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IMPLEMENTATION OF THE ADDITIVE MANUFACTURING FOR METALS APPROACH: THE PRODUCTION OF THE ACCELERATION GRIDS FOR DTT NBI PROJECT

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Abstract

Acceleration grids of the Neutral Beam Injector in nuclear fusion reactors must be extremely accurate and satisfy specific geometrical requirements to work properly. The implementation of the additive manufacturing technology was proposed since 2017 starting the characterization of pure copper up to the recent excellent results in terms of density, process reliability and repeatability. To assure the required performance and maximize the beam optics and the overall system efficiency, an intense study of the geometry of these components was performed, adopting a spherical aspect of planes. The material selection was also an important step of the work. Pure copper and CuCrZr alloy were investigated for reaching the best material properties: parameters optimization was executed using different machines and laser beams, and several post processes were assessed. After the material characterization, which was focused on the evaluation of density, thermal conductivity and mechanical strength of the AMed parts, the first AM prototypes of acceleration grids have been manufactured.

INTRODUCTION

Neutral Beam Injectors (NBIs) are one of three auxiliary heating systems used to heat the plasma inside the tokamak reactors. This system is studied and developed in important research projects such as ITER (International Thermonuclear Experimental Reactor), DEMO (DEMOnstration Fusion Power Plant), and DTT (Divertor Tokamak Test facility) [1]. The Padua division of INFN is the Project Leader for the creation of the acceleration grids of the DTT NBI system. The accelerator grids are one of the system's components. Figure 1 shows the conceptual design of the NBI.

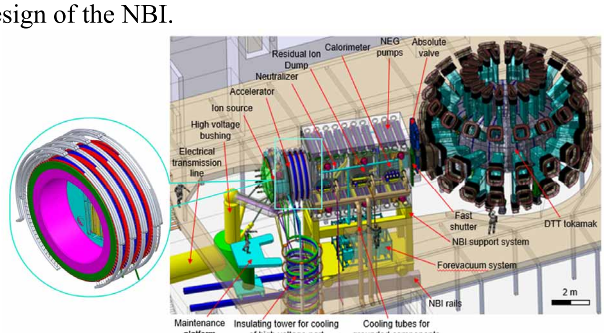

Figure 1: Conceptual design of NBI.

The accelerator's purpose is to accelerate the negative ion beam by creating a strong electric field between different grids. The grids have a rather complex design: a single grid consists of a copper plate with several openings for the beamline, cooling channels for dissipating the heat, and grooves for the positioning of the magnets [2].

The implementation of the AM technology Laser Powder Bed Fusion (LPBF) for the manufacturing of the grids leads to many benefits such as the improvement of the design for both cooling and aiming of the ion beams, a faster and easier production process, and reduced costs.

This work first reports the results of the characterization process of pure copper and the CuCrZr produced via LPBF using different LPBF machines. Then, the improvement of the grid's design is shown. Finally, the first acceleration grid prototypes produced via LPBF are presented.

MATERIAL CHARACTERIZATION

Since copper has a high reflectivity towards the near-infrared wavelength, the only LPBF machines that can process this material use high power (1000 W) infrared wavelength or green wavelength [3]. Three LPBF machines have been tested, pure copper has been processed using a 1000 W infrared laser and 1000 W green laser LPBF machine, while the CuCrZr has been manufactured using a 1000 W infrared laser LPBF machine.

The characterization was focused on measuring the porosity of the printed parts, their mechanical properties and their thermal conductivity. The CuCrZr alloy has been tested in the heat-treated condition. Two heat treatments have been performed, solubilisation at ~ 980 °C for 30 min, water cooling to room temperature, and ageing at 430 °C for 3 h, slow cooling.

Two approaches were used to determine the porosity: by analysing the optical cross-section of a sample and by confronting the actual density of the sample with the density of bulk pure copper. The density of the samples was measured using the Archimedes method following the ASTM B311-17 standard.

The thermal conductivity measurements were performed using an experimental method based on the physical principle of Fourier law. The ASTM E12225-20 standard was followed. The measurements have been performed on test cylinders manufactured in both vertical and horizontal directions of printing.

Tensile tests have been performed in accordance with ASTM E8/E8M-16a standard on cylindrical dog bone tensile specimens. The tensile samples have been manufactured in horizontal (XY plane) and vertical (XZ plane) directions.

