Laser Powder Bed Fusion: an innovative production method for creating components and devices for Nuclear Physics

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INFN PADOVA — DIAM Development & Innovation on Additive Manufacturing

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Introduction

In the Nuclear Physics research field, components and devices can be very complex. The traditional subtractive manufacturing approaches are sometimes a limiting factor for the realization of such parts. Additive Manufacturing can overcome many manufacturing issues, but it is not free from challenges.
The research of DIAM laboratory (INFN – Section of Padova) focuses on the AM of copper and copper alloys and refractory metals via Laser Powder Bed Fusion (LPBF) technique. The aim is the production of the acceleration grids for nuclear fusion reactors and components to be applied within the several experiments of interest of the National Institute for Nuclear Physics (INFN).

ISSUES
- High reflectivity of copper in IR domain
- High surface roughness of AM parts
- Difficult heat management
- Refractory metals (Mo and W) show cracks formation

OBJECTIVES
- Process parameters optimization
- Material characterization
- Production and test of prototypes

Our machines

Laser characteristics:
Yb fiber laser
Spot diameter: 40 μm
λ = 1064 nm
Nominal power: 200 W
Building volume:
Diameter: 100 mm
Height: 95 mm

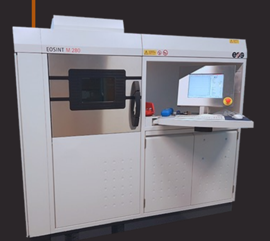
EOS M100

Laser characteristics:
Yb fiber laser
Spot diameter: 80-100 μm
λ = 1060-1100 nm
Nominal power: 400 W
Building volume:
Area: 250x250 mm^2
Height: 300 mm

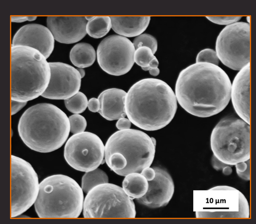
EOSINT M280

Copper and copper alloys

Materials and methods

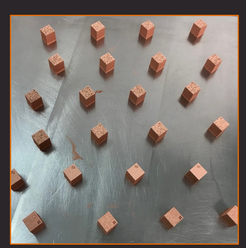


EOSINT M280

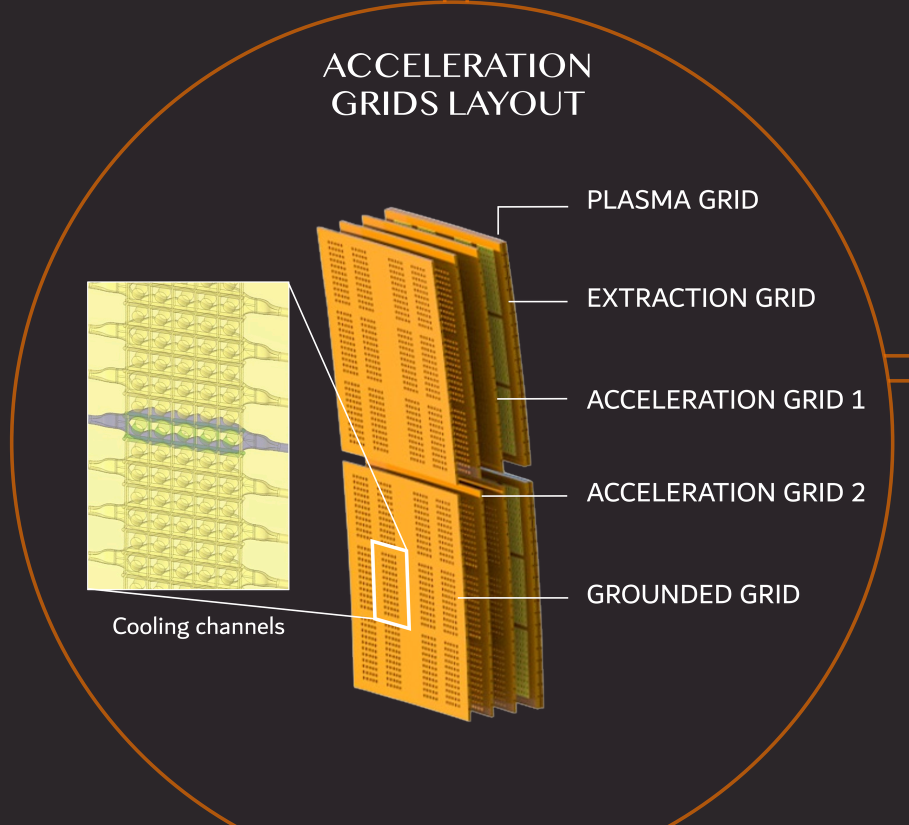


POWDER CHARACTERIZATION
- Morphology
- Chemical composition
- Particle size distribution

