Experiences of Additive Manufacturing for nuclear fusion applications: the case of the wishbone of the divertor of DEMO project

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Abstract. The aim of this work is to describe some collaborative experiences of additive manufacturing - AM - for nuclear fusion applications. In this work a first case study is introduced, which served to test and validate this method. It is the realization of a scale prototype of an in-vessel component for tokamak nuclear fusion reactors, a wishbone of the deflector in Ti-6Al-4V alloy. The 3D model of the wishbone component was designed, optimized, and then fabricated using AM in collaboration with the Laboratory for Advanced Mechatronics - LAMA FVG - and the researchers at the University of Udine. For the construction of the prototype, an SLM machine using powder bed metal laser melting was used. The design, simulation and fabrication activities of the mock-up are presented in this paper, discussing the main limitations and possibilities arising from the titanium alloy 3D printing technique. In addition, a further prototype of the wishbone was fabricated using conventional milling techniques, allowing an economic comparison and evaluation of the two manufacturing processes. The prototypes will then be used for a future evaluation of the mechanical properties of this material (Ti-6Al-4V), first on samples and then on the mock-ups, under irradiations conditions, due to nuclear fusion applications.

Keywords: Additive manufacturing; SLM, Ti-6Al-4V alloy; nuclear fusion; divertor; cost evaluation.

1 Introduction

High-energy physics is becoming increasingly important in modern society, yet it inevitably remains a special field of application. Structures are limited to a few units, and the parts needed to build them are often produced in very small batches. It is in this context that the description of this collaborative experience on the use of Additive Manufacturing – AM – methods for the research activities of the EU-DEMO project promoted within the EUROfusion Consortium fits in. Among the several DEMO systems, the divertor is a key in-vessel component, as it is responsible for power exhaust and impurity removal under very high heat flux loads. One main challenge in the DEMO divertor design is the cassette-to-VV attachment system (Fig. 1a and Fig 1b). Its design shall meet some competing high-level requirements, as the compatibility with remote handling operations, the kinematic feasibility, and the material compatibility with the in-vessel environment, as described in [1-3]. At the current design stage, the outboard fixation system of the DEMO divertor is based on the wishbone configuration shown in Fig. 1. It aims to improve the flexibility of the outboard fixation system avoiding the introduction of complex spring mechanisms.

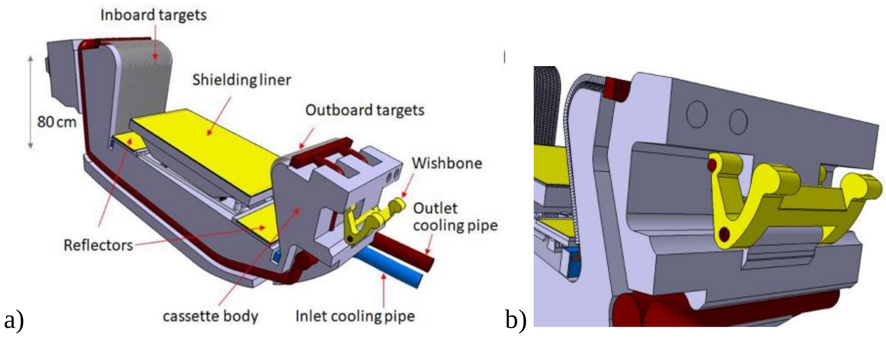

Fig. 1. a) A typical divertor cassette module; b) outboard cassette fixation system with the wishbone, [2].

It is precisely in cases like these that AM processes can provide significant advantages. A first case study to produce an SLM mock-up of the wishbone is described presenting the different manufacturing activities of the mock-up and discussing the main limits and possibilities coming from the Titanium alloy 3D printing technique.

The article is organized as follows. After introduction section, section 2 deals with the methods and material used in the AM experience. Section 3 describes the case study of the wishbone mock-up. In particular, the aspects related to the simulation phase of the AM process and the construction of the wishbone mock-up are highlighted. In section 4 the results obtained are discussed in the form of an economic evaluation of the two different construction techniques, SLM and milling, used. Finally, possible future developments are pointed out.

