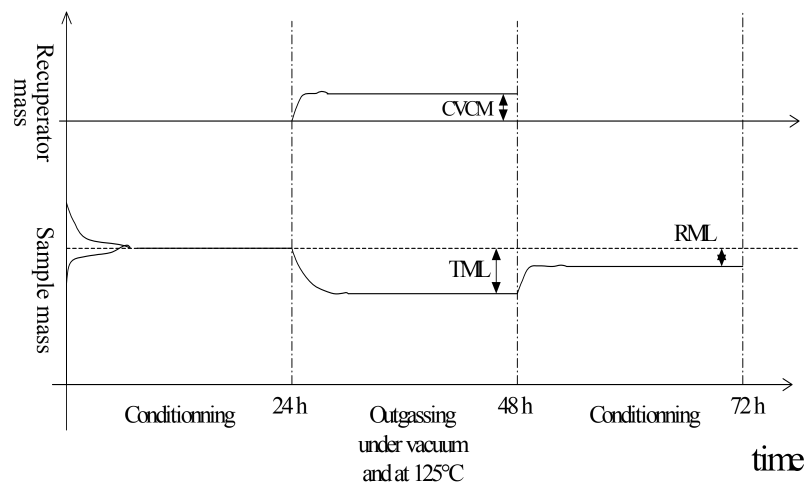
Space requirements (2)

Selection of a material : mainly mechanical, thermal and/or electrical properties.

Specific space requirements: the ***cleanliness, the vacuum resistance and the resistance to radiations.***

Radiation resistance *of the polymers has not been checked in the frame of this project*

The most promising materials (on a mechanical/thermal/electrical point of view) have been tested for ***vacuum resistance according the µVCM test*** *(ECSS-Q-70-02A)* (maximum outgassing rate/quantity of material). **Relative total mass loss (TML) < 1 %. Collected volatile condensed material (CVCM) < 0.1 %.**



Tested samples are Tooling B, Watershed, Polyamid; Injected polyamid; Waterclear, Nylon GF sand blasted; bronze infiltrated stainless steel (prometal) and SiC.

For Watershed, the procedure has been adapted due to the fact that the maximum allowed temperature for watershed is around 60°C. The heating temperature has then been limited to 50°C but the duration has been increased to 5 days. This material was out of specification (mainly because of its low maximum authorised temperature not compatible with standard testing).

ESTEC complete outgassing qualification for: Tooling B, Polyamide PA 2200, Polyamide PA 2200 impregnated with epoxy resin and sintered SiC nanopowder.

Full acceptance for Polyamide, Tooling B and SiC Nanopowder and marginality for impregnated polyamide,

Space requirements (3)

– <u>Cryogenic resistance</u>

- A known phenomena when cooling sintered powder down to liquid helium temperature is a loss of integrity and a return to powder state. A test has been made on sintered SiC and was successful.

– *<u>Needs</u>*

- Full density seems mandatory in space material to avoid contamination that can be trapped in the porosities. (Contamination is difficult to remove a priori and also difficult to prevent). (Except with a coating ?)
- Accuracy is the main problem of rapid manufacturing because the building process implies the use of local thermo-dynamical/chemical process which envelope is not easily defined and localised.
- The materials that are often used in space are aluminium, titanium and SiC. These materials are known to be possible material for RP/RM but only little effort was made up to now to develop them.
- Ti-6Al-4V is studied a lot nowadays !
- *Need for good knowledge and predictability: confidence in the final result predictability and repeatability is required for space where high reliability is necessary. (A lot of parameters in the process to be measured and fixed)*

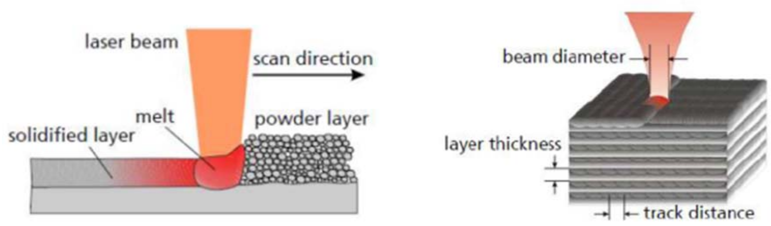
Outline of the presentation 3

- Space instrumentation and Space Environmental testing activities at CSL
- Dreams, a priori expectations and space specificities
- **Advanced Manufacturing Techniques considered in our studies**
- First steps realizations years ago
- More concrete and more recent examples
- Conclusions and future activities

Advanced manufacturing methods

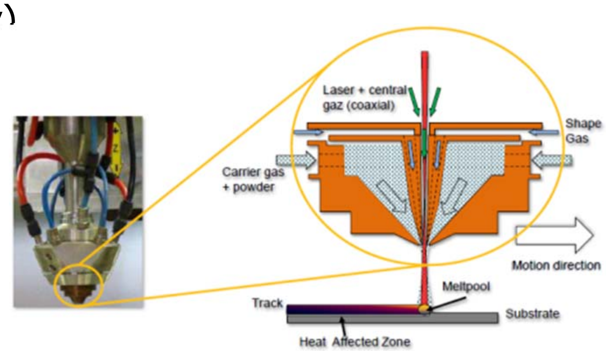
LBM, EBM, L Cladding, aerosol jet printing, LW, EW, Salt Dip brazing, ...

- **Additive manufacturing techniques**
  - Material is added to the part and not removed from a raw block of material
  - Part is built layer by layer (more common method)
    - Some techniques imply the direct injection of powder in the laser beam (laser cladding) allowing 3D building and repair of parts
  - Power sources
    - Laser
    - Electron beam
  - Materials available:
    - Polymers
    - Metals: aluminium, titanium, stainless steel …
  - Improvement of the techniques implies that the pure metal powder is directly melted to form the part (no binding material)
    - Ease manufacturing process and reduce risk (less steps)
    - Improve mechanical properties of material (almost full density)



Pictures from ILT

Laser Beam Melting

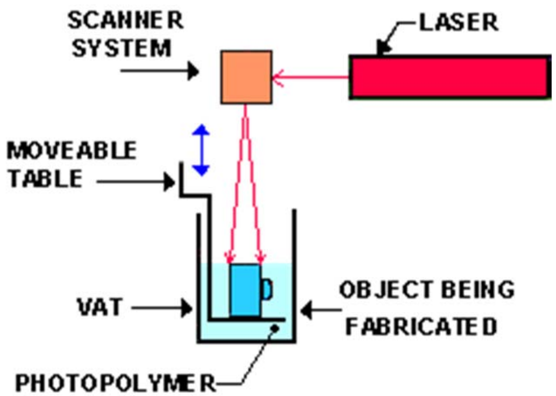


Laser Cladding

Future Flight Vehicle Innovation Competition
www.Futureflightvehicle-competition.org

Rapid prototyping – rapid manufacturing

Stereolithography (SLA)

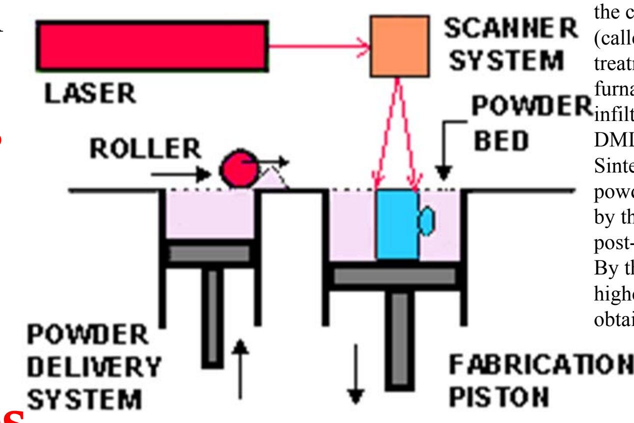


An important variant of this process is based on **paste** polymer

Optoform process

paste can be filled with solid reinforcement (metal or ceramic powder for example). Further treatment (debinding) can also remove completely the original binder component to only keep the metal or the ceramic.

Selective laser sintering/melting (SLS/SLM)



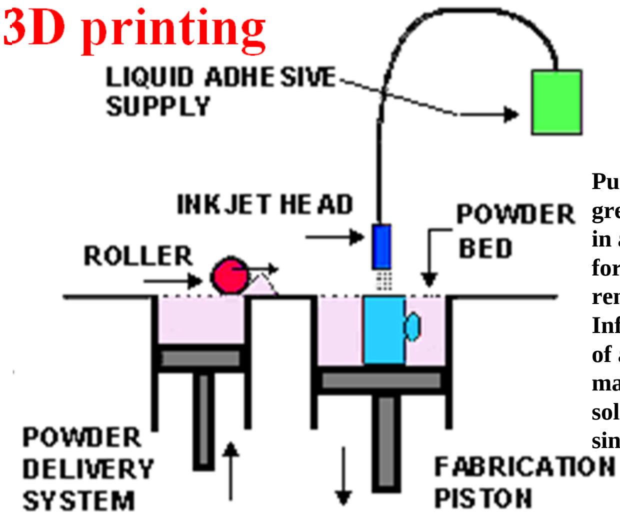
pure polymeric powder, sometimes filled with ceramic or metallic particles (SLS). A low melting point material is melted by the laser and ensures the cohesion of the built part (called green part). Further treatment is performed in a furnace (debinding and infiltration).

DMLS : Direct Metal Laser Sintering). Only one kind of powder and it is directly melted by the laser. No additional post-processing required.

By this method a density higher than 99.5 % can be obtained directly.

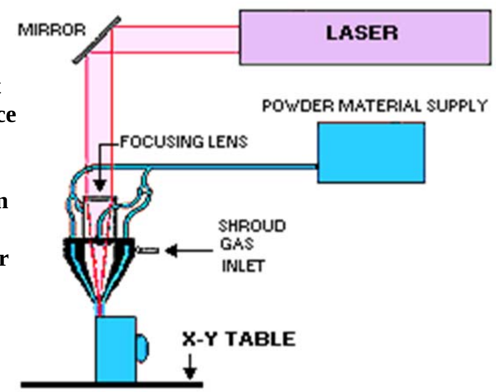
Jet based technologies

3D printing



Put the green part in a furnace for binder removal Infiltration of a filler material or solid state sintering.

Laser cladding



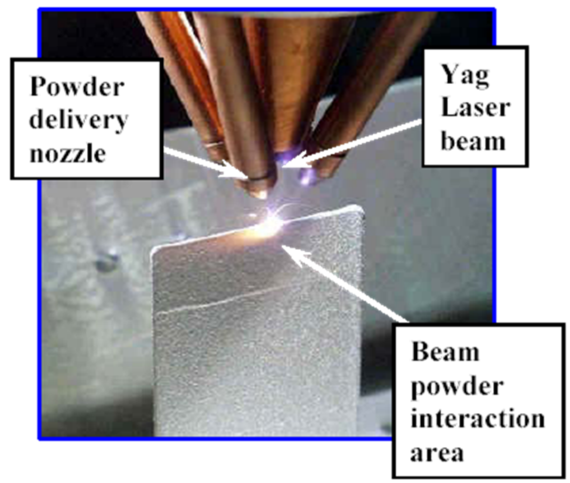
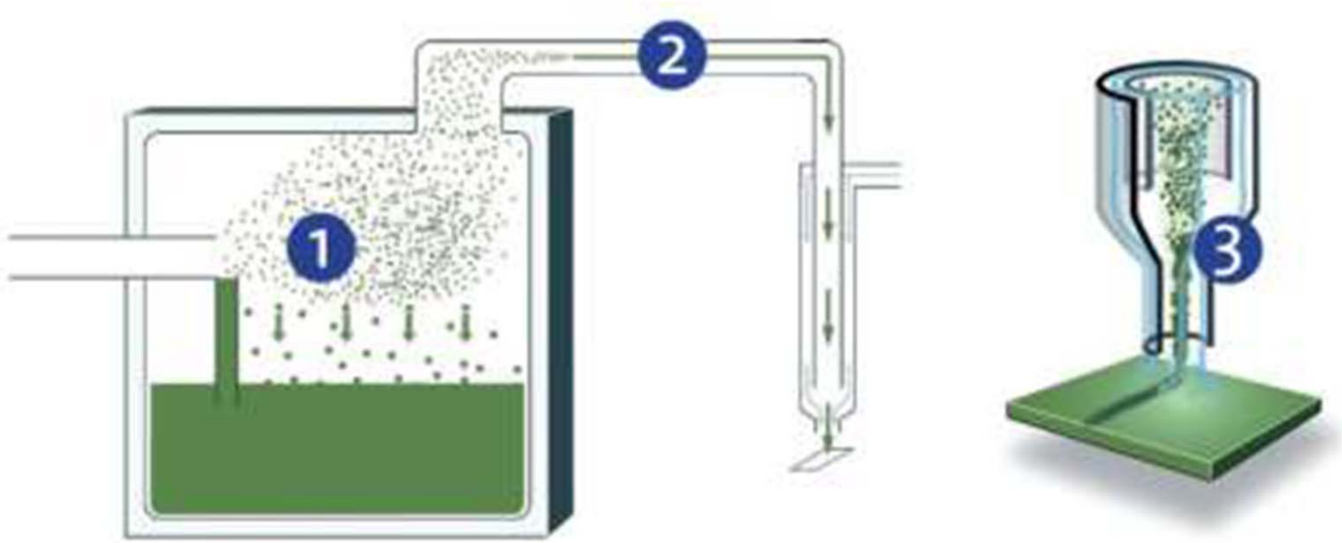


Figure 2-4: Laser cladding technique

Aerosol Jet Printing

Aerosol Jet printing (AJP) is a particularly innovative technique for the selective, maskless deposition of materials (conductive, dielectric, …) at micron- scale, onto any flat but also non-flat , flexible or 2.5 , 3D substrate.
In this technology, an ink (solution or suspension of nanoparticules) in a jar is atomized by ultrasonic or pneumatic mechanism. Resulting aerosol jet is then transfer red (2) to a writing nozzle (3) where it is driven (thanks to a sheath gas) towards an X-Y-moving substrate. Moreover , z-axis is al so motorized, which al lows 3D substrates to be considered for any printing job. The printed material is directly and locally sintered by a laser



Aerosol Jet Printing : principle

The four most important processes: laser melting, electron beam melting, laser cladding and 3D Printing.

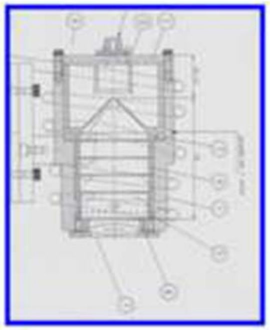
Two main categories.

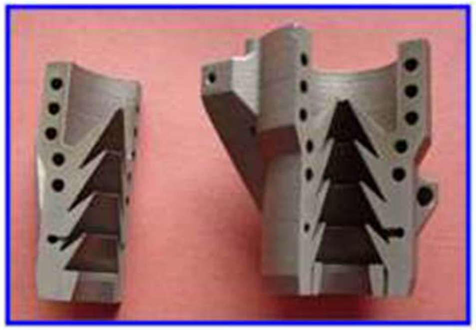
1. **DIRECT processes**: DIRECT meaning that the final parts are obtained directly out of the machine at the end of the building.
2. **INDIRECT** :they need a complementary step to finish the process. Generally, the additional process is a passage in the oven for debinding and sintering, welding or casting steps.

Typical applications

New design concepts

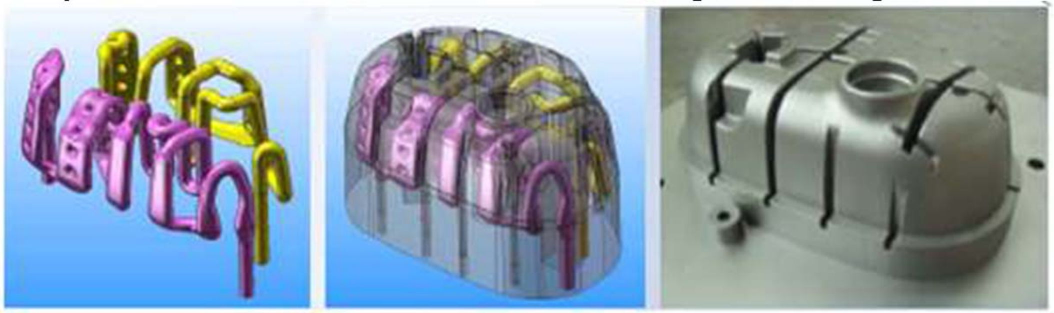
The additive manufacturing allows new design concepts for instance by replacing several elements by one component including different functions. This capacity give a new way for conception and allows to decrease time and costs.





Internal geometries

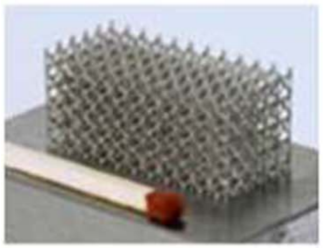
These processes also allows to create directly internal geometries like 3D channels or cavities for thermal management, flow control, sensor positioning,… This is well used to create conformal cooling in the injection molding applications with the aim to optimize the thermal operations and decrease the injection cycle time by 15 up to 35%.

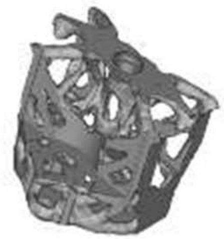


Typical applications

Lightweight parts

One of the most interesting capacity is the possibility to build complex structures like lattices and cellular structures to obtain light parts, bone regeneration, filters, topological optimization structures…





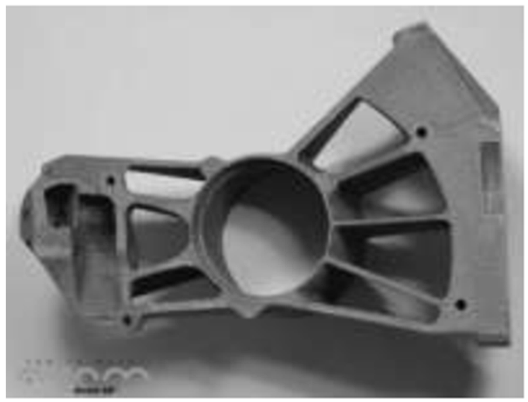
Porous parts

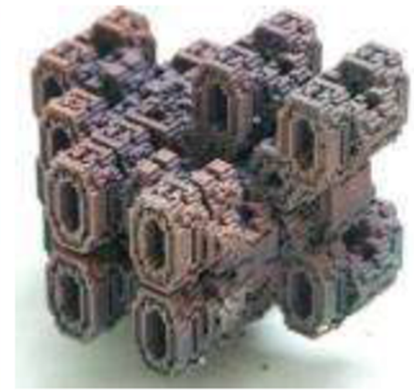
The 3DPrinting process allows to produce controlled porous parts by managing the sintering parameters, the composition of the powder mixture or the addition of organic fillers. The result of this development is already used for nano-production system components for instance. Laser Melting and Electron Beam Melting have also capacities to produce non-full dense parts. The result it is not a real porosity, but rather like filter parts.

Typical applications

Complex parts

The main common property of these processes is the ability to produce very complex geometries even sometimes, impossible to build with conventional



Repairing of expensive parts

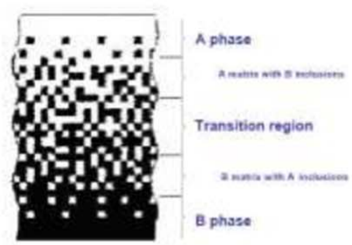
The Laser Cladding process has possibilities for repairing operations. The first step is to remove the defect area by milling. The second step made by Laser Cladding is to add new materials following the initial 3D geometry and finalize by a finishing step to be in accordance with the accuracy and the surface quality.

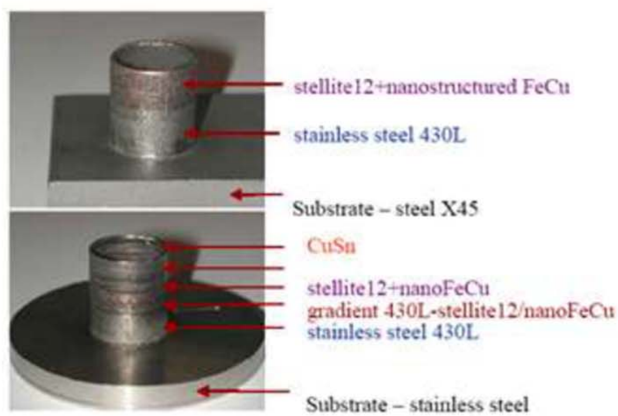
Typical applications

Functional Graded Materials (FGM)

Some of these processes (cladding mainly because it is not a powder bed) have a real potential to develop bi-material or graded material components. The potential applications are for instance:

- molding inserts including good thermal properties for the core and good wear resistance for the skin
- parts with different properties (impact resistance, fatigue, creep, wear) depending on the area
- coating to improve the wear resistance
- repairing of expensive parts

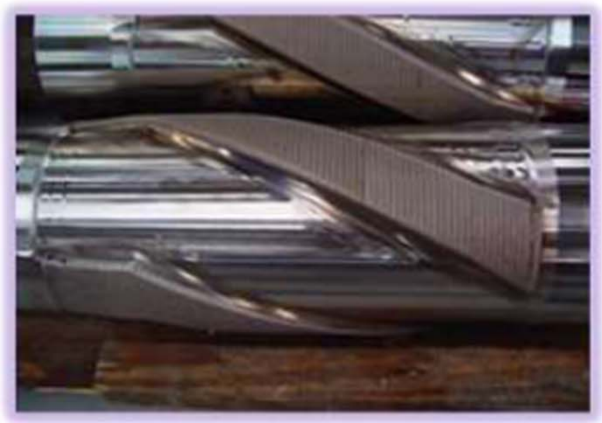




Typical applications

Coating

It is an easy way to coat any part by laser cladding process to improve properties such as wear resistance, corrosion resistance and hardness.



