Metal Additive Manufacturing at INFN-LNGS Laboratory: Facilities, Testing and Future Capabilities

D. Orlandi[1, a)] and D. Cortis[1, b)]

[1]*INFN - Laboratori Nazionali del Gran Sasso (LNGS), 67100 Assergi (L'Aquila), Italy*

[a)] *Corresponding author: donato.orlandi@lngs.infn.it*
[b)] *Electronic mail: daniele.cortis@lngs.infn.it*

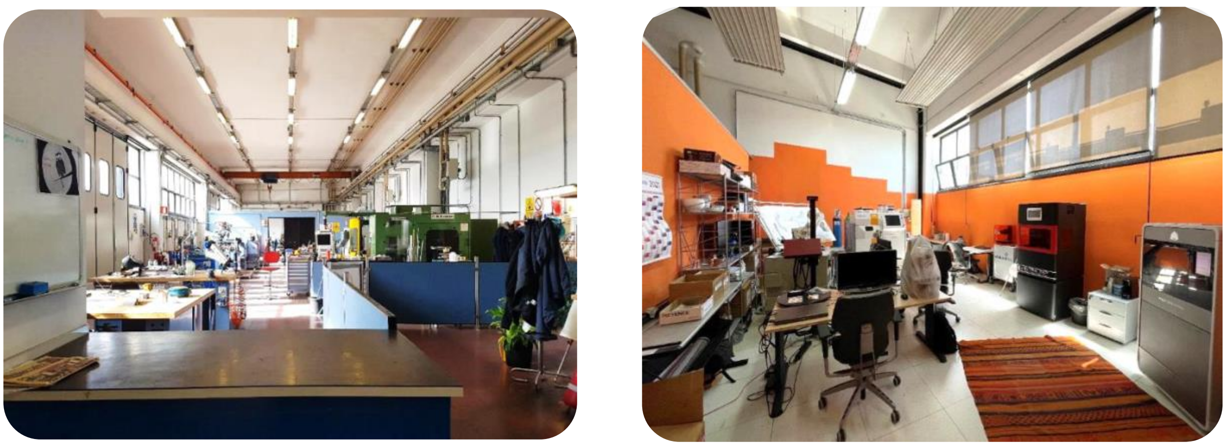
Abstract. INFN "Gran Sasso National Laboratory" (*Laboratori Nazionali del Gran Sasso* - LNGS) is the largest underground laboratory in the world devoted to neutrino and astroparticle physics. Internally, the Mechanics service is focused on design and manufacturing of complex devices for both nuclear and astroparticle physics research and industrial technology transfer. Among its activities there are: traditional and CNC machining, quality control, mechanical design, multi-physics simulations, reverse engineering, and Additive Manufacturing (AM) both for plastic and metallic materials. In the INFN context, it poses itself as a reference for Additive Manufacturing (AM), quality analysis and chemical characterization. Intense activities, often in collaboration with other international laboratories, universities, and industries, are ongoing in this field. The service is equipped with an L-PBF machine, based on the Selective Laser Melting (SLM) technology. Materials such as Copper (e.g., OFHC / 99.8%), Copper alloy (e.g., CuCrZr), Steel alloys (e.g., AISI 316L) and Aluminum alloys (e.g., SCALMALOY®) are currently used.

INTRODUCTION

The Italian "National Institute for Nuclear Physics" (*Istituto Nazionale di Fisica Nucleare* - INFN) is the research agency dedicated to the study of the fundamental constituents of matter and the laws that govern them, under the supervision of the Ministry of Universities and Research (MUR). It conducts theoretical and experimental research in the fields of particle, astroparticle, nuclear and theoretical physics, along with technological research. All the INFN research activities are undertaken within a framework of international competition, in close collaboration with Italian universities based on solid academic partnerships over decades. Fundamental research in these areas requires the use of cutting-edge technology and instruments, developed by the INFN at its own laboratories and in collaboration with industries. INFN history is characterized by scientific successes that also result in industrial successes in the fields of electronics, mechanics, vacuum and cryogenics, and in all the application sectors where it is possible to develop solutions in line with the frontier of the most advanced technology. The INFN pays great attention to all applications that have a significant impact on society, the territory, and its productive fabric, and thus constitute an important stimulus for technological innovation in the country.

