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Designing for Metal Additive Manufacturing: a case study in the professional sports equipment field

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Abstract

In this paper, we discuss the possibilities available as well as the challenge to be faced when designing for metal additive manufacturing through the description of an application of the Selective Laser Melting technology within the professional sports equipment field. We describe the redesign activity performed on the cam system of a compound bow, starting from the analysis of the functional, manufacturing and assembly constraints till the strategies applied to guarantee the printability of the object. This activity has thus provided the opportunity to analyse the difficulties currently encountered by practitioners when designing for additive manufacturing due to the lack of integrated design approaches and the high number of aspects that need to be simultaneously taken into account when performing design choices.

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Keywords: Metal Additive Manufacturing; Design for Additive Manufacturing; Selective Laser Melting; Sports Equipment

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1. Introduction

Attention and interest in Metal Additive Manufacturing (MAM) technologies are continuously growing, especially in those industrial fields (e.g., aerospace and biomedical), where the need for lightweight and customized shapes acts as one of the market drivers (e.g., see [1]). However, the wide possibilities offered by these technologies have to be counterbalanced with the necessity to guarantee the economic feasibility of the selected manufacturing routes. This means acting simultaneously at two levels: improving/controlling the efficiency of the printing process; getting the maximum added value exploring all the design possibilities. Hence, design choices should be made exploiting the capabilities of the selected MAM technology, also considering its constraints and limits, which means to *Design for Additive Manufacturing* (DfAM) (see [2]). However, this implies that a wide range of aesthetic/functional/manufacturing requirements needs to be taken into account in order to make as linear as possible the transformation of the CAD model into a finished good. Implementing such an approach is still challenging; it requires a strong and quick integration of competencies from different experts and the use of design tools able to provide to users an integrated and holistic view of the design problem. However, the fulfillment of these requirements has to deal with the rapid evolution of these technologies as well as with the high number of different MAM technologies available (e.g., see [3]) which makes complex the identification of recognized design and manufacturing practices. To help practitioners to build a new design mindset, the research community is thus investing effort in: extrapolating design guidelines/rules tested with specific MAM technologies and materials for driving the generation of shapes that are, e.g., easy to print; defining new DfAM methods and tools (e.g., see [4]) also on the basis of the experience gained through real industrial cases.

In this paper, we aim at contributing to the definition of these design methods describing an implementation of MAM technologies, specifically the Selective Laser Melting (SLM), for a sport such as archery. The objective was to 3D print a sub-system of a compound bow, i.e. the cam module. This one is placed at the extremity of the limbs of the bow, and it has the role of modifying the draw force (e.g., see [5, 6]). An ad-hoc redesign activity has been implemented to decrease the system part-count. This change has been performed with the intent of reducing assembly steps. Then, this new geometry has been modified in order to make it printable reducing as much as possible the non-functional portions of the object so as to decrease the amount of supports needed.

The paper is structured as follows. Section 2 provides a discussion of the state of the art within the field of DfAM as well as of applications of AM technologies for sport. Section 3 describes the approach followed to perform the redesign activity of the system. In Section 4 conclusions are drawn.

2. Background

One of the main objectives driving the development of DfAM approaches is the optimization of the links among the following steps: the generation of the 3D model of the object to print; the elaboration of the printing path and definition of the characteristics of the printing job (e.g., number of components to be printed contemporary, their orientations, printing parameters and strategies); the planning of the operations to be carried out to get the finished good. Optimizing this process implies reducing re-design and post-processing cycles and crossing out inefficient/costly operations. This target can be reached through: an in-depth understanding of the physics and of the technical and operational aspects characterizing the selected manufacturing process; the integration of this knowledge into design tools that enable practitioners taking into account, when designing, the constraints as well as the potentialities set by the technology used. Performing such integration is not an easy task. First, the wide availability, of both printing technologies and materials, as well as the rapid development of additive manufacturing technologies make complex the extrapolation of global parameters/factors characterizing the specific printing process. However, interesting results/discussions are already available in the literature (e.g., see [7, 8, 9, 10]). Second, the wide design freedom, for example in terms of the complexity of the shapes that can be modelled and manufactured (e.g., see [11]), makes current CAD tools not fully tuned to support this activity. An example is represented by lattice or cellular structures (e.g., see also [4]). A second example is represented by the design of the supports that need to be included to deal with gravity effects and to guarantee the heat dissipation especially in laser-based technologies [12]. Supports can nowadays be designed mainly using STL Editor software. That is a limit since supports could be an integral part of the model acting also as functional elements (e.g., like ribs). In this case, they do not have to be removed during the finishing phase, which is an aspect that does not have to be underestimated when evaluating manufacturing costs. A third example is represented by the possibility to look for amorphous shapes such as the ones generated using topology optimizer software (e.g., see [13]) which is a completely new strategy for designing components with respect to solid and surface modelers.