2 Methods and materials

2.1 Selective Laser Melting

Selective Laser Melting – SLM- is an increasingly popular technology for the AM of products in primary and strategic sectors. By dramatically shifting the production limits of manufacturing, this process is driving technological progress in many sectors, and the competitive advantage it provides is now clear to the many users who use it. Traditionally, industrial applications of SLM mainly concerned the medical and aerospace fields [4]. However, recent technological advances enabled the application of this manufacturing process to several other sectors, including automotive, naval, energy, electronics, and conventional industry to produce molds, tools, and equipment [5-11]. Nevertheless, also consumer applications such as furniture, fashion apparel and jewellery [12] are becoming more and more common.

SLM is a powder bed AM process in which pure metal powders, in the form of a chemical element or, more often, an alloy, are selectively melted by a laser beam to build the desired product [13]. Operationally, the process takes place through the construction of successive layers in which two-dimensional sections of the component produced are made, which are progressively added together to generate a solid. The processing of each layer takes place in two stages. First, a layer of powder is layered by the coater onto the bake platform. Then, in a second stage, the actual fusion takes place through the operation of a continuous wave fibre laser guided by two mirrors along predefined trajectories. These trajectories are chosen to guarantee both a correct control of the microstructure, resulting from the solidification of the material, and an optimisation of the properties of the external surface of the part through a special contour scan along the perimeter of each layer. The whole process takes place in an inert atmosphere to prevent oxidation of unmelted powders, and to protect the plant from the risk of combustion and explosion induced by the presence of fine metal powders. Once processing is complete, all the unmelted powder is removed, and the workpiece can be extracted from the machine and undergo any post-treatments required by its specific application. The SLM technique differs from its precursor, Selective Laser Sintering – SLS -, in the type and therefore the power of the energy source used, which is such that it allows the complete melting of pure metal powders. This, together with the fineness and morphological regularity of the metal particles constituting the powders [14], makes it possible to create products consisting solely of the desired material with very high-density levels. As a result, the mechanical properties of the products obtained are also excellent [15] enabling the use of this technology to be considered not only for the manufacture of prototype parts, but also for real functional products.

2.2 The Ti6Al4V ELI alloy

The material chosen to realize this work was the extra-low interstitial grade of the Ti6Al4V ELI alloy. It is characterised by high mechanical strength and toughness combined with low density, low Young's modulus, excellent corrosion resistance, exceptional biocompatibility, and low radioisotope transmutation under neutron bombardment. These characteristics enable many advanced applications in strategic industrial sectors such as aerospace, automotive, energy, petrochemical, biomedical and nuclear [16]. At the same time, Ti6Al4V ELI is particularly suitable for use in AM applications due to its exceptional machinability, which allows complex, high-quality products to be obtained while limiting process times and minimising post-processing operations. It follows that the combination of this alloy with the SLM process is of great technological relevance, as it promotes the effective evolution of critical products in strategic sectors.

3 The case study application: SLM wishbone mock-up of the DEMO diverting device

3.1 Description and 3D CAD modelling of the wishbone mock-up

As extensively described in [1,2], the wishbone component was chosen to test this new manufacturing method. Indeed, it plays a fundamental role within the divertor cassette module. In addition to fixing function, the wishbone provides elastic compliance and static resilience to accommodate the mismatch in thermal strains between the cassette body – CB - and the VV attachment system (Fig. 1). Considering the amount of radial displacement due to thermal deformation during the normal operation and during baking, the wishbone must have sufficient strength under these displacement loads. For these reasons Ti-6Al-4 V alloy was selected as material for the wishbone manufacturing to exploit its high elasticity and strength. In Fig.2 two different designs of the wishbone component are presented, the initial model in Fig 2a has been replaced by the alternative design presented in Fig 2b because it is more meaningful to be tested in AM. The shape and the geometrical dimensions shown in Fig 2b) comes from the results of stress analyses. The idea behind this concept is to achieve a proper elasticity by the system itself allowing radial expansion and transferring vertical and toroidal loads at the same time. For this element it is expected a degradation of elasticity after 2 full power year (fpy) irradiation. The comparison of the candidate materials has shown shows that the titanium alloys have a high yield strength, the highest flexibility, and the best U parameter (resistance to impact loading), because of the relatively high strength (~ 900 MPa) and low Young's modulus (approximately a factor of two less than Inconel 625 and SS 316).

