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Redesign and manufacturing of a metal towing hook via laser additive manufacturing with powder bed

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Abstract

An approach to redesign and manufacture a metal towing hook via Selective Laser Melting is discussed. Some reference criteria and general guidelines are considered step-by-step to concurrently address lightening, manufacturability and job planning. Grounds are given for the application of Additive Manufacturing for complex components to the purpose of material saving and increased safety factor.

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Keywords: Additive Manufacturing; Selective Laser Melting; topological optimization.

1. Introduction

According to the ASTM Standard [1], Additive Manufacturing (AM) is "the process of joining materials to make objects from 3D model data, as opposed to subtractive manufacturing methodologies, such as traditional machining". It has been widely discussed in the literature [2] that plastic parts produced via AM are a convincing cost effective alternative to conventional manufacturing (e.g., injection molding) for medium lot production. Moreover, thanks to recent improvements, AM has been shifted from rapid tooling to rapid manufacturing of metal parts, even for

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applications where strict standards apply, such as aerospace and automotive [3], the latter receiving special increased interest in the frame of electric vehicles. Namely, a number of main advantages [4] result: assemblies are turned into single parts, hence streamlining of manufacturing and potential elimination of tooling are benefited with reduced waste [5]; optimized functions (e.g., cooling channels in molds) are specifically addressed [6]; customization is allowed and the mechanical strength of the bulk is achieved upon proper set-up of the processing parameters; quick changes to the original design are possible; new possibilities in lightweight design are offered [7]. On the other hand, conventional processes are suggested for higher production rate and lower complexity.

Given the need to produce near-net-shape structural components, metal alloys have been investigated and two main methods are available: Directed Metal Deposition (DMD) and powder bed processes. A single-stage process is in place in DMD: a metal in the form of loose powder or wire [8] is fed to a melting pool resulting from energy delivery, the method being feasible to keep parts and devices in working order when local manufacturing imperfections or demanding conditions of temperature, wear and mechanical stresses have been experienced [9]. In particular, laser-aided DMD is thought to be capable of producing sound clads to successfully perform coating for maintenance, repair and overhaul of condemned products. At present, supplying the metal in form of wire has been reported to produce lower surface quality and bonding strength, with porosity and cracks as well [10], although being cheaper and wasting less material compared with powder feeding which is flexible in materials, robust and effective [8].

As regarding powder bed processes, a two-stage process is in place: the base metal in form of loose powder is laid, then fused by means of laser in inert atmosphere [11, 12] or electron beam in vacuum chamber [13]; namely, Selective Laser Melting (SLM) or Electron Beam Melting (EBM) is performed, respectively. With respect to DMD, manufacturing of more complex parts is feasible; even functional grading is allowed upon proper setting of the processing parameters [14]. Increased manufacturing rate is benefited in EBM thanks to higher energy and thicker layers; on the other hand better accuracy is achieved in SLM, although post-processing is required [15] to improve the surface finishing, depending on the applications.

It is widely understood in common practice that redesign for manufacturability must be performed aiming to lightening and topological optimization of the original part in order to fully benefit from the advantages of AM [16]. Therefore, the optimization of both shape and structure is suggested, inner lattice, trabecular and similar-to-foam arrangements are set [17].

In the frame of AM-oriented redesign, this paper is aimed to offer an approach to perform the topological optimization of a test-article, a conventional metal towing hook, prior to SLM. Some reference criteria to concurrently address lightening, manufacturability and job planning are given. A number of simulations are discussed to match the nominal loading and increase the safety factor. Eventually, the part has been manufactured and proper dimensional checks have been conducted.

2. Redesign

A stainless steel, annealed S17400, metal towing hook for pulling (Fig. 1) resulting from welding of a number of casted parts has been chosen, being it a valuable test-article of reasonable complex shape offering a number of crucial geometrical items (i.e., curvature, holes and functional grooves). As the nominal loading conditions of the real part must be kept in the redesigned component, a simulation has been conducted to evaluate the Von Mises stresses. Namely, a 15 kN pulling load representing the maximum allowed load has been considered (Fig. 2): a maximum local stress of 505 MPa has been found, resulting in a safety factor of 1.5 with respect to a referred 760 MPa yield strength.

Redesign has been conducted with dedicated software to the concurrent purposes of smoothing the edges and lightening, aiming to increase the safety factor in turn (Fig. 3). At first, it is worth noting that the original metal assembly has been turned into a single part and significant saving of metal has been benefited. Nevertheless, manufacturability in SLM must be allowed.