Outline of the presentation

4

- Space instrumentation and Space Environmental testing activities at CSL
- Dreams, a priori expectations and space specificities
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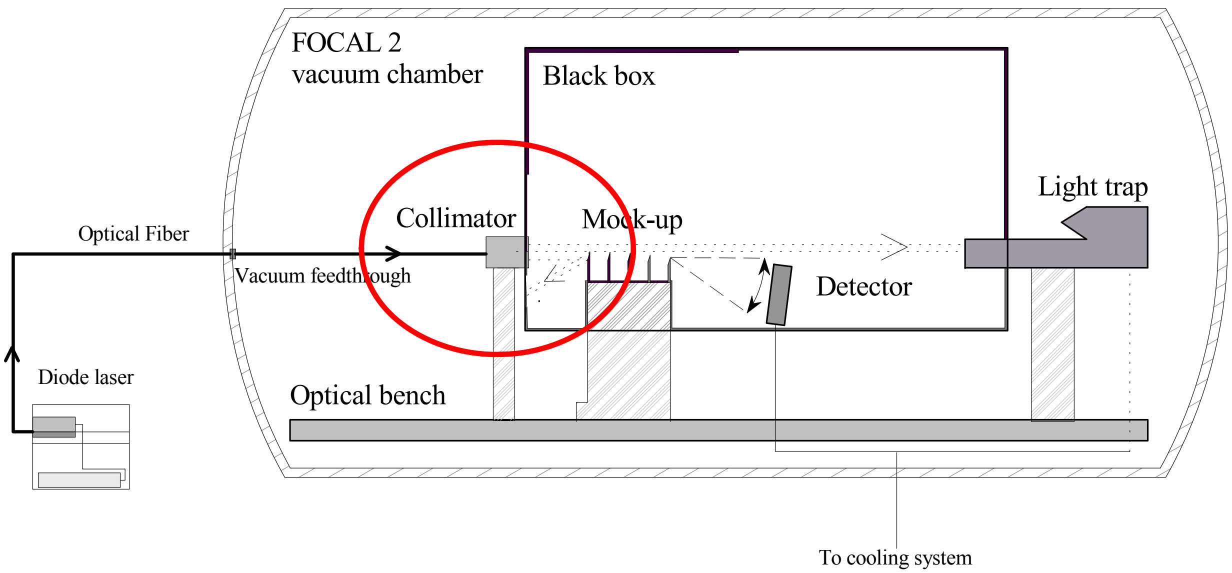
Example of case study – Laser collimator (1)



STEREO SECCHI HI
NASA

Set-up for straylight measurement
High power laser as a source. For this the laser beam is brought in a “black tent” by a fibre and a collimator is installed, converting the exit of the fibre into a collimated beam. The requirement for this collimator is to absorb the large amount of light that is not oriented towards the collimating lens. This absorption can lead to a high level of energy to evacuate out of the collimator.

- correctly positioned lens with respect to the fibre exit;
- internal baffles to attenuate straylight;
- internal black coating;
- fluid circulation for heat evacuation.

Example of case study – Laser collimator (2)

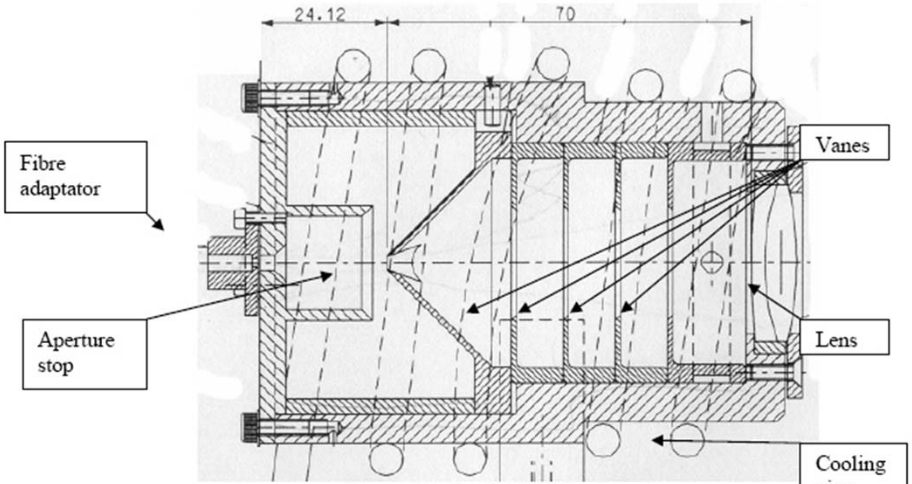


Figure 6-1: Classically built collimator

As a good thermal conductance was required, it was decided to use SLA with Bronze

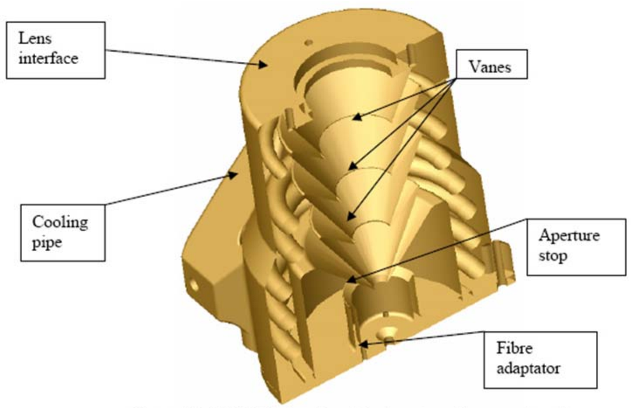


Figure 6-2: RP/RM designed part (note: only surfaces are shown)

Classical **15 different pieces to be assembled**: a tube as the housing, several incorporated inside as baffles, a copper pipe brazed on the external side.

Design adaptation for RP/RM Direct Metal Laser Sintering (DMLS)

Two parts to ease powder removal and to allow internal black coating. Biggest part consists in the tube and all the vanes. The cooling pipe is directly included in the wall thickness and concentrated in the area that will gather the higher power.

Special post-machining

Post machining included the lens mounting flange, the aperture stop (first vane close to the fibre exit where a sharp edge was needed). Interface areas between parts have also been improved.

Finally taping of the holes (screws and pipe fitting) has been performed.

Two types of coating have been tested: classical (for space application) Aeroglaze Z306 and Kani-black (JPN).

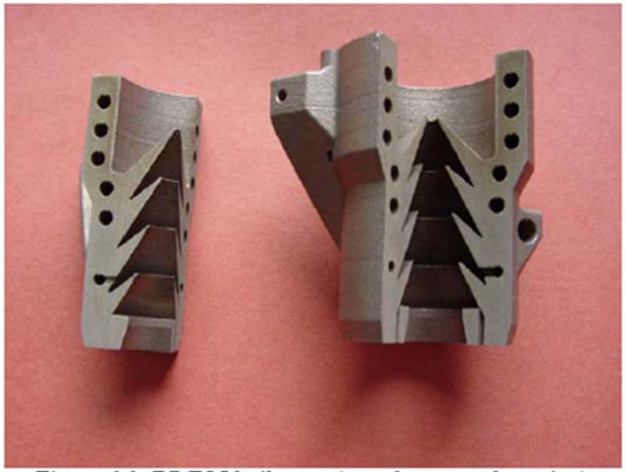
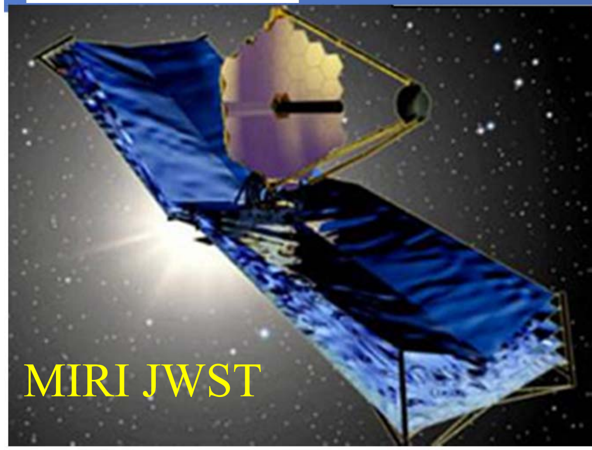


Figure 6-3: RP/RM built part (cut after manufacturing)

Example of case study - Structure IOC (1)



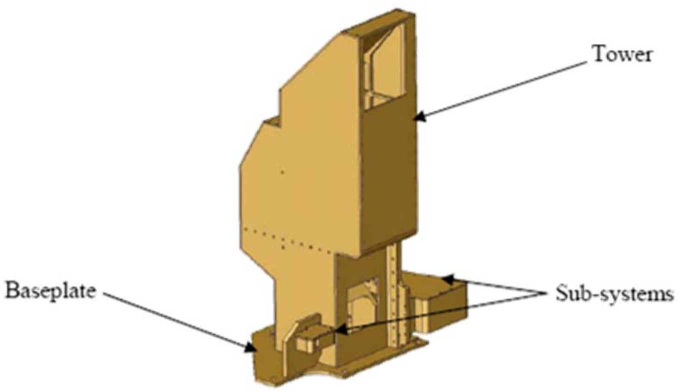


Figure 6-4: IOC STM

Input-Optics and Calibration module

Build in parallel a second IOC STM using RP/RM and to perform a mechanical validation of the design.

As a summary:

- based on original CAD model, adaptation of the design to have it compatible with RP/RM;
- mechanical analysis of the adapted design (stiffness and strength prediction);
- mechanical testing of the model;
- correlation of the model prediction with the test results

Tooling B material for its good mechanical properties and good knowledge of the material. Tooling B was also tested for its compatibility with vacuum environment and is considered during this project as the "best" RP/RM plastic material for space. Stereo-lithography-based Optoform machine.

The original design is an assembly of plates including a lot of screwed connections. The global shape consists in a tower of 500 mm height with a base of ~150 mm by ~150 mm. This tower is mounted on a plate (interface plate) and several sub-systems are mounted on the tower walls. A simulator of the top mirror is included in the design to evaluate the strength and thermal properties of insulating feet.

Example of case study - Structure IOC (2)

Design adaptation for RP/RM

Since the piece will be built-up layer by layer, we can do it in one piece and suppress by the way all the fasteners. Due to the size limitation of the machine, we had to cut the piece in two main parts. The subsystems are not included.

Special post-machining

There is limited post-machining requested since only the global structure will be verified and no details are

checked. The most important process is the gluing of the different parts. For this Stycast 2850 has been used as this is the most used glued in space-cryogenic systems. The interfaces for the screws connection between the baseplate and the testing tool were adapted to support the high preload.

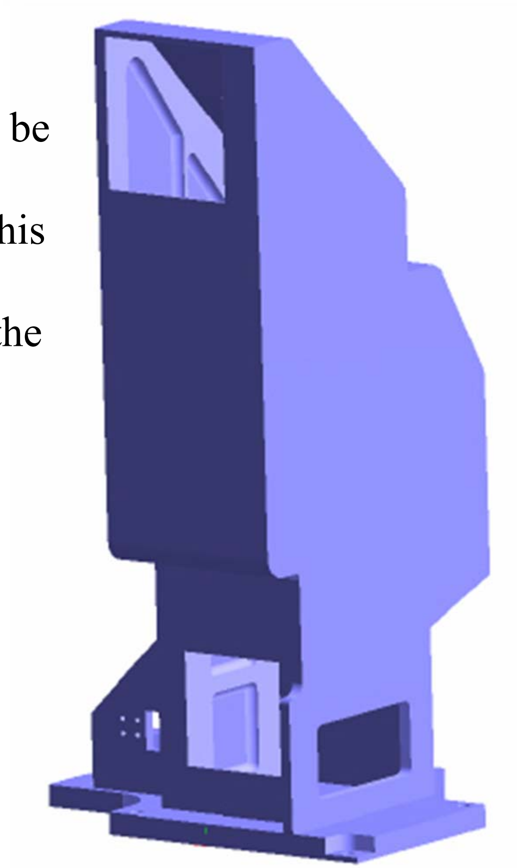
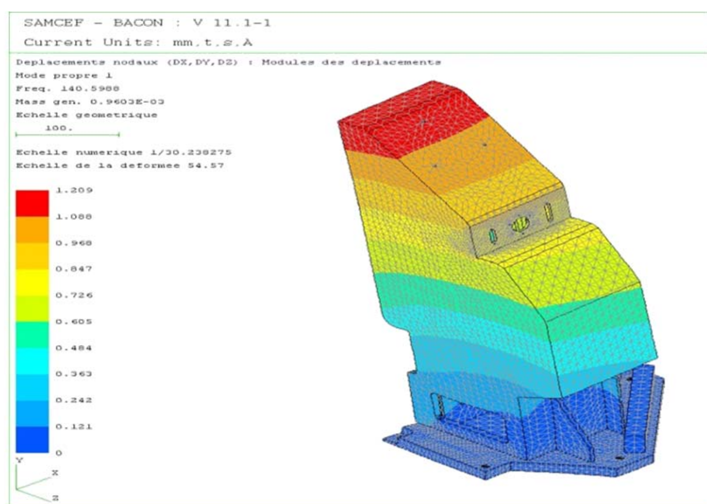


Figure 6-5: IOC with RP/RM



Example of case study - Structure IOC (3)

Frequency (Hz)	Observed direction	Equivalent mode number	Frequency at FEM (Hz)	Direction (Max Meff)	Difference (Hz (%))
136.8	Z	1°	136.4	Z	0.4 (0.3)
145.9	X	2°	150.1	X	4.2 (2.9)
310.6	θY	3°	351.5	θY	40.9 (13.2)
381.2	Z	-	-	-	-
554.6	X	4°	541.7	X	12.9 (2.3)
584.6	X	5°	569.6	X	15 (2.6)

Good correlation with the predicted frequencies for the modes up to 1000 Hz.
The RM built IOC showed perfect resistance to the 20 g environment.

The **quite low damping coefficient** (around 1 %) is probably due to the reduced number of components and the good joining. This is common to improved manufacturing techniques which often produce very good joints in structures reducing the amount of natural damping in structures. For instance, removing welds in bladed disc assemblies caused increased blade fatigue because of the reduced damping.

Other case studies

By means of SLM a stainless steel cold plate is produced.

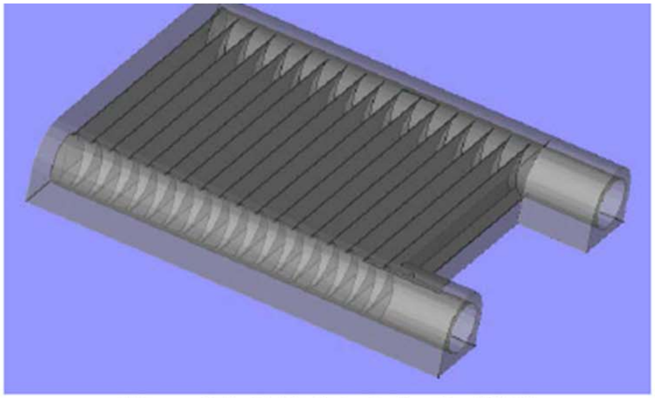


Figure 6-4: Cold plate design for SLM

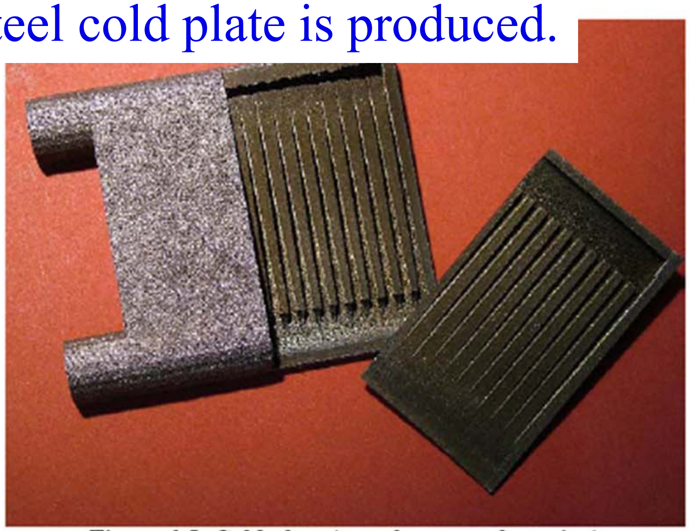


Figure 6-5: Cold plate (cut after manufacturing)

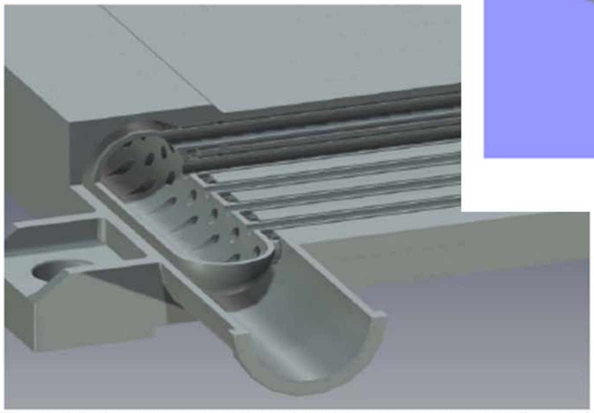


Figure 6-5: Cross section of the original heat exchanger (CAD model)

Heat exchangers of stainless steel by SLM

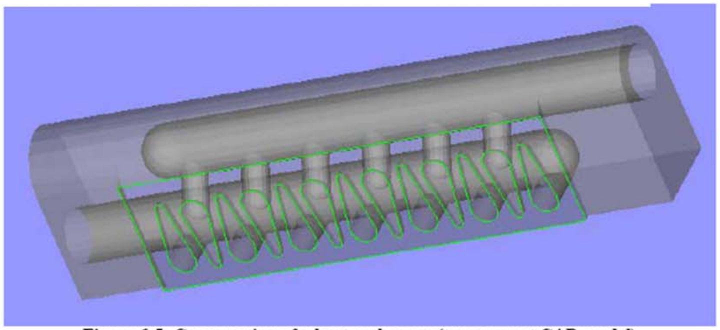


Figure 6-5: Cross section of a heat exchanger (transparent CAD model)

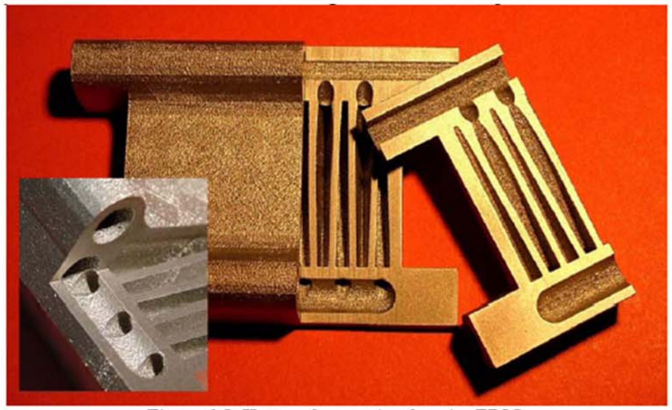


Figure 6-5: Heat exchanger (cut by wire EDM)

Figure 6-5: Cross section of a spiral heat exchanger (cut by wire EDM)

Outline of the presentation 5

- Space instrumentation and Space Environmental testing activities at CSL
- Dreams and a priori expectations
- Advanced Manufacturing Techniques considered in our studies
- First steps realizations years ago
- **More concrete and more recent examples**
- Conclusions and future activities

Objectives of the present project

- **Partners of the project**
  - CSL is the coordinator of the project and is largely experienced in the development and testing of flight hardware
  - SIRRIS is the technology provider, either based on in-house capabilities or via sub-contractors
  - TAS-F and ALMASpace are the case studies providers, defining the requirements and playing the role of « customers »
  - ESA participated in the selection
- **Organisation of the project**
  - Step 1: Review of the advanced manufacturing methods
    - Additive manufacturing, advanced joining techniques, advanced forming methods, coatings…
    - Presentation was given to all partners to emulate their imagination to provide case studies : **LBM, EBM, L Cladding, aerosol jet printing, LW, EW, Salt Dip brazing, …**
  - Step 2: Level 1 case study
    - Reproduction of an existing part by advanced techniques in order to evaluate pro's/con's of the techniques and get some first experience
    - Full testing of the case studies to verify the compliance to the main requirements

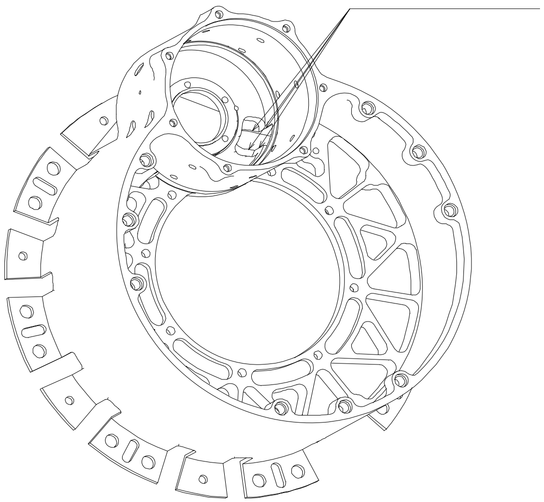
Objectives of the project

- **Organisation of the project (cont'd)**
  - –Step 3: Level 2 case study
    - Design driven by application requirements i.e. designing the part and the manufacturing flow to maximise part performances
    - Full testing of the case studies to verify compliance to requirements
  - –Step 4: Level 3 case study
    - Part design driven by the subsystem to which it belongs i.e. designing the part and the manufacturing flow to maximise the sub-system performances
    - Full testing of the case study to verify compliance to requirements
  - –Step 5: Summary of all lessons learnt
    - Reporting all lessons learnt in order to better define the engineering process of designing and manufacturing a part in order to take full advantage of the advanced manufacturing techniques and minimise the risks

Case studies description

- **Level 1 case study**
  - 2 case studies selected:
    - Structural case for space mechanism (TAS-F)
    - Reaction/Momentum Wheel Housing Assembly (ALMASpace)