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Results and Discussion

Table 1: Material characterization of pure Cu and CuCrZr alloy produced via different LPBF machines, H = horizontal samples V = vertical sample

	1 kW Infrared Laser Pure copper	**1 kW Infrared Laser CuCrZr**	**1 kW Green Laser Pure copper**
Porosity Archimede	0.38 %	0.63 %	1.02 %
Porosity Optical	0.18 %	0.29 %	0.29 %
Thermal conductivity [W/mK]	H 375 ± 19 V 376 ± 19	H 300 ± 15 V 323 ± 16	H 370 ± 19 V 374 ± 19
Yield Strength [MPa]	H 159.3 ± 0.6 V 161.7 ± 1.2	H 199.3 ± 4.7 V 169.3 ± 27.0	H 140.3 ± 1.5 V 142.3 ± 3.8
Ultimate Tensile Strenght [MPA]	H 225.9 ± 0.1 V 224.9 ± 0.6	H 340.9 ± 3.0 V 283.3 ± 20.5	H 211.6 ± 4.1 V 192.7 ± 4.8
Young Module [GPa]	H 117.1 ± 7.02 V 126.6 ± 4.16	H 128.2 ± 0.6 V 106.3 ± 3.5	H 112.8 ± 4.5 V 112.1 ± 5.9

The characterization results are summarized in Table 1. All the manufactured samples were nearly fully dense. Archimedes' method measured higher porosities, while the optical inspection showed lower levels. The actual porosity level might be in between the ones obtained with Archimedes' method and the optical one.

Pure copper samples show thermal conductivity over 370 W/mK with no anisotropy. The CuCrZr alloy, on the other hand, presents lower values: 300 W/mK for the horizontal sample and 323 W/mK for the vertical one.

The tensile tests of the pure copper show that the pure copper manufactured using the infrared wavelength has higher mechanical properties compared to the green laser one. The yield strength obtained with the 1kW infrared laser was ~160 MPa, while with the green laser, it was ~140MPa. This was due possibly to the lower porosity of the samples. No mechanical anisotropy was observed.

The CuCrZr alloy has much higher mechanical properties: almost 200 MPa of yield strength for the horizontal samples. The results obtained with the vertical specimens have a much higher standard deviation. The anisotropy observed for both mechanical properties and thermal conductivity might be attributed to the post process heat-treatment. The vertical specimens might have been treated at higher temperatures (or for a longer time). The over-ageing of the CuCrZr alloy generates bigger precipitates that lead to lower mechanical properties, but higher conductivities.

DESIGN IMPROVEMENTS

The implementation of the LPBF technology led to some relevant modifications: the concept design has been changed, and the whole design of the grids has been reconsidered maintaining the beam optics points. To focus the ion beam, the previous design of the grids was a series of flat surfaces with low inclination angles between them (extremely difficult to manufacture traditionally). The new shape of the grids is now spherical. The spherical design improves the aiming of the grids and also increases the overall rigidity of the grid. The machining's precision is improved by having a unique surface front and back respectively. Each beam has its own direction which translates into better beam optics. Another important element there is the opportunity to obtain multi-focal points in the horizontal plane by using 2 additional elements called HyperLens & Kerb. The principle scheme is shown in Fig. 2.

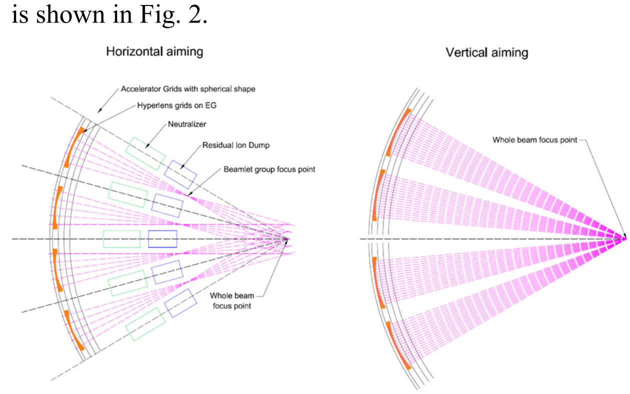

Figure 2: Aiming principle scheme.

Another important modification consists of increasing the grids' thickness from 11 to 15mm. The main reason is the minimum wall thickness of only 1.5 mm on the inlet

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and outlet of the cooling pipes' areas. By increasing from 11 to 15 mm the critical zone is consolidated at 3mm. It was necessary to apply this modification only on four of the five grids that compose the acceleration system.

Finally, the design of the cooling channel was drastically improved, from channels with rectangular areas to conformal cooling channels with complex designs. The optimization process has been performed through computational fluid dynamics analysis and experimental tests [4]. However, the result of the optimization process is not reported in this work. Figure 3 reports the modification that has been made to the grids.