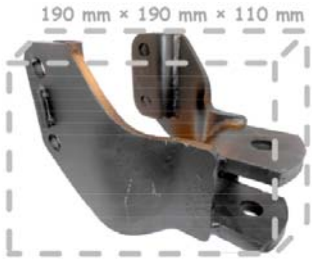

Fig. 1. Metal towing hook, S17400, original fashion.

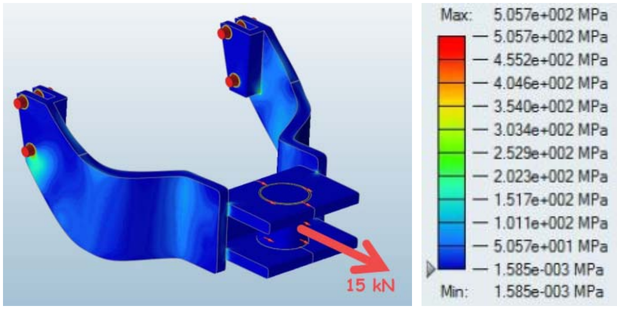

Fig. 2. Distribution of Von Mises stresses in nominal loading of the towing hook, original fashion.

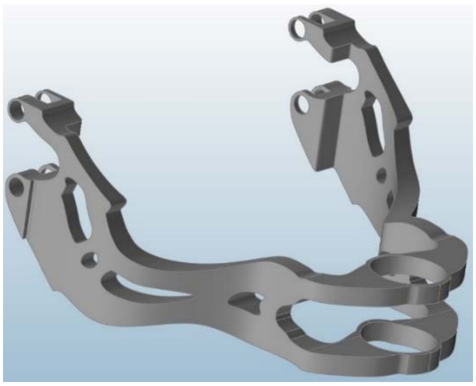

Fig. 3. Metal towing hook, redesign at first stage.

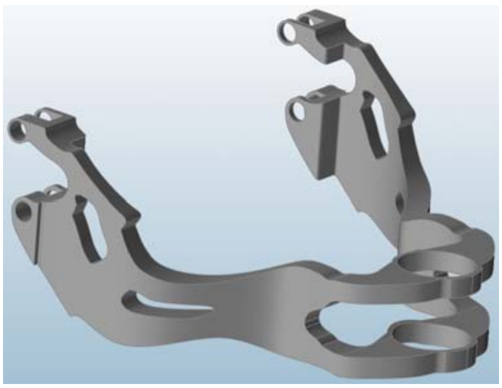

Fig. 4. Metal towing hook, further redesign for manufacturability.

In this frame, two general guidelines apply, even in compliance with the technical constraints of the building machine:

- a minimum gap must be allowed among adjacent slots, grooves or channels, to prevent them from being merged together during manufacturing;
- thin walls must be designed above a 0.4 mm threshold to prevent them from being removed by the recoater blade when laying the powder.

As a result of these, additional minor changes have been made to the part (Fig. 4). Eventually, 3.0 out of 6.6 kg have been saved, resulting in a 45% overall reduction of weight, the base metal being the same of the conventional part.

Soundness and continuity are aimed upon SLM in the optimized processing strategy, therefore the mechanical properties of the bulk must be expected. Nevertheless, in order to take account of possible AM-induced anisotropy [18] of the metal, a lower reference yield strength of 550 MPa [19] has been considered. Under nominal loading conditions, a maximum local stress of 265 MPa has been found (Fig. 5), anyway: therefore, an increased safety factor of 2.1 has been benefited when assessing the distribution of Von Mises stresses. Based on the simulation, redesign is thought to be effective.

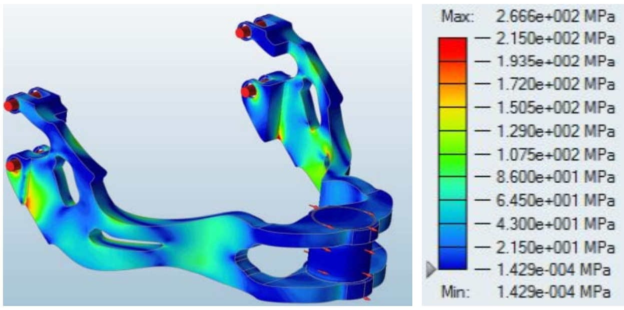

Fig. 5. Distribution of Von Mises stresses in nominal loading of the towing hook, redesigned.