Solar array drive mechanism



Structural case initial design

Reaction/momentum wheel housing manufactured by standard methods

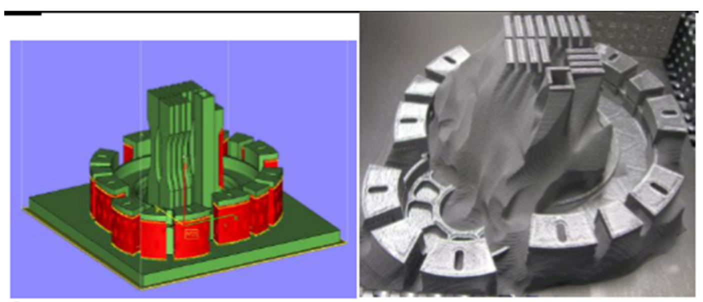
Case studies description

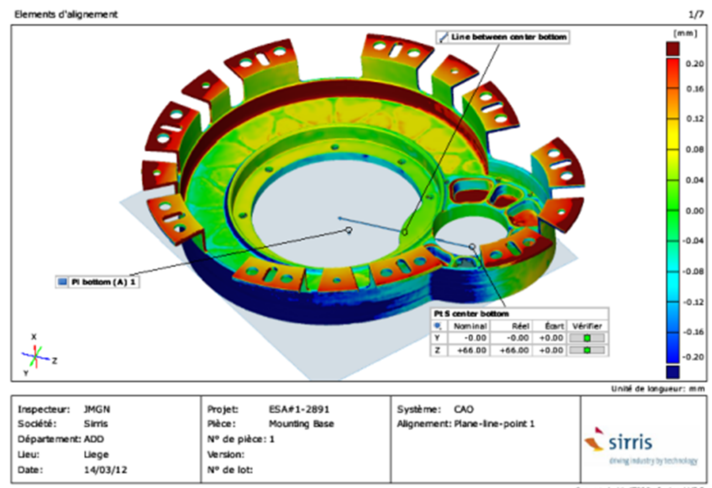
- **Structural case for space mechanism**
  - Main part of **a solar array drive mechanism**
  - Structural part containing mechanism elements : in the front side are mounted the balls bearing and the potentiometer, in the back side the collector and the stepper motor. So it is strongly loaded since being the link between solar panel and spacecraft.
  - Made of Titanium alloy Ti6Al4V
  - Selected method: Electron Beam Melting of Titanium
    - Advantages:
      - Well suited for large, massive parts in titanium
      - Reduced building time
      - No heat treatment required due to high temperature of the process (limited residual stresses)
    - Disadvantages:
      - Higher roughness
      - Less accuracy

Case studies description

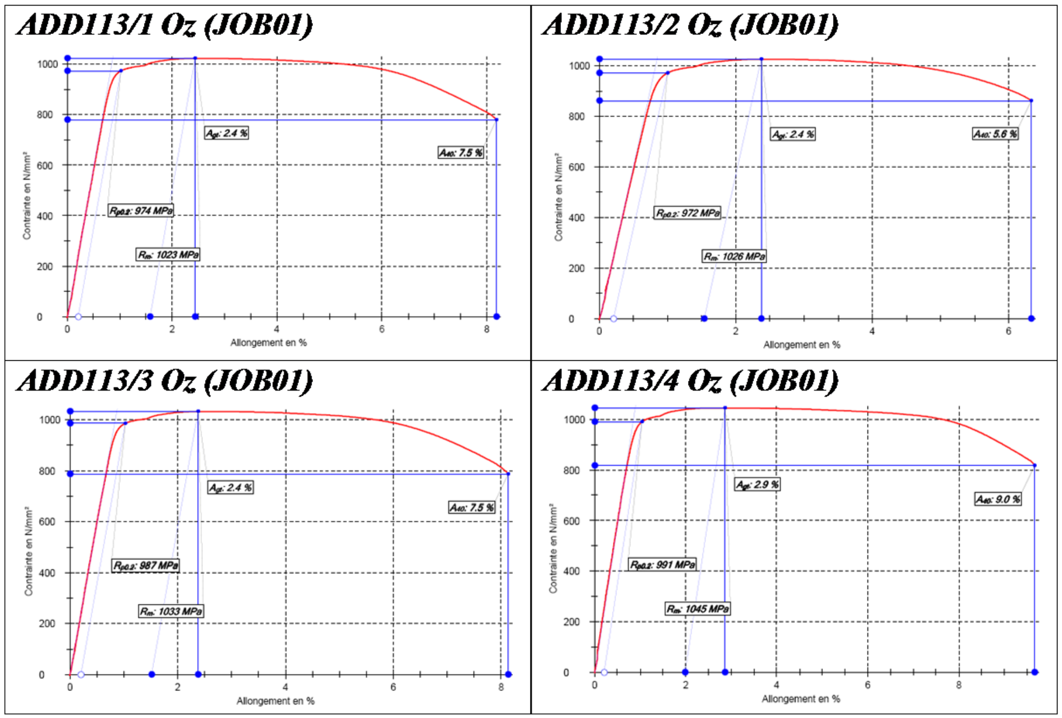
- **Structural case for space mechanism (cont'd)**
  - Building included **several samples for properties measurements** (density, strength, fatigue)
  - Several minor problems during building required several trials
    - Powder excessive charging
    - Processes interruptions
  - Post machining faces few problems
    - Post machining required for interface surfaces and fitting diameters
    - Legs vibration due to lack of support
    - Flatness not reached due to non-flat clamping surfaces
    - Question raised about the transfer of references between additive manufacturing and standard post-machining (similar to casting)

Case studies description





Case studies description



Mechanical properties of vertical sample (building direction)

Index	Rp0.2	Rm	Agt	A40	Z
	(Mpa)	(Mpa)	(%)	(%)	(%)
ADD113/1	974	1023	2,4	7,5	39,6
ADD113/2	972	1026	2,4	5,6	33,4
ADD113/3	987	1033	2,4	7,5	40,5
ADD113/4	991	1045	2,9	9	39,2
ADD113 Oz (Arithmetic mean)	981	1032	2,5	7,4	38
Typical Ti6Al4V	880	950		14	36

Rp0.2% Yield strength
Rm Ultimate strength
Agt Maximal uniform elongation under maximal load (elastic + plastic)
A40 Elongation at break
Z Necking measured after test
E Young Modulus
Parameters definition

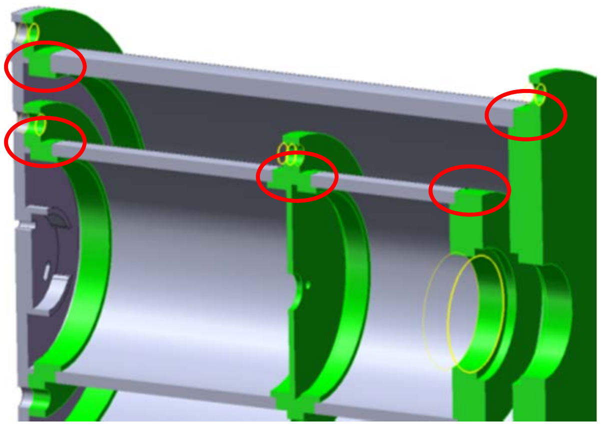
Case studies description

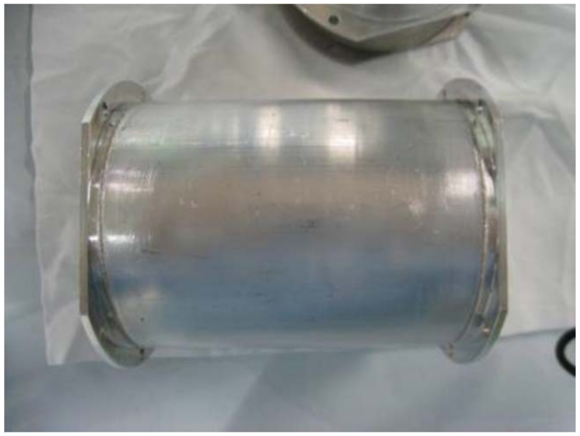
- **Reaction/momentum wheel housing assembly**
  - –Contain the reaction/momentum wheel and its mechanism
  - –Is composed of several parts to be assembled
  - –Has to withstand the loads due to the launch and then to maintain in the correct position the rotating masses inside itself.
  - –Originally manufacturing from block of materials
  - –Goal: minimise the manufacturing complexity and time
  - –Selected method:
    - Standard manufacturing + electron beam welding for the upper part
    - Laser beam melting of stainless steel for the base
      - – Aluminium was not available at that time and stainless steel should be the closest in terms of manufacturing process
      - – Post machining for the interface surface and for the mounting holes

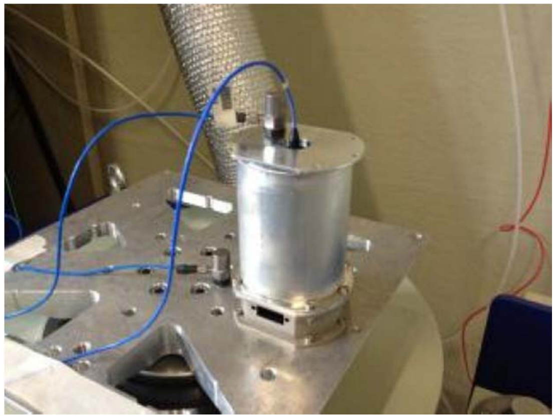
Case studies description

- **Reaction/momentum wheel housing assembly (cont'd)**
  - Design was adapted for the welding
    - Standard tube diameters were chosen (for cost reduction)
    - Additional thicknesses and support at the level of the joins
  - Only problem reported was a deformation of the interface flange
    - Due to the proximity of the welding → post-machining would be necessary
    - Could be use-as-is in the application
  - Base made by laser beam melting didn't face major problem
    - Only parameters adaptation (hull and core) was required to minimise delamination
    - Post machining required for interface surfaces and fitting diameters
    - Legs vibration due to lack of support
    - Flatness not reached due to non-flat clamping surfaces
    - Question raised about the transfer of references between additive manufacturing and standard post-machining (similar to casting)

Case studies description







Case studies description

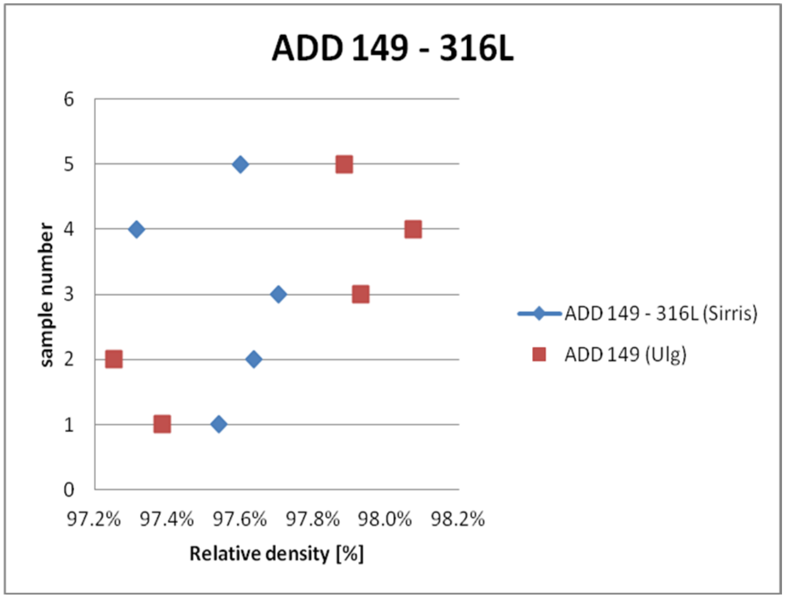
Main EUT	I eigenfrequency	II eigenfrequency
Beginning	1480	-
Middle	1480	1780
End	1477	1785
Secondary EUT	**I eigenfrequency**	**II eigenfrequency**
Beginning	1460	1760
Middle	1460	1760
End	1531	1764

Eigenfrequencies of a reference model (Secondary) and of the built model (Main) before and after random and shock testing performed at ALMASpace

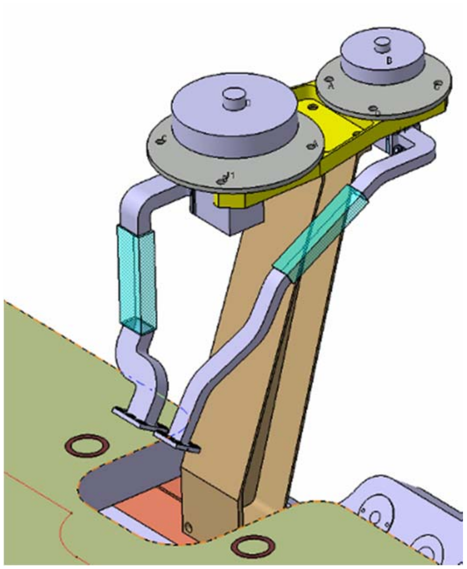
Index	Rp0.2	Rm	Agt	A40	Z	E
	(Mpa)	(Mpa)	(%)	(%)	(%)	GPa
ADD132/1	318	354	2,4	3,6	41,8	89
ADD132/2	448	552	10	10,6	29,2	122
ADD132/3	380	472	8,9	9,5	15,9	108
ADD132/4	387	482	11,9	15,9	18,9	120
ADD132/5	384	485	11,7	13,6	22,7	163
ADD132/6	427	535	8,6	9,7	20	136
ADD132 Oz (Arithmetic mean)	405	505	10	12	21	130
Typical AISI316L	290	560		50		193

Mechanical properties of vertical sample (building direction)

Relative density along the height of a sample (bottom to top → 1 to 5)
Measurements by SIRRIS and by ULg

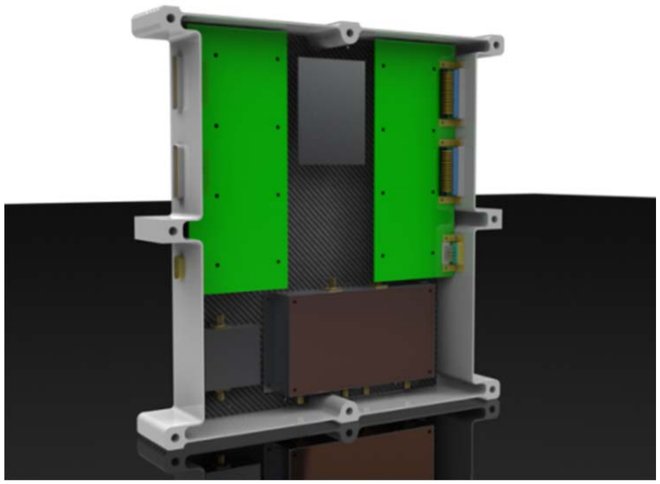


- **Level 2 case study**
  - –2 case studies selected:
    - Antenna support (TAS-F)
    - ALMASat-class Microsatellites Modular Tray (ALMASpace)



Antenna support preliminary design

Modular tray CAD model



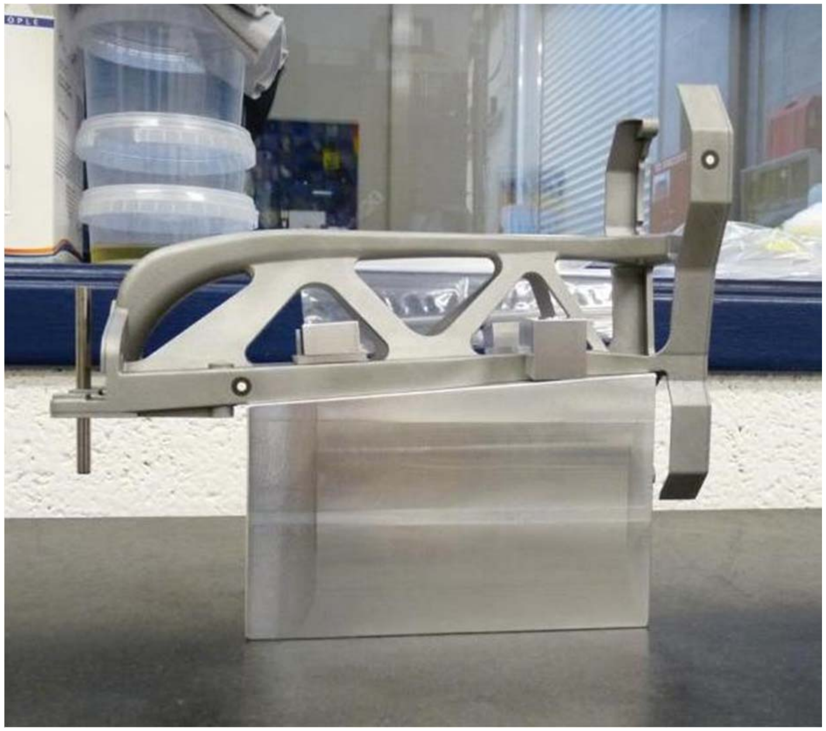
Case studies description

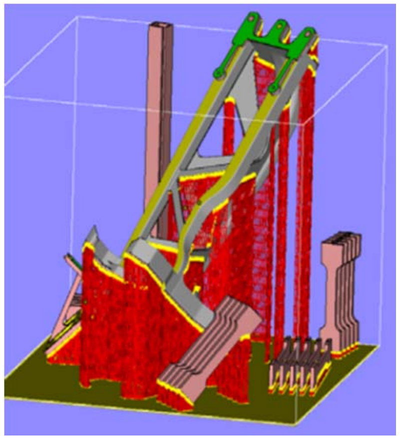
- **Antenna support**
  - –Supports 2 antennas
  - –Is connected to the satellite main frame
  - –Some constraints for the routing of the waveguides
  - –Only preliminary design exists
  - –Goal: design a structure to support the antennas with minimal mass and sufficient stiffness and strength
  - –Selected method:
    - Design by topological optimisation
    - Manufacturing in aluminium by laser beam melting
    - Post machining for interface surfaces and holes

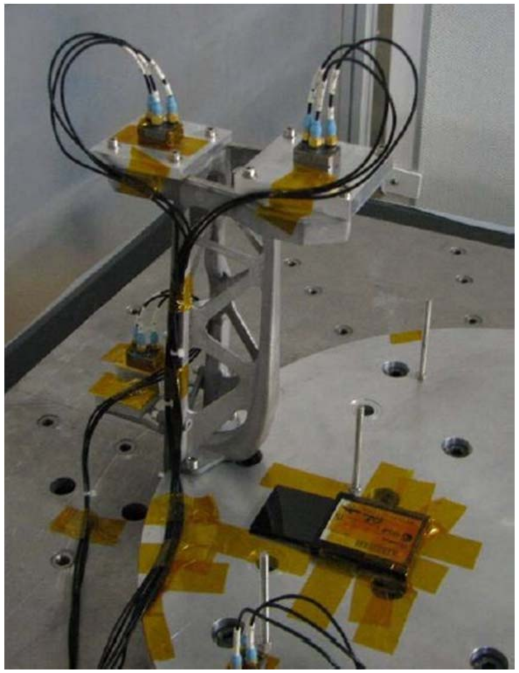
Case studies description

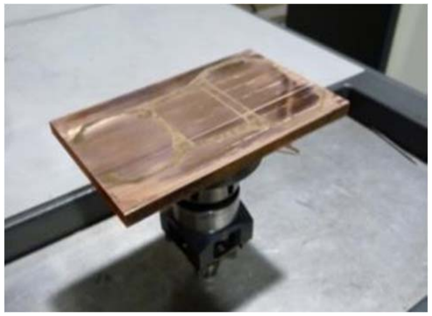
- **Antenna support (cont'd)**
  - Topological optimisation goal: obtain the correct stiffness by minimising the mass
  - Optimisation parameters such as to limit intermediate density elements
  - Part is re-drawn manually for further analyses (strength analysis) and manufacturing

Case studies description



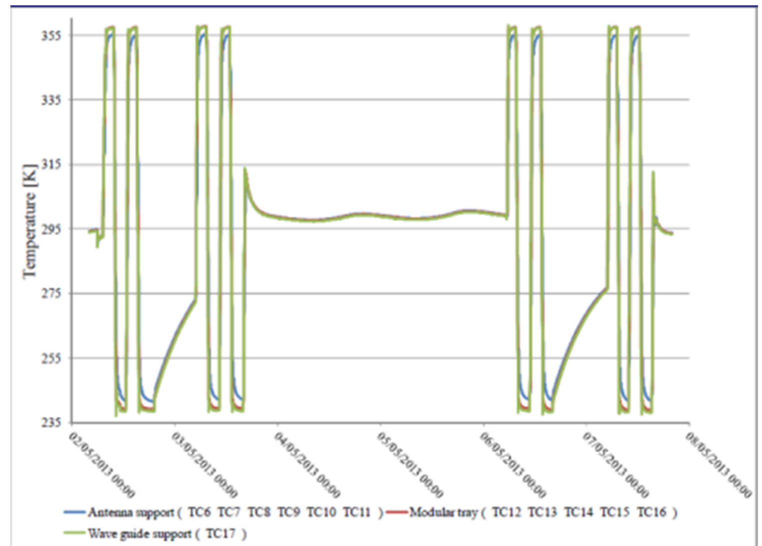






Case studies description

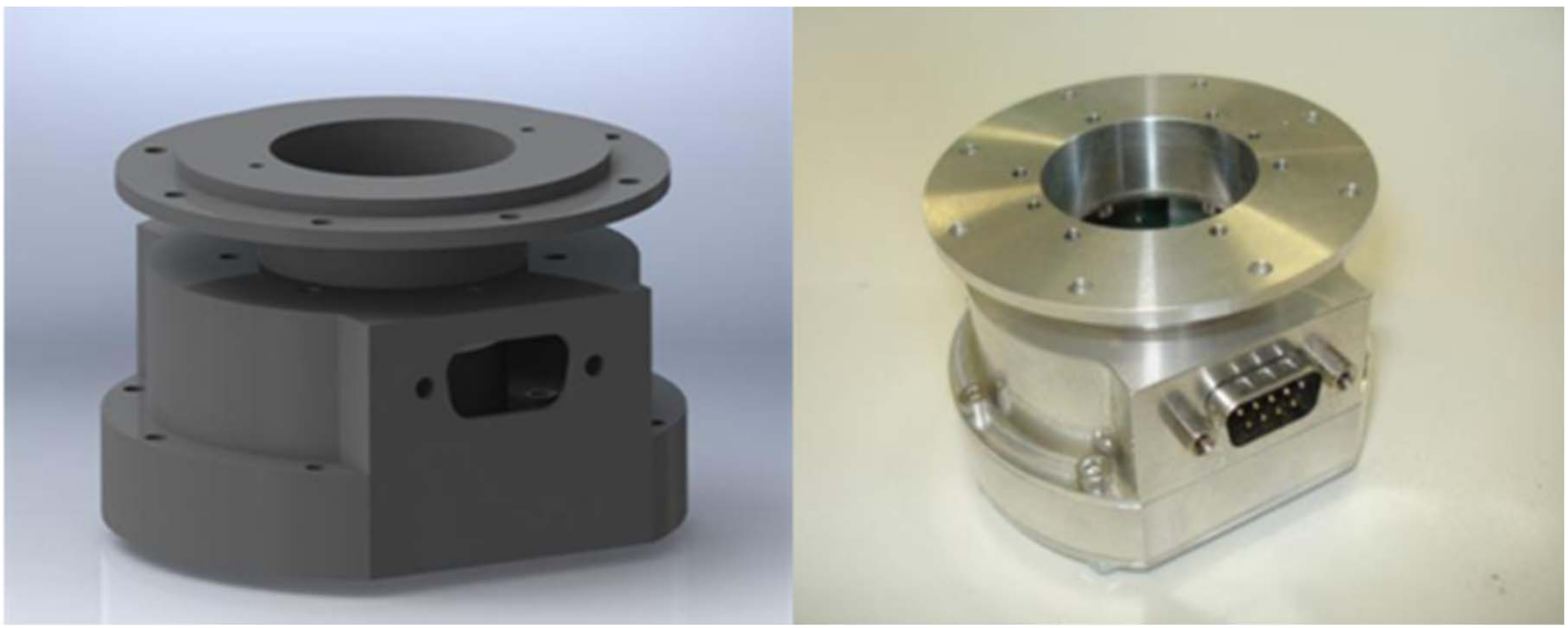
- Vibration test at CSL
  - Low level sine performed before and after each high level
  - High level sine up to 20g, up to 100 Hz
  - No variation before-after high level in all axes
  - First eigenfrequency at 165 Hz (Computations at 143 Hz and 212 Hz depending on the interface conditions)
  - Cleanliness control indicates still some particles coming out of the tubes