(a) (b)

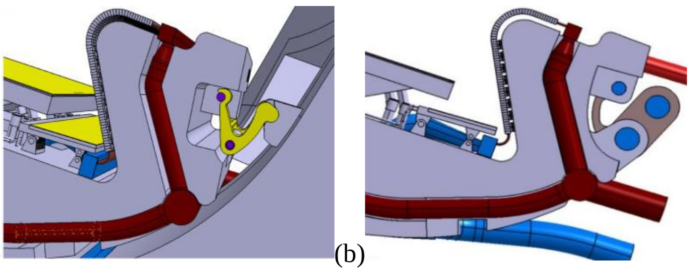

Fig. 2. The wishbone of the DEMO diverting device: a) initial design; b) alternative design used of the SLM mock-up.

Therefore, high strength titanium alloys are preferred for this application. Also, Ti alloys have lower resistance to buckling in comparison with high strength nickel alloys, since the buckling stress limit is proportional to Young's Modulus. The ITER R&D activities show that, despite degradation of ductility and fracture toughness due to irradiation, all properties of Ti-6Al-4V alloy remains at a satisfactory level (in all experiments, even at dose ~0.4 dpa, the uniform elongation remained above 2%).

3.2 Simulation and prototyping of the SLM wishbone mock-up

The SLM mock-up was produced from metal powders of Ti6Al4V ELI alloy with the chemical composition shown in Table 1. Fabrication was carried out using the Concept Laser M2 Cusing machine installed at the Laboratory for Advanced Mechatronics - LAMA FVG - of the University of Udine, which is equipped with an ytterbium-doped CW single-mode fiber laser. The deliverable power is variable in the range 50 - 400 W and it can be focused on a spot with a dynamically adjustable diameter between 50 and 500 μm by means of a dynamic laser beam focusing system.

Table 1. Chemical composition of powders for SLM (Ti6Al4V ELI alloy).

Material	Al	C	Fe	Ti	V	O	Other
Ti6Al4V ELI [wt. %]	5,96	0,01	0,22	89,37	4,13	0,1	0,21

Simulation of the SLM process

The size of the mock-up and its mass represented a critical aspect for the design of the production process since they had the capability of inducing very intense thermal stresses. To identify the best production strategy, the process was numerically simulated by means of the Simufact Additive software (https://www.simufact.com/simufact-additive.html). A preliminary calibration phase allowed to establish the most suitable simulation parameters. Four manufacturing strategies, corresponding to four simulation cases, were compared:

1. build the mock-up on a base of block supports combined with solid cylindrical supports, both dense;
2. build the mock-up on a base of sparse solid cylindrical supports;
3. build the mock-up connecting the main body to the building platform by a solid block;
4. build the mock-up inclined at 45° with respect to the building platform, on a base of block supports combined with solid cylindrical supports, both dense.

The selected evaluation criteria were the equivalent stress (Von Mises), Fig. 3a and the maximum principal stress, Fig. 3b. As shown in Fig. 3, the analysis showed that the most suitable solution from the process perspective consisted in building the mock-up with the main body connected to the building platform by a solid block (Case 3). When stresses are minimal, the risk of cracking and deformation of the material during the manufacturing process is minimized. Breakage and deformation could cause the construction process to stop and create defects and/or non-conformities in the manufactured part. Furthermore, this solution also appeared to be optimal in relation to the function that the part must perform within the divertor, since the main stress it must withstand is the bending of the arm. In fact, the available simulation data suggest that the maximum strength and stiffness of the molded material is found along the directions parallel to the construction plane, while ductility is slightly higher along the vertical direction (Fig. 4) but is still better in case 3 than in case 4 oriented at 45°.