3. Job planning

Supporting is required underneath any overhanging surface when manufacturing via SLM. With respect to this issue, a proper evaluation must be conducted when planning the job. Indeed, whether a part of a component is an overhanging structure or not depends on the orientation and the growing direction [20]. Specific guidelines are offered by the general literature about AM [21] to address the issue of positioning on the building plate, since infinite theoretical directions of growing can be found depending on the geometry. In general, one should assume that:

- positioning the part so that its largest cross-surface is parallel to the building plate results in wide and many supports, but reduced building time;
- positioning of the part so that its largest cross-surface is orthogonal to the building plate results in increased building time, but reduced amount of supports, hence better surface quality.

As a consequence of these, a compromise should be made to find the optimal direction of growth [22]. Moreover, sensible positioning should be decided to allow manufacturing of more components on the same plate, hence in the same manufacturing job, depending on the size of the parts and the building chamber. Costs and quality would be evenly balanced.

With respect to the case study, both parallel and orthogonal positioning of the largest cross-surface with respect to the building plate are deemed to be improper: lots of supports, with consequent difficult removal, would be required in the former (Fig. 6A); the total height of the component would be incompatible with the building chamber in the latter (Fig. 6B). A compromise has been found, a tilting angle of the main axis has been considered with respect to the building plate (Fig. 7).

Once positioning has been accomplished, anchor supporting to the building plate can be set (Fig. 8) and the overhanging surfaces are clearly identified. Again, some guidelines are available in the literature: namely, a flowchart has been suggested [20] to recognize which surface is required to be supported, based on the evaluation of a threshold angle depending on the technology, the material and the building machine. At this stage of planning, additional changes may be arranged on the component to improve the manufacturability as well as the eventual removal of the supports.

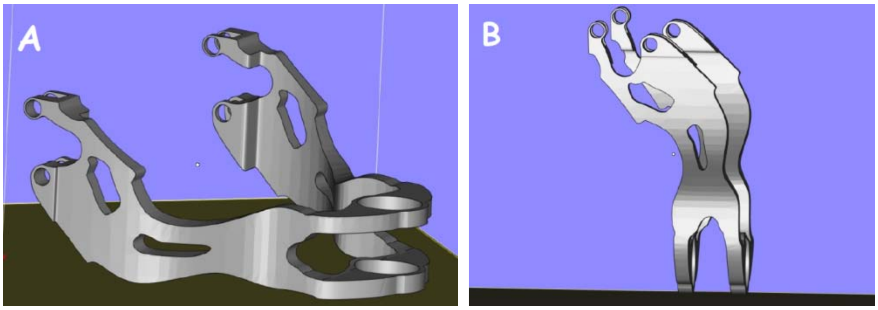

Fig. 6. Improper positioning: (A) lots of supports would be required, (B) incompatible height.

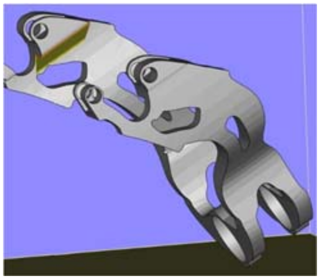

Fig. 7. Eventual positioning and direction of growing of the part.

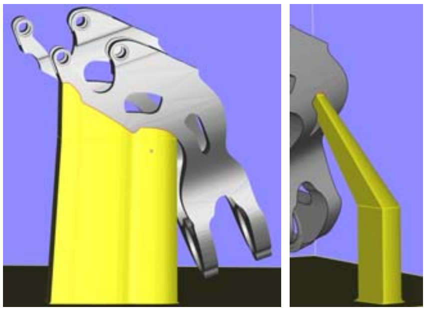

Fig. 8. Example of anchor supporting of the part to the building plate.

As an example, the shape of the slots from first-stage lightening of the part would result in tight gussets at the inner side and difficult removal (Fig. 9A). Therefore, new smoothing has been performed (Fig. 9B) before supporting (Fig. 9C). It is worth noting that any further change in shape upon first checking of the nominal loading should undergo new simulation under loading to assess the local safety factor. This is deemed to be redundant in this case, since even smoother slots are expected to provide increased consistency in the distribution of the stresses.

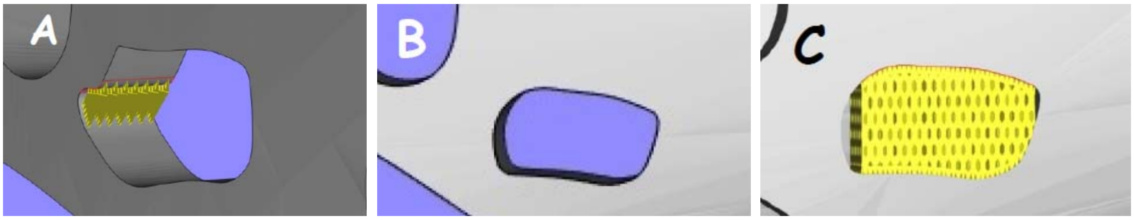

Fig. 9. Lightening slot: (A) detail of gussets at the inner side, (B) redesign, (C) final supporting.