INFN "Gran Sasso National Laboratory" (*Laboratori Nazionali del Gran Sasso* - LNGS) is the largest underground laboratory in the world devoted to neutrino and astroparticle physics [1]. It is founded by the INFN in the 1985 and it is located between the town of L'Aquila and Teramo, at about 120 kilometers from Rome. The underground structures are on one side of the 10-kilometre-long highway tunnel which crosses the Gran Sasso massif. The underground complex consists of three huge experimental halls (each 100-metre long, 20-metre large and 18-metre high) and bypass tunnels, for a total volume of about 180,000 m^3. Access to experimental halls is horizontal and it is made easier by the highway tunnel. Halls are equipped with all technical and safety equipment and plants necessary for the experimental activities and to ensure proper working conditions for people involved. The 1,400-meter rock thickness above the Laboratory represents a natural coverage that reduces the cosmic ray flux by roughly a factor of million [1]. The reduction of cosmic radiation provided by the rock coverage together with the huge dimensions and the impressive basic infrastructure, make the Laboratory unique in the detection of weak or rare signals, which are relevant for astroparticle, sub nuclear and nuclear physics. Outside, immersed in a National Park of exceptional environmental and naturalistic interest on the slopes of the Gran Sasso Mountain chain, an area of more than 23 acres hosts the external laboratories, the Mechanics, the Chemistry and Chemical Plant service, the Computing Centre, the Directorate, and several other Offices.

The Mechanics service, consisting of the Workshops and the Design & Additive Manufacturing department (Fig. 1), is focused on design and manufacturing of complex devices for both nuclear and astroparticle physics research and industrial technology transfer. Among its activities there are: traditional and CNC machining, quality control, mechanical design, multi-physics simulations, reverse engineering, and Additive Manufacturing (AM) both for plastic and metallic materials. For the latter, technologies such as Stereolithography (SLA), Digital Light Processing (DLP) and PoliJet are employed, while for metallic one Laser Powder Bed Fusion (L-PBF) technology currently is used. Also, the Mechanics service collaborates with the Chemistry and Chemical Plant service for the screening and characterization of metallic and non-metallic materials for scientific and industrial use. In the INFN context, the LNGS Mechanics service poses itself as a reference for AM, quality analysis and chemical characterization. Intense activities, often in collaboration with other international laboratories, universities, and industries, are ongoing in this field. It is also leading the Hub for Additive Manufacturing, Materials Engineering and Research (HAMMER) of the INFN technology transfer [2].



(a) (b)

FIGURE 1. LNGS Mechanics service: (a) Workshops, (b) Design & Additive Manufacturing department.

METAL ADDITIVE MANUFACTURING

The LNGS Design & Additive Manufacturing department is equipped with an L-PBF machine, based on the Selective Laser Melting (SLM) technology. The SLM machines use a laser beam to selectively melt a powder bed material to produce a layer-by-layer component as done by the traditional AM solutions. A layer of metal powder is deposited on a construction platform using a recoater characterized by a ceramic, steel, or rubber blade according to the type of metal powder used. The melting of the powders is carried out with a high-power laser beam guided in the construction plan through appropriate galvanometric mirrors and the entire process takes place in a controlled atmosphere of inert gases. The machine installed at LNGS is a SISMA MySint100 PM/RM machine (Fig. 2), specifically developed for R&D activities. It is equipped with an infrared fiber laser up to 200 W, a laser spot diameter of 30 µm, a minimum layer thickness of 20 µm, a building platform of 100 mm of diameter / height and a dedicated glove box for the parts cleaning operations. The machine software allows the complete customization of the building process parameters, such as the hatch distance, the laser scanning speed, the layer thickness, the laser pattern, and inter gas flow velocity. The parts production can take place under an inert N_2 or Ar atmosphere with an oxygen level below 0.1%.

Materials that can be used with this machine are Steel alloys, Titanium alloys, Nickel alloys, Aluminum alloys, Copper alloys, precious metal alloys and Chrome Cobalt alloys. Materials such as Copper (e.g., OFHC / 99.8%), Copper alloy (e.g., CuCrZr), Steel alloys (e.g., AISI 316L) and Aluminum alloys (e.g., SCALMALOY®) are currently used for experimentation, research activities and technology transfer (Table 1). Moreover, when the alloy and application require it, heat treatments, such as ageing or stress relieving, are also carried out with the collaboration of LNGS Chemistry and Chemical Plant service.

FIGURE 2. SISMA MySint100 PM/RM machine [3].

TABLE 1. Mechanical properties of the materials used for experimentation, research activities and technology transfer [4].