- **Thermal cycling at CSL**
  - 8 cycles performed under vacuum between -30°C and +80°C
  - No contamination detected during test
  - No problem reported

Case studies description

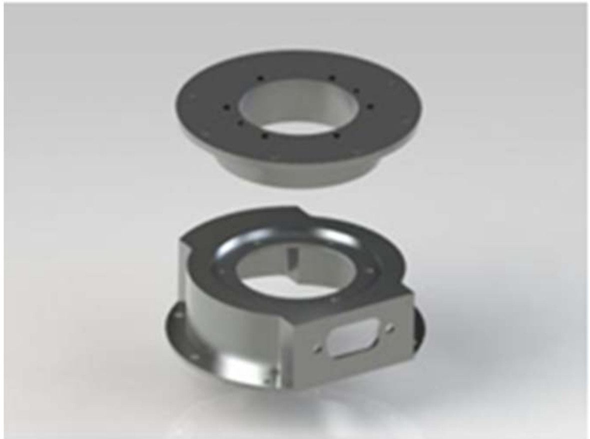
- **Level 3 case study**
  - 1 case study selected:
    - Sun sensor housing (ALMASpace)

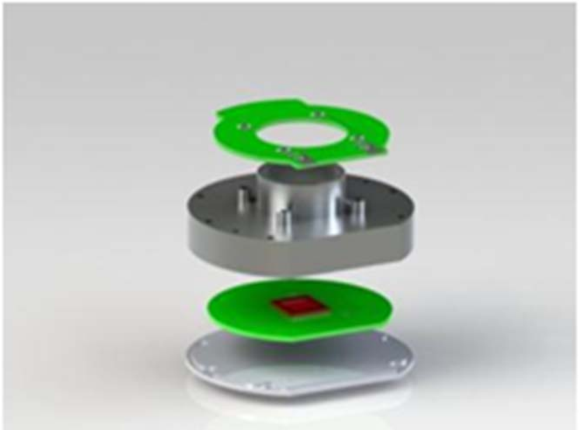


Sun sensor current design

Case studies description

- **Sun sensor**
  - Assembly including:
    - Commercial optical sub-system
    - Power conditioning PCB
    - Optical detector on proximity electronics PCB
    - Structure ensuring stiffness, strength and alignment

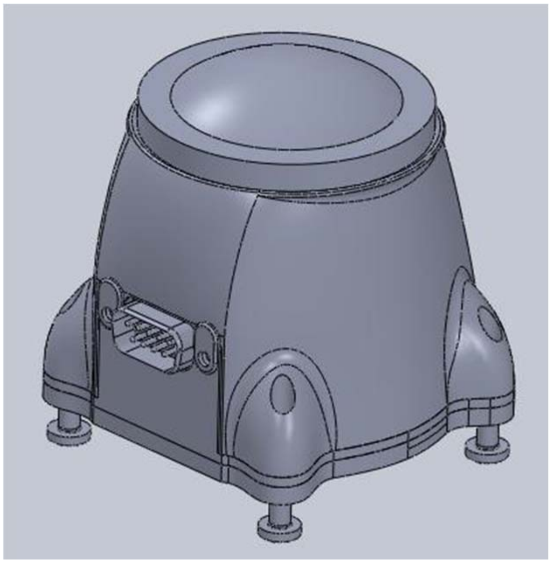


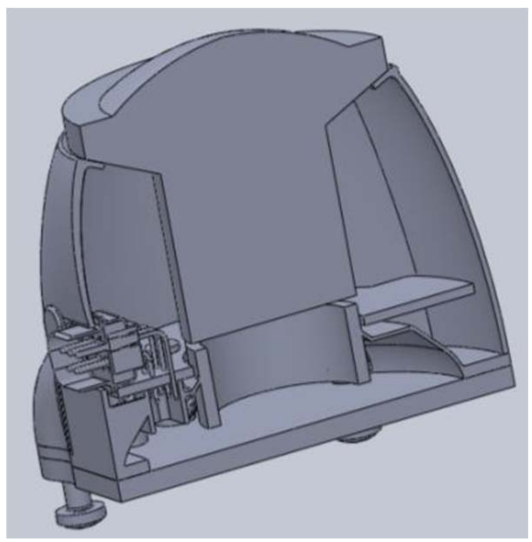


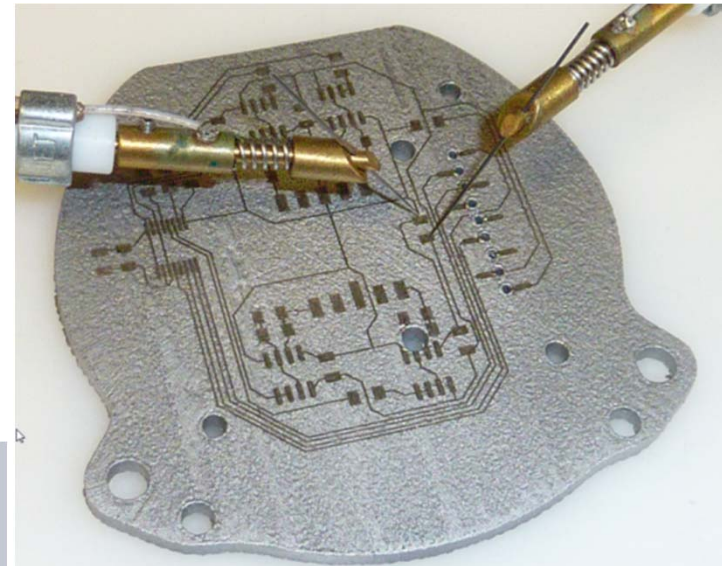
Case studies description

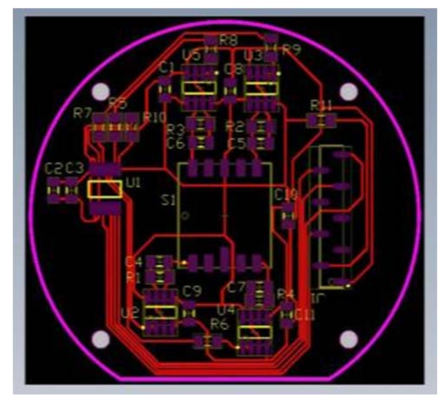
- **Sun sensor (cont'd)**
  - Structure is re-drawn to take advantage of additive manufacturing methods
  - Support mean of the optical sub-system is optimised (closer to cog) and the optical sub-system is measured by 3D measurement machine (fringe projection) to accurately know the geometry and ensure correct fitting close to optical (heavy) elements
  - Power conditioning PCB used as is (no improvement possible)
  - Optical detector PCB removed and optical detector and proximity components directly mounted on the back plate where the circuit is "printed" by aerosol jet printing
    - Aerosol jet printing allows printing of powder material (in binder) by projection (like ink jet printer)
    - The powder is sintered afterwards with a laser allowing a very local heating
    - In this application, a insulating under-layer is applied (by more classical method) to avoid short-circuit

Case studies description









Components

- **It was tested in vibrations, thermal cycling and performances**

Outline of the presentation

6

- Space instrumentation and Space Environmental testing activities at CSL
- Dreams, a priori expectations and space specificities
- Advanced Manufacturing Techniques considered in our studies
- First steps realizations years ago
- More concrete and more recent examples
- **Conclusions and future activities**

Current lessons

- **The project was a success**
  - We have learnt a lot of things about these techniques
  - Some of the case studies have prolonged their life after the project
- **The current lessons can be summarised:**
  - The work in **a team between the customer, the designer and the manufacturer is important** for these techniques
  - The designer has to change its way of thinking compared to standard manufacturing
  - The additive manufacturing are (**currently**) not the final solution, post machining remains an essential step of the manufacturing to reach the final tolerances and surface properties
  - **Post-machining steps shall be taken into account at the design phase** in order to optimise/minimise them
    - How to transfer references ?
    - What are the really useful interfaces ?
    - Is the structure stiff enough where I plan post-machining ?
  - Despite the improved confidence and repeatability of the building methods, the mechanical properties reached shall be verified by **addition of samples in the process**
- **Among the possibilities,**
  - topological optimisation can significantly reduce the mass of hardware (many tens of percentage),
  - suppressing interfaces leads to significant mass savings,
  - integrating several functions can allow new applications and limit controls and verifications.

We are progressing but Still limitations

- Costs of current technologies,
- Cost (and limitation) of raw materials
- Lack of open standards
- Quality control and repeatability
- Certification of process and materials
- New materials to be developed
- Accuracy and surface quality enhancements required
- Material structure depends on the process and thermal aspects
- Still needs to finalize the systems with classical manufacturing tools and the interface has to be optimized (Tooling points)

Thank You !

Questions ?

Steps on the way to space

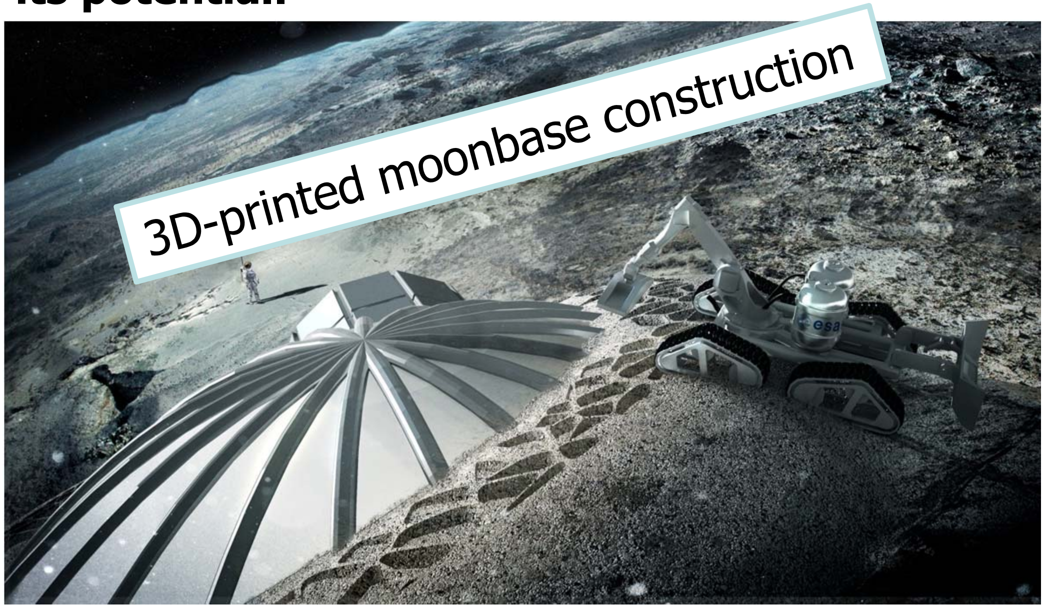
- **We're still a long-way from the routine use of AM parts in space. Problems like material post-processing, surface coating and ensuring the necessary precision geometries still need to be solved. And new qualification standards have to be written – but progress is being made.**
- **Occasional AM parts have already made it up to orbit: a 3D-printed plastic toolbox was flown up to Columbus last year.**
- **NASA has announced plans to fly a plastic 3D-printing machine to the Station. Meanwhile, ESA and the European Commission have embarked on a project to perfect the printing of space-quality metal components. The AMAZE project – Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products – involves 28 industrial partners across Europe.**
- **ALM will help Evolution of LEO Platforms in Compliance with the Space Debris Mitigation (SDM) Requirements**

Potential Future

- **How might AM transform space missions in future?**
- **An ESA project to design a lunar base using 3D-printed local lunar rock demonstrates the broad span of its potential.**

Manned missions could carry a 3D printer with them to ensure full self-reliance as they fly many months or years distant from Earth. Any broken item could be quickly and easily replaced.
This approach has already been validated by ESA by manufacturing and functionally testing parts that have required fixing during past manned missions, including screws, clamps and even plastic gloves.

Satellites in space could self-print new subsystems to provide new capabilities, in the same manner that today's space probes are still having their software written on the way to their destination.



Down on the ground, the possibilities are just as exciting: slashing the energy and mass needed for manufacturing could shrink the environmental footprint of the space industry hugely, the reason why AM is also of interest **to ESA's Clean Space initiative** – tasked with reducing the space industry's impacts on the environment.
NASA plans to install AM device in the ISS and architects Fosters and Partners have designed buildings made by AM on the Moon.

ALM will help Evolution of LEO Platforms in Compliance with the Space Debris Mitigation (SDM) Requirements

Chemical propulsion : Potentially useful for optimising thrusters catalyst bed, valves and filters.
Electrical propulsion : Can be useful for optimising valves, filters, neutralisers, flow control system, tanks, new thruster design
Optics :

- Need for demisable barrels, lenses and mirrors.
- Materials and component :
    - AlSi70 can potentially be a good replacement but its manufacturability and mechanical properties are not fully understood yet, and with respect to manufacturability it is proving difficult to machine due to its brittleness.
    - Lens materials are not demisable during re-entry mirrors could be used instead but has an important impact on the instruments design.
- **Additive Manufacturing (AM)**
    - Support manufacturing of optical benches, **to reduce micro-vibrations and mass**.
    - Design for demisable for LEO Optical PL
    - AlSi70 An interesting material that could be considered for ALM.

•LIDARs for atmospheric composition monitoring imply very complex internal shapes (e.g. channels) also requiring adequate surface treatment.

Materials

•Replacement of silicon carbide mirrors (used in payloads such as GAIA and Euclid) that may be used in future LEO missions such as Sentinel (possibly already used in Sentinel 2 or 3), demisability of this material should be assessed. The mechanical/elastic properties of AlSi70 shall be understood as this is a potential replacement for titanium in optical barrels.

ALM will help Evolution of LEO Platforms in Compliance with the Space Debris Mitigation (SDM) Requirements

Power

A few applications such as high voltage potting (deposit of potting locally on relevant parts instead of complete module potting)

RF payload system

Could be used for complicated wave guide structures, PEEK could also be used through ALM. Applications for this are the Feed Array, Waveguides, Filters (new complex shapes to increase performance), assembly of the front end elements, packaging of the RF subsystem.

THERMAL

During the design and construction of the satellite, the heating pipes could be integrated within the structure, perhaps in-between the double walls of the satellite.

Different materials could be used in different parts of the structure to pass the heat from one side of the spacecraft to the other.

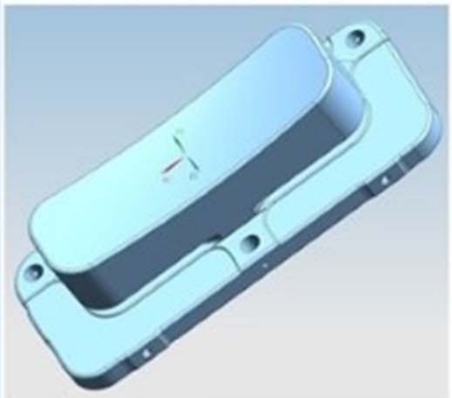
Carbon Fibre High Conducting Straps – Could be used for heat transfer from one side of the spacecraft to another. Would replace the current copper or aluminium straps which are used. Currently there are issues concerning outgassing and other small particles that will be released due to the manufacturing process.

Radiator Improvement – A radiator which could change its radiative effects based on temperature changes would be highly beneficial.

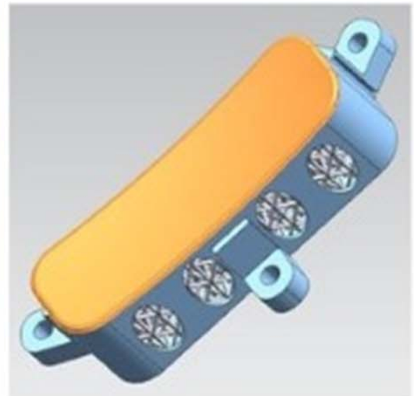
MLI – New MLI developments could be interesting where the effects on degradation due to micrometeoroid impacts would be reduced.

Coatings – A new coating on the batteries could be implemented which would lower the absorptivity but maintain the emissivity, as this would reduce the temperature at EOL, and reduce the risk of battery break-up.

Other examples at ESA: Tropomi mirror test redesign using ALM



Original design
Mass: 284.6 g
Material: Al 6061
1st eigen freq ~2100 Hz
NiP coating



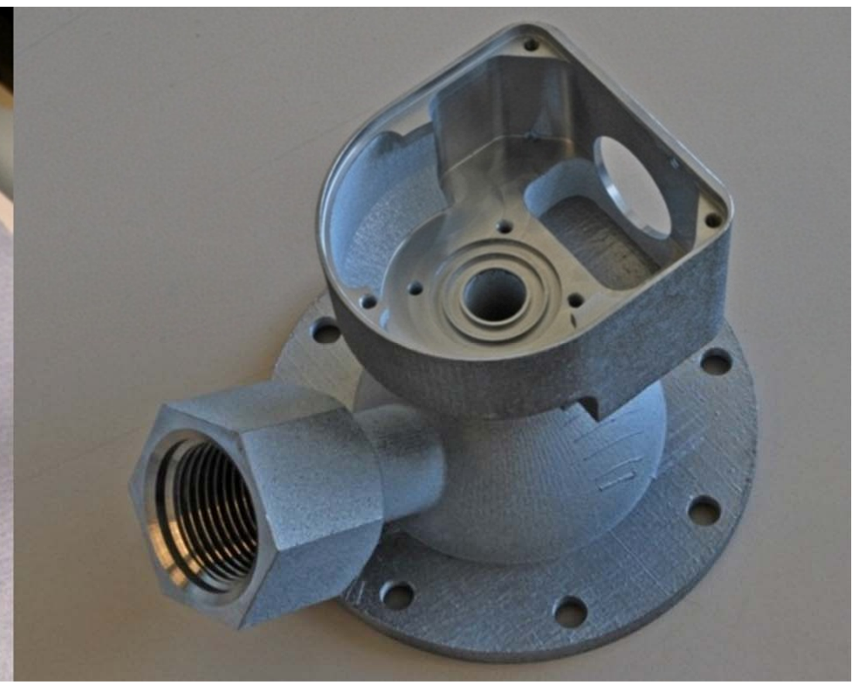
New design
Mass: 129.7 g

Selective laser melting
Mass: 127.7 g
Material: Ti6Al4V
1st eigen freq ~2100 Hz
NiP coating

“We took the original mirror design, manufactured in aluminium with a mass of 284.6 grams and a nickel phosphorous coating, and proceeded to redesign it for using selective laser melting ALM manufacture. We decided to make it out of titanium, which has a higher maturity for selective laser melting.”