From this brief overview, the following considerations can be derived. First, when designing for AM, practitioners need to use a number of different software tools. This way of designing could lead to frequent redesign cycles considering that design and manufacturing requirements are strongly correlated in case of AM. The research community has then started not only to ideate solutions for improving each design task (e.g., topology optimization, support generation) but also to develop integrated solutions. An attempt in trying to provide a comprehensive perspective, as already underlined in [2], is described in [14] where the authors propose a methodology made up of three main steps (i.e., *part orientation*; *functional optimisation*; *manufacturing paths optimisation*). The aim of our work is to highlight, through the description of the re-design activity performed using the software tools currently available on the market, the number of heterogeneous aspects that need to be taken into account when designing for AM in order to fulfil all the functional, technical and manufacturing requirements set. The intent is to use the acquired experience for reasoning about the possible strategies that have to be put in place to better synthesize functional and process-based aspects, as suggested in [11]. In years, several interesting applications of additive manufacturing technologies have been developed for sport; for example, there is a strong interest on the possibility of providing personalized and custom-fit solutions (e.g., footwear, helmets or prosthesis [15, 16, 17]). Interesting applications exist also within the field of e.g., car racing and motorsport in general (e.g., see [18]). In this case, MAM technologies are used, for example, to create components/systems having innovative shapes that allow for better performances and weight savings. However, further applications need to be still explored considering the great advantages that MAM, and AM technologies in general, can provide. Hence, in this paper, we describe the implementation of the SLM technology to print equipment for archery and, specifically, the cam system of a compound bow. Through the description of the performed design and printing activity, the paper aims to reflect upon the open issues and challenges which characterize the design tools currently used by practitioners when designing for AM.

3. The re-design and printing of the cam system

In this Section, we first provide a brief overview of how a cam system of a compound bow works. Then, we discuss the workflow we followed to redesign and print the new system. This discussion has been structured taking as reference some aspects that have been raised in other redesign activities available in the literature (e.g., see [19, 20]) as well as by the indications provided in [7, 21].

3.1. The cam system of a compound bow

Several configurations of compound bows are available (e.g., see [22]); they make use of eccentric pulleys (i.e. the cam system) fixed at the extremities of the bow limbs [5, 22] (see also Figure 1a) to ease the force application by the athlete (e.g., see [6]). Different configurations of these systems exist on the market, each one having its peculiarities and different type of components; they are usually made of aluminum and manufactured using conventional processes. For the development of the case study, we used the geometry represented in Figure 1, which has been created starting from a commercial model. This system is made up of the following components: two external string cams and a central cable cam. Each cam has a track to hold the strings and the cables, respectively, which are free to wrap and unwrap when the string is drawn since the system is mounted on a pin and it can freely rotate [22]. In Figure 1a the bottom cam rotates counterclockwise. The rotation of the system compresses the limb, which starts to bend. When the athlete releases the string, the great part of the potential energy of the limb is transferred back to the arrow [5]. Figures 1a and 1b also show how the system, the cables and the strings are assembled; anchors are used to fix in position the strings and the cables.

MAM technologies, in this field, could be used both for prototyping and, potentially, manufacturing innovative and customized solutions. Besides, since MAM technologies allow reducing the number of components of a system, they could also be used to manufacture integrated solutions in order to, e.g., reduce the risk related to unexpected loosening of the connections; this change could imply an ad-hoc redesign of the system in order to guarantee the possibility to perform all the needed regulations.