Material	Density [g/cm^3]	Modulus of Elasticity [GPa]	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]	Elongation at Break [%]	Thermal conductivity [W/mK]
Cu OFHC / 99.8	8.94	117	49 - 78	215 - 254	35 - 55	383 - 391
CuCrZr *	8.90	128	210	340	40	340
AISI 316L *	8.00	193	205	515	60	14 - 16
SCALMALLOY® *	2.65	70	525	575	10	140

(*) heat treated condition.

QUALITY ANALISYS

Among the activities of the LNGS Design & Additive Manufacturing department, there is also the quality analysis. This activity is carried out both for components produced by classical subtractive technologies (e.g., CNC) and for those produced by AM, especially for metallic parts. The design requirements of AM components are in fact different from those produced with classic technologies and they require a specific post-production assessment. For example, the removal of printing supports can generate some geometrical non-conformities that must be considered and corrected with dedicated machining operations (e.g., sandblasting, milling, etc.). For this kind of operation, there are three types of instrumentation: (*i*) a 3D scanner GOM Atos Core 185 with a resolution up to 70 µm, (*ii*) a 4K KEYENCE VHX-7000 optical microscope with a magnification up to 2500X and (*iii*) a KEYENCE IM series high-resolution automatic optical profilometer (Fig. 3).

(a) (b) (c)

FIGURE 3. Quality analysis instruments: (a) 3D scanner GOM Atos Core 185 [5], (b) 4K KEYENCE VHX-7000 optical microscope [6], (c) KEYENCE IM series high-resolution automatic optical profilometer [6].

The scanner is an optical 3D stereoscopic measuring instrument for scanning and inspection of industrial components, and it produces a point cloud that allows very complex geometries to be delineated and reconstructed in space. The quality analysis of the geometry and dimensions of a complex part is now essential to certify its function in scientific and industrial fields. On the other hand, the opportunity to obtain the geometry of a component subject to scanning becomes complementary to the AM technologies available in the laboratory, allowing the reverse engineering phase of a product. The optical microscope is a 4K high accuracy digital microscope capable of capturing high resolution images and measurement data for inspection and failure analysis. It is currently applied for assessing the quality of AM metal components, searching the presence of defects due to lack of fusion, especially in the last layers. It is also used to study the quality of surface: the microscope allows the measurement of surface roughness (Sa) according to the ISO 25178-2 standard by means the focus variation technology. Finally, the optical profilometer is an automatic visual inspection system that performs measurements in place of optical comparator, calipers/micrometer, measuring microscope, optical CMM, laser measurement, classical profile projector and other measuring systems. It is widely used for the geometric certification of AM manufactured components, especially to validate their functionality before final assembly.

FUTURE INVESTMENTS

To implement new production techniques and increase the analysis methods available in the field of AM and materials characterization, significant investments have recently been made in future capabilities. A new area of approximately 300 square meters is being planned and new machines are on-schedule or in the installation phase. Talking about the plastic components, a high-end Fused Deposition Modelling (FDM) printer is on the way for printing techno-polymer (i.e., PEEK, Carbon PEEK, Ultem, etc.), together with the possibility of creating one's own materials and filaments; while for metallic components, a new SLM machine with a building chamber up to 160 mm is in the process of being purchased. On the other hand, for material characterization, a universal testing machine, with the possibility of testing materials under cryogenic conditions, was planned together with an alloy heat treatment oven. Finally, a portable ATO LAB metal atomizer (Fig. 4) is in the installation phase: it will allow to create the metal powder to be used directly in the SLM machines and to create new customized metal alloys according to scientific and technological research needs. The atomizer uses a novel ultrasonic atomization technology to quickly produce metal powders with high flowability and narrow particle size distribution, from a simple rod of the chosen material. For example, for a frequency of 35 kHz, 70% of 316L steel particles are in the diameter range of 40 to 60 µm. Also, new materials will be processed with SLM technology, such as AlMg10Si, Bronze and Steel 16MnCr5.

FIGURE 4. ATO LAB metal powder atomizer machine [7].