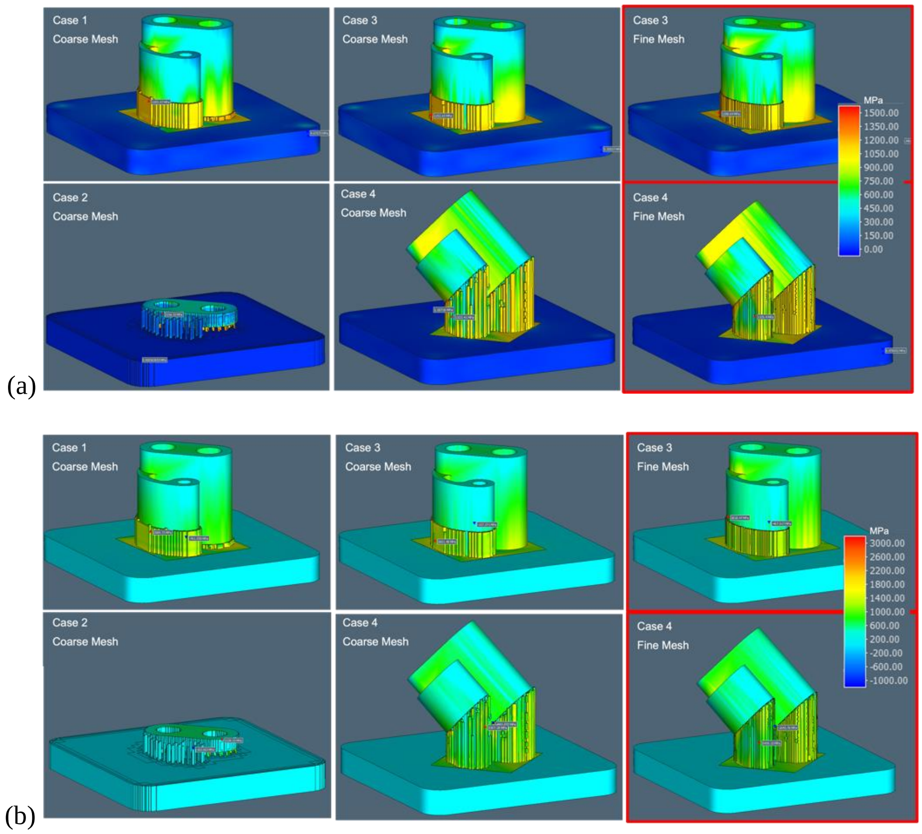

Fig. 3. Numerical simulation of the SLM process for producing the wishbone mock-up of the DEMO diverting device by means of SLM: (a) equivalent stress (Von Mises), (b) maximum principal stress.

Similarly, the fatigue behavior is also improved when the stress is parallel to the construction plane. The potentially most interesting solutions (case 3 and case 4) were then validated by means of an in-depth simulation, performed with a very refined mesh (see Fig. 3 highlighted parts).

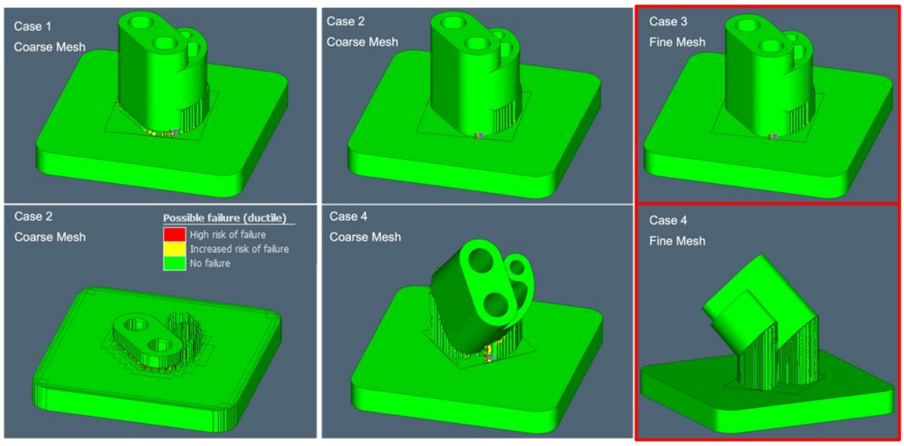

Fig. 4. Numerical simulation of the SLM process for producing the wishbone mock-up of the DEMO diverting device by means of SLM: prediction of the ductile failure.

Construction of the SLM mock-up

The mock-up was then built with the main body connected to the building platform by a solid block (Case 3). The process parameters used for production are reported in Table 2.

Table 2. Process parameters used for the manufacturing process.