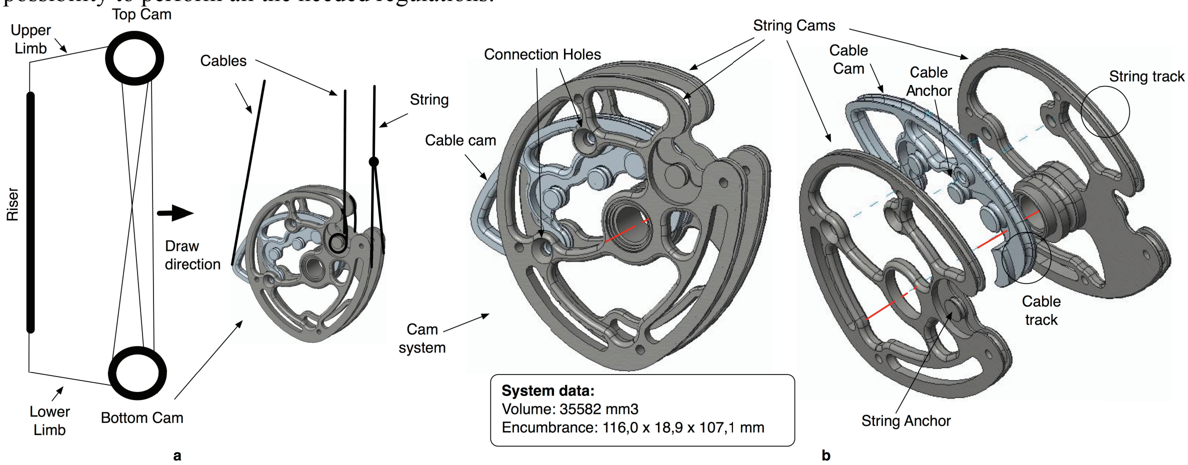

Fig. 1. (a) A schematic of how a cam system is assembled to the compound bow; (b) the main features/elements of the system and an exploded view highlighting the housing and anchoring elements for strings and cables.

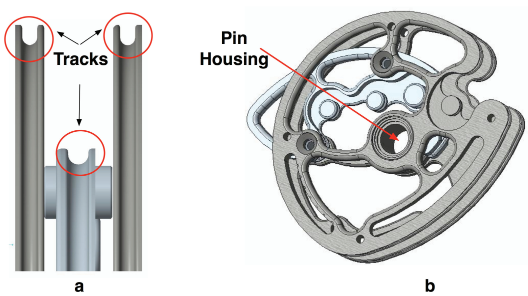

Fig. 2. (a) A detail of the geometry of the tracks; (b) a detail of the pin housing.

3.2. Exploring functional, assembly and manufacturing constraints

We started the redesign activity by firstly exploring *functional*, *assembly* and *manufacturing* constraints. For what concerns *functional* constraints, we considered the following: preserving the geometry and the shape of the anchors; keeping the encumbrance values of the system; guaranteeing an easy insertion and housing of the strings and cables in the tracks (Figure 2); preserving the geometry of the cams curvatures. For what concerns *assembly* constraints, we considered the need to guarantee the housing of the pin in order to enable the system rotation and its connection to the bow limb (see Figure 1 and Figure 2), as well as the connections among the three components. As *manufacturing* constraints, we considered the printability of the object as well as the need to guarantee the efficiency of the printing and post-processing activities. The first aspect implies taking into account a number of design rules (e.g., see [8]). Furthermore, it involves also the design of the supports. However, the object printability can be checked only once its orientation, on the build plate, has been selected. Actually, this aspect determines the efficiency of the process in terms of: the number of systems that can be simultaneously printed; the time and the amount of material needed for printing; the kind and the number of finishing operations that need to be performed. Hence, once settled the main requirements, we started the redesign activity identifying the best printing orientation.