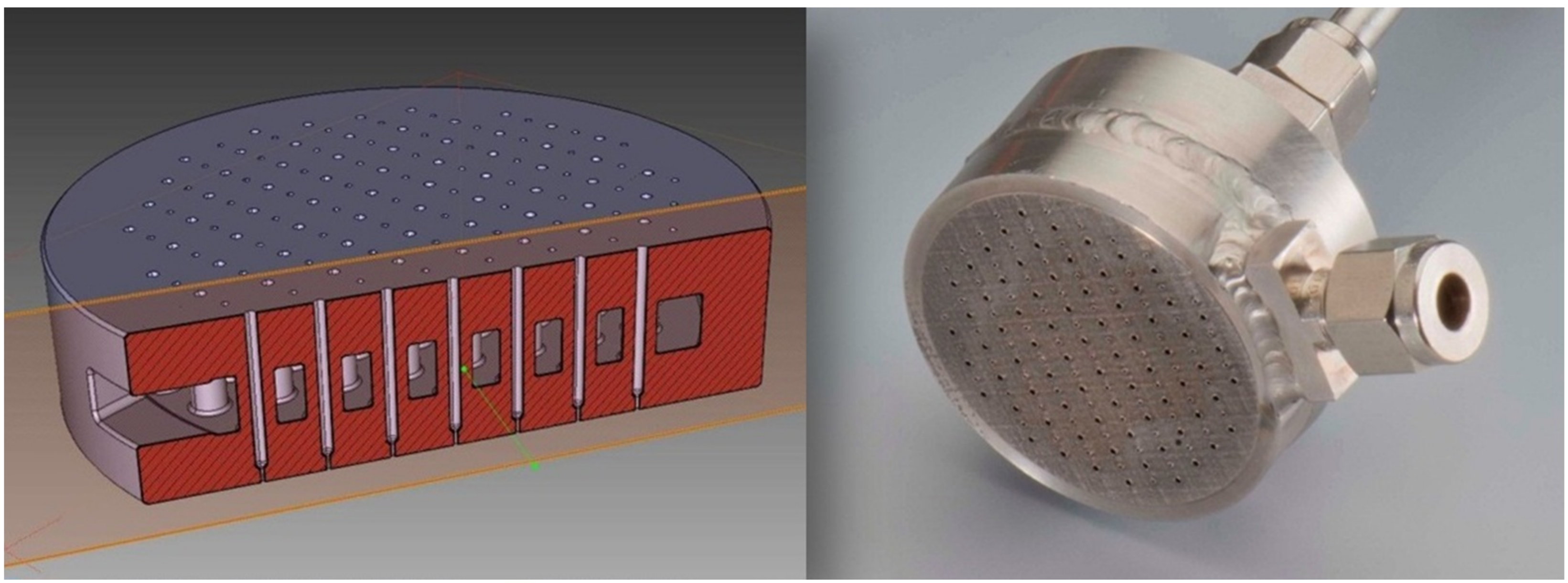
Other examples at ESA:
3D-printed test items

- **Use ALM to reproduce items that had actually flown in space.**
- **A titanium copy of a stainless steel 'woov' (water on-off valve)**
- **This has been flown on ESA's Columbus Space Station module, as part of its plumbing.**
- **Woov contains both thick and thin walls, as well as a weld.**
- **With the AM version we were able to remove the weld – an unwanted point of weakness – reproduce the part in titanium at an affordable cost and, through changing the material, reduce the item mass by 40%."**



Other examples at ESA:
RF filters and engine parts

- **Follow-up test items included an antenna support strut, where mass was reduced by 46% and a radio-frequency filter possessing an internal silver coating – normally produced by bolting halves together – had its mass reduced by 50% and its manufacturing time slashed by several weeks. Its internal geometry was also made more wavy: the silver coating required to optimise its radio-frequency performance is far easier to apply than when dealing with sharp corners encountered in today's state-of-the-art hardware. Such tailored design is another advantage of AM. ESA's Propulsion Engineering section also took an early interest in AM, as a way of building the extremely complex shapes required by rocket nozzles and combustion chambers.**
- **Remaking a showerhead injector, with complex internal geometry and more than a hundred separate welds. The biggest challenge for the selective laser melting metal AM technology was achieving the 150 micron-diameter holes studding the 25 mm-diameter showerhead.**



Other examples at ESA: Lightweight lattices

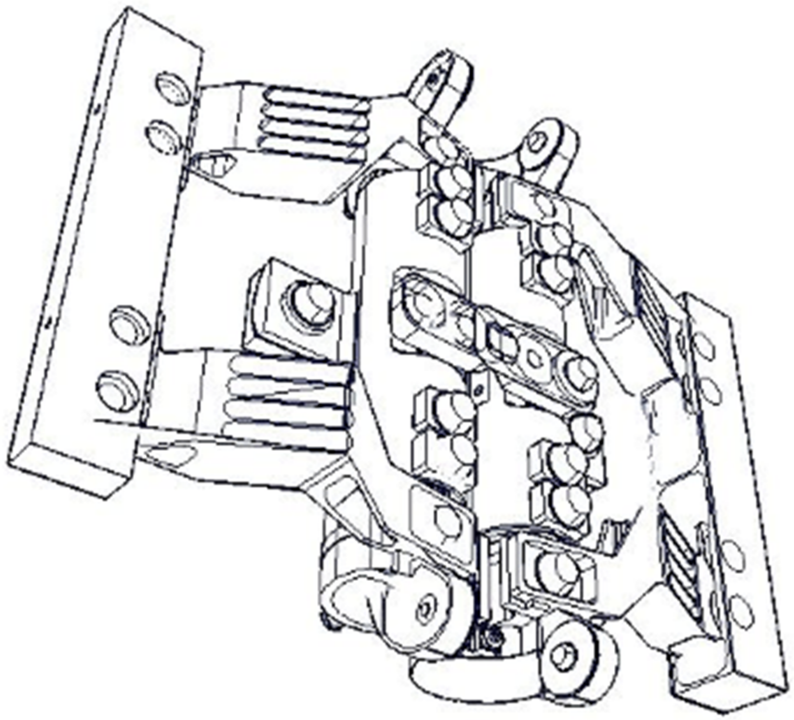
- The same kind of honeycombed lattices demonstrated by the titanium balls offer a way of reducing the mass and cost of rocket chambers and nozzles. They can also improve their thermal resilience, considering engine temperatures can rise as high as 2500°C. Such lattices have a hugely increased surface area compared to standard solid items, enabling increased radiative cooling.
- Similar AM-printed lattices are also being considered as more durable thruster catalyst beds, which will escape the typical degradation in performance of standard pellet-based catalysts over a propulsion system's lifetime.

- Carefully-tailored AM lattices have been investigated for 'propellant management devices' – sponge-like elements inside a propulsion tank that help prevent bubbles and ensure steady thruster performance.

- The broader potential of lattices to slash the mass of future satellite structure is also being considered.

Other examples at ESA:
3D printed deployable mechanisms (Image: Thales Alenia Space)

Other examples at ESA: Deployable structure frictionless hinge



- **Responsible: TAS**
- **The mechanism is made of 2 rolling brackets linked together by flexible blades. The two brackets are equipped with flexible helicoidally tracks witch act like springs and motorize the hinge. This principle is used for deploying solar array lateral panels but also any light space structures without any friction.**
- **State-of-the-art: The new design proposed in this study is issued from a old design witch have a very strong heritage since 1990 (XXX flying models). This new generation is now as the prototype state. Some tests have shown the capability to obtain a constant torque and also, if necessary, an adjustable torque in term of needs.**
- **Standard Manufacturing:**
- **Due to the shape complexity, the main brackets are done with 4 types of pieces glued together.**
- **A central cylindrical tube, receives the flexible helicoidally tracks and different blades support. The two brackets are very similar and are made with titanium material (TA6V).**
- **Limitation of standard manufacturing: This kind of piece is not realizable in only one part without a strong mass loss. Most of cavities are not accessible with conventional tools, and lots of manipulations of the piece are needed to manufacturing it.**

Possible technology improvements:

- Direct manufacturing process for mains brackets
- Specific deposit on blades and on brackets to increase (or reduce) the adhesion in localized zones.
- Specific deposit to “over thickened” the blades locally.
- Specific treatment on local parts of the brackets (Roughness reduction, and tribologic aspect)
- Hinge thermal stability improvement (carbon blades, ceramic pieces…)
- Mechanical lattice structure.

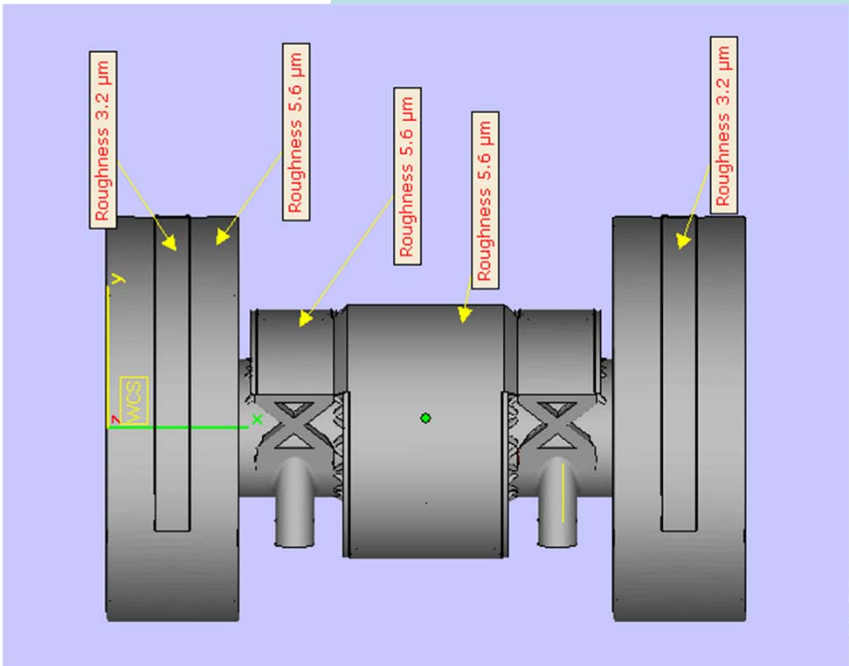
General Requirements:

- **Functional Req.: Non adhesion, flexion mechanical constrains on helicoidally tracks, Good roughness quality on tracks local parts.**
- **Operational & Performances Req.: Stiffness, limited thermal expansion, stability,**

Geometrical requirements:

Envelope:
Geometry is fixed by design. It should be kept similar.

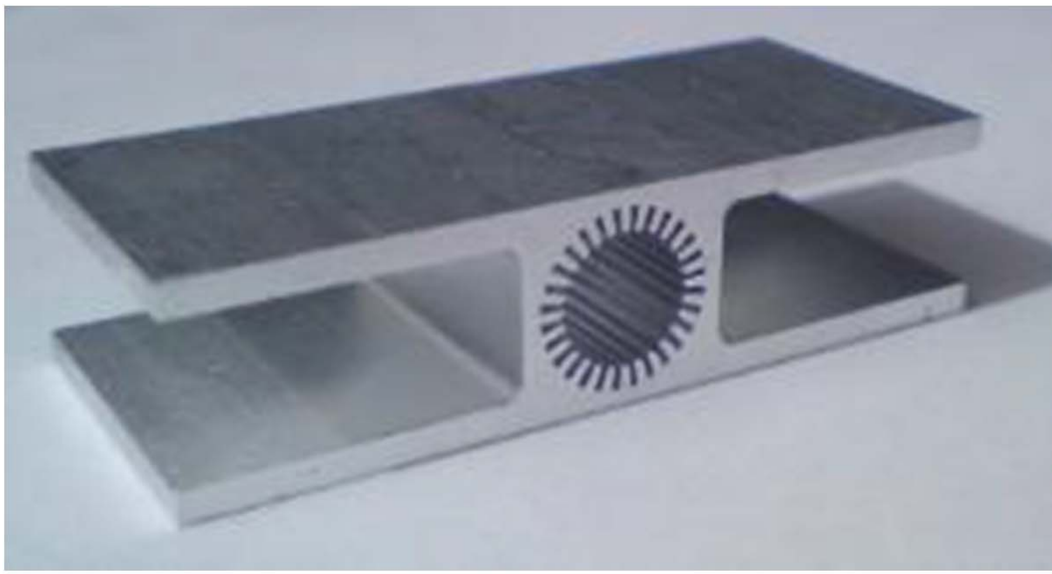
Surface finish/ interfaces:
Useful interfaces are shown on the pictures below. Low roughness is required

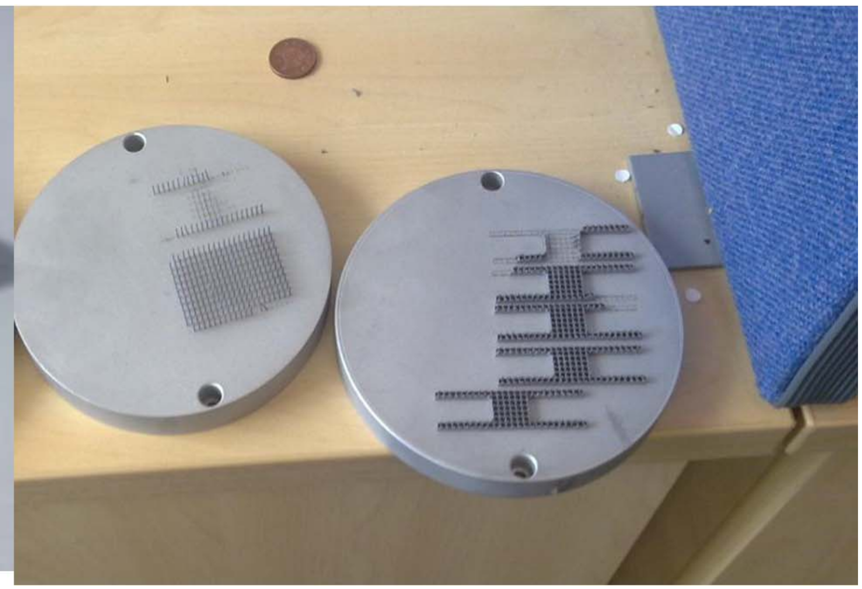


At Thermacore Europe
Sinter-style aluminium heat pipes

Thermacore have implemented selective laser melting (SLM) technique to produce sinter-style aluminium heat pipes.

Sinter-style SLM HPS have all the properties attributed to sintered heat pipes plus other advantages including porous wick design flexibility and simpler production process





In SLM machine, objects are formed onto a substrate and then are cut using a wire erosion process. Two substrates (Ø125mm) are shown with random geometry fabricated on their surfaces

Future work: Titanium Bellows

ESA has experienced in the last years an important number of failures and anomalies affecting mainly Titanium edge-welded bellows, used in critical applications for propulsion as well as cooling systems of spacecraft and scientific satellites, resulting in substantial delays and costs for the impacted Programme.

The defects leading to failure were observed most of the time on the welding joints of the bellows.

Additive Manufacturing technologies could be an alternative for manufacturing metal bellows for space applications, or be part of an "end to end manufacturing process".

Therefore bellows could be manufactured in one step, avoiding the critical welding phase.

These AM technologies offer possibilities and limits to the designers, different than the one known for conventional manufacturing. The current TRL for producing bellows with AM technologies is 1. The targeted TRL of this activity will be 4.

Future work at ESA

The Contractor shall address technologies applicable to as a minimum the following materials list:

- Aluminium and aluminium alloys
- Titanium and Titanium alloys (particularly Ti64)
- Stainless steel
- Nickel super alloys (particularly Inconel)
- Composite materials (e.g. metal matrixes, glass fibber)
- Polymers (particularly PEEK)
- Ceramics (particularly AlO3)

The set of AM technologies shall include, but not be limited to:

- Selective Laser Melting
- Direct Laser Deposition

Future work at ESA

This assessment shall have a strong multidisciplinary flavour to analyse **potential integration of different subsystems equipment** and possibility to **extend functionalities of certain parts of the system**. The study cases shall include as a minimum:

- structure with imbricated heat pipes;
- structural antennas and conductive surfaces;
- support structure for tanks;
- instrument-specific geometries (optical baffles, micro machined surfaces);
- propulsion piping and feeding system.

The analysis shall also address specific configurations (e.g. single parts replacing complex assemblies). New functionalities (e.g. printed sensors and electronics, printed RF-IT tags) shall also be assessed.

Future work at ESA
Surface Engineering for Parts Made by ALM

Objective: **Improve the bad surface finish obtained on the as-manufactured material.**

It is today not as good as the one obtained by conventional machining and the impact that such finishing has on the material properties and on the design is not well established. Therefore, a better understanding of the impact of surface characteristics on the material behaviour is needed to expand the use of ALM for high performances parts.

Needs:

1. Establish surface finishing techniques allowing reducing the roughness of the material while keeping a tight control on dimension accuracy
2. Define the limits that these finishing techniques have in terms of geometry and applicability.
3. Verify that the surface treatments commonly applied on the space hardware are not adversely impacted by these finishing techniques
4. Revisit the design rules applied to space hardware in terms of surface characteristics and surface accuracy.

Evaluate surface finishing techniques for parts made by the ALM technologies having the highest geometrical accuracy, i.e. SLM and EBM, in order to derive guidelines for future applications.

- The impact in surface characteristics shall be quantified as well as the impact on the shape accuracy induced by the surface finishing techniques.
- The impact of surface engineering on mechanical properties shall be established
- The compatibility of the finishing techniques with the primers and paints, surface conversion, passivation and anodising treatments commonly used in space industry shall be evaluated.

The different levels of surface finish to be targeted shall aim at ensuring that:

1) no particles remain that could detach from the surface.
2) the surface is smooth to a level compatible with potential space applications
3) the surface is clean and will not induce contamination due to fluid entrapment or promote corrosion
4) the coating generally used in space hardware can be applied to the surface.

Aim for a technology maturity of TRL 4.

Metallic material surface finishing state of the art.

Non exhaustive list:

- Mechanical / conventional machining techniques
- Physical deposition coating techniques
- Chemical deposition coating techniques
- Electro-chemical deposition coating techniques
- Chemical etching techniques
- Electro-chemical etching techniques
- Laser-based surface finishing technologies
- Mechanical abrasion technologies
- Local impact surface treatments
- Surface hardening treatments
- Paints and surface conversion

Focus on the applicability of the finishing techniques to the selected materials.

Surface improvement methodology optimisations

Verification plan shall include as a minimum:

- Static mechanical properties
- Dynamic mechanical properties and fracture mechanisms
- Corrosion resistance and corrosion mechanisms
- Stress corrosion resistance and fracture mechanisms
- Shape accuracy
- Surface features
- Surface contamination
- Anisotropy
- Impact of surface characteristics on friction behaviour
- Compatibility with the NDI technologies used in space industry, X-Ray, dye penetrant, eddy current, ultrasound.

Evaluation of the compatibility of the AM surface finishes to widely used in space industry surface treatments.

The compatibility with the following treatments shall be verified:

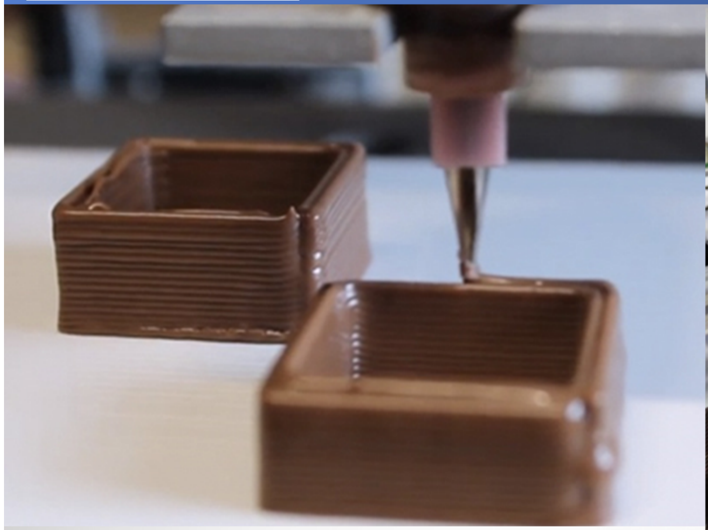
- Nickel coating of aluminium alloy
- Nickel coating of steel
- Passivation of stainless steel
- Anodising of titanium alloy
- Surface conversion of aluminium alloy
- Anodising of aluminium alloy (TBD: depending on the nature of the selected aluminium)
- Painting of aluminium alloy
- Painting of steel

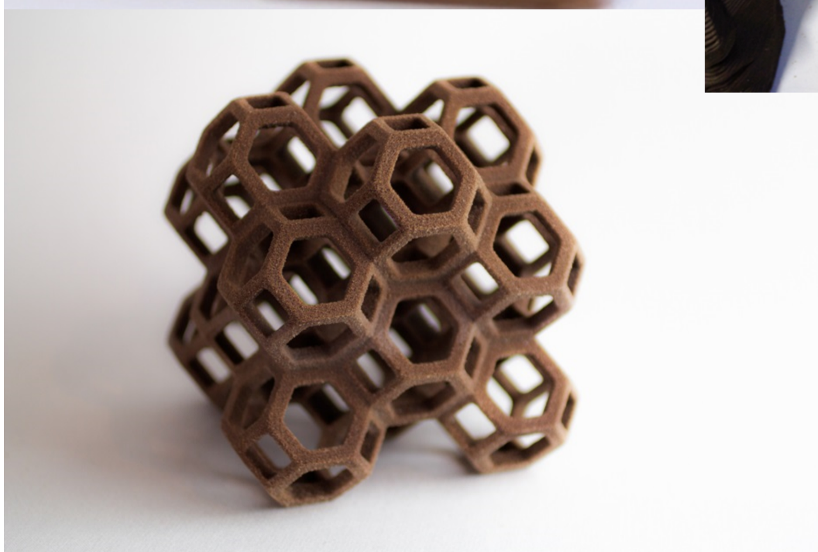
Success factors

This table provides an overview of the most important success factors from today‘s perspective. The most relevant success factors for increasing the market penetration by AM across the analyzed industries are the following:

- Design rules;
- Surface quality;
- Process reliability and part reproducibility;
- New materials;
- Quality assurance systems;
- Layer thickness;
- Process costs;
- Multi-material processing;
- Certifications.

3D food printing





Publications

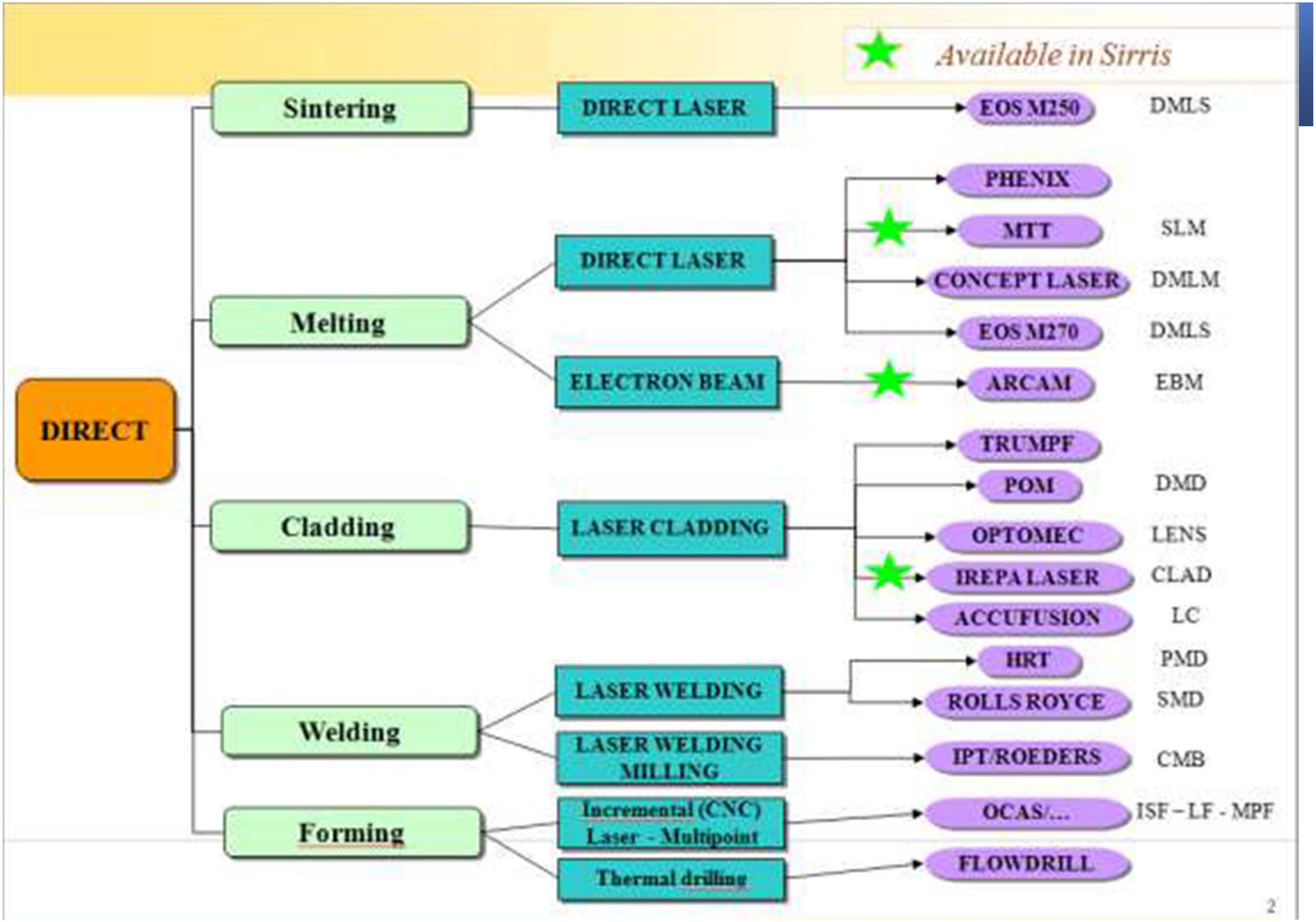
- 65th International Astronautical Congress, Toronto, CanadaIAC-14,C2,8,3,x21186; New applications of Advanced Manufacturing Methods for space instrumentation and Systems of Nanospacecraft, P. Rochus, J-Y Plesseria, A. Corbelli, L. Pambaguian, Ch. Masse, O. Rigo, B. Bonvoisin