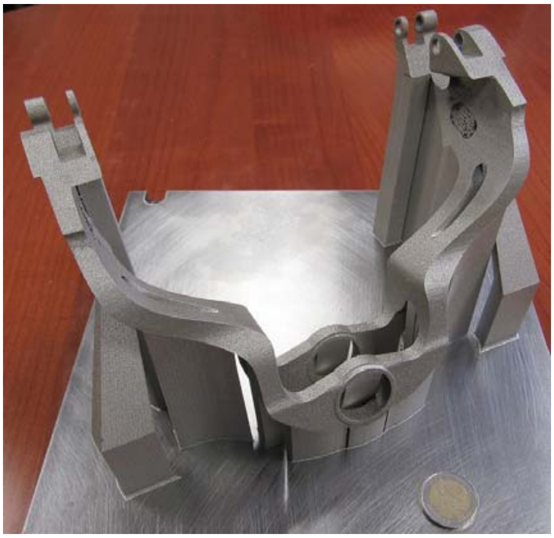

Fig. 10. The part, as manufactured, with anchor supporting on the building plate.

Eventually, the part has been manufactured (Fig. 10) by means of commercial EOS M270 X-Tended laser sintering system, Yb:YAG based. Pre-alloyed, argon gas atomized virgin commercial EOS GP1 stainless steel powder, 20 µm mean grain size, corresponding to standard UNS S17400 chromium-copper precipitation hardening steel in terms of nominal chemical composition has been considered. Processing power, speed, layer thickness, and hatching strategies are based on preliminary trials aimed to optimize the process to the purpose of full dense structure (Table 1); a nitrogen inert atmosphere has been arranged. As suggested by the powder manufacturer [19], stress relieving by means of thermal treatment at 650 °C for 1 hour has been performed prior to removal from the building plate to prevent shrinkage and deformation.

Table 1. Main features and processing parameters in SLM of stainless steel powder.

Parameter	Value
Operating laser power	195 W
Linear processing speed	1 $m \cdot s^{-1}$
Hatch spacing	0.10 mm
Layer thickness	20 µm
Focused spot diameter	90 µm

4. Checks

Dimensional checks have been conducted by coordinate measuring. Crucial items for the assembly have been considered (Fig. 11); the mismatch with respect to the nominal dimensions has been measured (Table 2). Typical precision of 0.2% [19] is expected for large parts (i.e., whose size approaches the building chamber); although this has not been matched for 2 out of 3 items, it is worth noting that defective dimensions have been found, therefore full compliance with the intended geometry can be achieved via post-processing machining. As an alternative, a proper compensation can be implemented to the original CAD model prior to manufacturing.

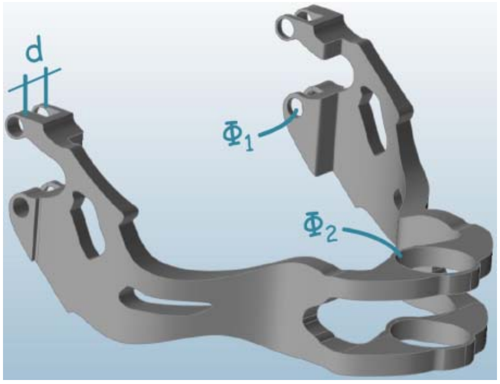

Fig. 11. Dimensional items to be checked upon manufacturing.

Table 2. Nominal, actual and percentage mismatch for each measured item

	Nominal [mm]	Actual [mm]	Percentage mismatch [%]
Φ_1	6.40	6.296	-1.6
Φ_2	25.60	25.550	-0.2
d	9.00	8.936	-0.7

5. Conclusions

Topological optimization resulting in material saving and increased safety factor of a mechanical part can be accomplished by means of Additive Manufacturing. Namely, as regarding this case study, a 45% overall reduction of weight has been benefited, with an increased safety factor of 40% with respect to the conventional part, for a given condition of loading.

A number of general guidelines are available in the literature. Nevertheless these must be properly addressed based on the part to be manufactured. Therefore, an AM-oriented redesign is mainly based on an interdisciplinary expertise of the designer in terms of design, manufacturing and job planning.

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