3.3. Selection of the printing orientation

As already mentioned, the printing technology we used is the Selective Laser Melting one. This MAM technology provides the advantage of allowing printing fully dense objects starting from both ferrous and nonferrous powders (e.g., see [23]); however, since this powder undergoes a melting process, strong attention should be paid, for example, in setting the parameters of the melting process in order to avoid e.g., the risk of shrinkage and cracks during the solidification of the molten material (see [23]). In addition, also the orientation of the object to be printed over the build platform has to be carefully checked in order to find the optimum trade-off among the amount of powder needed for printing, printing times, the number of objects that could be simultaneously printed. In addition, the build orientation could also influence the mechanical properties of the object (e.g., see [24, 25, 26]).

Orientation optimizer algorithms can be of help to the designer for selecting the best printing orientation and scanning strategies according to the design requirements settled and expected anisotropic material properties. Advanced algorithms, such as the one available e.g., in the Materialise Magics software V19 (www.materialise.com/en/software/materialise-magics) that we used, propose possible orientations on the basis of the analysis of the following parameters: *z-height*, *XY projection*; *Support surface*; *Max. XY section*.

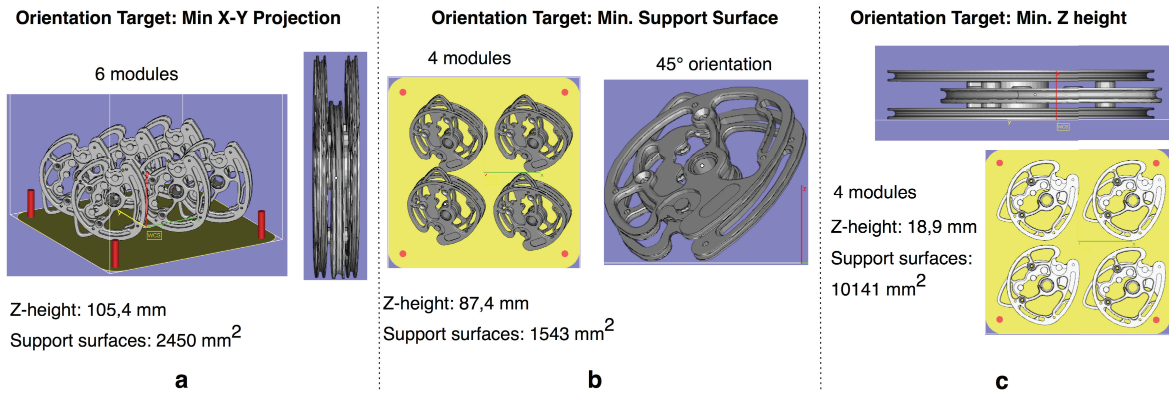

Fig. 3. Optimisation of the AS IS cam system orientation considering as target the minimization of: the X-Y projection (a); the area of the needed support surface for each system (b); the z-height of the object with respect to the printing platform (c).

The *z-height* parameter is used to minimize the height of the object along the building axis. This value directly affects the building time (the higher is this value, the higher is the number of layers to be printed) and the amount of powder that needs to be available in order to completely fill the working volume of the machine (the higher is this value, the higher is the amount of powder needed) while it indirectly affects the number of objects that can be contemporary printed. The *XY projection* parameter takes into account the dimensions of the projected area on the XY plane of each section; it directly affects the number of objects that can be simultaneously printed while it indirectly affects the building time and the amount of powder needed. The *Support surface* parameter evaluates the amount of surface of the object that needs to be supported and it inevitably affects: the building time; the amount of powder; the number of objects that can be simultaneously printed; the number and the time for the finishing operations required to clean the object. Finally, the *Max XY section* parameter takes into account the value of the area of each layer cross-section (the higher this value is, the higher is the risk to have excessive thermal gradients within the object, increasing the risk for residual stress buildup and generation of cracks during solidification and cooling of the melted powder). Obviously, this value could negatively affect the aspects already discussed.