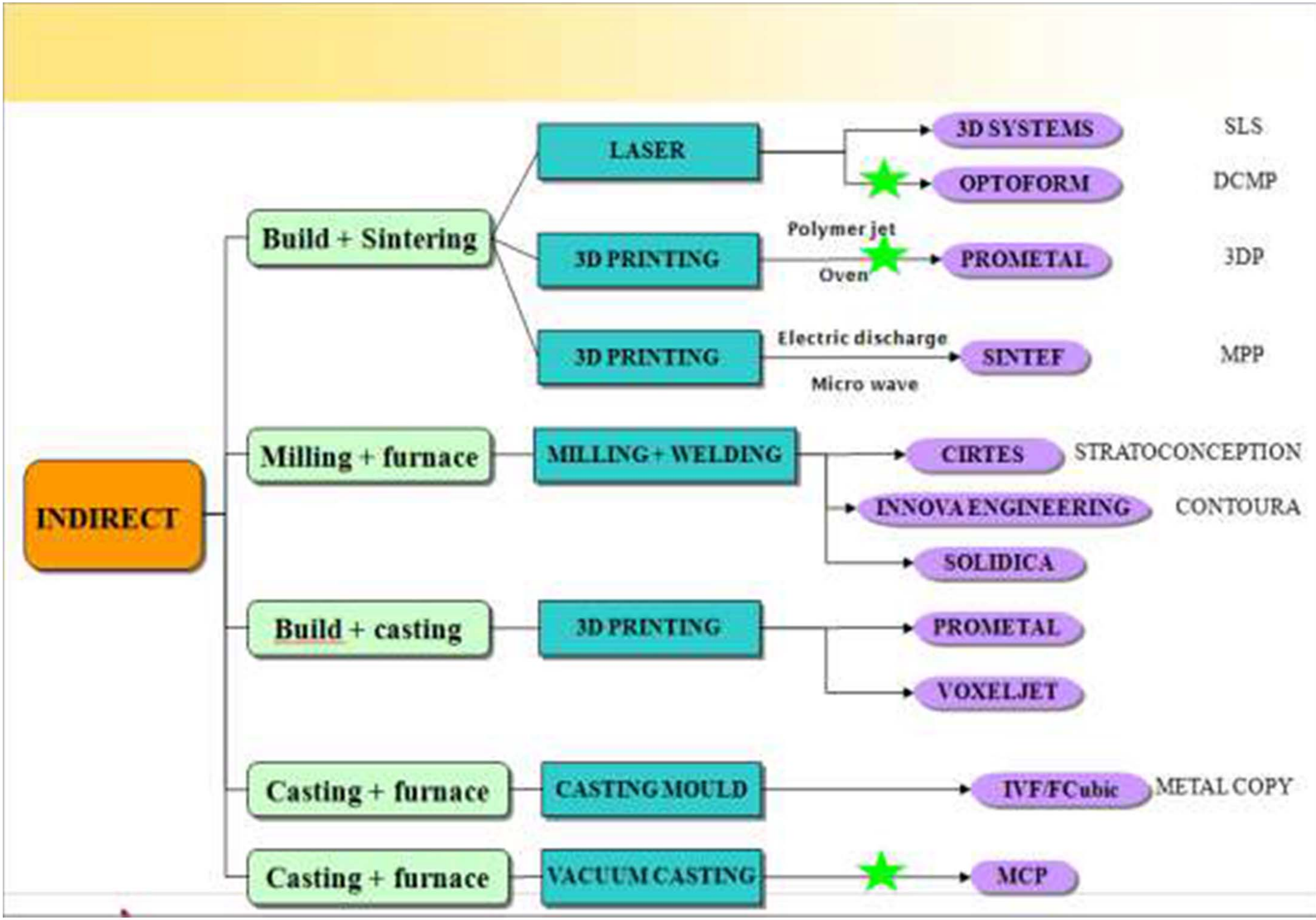
Overview of the metal additive manufacturing technologies

The four most important processes: laser melting, electron beam melting, laser cladding and 3D Printing.

Two main categories.

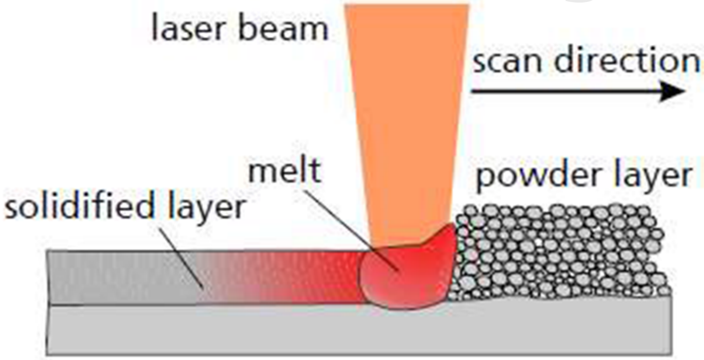
1. DIRECT processes: DIRECT meaning that the final parts are obtained directly out of the machine at the end of the building.
2. INDIRECT :they need a complementary step to finish the process. Generally, the additional process is a passage in the oven for debinding and sintering, welding or castingsteps.

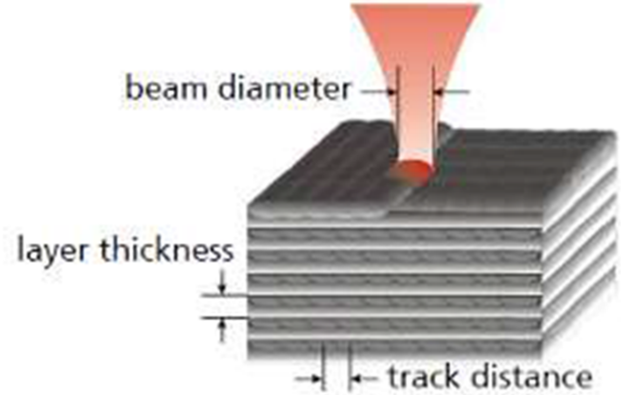

Available in Sirris
DIRECT
Sintering
DIRECT LASER
EOS M250
DMLS
Melting
DIRECT LASER
PHENIX
MTT
SLM
CONCEPT LASER
DMLM
EOS M270
DMLS
ELECTRON BEAM
ARCAM
EBM
Cladding
LASER CLADDING
TRUMPF
POM
DMD
OPTOMEC
LENS
IREPA LASER
CLAD
ACCUFUSION
LC
Welding
LASER WELDING
HRT
PMD
ROLLS ROYCE
SMD
LASER WELDING MILLING
IPT/ROEDERS
CMB
Forming
Incremental (CNC) Laser - Multipoint
OCAS/...
ISF – LF - MPF
Thermal drilling
FLOWDRILL
2



INDIRECT
Build + Sintering
LASER
3D SYSTEMS
SLS
OPTOFORM
DCMP
3D PRINTING
Polymer jet
Oven
PROMETAL
3DP
3D PRINTING
Electric discharge
Micro wave
SINTEF
MPP
Milling + furnace
MILLING+ WELDING
CIRTES
STRATOCONCEPTION
INNOVA ENGINEERING
CONTOURA
SOLIDICA
Build + casting
3D PRINTING
PROMETAL
VOXELJET
Casting + furnace
CASTING MOULD
IVF/FCubic
METAL COPY
Casting + furnace
VACUUM CASTING
MCP

Laser melting





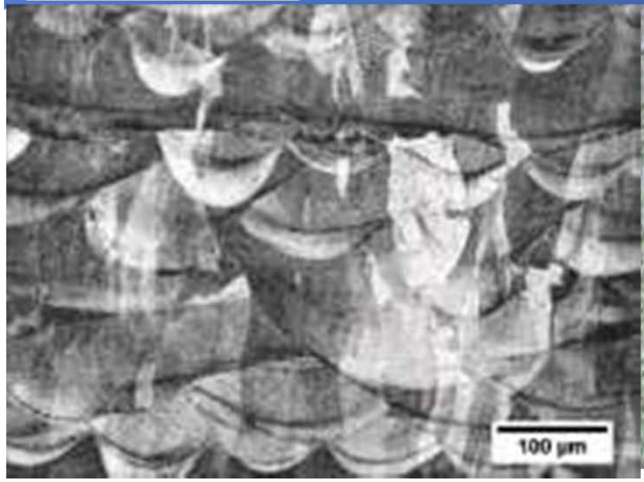
The laser melting process uses a powered laser to fuse fine metal powders together layer by layer directly from 3D CAD data to create functional metal parts.
After each layer a powder recoating system deposits a fresh layer of powder with a thicknesses ranging from 20 to 100 µm.

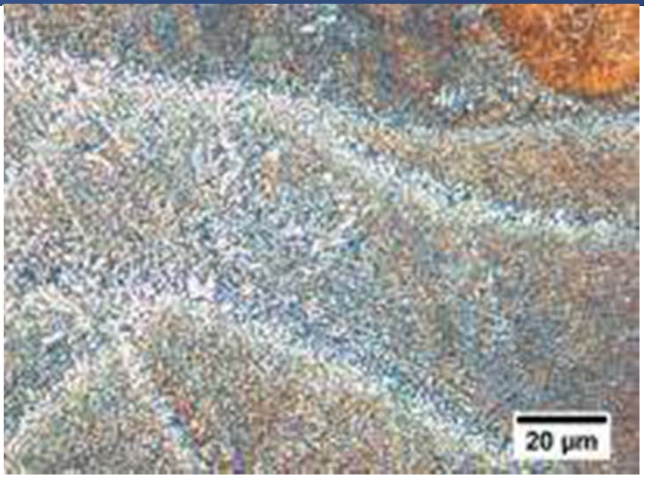
Materials
Our system uses commercially available gas atomized metallic powders to produce fully dense metal parts in materials including

- Titanium (Ti grade 1, TiAl6V4, Ti Al6Nb7),
- Stainless Steel (316L, 1.4410),
- Cobalt Chrome (Co212f),
- Tool Steel (1.2709, H13),
- Aluminum (AlSi12, AlSi10Mg),
- Inconel (618, 625).

The grain size of all powder materials is between 10 and 45 µm.
Components produced by selective laser melting show a homogenous and dense structure. If require, the structure can be heat treated to achieve the required conditions.
Porosity results: For all samples, the density is more than 99.2%. The best result is obtained for titanium (99.75%). These values must be confirmed after parameters optimization.
Steel : 0.6% Ti : 0.25% Al : 0.8%
The porosity is strongly depending on the exposure parameters used to build the part. It is even possible to create parts including large porosities.

Microstructures results (benchmark):





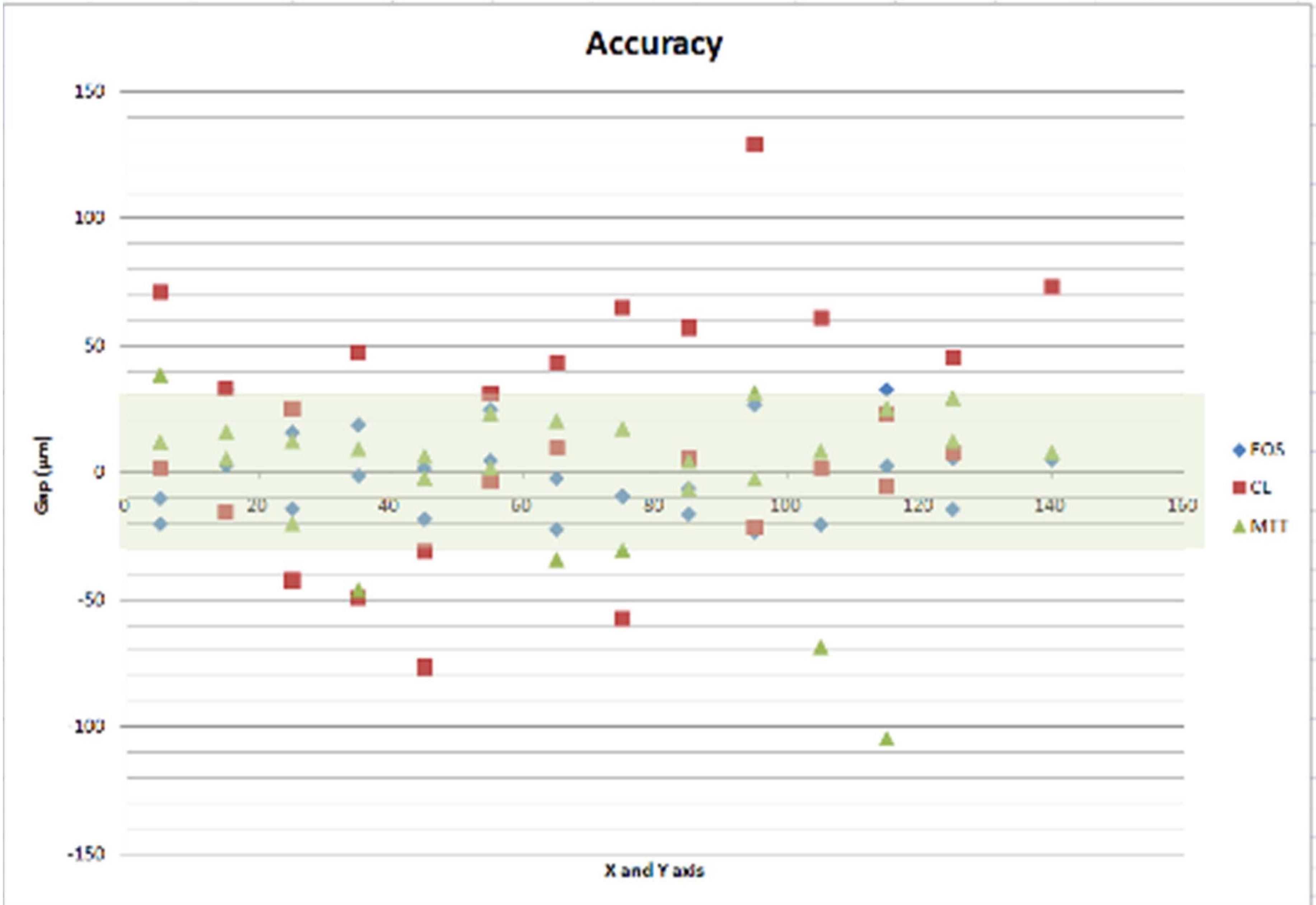
Steel Titanium Aluminum

Microstructure analysis

A part built by laser melting can be considered like a set of parts melted of 100-200µm welded together. Due to the small size, each of the melt pool is very quickly cooled and the solidification speed is very high (10^2 up to 105 K/s). The microstructures obtained are not equilibrium microstructures. The melt pools revealed by the metallographic attack show that there are chemical segregation or solidification texture at the scale of the melting pool. The characteristic size of the microstructure elements (phases, cells) are for each of the materials about 1 micron. This fineness is the result of the quick solidification who tends to limit the diffusion phenomena on a large scale.

The fineness of the microstructures logically tends to increase the mechanical resistance comparatively to large homogeneous and isotropic grain microstructures.

The few data from the literature confirm this trend. Mechanical tests should confirm this.



Comparison of the accuracy on benchmarks produced for Sirris on EOS, MTT and Concept Laser machines.

Electron Beam Melting (EBM)

The electron beam melting process is quite similar to the laser melting. The main difference is due to the energy supply who is coming from an electron beam gun instead a laser.
The second main difference is the vacuum chamber unit eliminating impurities and resulting in high strength properties of the material. The standard layer thickness is 100 microns (70 µm up to 200µm).

Materials

The system uses commercially available gas atomized metallic powder to produce fully dense metal parts in material including
Titanium (Ti6Al4V and Ti6Al4V ELI) and CoCr alloy.
The grain size of the powder materials is between 45 and 75 µm.
Components produced by electron beam melting show a homogenous and dense structure. If required, the structure can be heat treated to achieve the required conditions.
High build temperature provide good form stability and low residual stress in the part and thus good properties (strength, elasticity, fatigue, chemical composition, microstructure)

For all samples, the density is more than 99.9% (99.92% - 99.97%). The porosity is strongly dependent on the exposure parameters used to build the part. It is even possible to create parts including large porosities. Most of the porosities are spherical. This form of porosity is less damageable than non spherical forms.

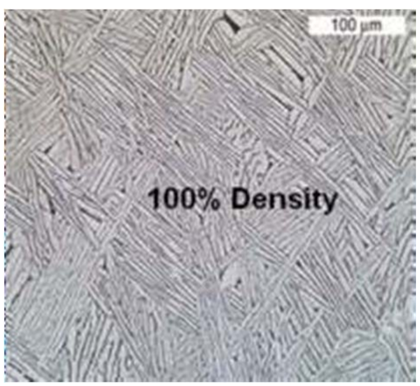
Microstructures results

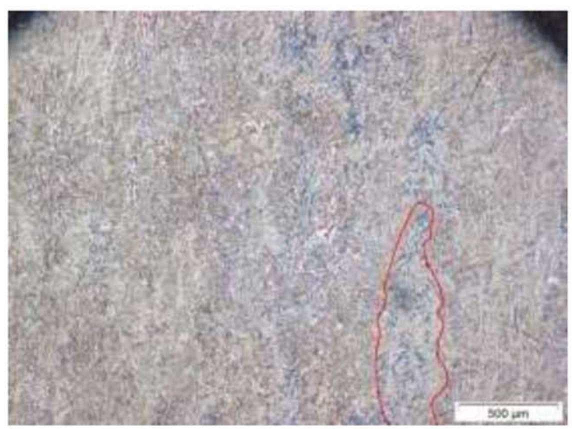
The first microstructures shows α phases (needles aspect) in β phases similar to Widmansttäten structure. These microstructures have to be analyzed more in details with good final parameters.

A part built by electron beam melting can be considered like a set of parts melted welded together. Due to the small size, each of the melt pool is very quickly cooled and the solidification speed is very high.

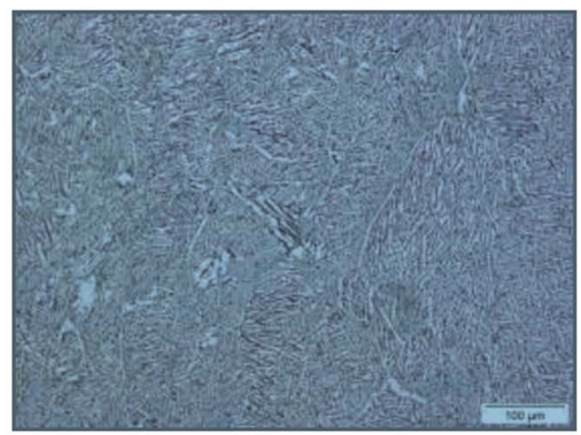
The fineness of the microstructures logically tends to increase the mechanical resistance comparatively to large homogeneous and isotropic grain microstructures.

The few data from the literature confirm this trend. Mechanical tests should confirm this





In red: β grain



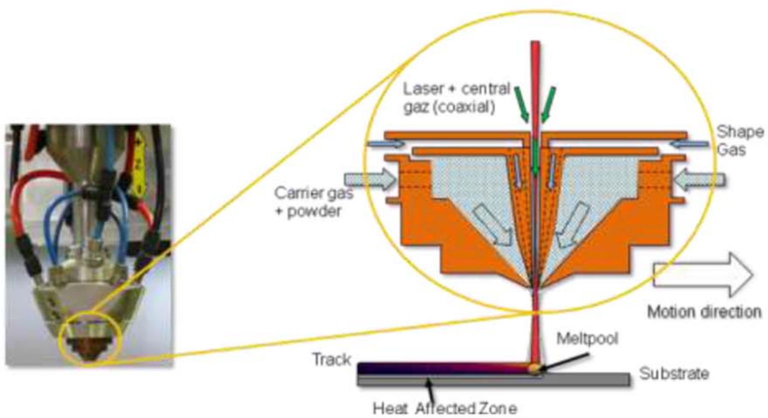
Advantages and limitations

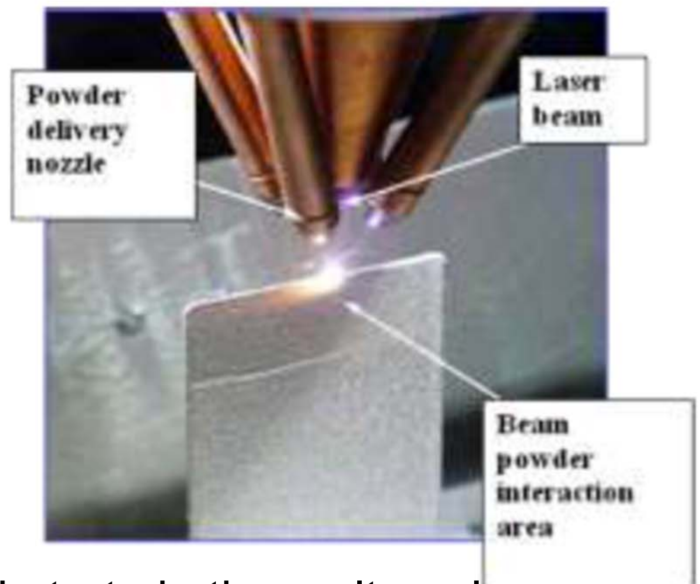
-Productivity: 10 up to 40 cm^3/h (related to the process, material, layer thickness, power, part geometry and surface roughness requirements) – even 90cm^3/h for lattice structures.
-Layer thickness: 70µm (50) up to 200µm
-High density: 99.9%
-Roughness: Ra = 15 up to 35µm
-Accuracy: +/- 300 up to 400µm (200µm in development)
-Resolution: 0.6 up to 1mm (depending of exposure parameters)
-Need substrate plate or supports for cantilever features, but easy to remove

Laser Cladding

Principle

Basically, the process is similar to a laser welding technology.
One (or two for graded materials) different powders are blown by an argon flow up to the specific nozzle. Then, the resulting mixed flow of material gets through the laser beam, which is coaxial to the nozzle.