	Core	Skin	Contour 1	Supports
Laser power	370 W	200 W	200 W	180 W
Scan speed	1500 mm/s	1200 mm/s	1250 mm/s	1300 mm/s
Laser spot diameter	180 µm	145 µm	50 µm	100 µm
Hatch distance	0.095 mm	0.1 mm	-	-
Layer thickness	50 µm	25 µm	25 µm	50 µm

The part was scanned according to the island exposure strategy (Fig. 5a), which consists in a checkerboard pattern of 5 × 5 mm squares bi-directionally scanned along mutually perpendicular directions.

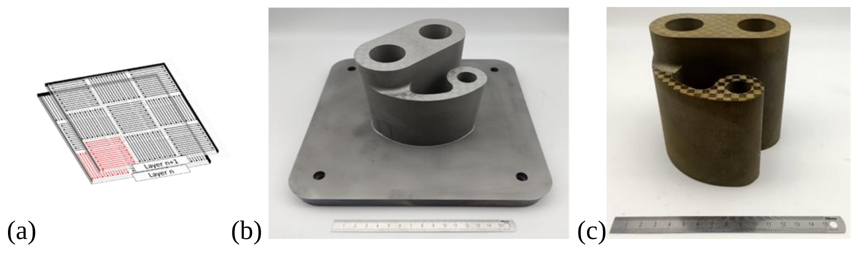

Fig. 5. Manufacturing of the mock-up. a) the island exposure strategy used; b) prototype of the wishbone mock-up of the DEMO obtained by SLM; c) prototype of the wishbone mock-up after separation from the building platform.

Adjacent islands were spaced 0,105 mm apart, and each of them underwent an angular shift of 90° and an XY shift of 1 mm at each layer to promote structural evenness within the processed material. At the end of the manufacturing process (Fig. 5b), the product was cleaned, and subsequently it was heat treated to relieve residual stress. The treatment consisted in heating the part up to 840°C in 4 hours, maintaining this temperature for 2 hours, and cooling the part in the oven down to 150°C. The treatment was carried out in an inert argon atmosphere, obtained by means of a protective gas box. Subsequently the part was separated from the building platform by using a band saw machine (Fig. 5c), and both the support structures and the allowances on the upper and lower flat surfaces were removed by means of a CNC milling machine. Eventually, the part was finished with the aid of manual tools to obtain the surface quality prescribed for the use (Fig. 6).

3.3 Prototyping of the wishbone mock-up by milling

To compare the performance of a part produced by SLM with that of the same part produced by traditional processes, the wishbone mock-up was also produced by milling a forged Ti6Al4V ELI block. The raw material used for this purpose was provided by the New Tech s.n.c.. The chemical composition and the mechanical properties of the material declared by the supplier are shown in Table 3 and Table 4 respectively.

Fig. 6. Milled and SLM wishbone mock-up of the DEMO diverting device.

The HAAS VF-2TR milling machine at the Laboratory for Advanced Mechatronics - LAMA FVG - of the University of Udine was used to machine the forged blanks. The machining process included a preliminary phase to obtain the alignment features necessary for correct positioning of the part during the subsequent phases. The blank was then clamped using a specially made fixture and machined in one set-up, except for the region under the arm. This was machined at a later stage, where the part was gripped on the opposite side. The entire production cycle was first successfully validated on a disposable POM-C polymer blank. The resulting part is shown in Fig. 6.

Table 3. Chemical composition of the forged blank (Ti6Al4V ELI alloy)

Element	Al	C	Fe	Ti	V	O	Other
Ti6Al4V ELI [wt. %]	5,8	0,028	0,08	89,5	4,1	0,07	0,42

Table 4. Mechanical properties of the forged blank (Ti6Al4V ELI alloy)