Figure 3 is used to explain the considerations we made to select the best printing orientation for the cam system. In this case, we did not take into account the *Max XY section* parameter since small distortions can be expected, and, anyhow, their impact on the system functionality can be erased through an ad-hoc machining of the pin housing and of the tracks. The number of systems that could be potentially printed simultaneously can be visually checked, through the software, since the dimensions of the bed platform represented in the graphic area are automatically derived by the settings of the machine used for printing (i.e., the Renishaw AM250, www.renishaw.com, whose working volume is 250x250x300 mm). It is worth underlying that this information (i.e., the number of items that could be simultaneously printed as shown in Figure 3) has been retrieved on the basis of only geometric considerations. Concerning the other 3 parameters, the minimization of the *z-height* of the object (Figure 3c) significantly reduces the number of layers, the printing time and the amount of powder required with respect to the other two configurations. However, the amount of surface to be supported is about six times higher, and the number of systems that could be simultaneously printed diminishes. However, we decided to explore the horizontal configuration on the basis of the following considerations. First, redesigning the system we would work for reducing the amount of support surfaces; second, printing time, layers and powder volume are significantly lower. Third, since the forces on the cam system act along the track centerline, the horizontal orientation guarantee the optimal mechanical behavior of the object with respect to the vertical (Figure 3a) and the 45° configurations (Figure 3b). It is worth underlying here that commercially available orientation optimizer algorithms do not consider aspects related to the working conditions of the object to be printed while, this aspect is significant since, as already mentioned, the build orientation has an impact on the mechanical properties of the object.

3.4. The generation of the new geometry and final print

The discussion about the generation of the geometry of the new system will be structured following the analysis of the requirements presented in Section 3.2. Figure 4 summarizes the main interventions performed on the geometry.

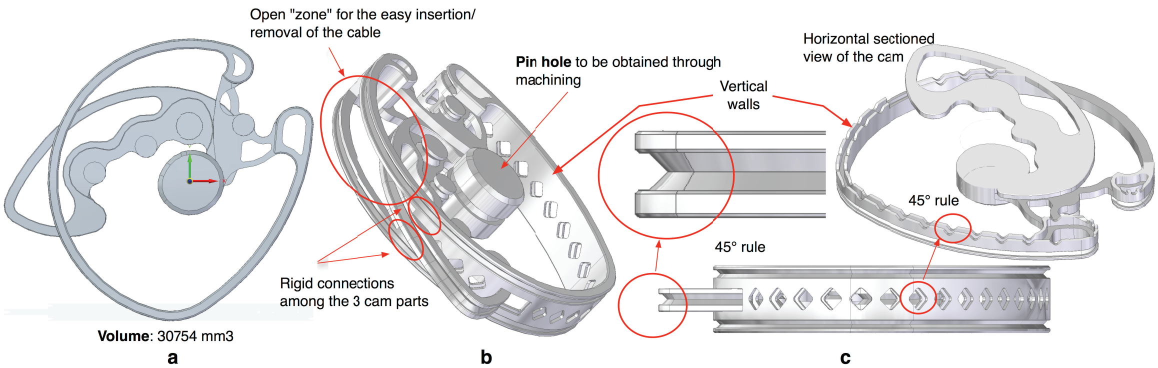

Fig. 4. (a) A frontal view of the new cam geometry; (b) main changes implemented to reduce the system part-count, the amount of support needed and to guarantee an easy insertion of the cable; (c) examples of design rules implemented to guarantee the printability of the object.

It is worth underlying that the design process of the system was not linear, but it underwent iteration cycles among different software tools (i.e., the CAD and the STL Editor) to guarantee the fulfillment of all the design requirements. We started the redesign activity firstly with the intent of reducing its part-count, guaranteeing that it could act as a monolithic structure. Then, we modified this new geometry in order to reduce the presence of non-functional volumes. This further change has led to a reduction of the overall system volume. Before starting the redesign phase, we decided the material to be used for printing since, according to this choice, manufacturing considerations in terms of design rules to be taken into account, can vary. We decided to print the new cam using steel since it was the powder available at that time. However, apart from some minor changes, the geometry of the cam would not significantly change if aluminum- or titanium- based powders will be used instead.