By this way the powder melts and reaches the substrate in the melt pool.
By moving the laser head (nozzle + optic) on five axis, it is possible to create tracks, thick layers and walls.

Materials

The system uses commercially available gas atomized metallic powder to produce fully dense metal parts. The powder used is a spherical powder of 45 – 75µm size (meso) and 50 – 150µm size (macro). The materials already used by IREPA-Laser are:

Materials	Applications	CLAD	Recoating
SS 316L	Corrosion resistance	xxx	xxx
Cp Ti	Biomedical	xxx	
TA6V	Structure parts, biomedical	xxx	xxx
Ti 6-2-4-2	Aeronautic	xxx	
Gold (yellow)	Jewelry	xx	
Cu base	Reinforcement of Al surfaces	xx	xxx
Al (SI,...) alloyes	Repairing	x	xx
INC 718	High T° resistance	xxx	xxx
INC 625	Aeronautic	xx	xx
Stellite 1	Wear resistance		x
Stellite 6, 12, 21, 25	Wear resistance		xxx
WC + base Ni,Co,...	Wear resistance		xxx
Tool steel H13, D7, T15	Moulds,...		xx
Tool steel CPM, 10V, M2	Moulds,...	xxx	xxx
Waspalloy	Aeronautic		xx
SS 410, 440,...	Light corrosion resistance		xx => xxx
Hadfield steel	Wear resistance		xxx

Porosity & Microstructure results

Components produced by laser cladding show a homogenous and dense structure.

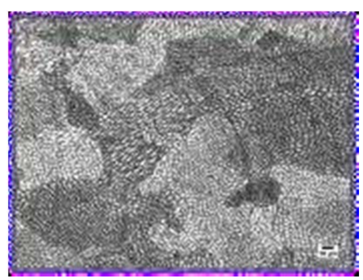
Porosity results

Once the technology is mastered, the structure is free of cracks or porosity and has only low powder/substrate dilution.

Microstructure results

A part built by laser cladding can be considered like a set of parts melted welded together. Due to the small size, each of the melt pool is very quickly cooled and the solidification speed is very high(103 – 104 K/s). This contribute to obtain fine microstructures and this logically tends to increase the mechanical resistance comparatively to large homogeneous and isotropic grain microstructures.

The few data from the literature confirm this trend. Mechanical tests should confirm this.



Advantages and limitations

-catchment efficiency: >90% in coating mode - 60% on a thin wall

-wide track meso: 0.7 – 1.1mm

-wide track macro: +/-2mm

-mean track section macroCLAD: 2 x 0.7mm

-productivity meso: 3 – 15 cm^3/h

-productivity macro: 40 – 250 cm^3/h

-layer thickness meso: 100 – 200µm

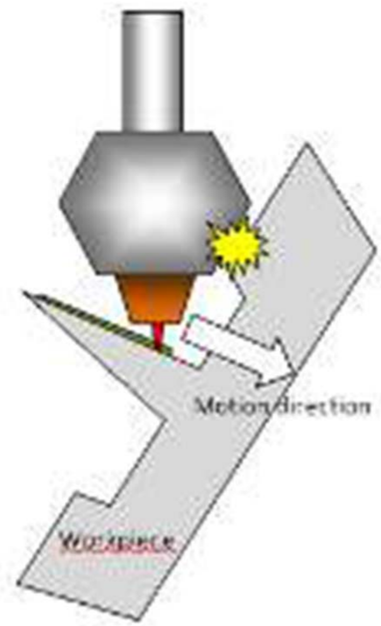
-layer thickness macro: 600 – 1000µm

-high density: 99.9%

-roughness: Ra = 20µm (meso)

-limitation access due to the nozzle space

-no supports



3D Printing Prometal

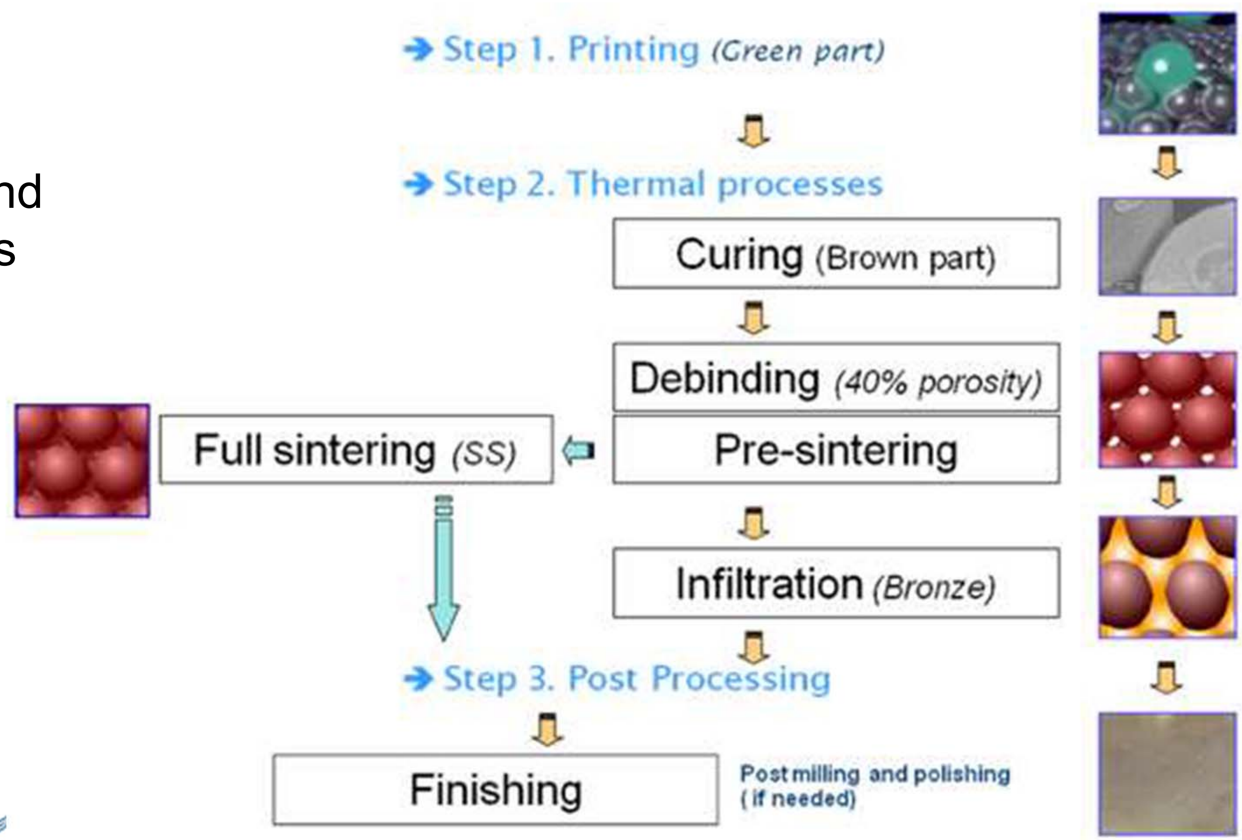
Principle

During the first step (printing), a print head applies a layer of binder to the metal powder to form a layer of the part. The binder is applied to bond the metal particles together and to the previous layer. The process repeats until the entire part has been printed.

The second step is a thermal process to be applied on the "green" part in a furnace. As the part is heated, the binder burns away (curing and debinding) and the steel is sintered together (pre-sintering), creating a porous perform of 60% density. Molten bronze infiltration via capillary action occurs during the thermal cycle to produce a fully dense composite (60% SS steel and 40% bronze) part.

The part is ready for final machining.

An alternate way is to avoid the bronze infiltration step and continue the thermal process to obtain a full density steel part or a controlled porosity part.



Materials

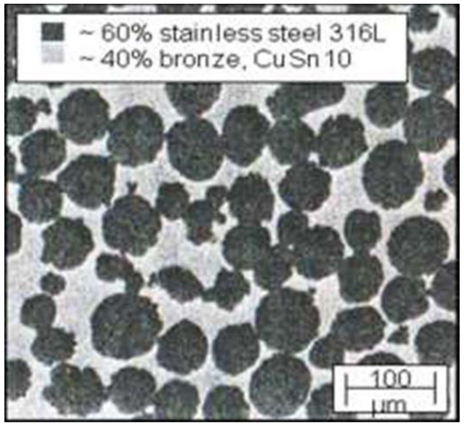
The system uses commercially available gas atomized metallic powder to produce composite (60% stainless steel(316L or 420) / 40% bronze) metal parts.

The powder used is a spherical powder of 45 – 105µm size.

The materials commonly used are:

- -60% SS 316L and 40% bronze
- -60% SS 420 and 40% bronze

-Basic properties: UTS +/- 500Mpa



Advantages and limitations

-No support: freedom for external and internal complexities

-Materials: basic (composite SS + bronze or porous SS)

-Layer thickness: 70 – 170µm

-99.9% density

-Roughness: similar than sand casting (Ra = 60µm)

-Big productivity (> 100 cm^3/h), but additional furnace step

-Resolution: 300µm, but commonly 500µm

-Accuracy: +/- 300 up to 400µm

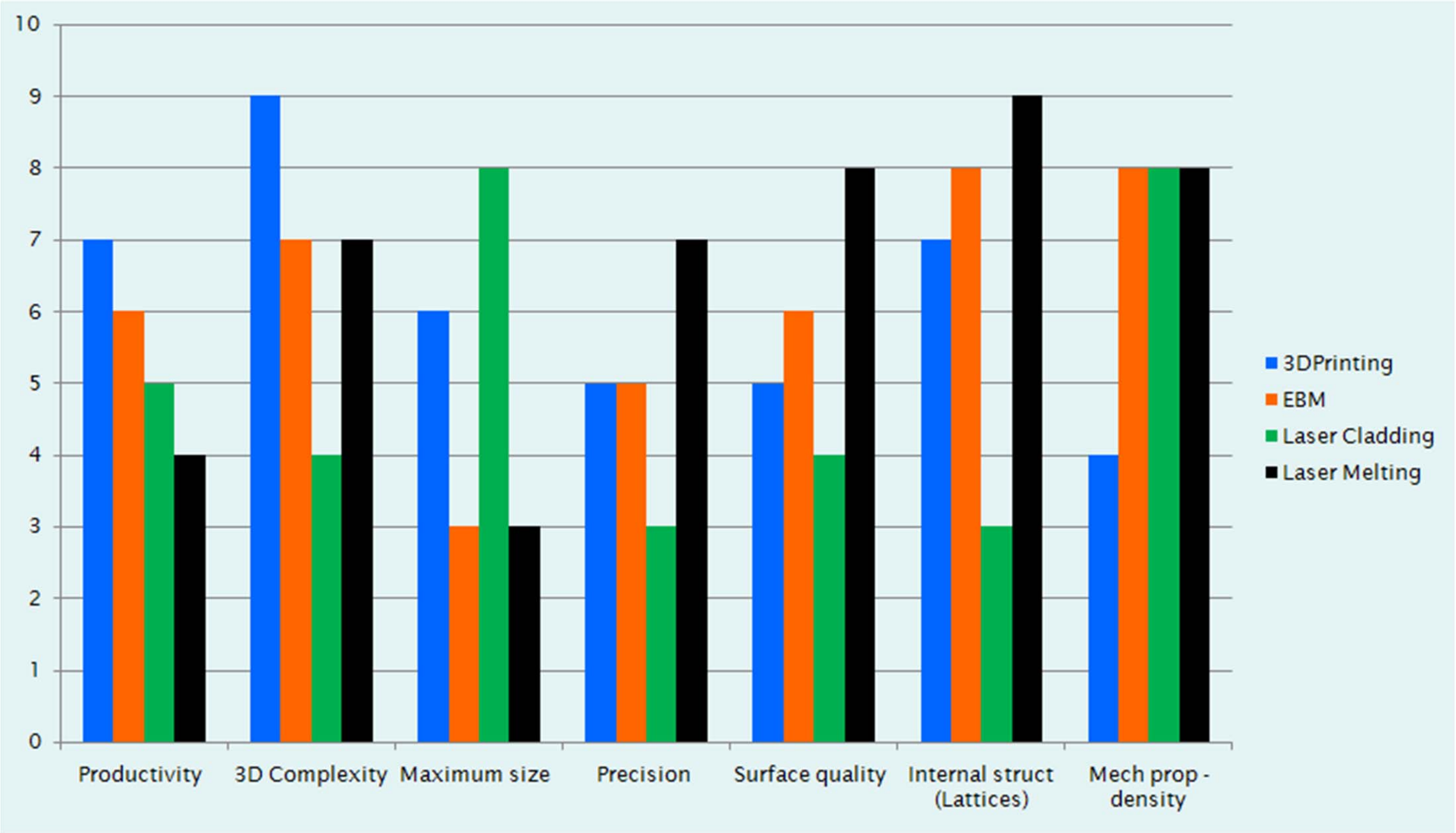
-Minimum wall thickness: +/- 1mm

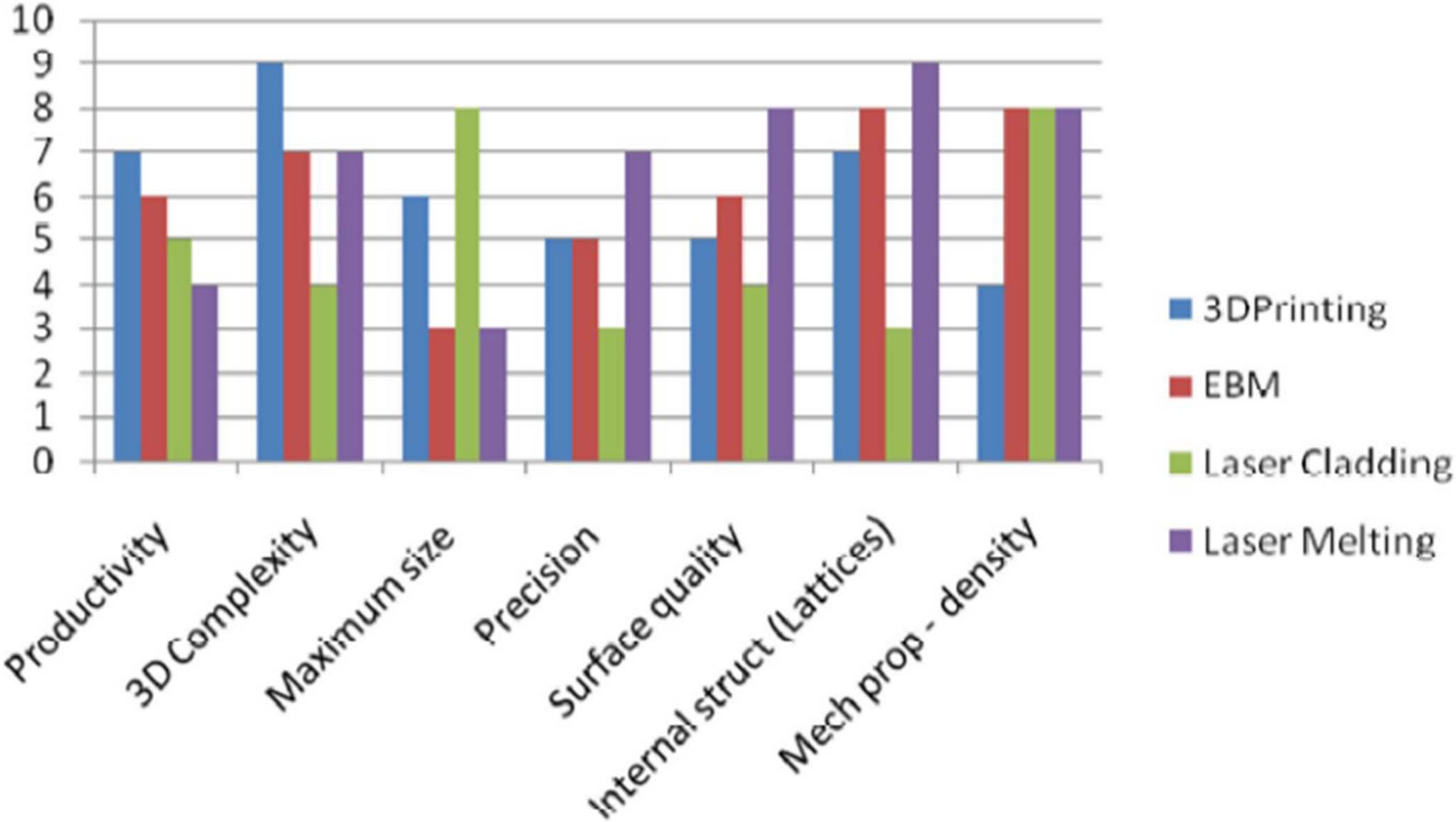
-Size: relative big parts (limitations due to the furnace size) +/- (300 x 300 x 220 mm or 450 x 250 x 220mm)

Processes comparison

	3DPrinting	*EBM*	*Laser Cladding*	*Laser Melting*
Source	Printhead	Electron Beam	Laser	Laser
Powder feeding	Powder bed	Powder bed	Nozzle	Powder bed
Materials	S Steel + Bronze	Ti CoCr	Ti steel …	Ti Alu Steels Inco
Controlled porosity	Yes	No	No	No

Processes comparison




10
9
8
7
6
5
4
3
2
1
0
Productivity
3D Complexity
Maximum size
Precision
Surface quality
Internal struct (Lattices)
Mech prop - density
3DPrinting
EBM
Laser Cladding
Laser Melting

Processes comparison

Depending on the process and exposure parameters, the gap of the building speed (productivity) is 3 cm^3/h up to 250 cm^3/h. The productivity is between 5 and 20cm^3/h for the Laser Melting process, between 10 and 40 cm^3/h for the Electron Beam process and until 250cm^3/h (and more) for the Laser

Cladding process and the 3DPrinting process.

-3D complexity is easier with 3DPrinting process, due to the no necessity to have supports and remove them.

-3D complexity is more difficult with Laser Cladding due to the 5 axis management and potential collisions.

-The maximum size limitation for Electron Beam Melting and Laser Melting is mainly due to the focal distance. Some developments should increase the laser power and the volume of the build chamber.

-The accuracy is much higher for Laser Melting (20 – 50µm) than other processes (200 – 500µm).

-The roughness (surface quality) is also better for Laser Melting (Ra = 5 – 10µm). it is quite similar for Electron Beam Melting (Ra = 15 – 35µm) and Laser Cladding (Ra = 20 – 40µm).

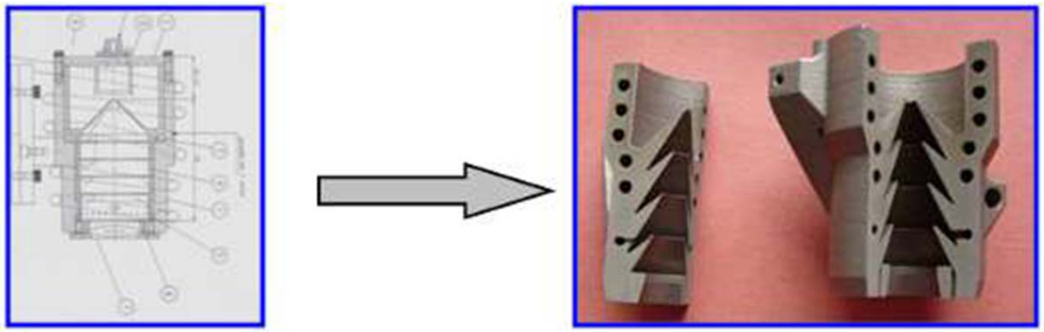
-Due to the 5 axis, Laser Cladding it is not the best way to build some internal or complex structures like lattices. The 3DPrinting process is well adapted for internal and complex structures, but it is limited by the minimal thickness due to the fragility during the cleaning step.

-Except the 3DPrinting process with basic materials, the other processes have the possibility to product very good material properties, rather similar and even sometimes better than the conventional materials.

Typical applications

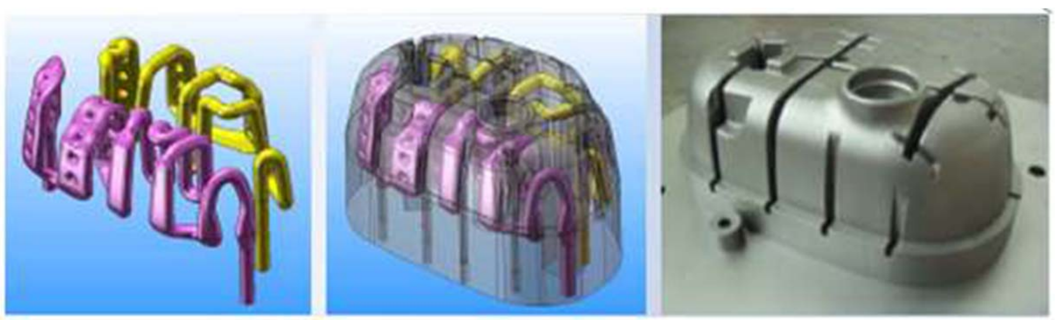
New design concepts

The additive manufacturing allows new design concepts for instance by replacing several elements by one component including different functions. This capacity give a new way for conception and allows to decrease time and costs.



Internal geometries

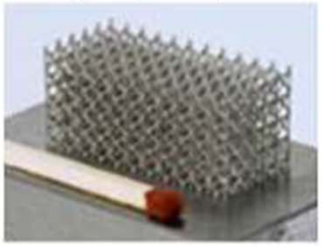
These processes also allows to create directly internal geometries like 3D channels or cavities for thermal management, flow control, sensor positioning,… This is well used to create conformal cooling in the injection molding applications with the aim to optimize the thermal operations and decrease the injection cycle time by 15 up to 35%.