PROCESS PARAMETERS OPTIMIZATION
- Laser power
- Scan speed
- Hatch spacing
- Layer thickness
- Scanning strategy

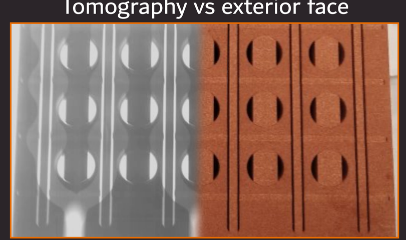


MATERIAL CHARACTERIZATION
- Density (Archimedes method)
- Microstructure
- Mechanical properties
- Thermal and electrical properties



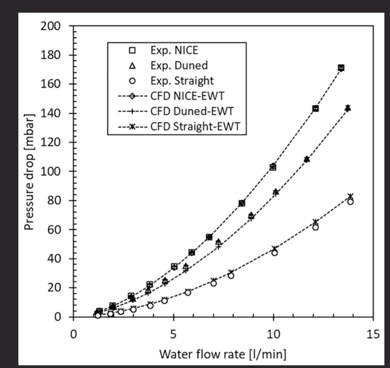
PROTOTYPES PRODUCTION AND TESTS
- Non disruptive inspections
- Leak tests
- Power tests

Tomography vs exterior face



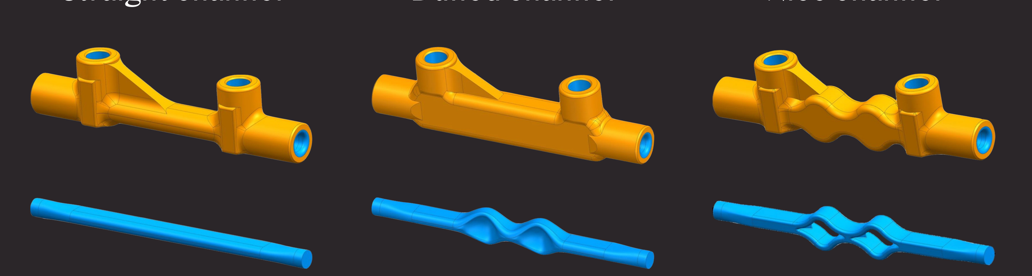
Cooling channels

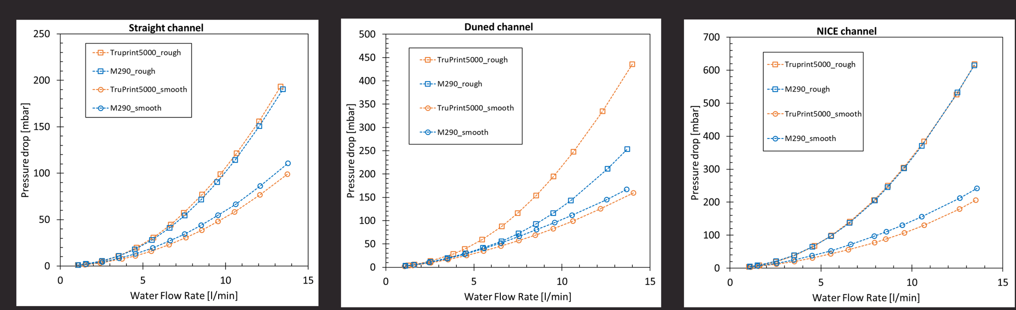
In components like the acceleration grids for NBI systems, a cooling system is needed for preventing overheating during operation. An intense study was carried out, in order to determine the most efficient geometry of cooling channels between the three considered: "straight", "duned" and "nice".
CFD analyses were performed, then the numerical results were compared with the experimental ones.



[1]

Straight channel — Duned channel — Nice channel



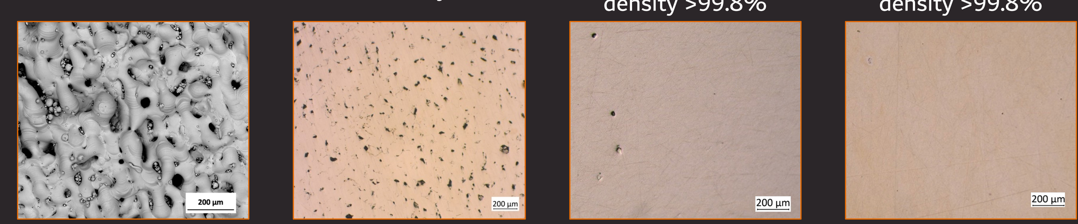


Copper vs. copper alloys

Pure copper

Commercially available LPBF machines are provided with lasers having an infrared wavelength. Pure copper shows high reflectivity within the IR domain. Also, the excellent thermal properties of copper do not allow to have an adequate retention of heat. Thus, the energy provided by the laser beam is for the greater part dissipated by the material. These aspects make the printing of pure copper a very challenging process.
Possible solutions: higher laser power; green/blue lasers; copper alloys.