Figure 4a shows the frontal view of the new cam. We created some rigid connections among the three functional elements of the system, as shown in Figure 4b; then, we started removing, considering the selected horizontal building orientation (see Figure 3c), all the non-functional portions of the object that would have required supports. With the geometry represented in Figure 4a we reached a volume reduction of about 14%. Actually, the final geometry will have about 20% of volume reduction. Indeed, in order to guarantee the proper dimensional and geometric tolerances for the housing of the pin, we preferred not to model the hole (see Figure 2 and Figure 4b) and to have it manufactured by standard machining. To reduce the amount of supports needed, we also connected the two external cams with two walls whose cross section is represented in Figure 4c. We could not close the second half of the cam (Figure 4b) to guarantee the insertion of the cable. Figure 4c also shows a detail of the redesign of the tracks implementing the 45° rule in order to create self-supporting surfaces and reduce the amount of supports needed. The drawback of this solution is the necessity to machine them, after the printing, to guarantee the housing of the strings/cable. The same rule has been implemented to design the holes on the two lateral walls. All non-supported overhangs surfaces have been checked to guarantee the fulfillment of the suggested 1÷2 mm safety limit in case of steel-based powder (e.g., see [8]).

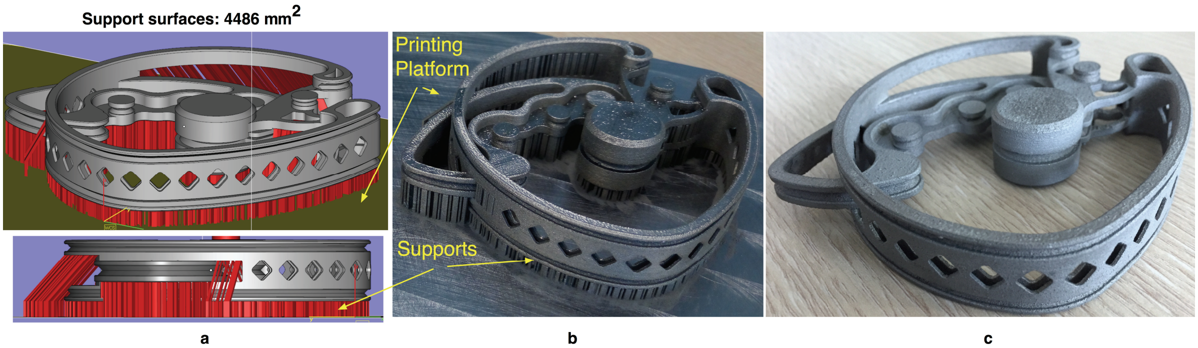

Fig. 5. (a) An overview (in red) of the supports needed in order to guarantee the printability of the object; (b) the printed cam; (c) the new cam after the supports removal and sandblasting.

The STL file of the new cam has been used to generate the supports and the printing instructions. To perform these two steps, we used the software Magics 19.0. Figure 5a illustrates the new geometry with, in red, the supports while Figure 5b shows the final output built by the printer. Supports were needed not only for overhanging surfaces below 45° limit and to remove heat, but also in the bottom part of the object to allow an easy separation of the object from the platform. The amount of surfaces to be supported is about half of the initial value (see Figures 3c and 5a). Finally, Figure 5c shows the printed object after the supports removal and the sandblasting. As already discussed, further finishing activities are needed.

4. Conclusions

In this paper, we have described a new application of the SLM technology in the field of professional sports equipment. Through the description of the redesign activity performed on the cam system of a compound bow for archery, this paper aims to strengthen the industrial potentialities of MAM technology and also to derive a number of considerations related to the design process. First, the discussion has further highlighted what has been already underlined in literature, i.e. the lack of integrated design tools in order to reduce design iterations given by the necessity to frequently check the printability of the solution when complex changes in the geometry are implemented. Second, there is also a lack of tools and consolidated procedures to support decisions about the selection of the optimal trade-off among the various functional/technical/manufacturing requirements to be taken into account when designing for AM. For example, orientation optimizer algorithms are of great help for designers, but the indications they provide should always be carefully reviewed in light of the requirements to be fulfilled. Hence, here the expertise of the designer for what concerns the physics of the printing process, the post-processing phases to be performed and the best printing configuration to guarantee the process efficiency is determinant. As a concluding remark, it is worth underlying that the paper presents an exploration of the possibilities offered by MAM technologies in the archery field; the results obtained have nevertheless to be further validated by means of functional and technical tests on the prototypes. The economic feasibility of the proposed application is another field of investigation that still needs to be explored.

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