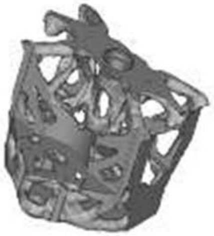


Typical applications

Lightweight parts

One of the most interesting capacity is the possibility to build complex structures like lattices and cellular structures to obtain light parts, bone regeneration, filters, topological optimization structures…





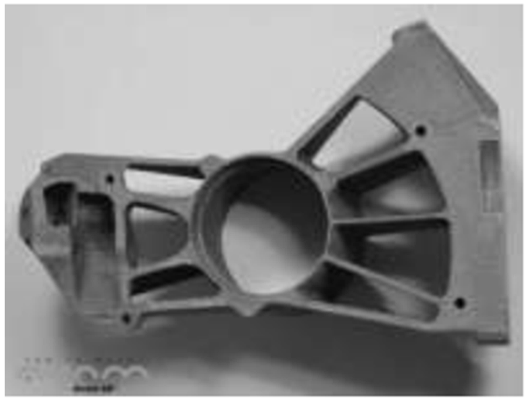
Porous parts

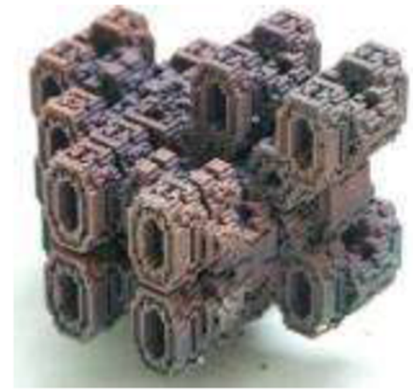
The 3DPrinting process allows to produce controlled porous parts by managing the sintering parameters, the composition of the powder mixture or the addition of organic fillers. The result of this development is already used for nano-production system components for instance. Laser Melting and Electron Beam Melting have also capacities to produce non-full dense parts. The result it is not a real porosity, but rather like filter parts.

Typical applications

Complex parts

The main common property of these processes is the ability to produce very complex geometries even sometimes, impossible to build with conventional





Repairing of expensive parts

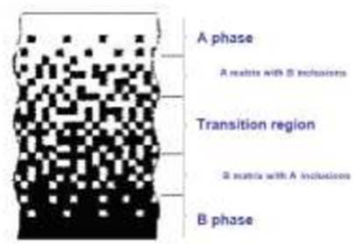
The Laser Cladding process has possibilities for repairing operations. The first step is to remove the defect area by milling. The second step made by Laser Cladding is to add new materials following the initial 3D geometry and finalize by a finishing step to be in accordance with the accuracy and the surface quality.

Typical applications

Functional Graded Materials (FGM)

Some of these processes (cladding mainly because it is not a powder bed) have a real potential to develop bi-material or graded material components. The potential applications are for instance:

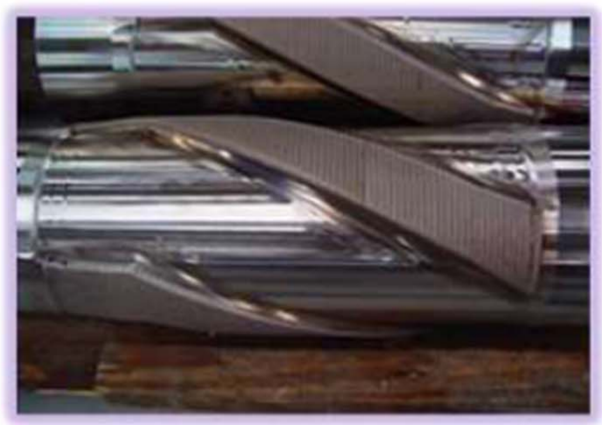
- molding inserts including good thermal properties for the core and good wear resistance for the skin
- parts with different properties (impact resistance, fatigue, creep, wear) depending on the area
- coating to improve the wea
- repairing of expensive part



Typical applications

Coating

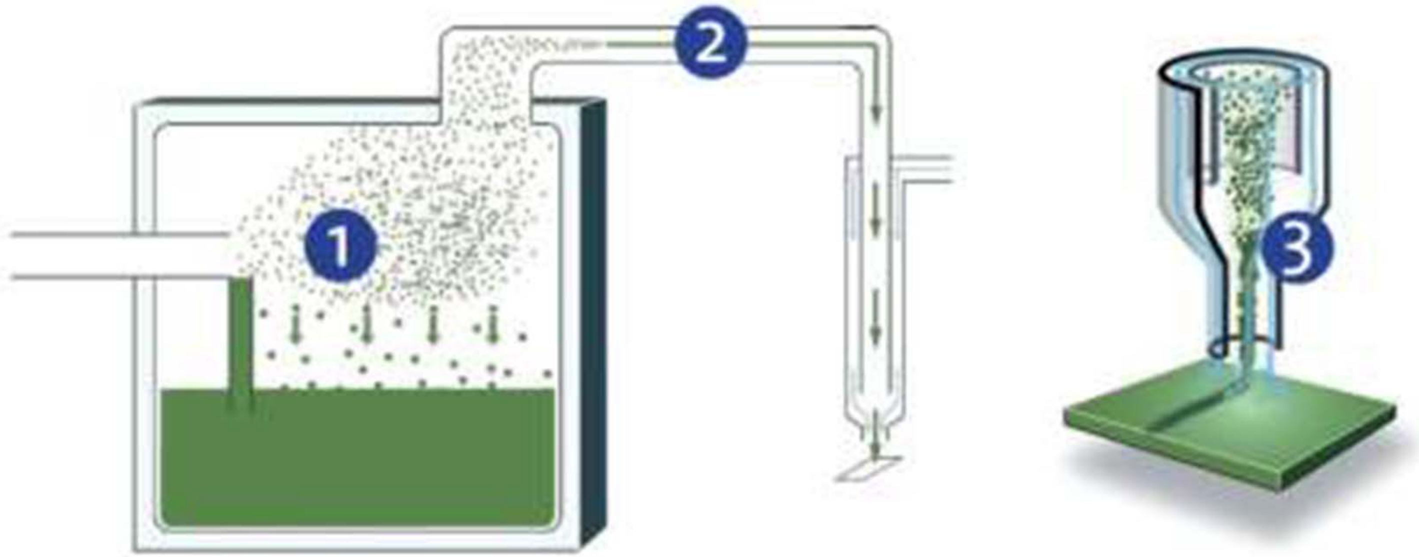
It is an easy way to coat any part by laser cladding process to improve properties such as wear resistance, corrosion resistance and hardness.



Aerosol Jet Printing

Aerosol Jet printing (AJP) is a particularly innovative technique for the selective, maskless deposition of materials (conductive, dielectric, …) at micron- scale, onto any flat but also non-flat , flexible or 3D substrate.

In this technology, an ink (solution or suspension of nanoparticules) in a jar is atomized by ultrasonic or pneumatic mechanism. Resulting aerosol jet is then transfer red (2) to a writing nozzle (3) where it is driven (thanks to a sheath gas) towards an X-Y-moving substrate. Moreover , z-axis is al so motorized, which al lows 3D substrates



Aerosol Jet Printing : principle

Aerosol Jet Printing related advantages

- no mask required to create any micron-size pattern: gain in flexibility and reliability,
- high resolution: 10µm-width/150 nm- thick minimum feature size for high-resolution, CAD-driven patterning,
- local sintering by IR laser beam: compatible with thermally sensitive substrates or components ,
- versatility: large range of processable materials , from conductive to dielectric, and even semi-conductive materials ,
- 3D-compatible: equipment allows any material to be deposited at micron-scale onto flat but al so 3D or even flexible substrates .

Those various features make the technology quite advantageous for

jobs requiring high-resolution and/or 3D conformal deposition of a large range of materials onto various types of classical but also less ordinary substrates . Table 1 summarizes the main characteristics of classical printing techniques (screen printing and inkjet) and compares them to Aerosol Jet Printing specifications .

Aerosol Jet Printing Key- features

Features	Screen Print	Ink Jet	Aerosol Jet	Benefits
Minimum resolution	~ 100 microns	~ 30 microns	<10 microns *	Finer feature sizes
Single-pass Layer Thickness	100 microns	~ 0.1 microns	150nm-10 microns*	Improved process control
Material Viscosity	>10,000 mPa·s	5 to 15 mPa·s	0.7-2500+ mPa·s	Wider material choices and control over deposition thickness
Material Formulation Time	Months	Years	Months	Existing materials can be easily adapted
Pattern Generation	Hard Tooling - Screen Template	Digital - Raster	Digital - Direct Vector from CAD	Greater accuracy
Substrate Requirements	Planar - Screen fixed at ~ 1mm above substrate	Planar- Print head fixed at ~ 1mm above substrate	Planar or Non-Planar	Not sensitive to surface irregularities, enables conformal deposition.
3D Direct Writing	Fixed – planar only	Fixed – planar only	3-4+ Axis	3D capability

*Material Dependent

(SOFA 2008 / Credit: Optomec)

Table 1 – Comparison between screen, inkjet and aerosol jet printing techniques (credit: Optomec)

Aerosol Jet Printing Materials

Thanks to the flexibility and universality of the process , a large range of materials are processable by AJP. Beside the commercially available products, other tailor -made formulations can also be developed for AJP.
Table 2 highlights some of the materials that have already been tested with an AJP equipment (source: Optomec) .

Conductors

Nano Ag - UT Dots, Nanomas, Cabot, Nanosize, Harima, ANP...

Nano Au - UT Dots, Nanomas, Harima

Nano Pd - Nanomas

Nano Cu

Thick Film Au - Dupont

Conductive Polymer

PEDOT:PSS from H.C. Stark

SW CNT - Brewer Science

OE Semiconductor

P3HT, PQT, SW CNT...

Resistor

PTF Carbon - Asahi, Dupont

Metal Oxide - Dupont

Dielectrics

UV Epoxy - Norland, Locktite, Summers...

PMMA- Alpha Aesar, PVP - BASF

Polyimide- Huntsman

PTF Barium Titanate- Asahi

Teflon- 3M, Dupont

Novel Materials

MicroCat – MacDermid,
Nano Composite Polymers, Biomaterials...

Aerosol Jet Printing Applications

AJP applications are quite numerous , ranging f rom surface patterning and functionalization, printed electronics , sensors , to microfluidics or even medical and biotechnology. In this sect ion, we will focus on one of the most relevant application of the technology with respect to space – related systems : direct printing of embedded circuitry or sensors .

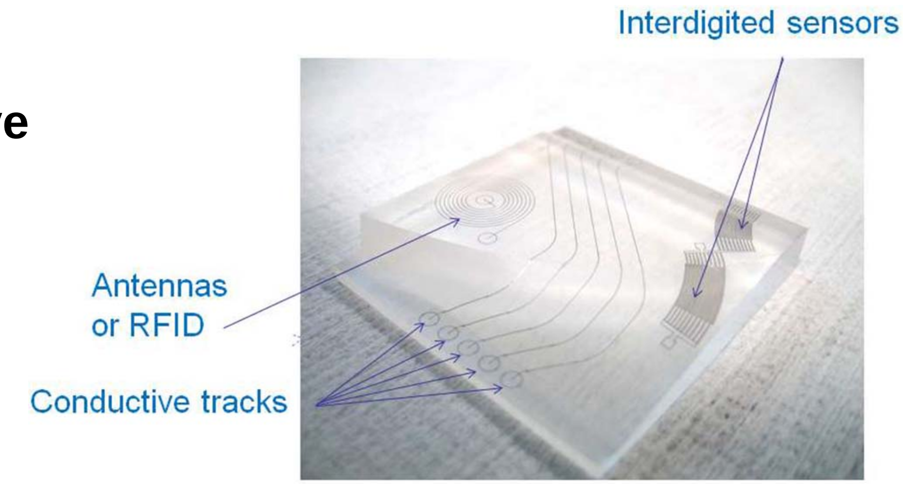
Indeed, main potential application of AJP technology to space domain can be foreseen in the framework of direct , conformal deposition of conductive circuitry onto payload wall or structure, component packaging, … as a substitute for conventional electrical wiring. The aim is to swipe out typical problems and sources of failure related to strapping,

accessibility, or weight is sues of traditional wiring.

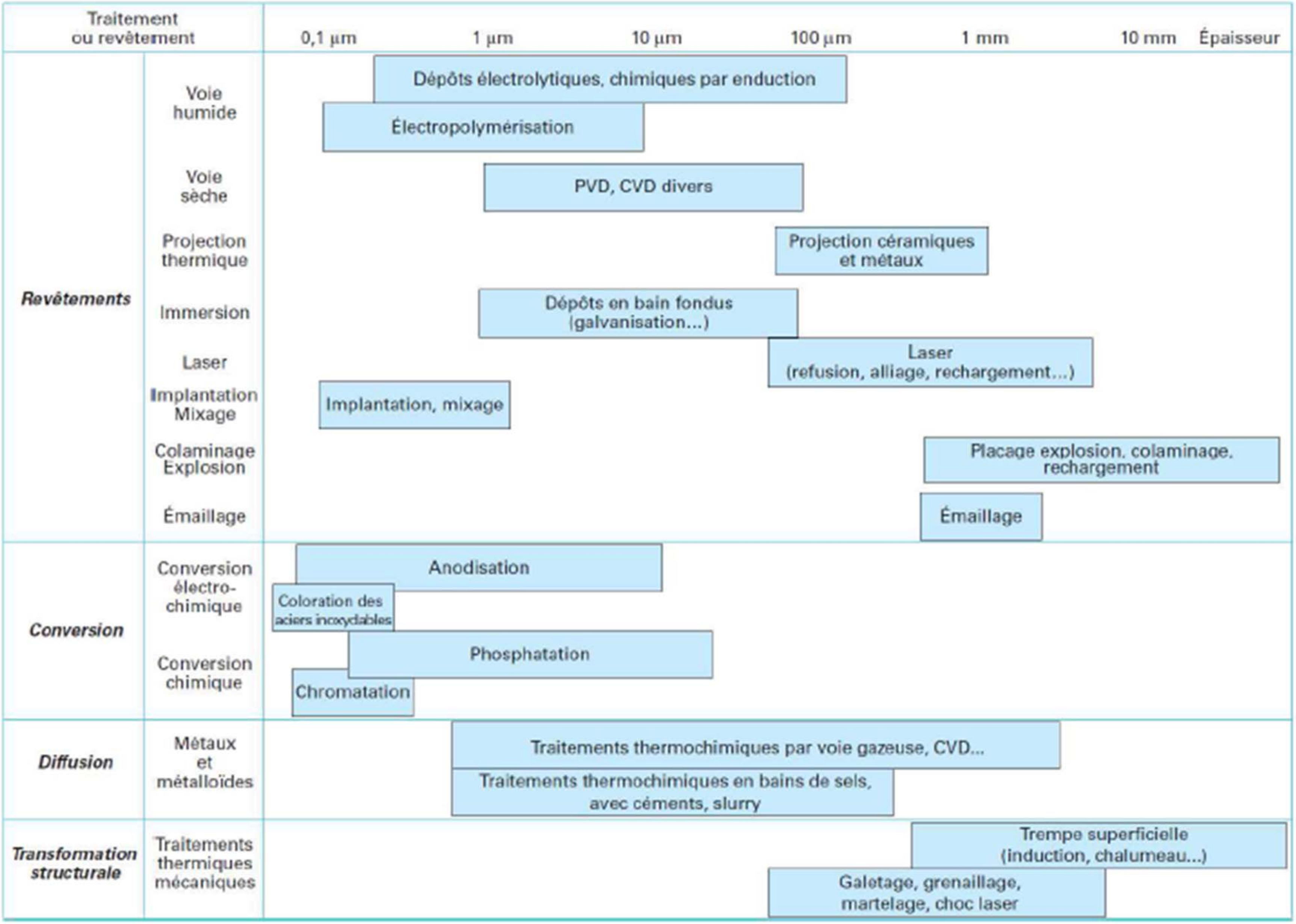
Some preliminary trials carried out at Sirris have al ready shown the versatility of the technology. As illustrated in the Figure, conformal deposition

of an RF antenna, several conductive tracks and interdigitated sensors have been performed and a 3D polymer substrate. Deposition is carried out on the basis of a specif ic toll path computed in a CAD software, then transferred to the equipment . Conformal deposit ion is possible by moving the Z-axis printing head according the 3D model of the substrate to be patterned.

Conformal deposit ion of conductive material on a 3D substrate by AJP



21.1 Coating and conversion/diffusion : thickness range[6] :



21.2 Coating and conversion/diffusion : global comparison[7] :

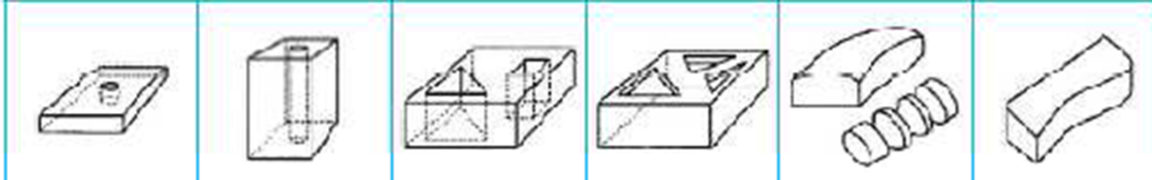
Process variation	Nature		Characteristics				Economical aspects	
	Substrate	deposit	thickness	Porosity	Adhesion	Miscellaneous	Deposition speed	Miscellaneous
Thermal spraying								
	Every materials	Metals, refractory alloys, some plastics	25 µm to ...	variable 0.5 – 20 %	Medium to strong depending on surface preparation	Transition layer maybe needed. Some difficulties with hollowed structure	fast (≤ 25 kg/h)	No dimensional limitations Simple process Interesting for repair and ceramic deposition
Chemical coating								
Displacement	Conductor	Only some mat.	≅ 0,2 µm	-	Very weak unless diffusion	Cathodic deposit only	-	• Significant surface preparation • Low energy consumption • Dimensional limitations
reduction	Every mat.		10 – 100 µm	low	good	Well distributed, high hardness after TT	< 20 µm/h	
Electro-chemical coating								
	conductor	Metals & alloys	0,5 µm – 0,5 mm Easy control	Depending on bath and deposit	Depending on thickness, strain, preparation	Variable thickness, H_2 embrittlement	< 1 µm/min	Same as chemical coating, but more energy needed
PVD								
Thermal evaporation	Every material	Metals, alloys & ceramics	0,X nm – X µm	Low or null	Medium to strong	Better coating with sputtering and ionic plating. Some trapped gases in sputtering	>1µm/min	• Under vacuum • Dimensional restriction • Expensive • Quite effective in multi-layers application
Sputtering							< 50 nm/min	
Ionic plating			X0 µm	Quite high	Very strong		>1µm/min	
Arc evaporation		Metals & alloys	0,5 – 20 µm	Low to medium	excellent	Droplet aspect on the surface	1-3 µm/h	
CVD								
	Conductor and insulator	Metals composed alloys	µm - mm	Depending on deposit type and T°	Very strong to excellent	Alloys deposition by diffusion, Hard or ductile Homogenous thickness	Some µm/min to 0,1 mm/min	• High T° => potential deformations • Strong dimensional limitations • Expensive
Conversion/diffusion								
	metallic	Metals, ceramics	µm - mm	Low to null	Good to excellent	Complexity of the layer (diffusion)	fast	• Dimensional limitations • Cheap

Machining characteristics depending on material and processes

Tableau 1 – Possibilité d'application des divers procédés d'usinage aux divers matériaux [7]									
Usinage	par ultrason	par jet abrasif	électro-chimique	chimique	par électro-érosion	par faisceau d'électrons	par faisceau laser	par arc à plasma	par coupe (fraisage)
Sigle anglais	USM	AJM	ECM	CHM	EDM	EBM	LBM	PAM	TM
Sigle français	UUS	UJA	UEC	UC	UEE	UFE	UFL	UAP	UT
MÉTAUX ET ALLIAGES									
Aluminium	C	B	B	A	B	B	B	A	A
Aciers	B	B	A	A	A	B	B	A	A
Superalliages	C	A	A	B	A	B	B	A	C
Titane	B	B	B	B	A	B	B	B	B
Alliages réfractaires	A	A	B	C	A	A	C	C	C
NON-MÉTAUX									
Céramiques	A	A	D	C	D	A	A	D	D
Polymères	B	B	D	C	D	B	B	C	B
Verre	A	A	D	B	D	B	B	D	C
Bois	D	B	D	D	D	D	B	D	A
Carbure	A	B	A	C	A	B	B	B	D

A = bonne application B = application possible C = application difficile D = inapplicable

Tableau 2 – Formes de pièces et usinages de finition réalisables par les divers procédés non traditionnels [7]



Usinage	Perçage de trous (longueur L diamètre D)				Découpe intérieure		Usinage de cavités		Surfaçage		Découpe extérieure		Usinages de finition			
	microperçage de précision		élancement						surface		épaisseur					
	$D < 25$ µm	25 µm $< D <$ 125 µm	$L/D < 20$	$L/D > 20$	de précision	standard	superficiel	profond	double contournage	de révolution	fine	forte	rectification	rodage	ébavurage	filetage
par ultrason			A	C	A	A	C	C	C		C		C	B	A	
par jet abrasif			B	C	C	B					A		A		A	
électrochimique			A	A	B	A	A	A	A	B	A	A	B	A	A	C
chimique	B	B			C	B	A	C			A				C	
par électroérosion		B	A	B	A	A	A	A	B		C		A		C	A
par faisceau d'électrons	B	A	B	C	C	C					A	B				
par faisceau laser	A	A	B	C	C	C					A	B				
par arc à plasma			B		C	C				C	A	A				C

A = aisé B = possible C = difficile

Performances comparées des différents procédé d'usinage

Tableau 3 – Performances comparées des divers procédés d'usinage									
Usinage	par ultrason	par jet abrasif	électro-chimique	chimique	par électroérosion	par faisceau d'électrons	par faisceau laser	par arc à plasma	par coupe (fraisage) (1)
Débit de matière (mm^3/min)	300	15	10^4	15	10^3 à 3.10^3 (2)	1	0,1	10^5	10^5
Tolérance dimensionnelle (µm)	7	50	50	50	15 à 120 (2)	25	25	1 000	50
Arrondi (mm)	0,025	0,1	0,025	1,25	0,025 à 0,12 (2)	0,25	0,25		0,05
Défaut de parallélisme (µm/mm)	5	5	1		1 à 10 (2)	50	50	10	
Rugosité R_a (µm)	0,25 à 0,5	0,15 à 1,5	0,1 à 2,5	0,5 à 2,5	0,25 à 12 2,5 à 40 (2)	0,5 à 2,5	0,5 à 1,2	élevée	0,5 à 5
Profondeur affectée *e* (µm)	25	2,5	5	5	100 à 300 (2)	250	100	500	25

(1) Fraisage d'un acier
(2) Électroérosion d'ébauchage

Advanced Manufacturing Methods Joining

- **ELECTRON BEAM WELDING**
- **DIFFUSION WELDING**
- **LASER BEAM WELDING**
- **MAGNETIC PULSE WELDING**
- **PLASMA WELDING and ·PLASMA**
- **TIG WELDING et µTIG**
- **Friction Stir Welding**