Ultimate Strength [MPa]	Yield Strength [MPa]	Elongation [%]
919	843	20

4 Results and discussion

As mentioned in the introduction, one of the objectives of this work was to evaluate the possibility of producing some components to be used for the divertor of the DEMO project using the SLM technique. In fact, AM techniques are usually preferred to traditional techniques when only a few units of parts or parts with a complex geometry must be produced. In particular, the wishbone was chosen because of its special function and rather complex shape. To assess this, the time and cost of producing the wishbone mock-up with SLM and milling were compared. Cost estimation is always a valid decision-making tool when it comes to making strategic choices regarding the manufacture of products that may require complex types of processing [17]. From the analysis of the data in Table 5, it can be observed firstly that the SLM process almost eliminated the administrative time for procurement and the cost required in milling to purchase specific blanks and tools. Secondly, the cost of the raw material itself was also lower in SLM, although the specific cost of metal powder was high compared to forged material. This was because the material required in the SLM was 65% lower, even though the workpiece analyzed in this article is bulky. However, the major advantages provided by additive manufacturing concerned process engineering and operations. On the one hand, the time required for part-program development was 95% shorter, and no pretesting of the process was necessary. Numerical simulation of the SLM process was essential to achieve this. In addition, the need to design and produce specific equipment was avoided. On the other hand, operator effort was reduced to a minimum thanks to the machine's autonomy. Regarding the manufacturing process, it is interesting to note that the actual duration was similar in the two cases considered. In this respect, it must be mentioned that the milling process could be slightly shortened by using a better performing machining center and by using a non-cube preformed blank. However, the SLM process might also be slightly shortened by using suitable combinations of process parameters such as high laser power and scanning speed or by increasing the laser spot size and the layer thickness [18,19]. This result therefore retains general qualitative validity, and contradicts the assumptions normally accepted in the evaluation of AM processes. On the contrary, the SLM process resulted in a slightly higher cost of the finishing phase, which however appears negligible compared to the other costs analyzed and is balanced by the higher cost of the milling consumables, mainly represented by the cutting tools.

Table 5. Economic comparison of cost for SLM and milled wishbone mock-up.

	Description	SLM		Milling	
		Q.ty	**Cost**	**Q.ty**	**Cost**
Project management	Purchase raw materials, tools and consumables	1 h	100,00 €	11 h	1100,00 €
Raw material Product	Ti Powder/Ti forged block	2,45 kg	597,80 €	7,0 kg	988,20 €
Raw material Preliminary tests	POM-C	-	-	5,74 kg	49,19 €
Process engineering Process design	Simulation, Slicer/CAM	8 h	800,00 €	71 h	7100,00 €
Preliminary tests Operator	Machine set-up, supervision, restore	-	-	58 h	2030,00 €
Preliminary tests Machine	Process time	-	-	58 h	1740,00 €
Equipment manufacturing Operator	Machine set-up, supervision, restore	1 h	35,00 €	21 h	735,00 €
Equipment manufacturing Machine	Process time	1 h	30,00 €	20 h	600,00 €
Product manufacturing Operator	Machine set-up, supervision, restore	6 h	210,00 €	90 h	3150,00 €
Product manufacturing Machine	Process time	90 h	2700,00 €	90 h	2700,00 €
Product post-processing Operator	Machine set-up, supervision, restore, manual polishing	8 h	280,00 €	3 h	105,00 €
Product post-processing Machine	Machining time for supports and allowance removal	5 h	150,00 €	-	-
Consumables	Process gas, building platform reconditioning/Tools	n.a.	522,57 €	n.a.	836,31 €
TOTAL			**5425,37 €**		**21133,70 €**

5 Conclusion and future developments

In this paper, an experience of AM to produce a component to be used within the DEMO project was presented through the description of a case study. In particular, the realization of the wishbone mock-up through the SLM technology has allowed to test and validate the production process and the use of a specific material, in this case the titanium alloy Ti6Al4V ELI. Moreover, having also manufactured an analogous component with traditional milling of the same material it was possible to carry out a comparison based on economic analysis of production costs, which revealed that, in this case, given the type of material and the particularity of the geometric shape of the component studied, the AM process through SLM proved to be more convenient and performing.

In conclusion, the results presented in this article have thus demonstrated that AM is an extremely effective technology in the production of small batches, even for simple and/or bulky parts. Should the material behavior also meet the requirements of high-energy physics, SLM would prove to be a suitable technology to promote development and sustainability in this field. Also, in the future, it is expected to compare the mechanical characteristics of the mock-up obtained in AM with those of the mock-up obtained in the traditional way with respect to irradiation conditions typical of applications for nuclear fusion activities.

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