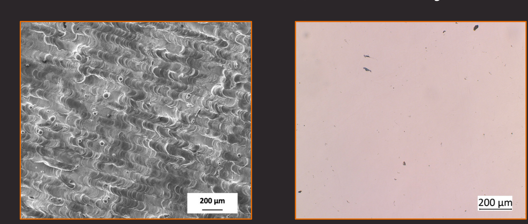
EOS M280 (400 W red laser): max density >89 % — 1 kW red laser: max density >99.8% — Green laser: max density >99.8%



CuCrZr

The introduction of alloying elements like chromium and zirconium can improve the mechanical performances of copper and, concerning LPBF process, making the material more processable. Indeed, the thermal conductivity of such alloy is slightly lower, compared to pure copper, as well as its reflectivity. So, higher densities can be easily achieved using less powerful laser sources.

EOS M280 (400 W red laser): max density >99.5%

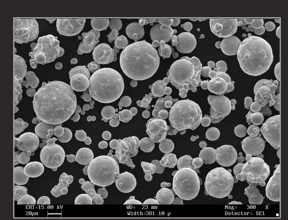


Refractory metals

Materials and methods

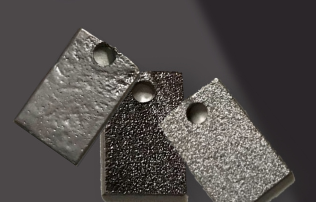
EOS M100

POWDER CHARACTERIZATION
- Morphology
- Chemical composition
- Particle size distribution



PROCESS PARAMETERS OPTIMIZATION
- Laser power
- Scanning speed
- Hatch distance
- Layer thickness
- Scanning strategy

MATERIAL CHARACTERIZATION
- Density (Archimedes method)
- Mechanical properties (room and high temperature)
- Thermal and electrical properties
- Surface roughness



SURFACE TREATMENTS
- Chemical treatments
- Mechanical treatments
- Electrochemical treatments

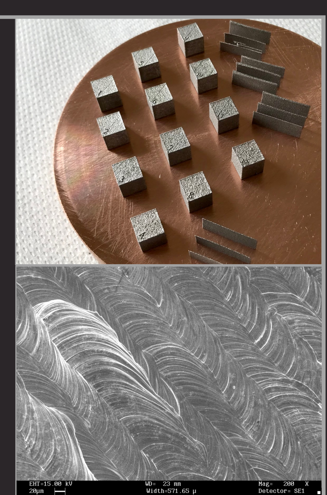
PROTOTYPES PRODUCTION AND TESTS
- Topological optimization
- Non disruptive analyses
- Experimental tests

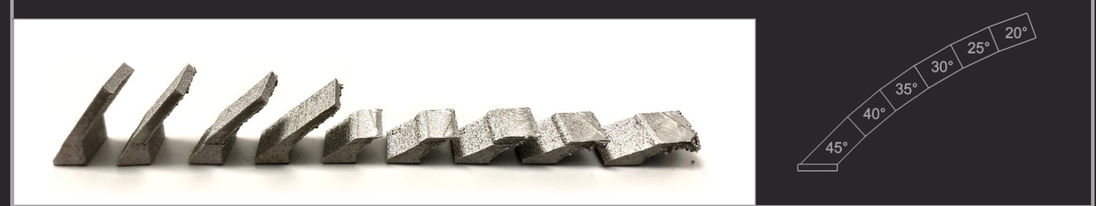
Niobium

Optimal laser power: 110 W
Layer thickness: 30 μm
Maximum density achieved: >99.8%

Metallographic analyses revealed the absence of cracks and a good stability of the melt pools.

For this metal, an intense study of the process parameters is in progress. Much emphasis is put on:
- reducing surface roughness of AM parts;
- reaching very small inclination angles.