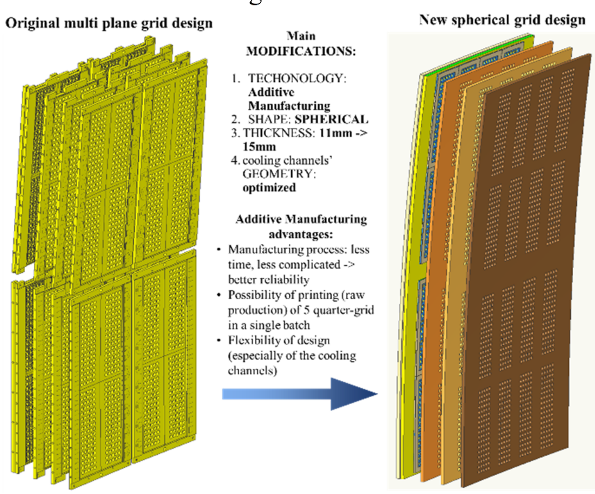

Figure 3: Grid's design modifications.

PROTOTYPING

Due to the dimensions of the entire grid (810×860mm) and the physical limitations of the 3D printing machines, in order to be able to manufacture, the grid has to be divided into 4 elements of 440 × 840mm.

Currently, only the AMCM 4K printing machine has printing dimensions (450 × 450 × 1000mm) that can fit the grid segment. The 4 elements will be joined together using Electron Beam Welding (EBW) technology or Laser Welding (LW). The welding lines are done on the solid-state areas of the grids where no cooling channel sealing is necessary. For this purpose, several tests of EBW are being carried out.

One CuCrZr prototype composed of 5×17 beam-lets has been produced using the AMCM 4K printing machine and fully machined in INFN-PD mechanical office with very promising results in terms of surface quality and precision. It has been extremely useful for defining manufacturing protocols in various phases. A computer tomography scan has been performed on the prototype. The tomography videos show that the internal cooling channels are manufactured. Figure 4 shows the CuCrZr prototype and a section of the tomography.

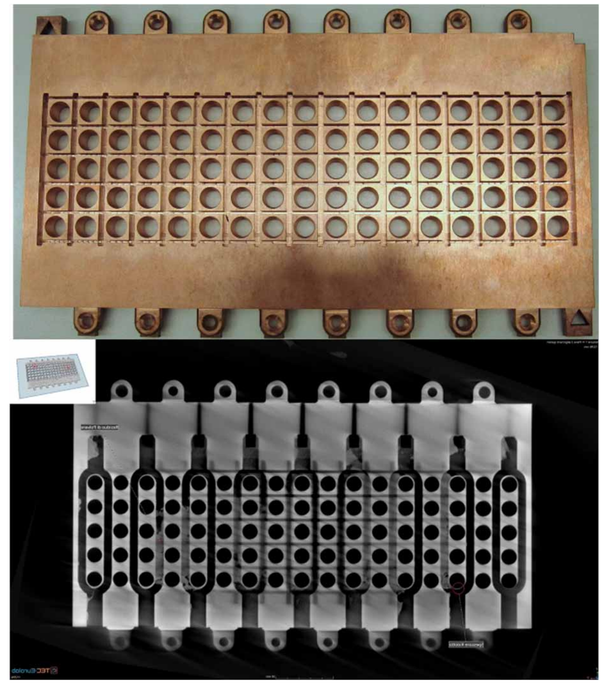

Figure 4: Acceleration grid prototype and radiography of the internal cooling channels.

The high quality of the first prototype has led to the production of two full-scale prototypes (440 × 840mm). These prototypes will be extremely useful to optimize the production process and also to test the efficiency of the additively manufactured grids.

CONCLUSIONS

This research work presents the characterization of copper and CuCrZr produced via LPBF. Pure copper has high thermal conductivity and low mechanical resistance, while CuCrZr presents a good combination of mechanical properties and thermal conductivity.

The good results obtained throughout the characterisation phase led to the selection of this technology for the production of acceleration grids. The new design brings several benefits: the optics and the cooling are improved, the structure is more rigid, and the process is cheaper and more reliable. Indeed the tomography of the first prototypes has shown that the internal parts of the grids are produced and the quality of the manufactured part is high.

The new full scale prototypes that are going to be manufactured will further improve the manufacturing process and the first experimental test can be performed on them.

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