RESEARCH ACTIVITIES AND CASE STUDIES

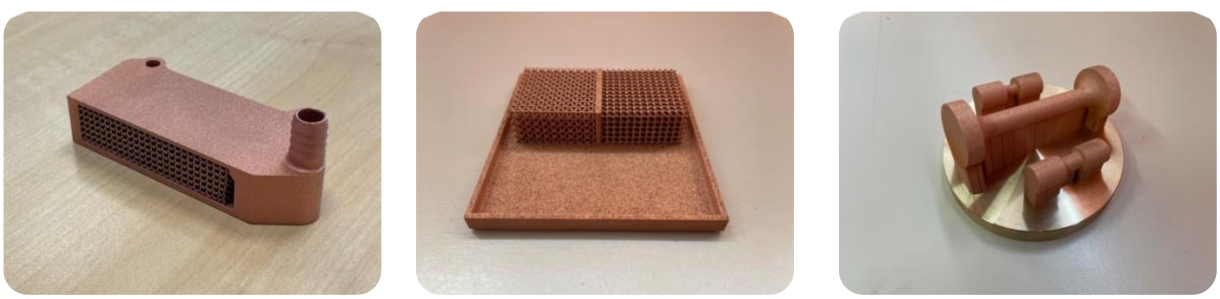
Since 2018, when the SISMA MySint100 PM/RM machine was installed, several components have been produced for INFN experiments, and numerous R&D activities have been performed by the LNGS Design & Additive Manufacturing department, also in cooperation with local universities and industrial companies.

For example, pure copper material (OFHC and 99.8%) has been widely studied [8] and used for the design and production of passive heat exchangers for custom electronic boards (Fig. 5a) and the prototyping of experimental waveguides for the PTOLEMY [9] experiment. Moreover, the design and the manufacture of silicone waffle holder (Fig. 5b) have been done for the BULLKID experiment [10] in collaboration with INFN-Roma1 and University of Rome “La Sapienza”, Department of Mechanical and Aerospace Engineering (DIMA). In the same way, an Ar-N experimental two-phase heat exchanger (Fig. 5c) has been designed for the condensation of Ar in the DARKSIDE experiment [11, 12].

(a) (b) (c)

FIGURE 5. Copper OFHC / 99.8%: (a) Electronic-board heat exchanger for PTOLEMY experiment, (b) Silicone waffle holder for BULLKID experiment, (c) Ar-N experimental two-phase heat exchanger for DARKSIDE experiment.

Recently, particular attention has been focused on CuCrZr copper alloy. This alloy represents one of the most successful industrial examples to increase the strength of pure copper without the reduction of its excellent thermal properties. Thanks to a collaborative research contract with KORAL Technologies, we have manufactured innovative cold plate exchangers for electronics based on specific lattice structures (Fig. 6a and 6b) in order to increase overall thermal efficiency. Also, a strong collaboration with the University of L'Aquila, Department of Industrial / Information Engineering and Economics (DIIIE), is leading to the static and dynamic characterization of this alloy [13, 14] produced by means SLM technology (Fig. 6c) and to its surface quality evaluation.



(a) (b) (c)

FIGURE 6. CuCrZr alloy: (a) Cold plate heat exchanger for KORAL Technologies (test-section), (b) Cold plate heat exchanger for KORAL Technologies (lattice structures), (c) Static and Dynamic test specimen for material characterization in collaboration with UNIVAQ.

Other research activities were also conducted by LNGS Design & Additive Manufacturing department for the design optimization and production of lightweight 316L stainless steel structures using lattice structures without any postprocessing machine operation (Fig. 7a). Thanks to this expertise, aeronautical components, such as the chassis of an electromechanical actuator (Fig. 7b), were topologically optimized for the OMA company using the

SCALMALLOY® material. Additionally, the study and the design of multi-material metal components (e.g., CuCrZr-AISI 316L) produced with SLM technology (Fig. 7c) was started in collaboration with the University of Rome "La Sapienza", Department of Mechanical and Aerospace Engineering (DIMA). Eventually, an innovative hybrid process, based on the electroforming of copper [15] to obtain pure raw material to be atomized and produce the powder material for SLM is in progress with "*Laboratorio Subterráneo de Canfranc*" (LSC).

In collaboration with the Chemistry and Chemical Plant Service and the Special Techniques Service, a dedicated process of analysis supported by high sensitivity analytical techniques such as ICP-MS, HPGe and NAA present at LNGS of the raw materials used and the manufactured products is currently being studied, so that any impurity conditions fed into the process itself can be monitored during each step to minimize them as much as possible. The Mechanics service facility focused on AM foresees technological research directed toward high-performance techno polymers for scientific and industrial use in cryogenics. AM Fused deposition technologies (FDM) of low radioactive materials as PEN, PEEK and Ultem will be studied and optimized in the coming months.

(a) (b) (c)

FIGURE 7. Steel and Aluminum alloy: (a) LNGS internal study for lightweight structures - AISI 316L, (b) Topology optimization of electromechanical actuator for OMA company - SCALMALLOY®, (c) LNGS and UNIROMA1 study of multi-material parts (CuCrZr-AISI 316L) produced with SLM technology.

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