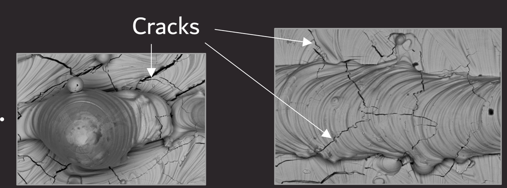


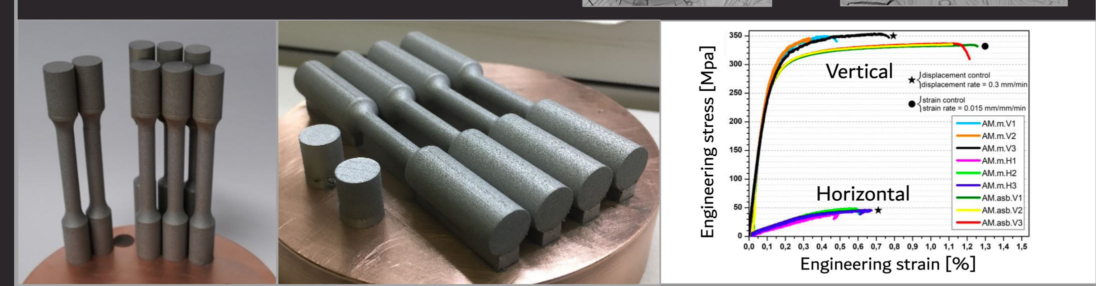


Molybdenum

Optimal laser power: 150 W
Layer thickness: 20 μm
Maximum density achieved: >99.5%
Mechanical strength: max 350 MPa in vertically oriented samples, max 50 MPa in horizontally oriented samples (standard Mo: max 700 MPa)
Thermal conductivity: > 60 W m^{-1}K^{-1} (standard Mo: > 120 W m^{-1}K^{-1}) at 600°C [2]

ISSUE
Pure Mo samples show a cracks network.



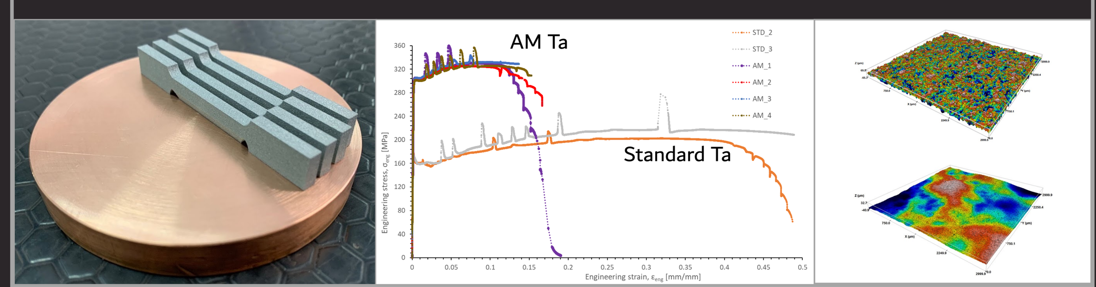


Tantalum

Optimal laser power: 110 W
Layer thickness: 30 μm
Maximum density achieved: >99.9%
Mechanical strength: max 330 MPa in horizontally oriented samples (standard Ta: max 210 MPa)
Thermal conductivity: > 20 W m^{-1}K^{-1} (standard Ta: > 60 W m^{-1}K^{-1}) at 600°C

AMed pure Ta does not show the presence of cracks.

Currently, several types of surface treatments are under investigation. The goal is to obtain a mirror-like finishing of LPBF parts.

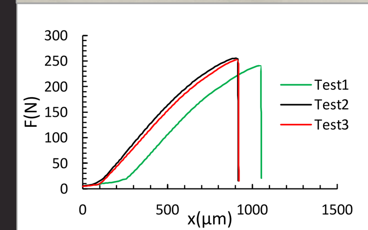


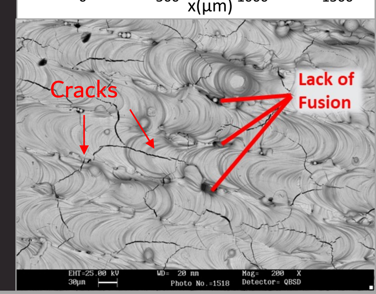
Tungsten

Optimal laser power: 170 W
Layer thickness: 20 μm
Maximum density achieved: >99.5% [3]
Mechanical strength (from 4-poins bending tests): max 170 MPa (standard W: max 980 MPa)
Thermal conductivity: > 35 W m^{-1}K^{-1} (standard W: > 120 W/m^{-1}K^{-1}) at 600°C [4]

ISSUE
Like Mo, also pure W samples show the formation of a cracks network.

POSSIBLE SOLUTIONS
- Introduction of alloying elements;
- Reduction of thermal gradients during the process.





Conclusions

- Additive Manufacturing can be adopted as manufacturing technique for Nuclear Physics applications, thanks to its many advantages (like short build cycles, freedom of shape, topological optimization).
- The issues related to the LPBF process of pure copper could be solved improving the energy transfer from the laser beam to the powder, by reducing the thermal conductivity (with the introduction of alloying elements, when possible), the reflectivity or even using much powerful red lasers or green/blue lasers.
- The suppression of cracks formation on molybdenum and tungsten parts need to be studied in deep. This problem could be mitigated by alloying pure metals.
- Surface treatments should be employed for reducing the surface roughness of the AMed parts.

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EUROfusion

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