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Towards a complex geometry manufacturing: A case study on metal 3D printing of topology optimised bicycle parts with lattices

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Abstract: Manufacturing metal parts with complex geometries using conventional methods has proven to be almost impossible due to tooling constraints. Additive Manufacturing (AM) or 3D printing has proven to be a solution for manufacturing such parts since the constraints imposed by traditional manufacturing are not applicable to AM. The research objective is to demonstrate the workflow from design to manufacturing complex geometry parts specifically for AM Selective Laser Melting (SLM) process, it also has its own constraints that are different than traditional manufacturing. AM provides a solution to manufacturing topology optimised complex geometries that cannot be manufactured using conventional methods. In order to demonstrate the possibilities and challenges of producing complex geometries with additive manufacturing, a case study of manufacturing topology optimised bicycle parts has been conducted at the University of Vaasa, Finland using SLM technology, based on the Powder Bed Fusion (PBF) process. The results of this research show that metal 3D printing is an enabler for manufacturing topology optimised complex geometries with challenges such as the need to edit and optimise the automatically-generated supports, and thermal solid support design for anchoring large flat surfaces, and possible boundary shells issues and post-processing planning.

Keywords: metal additive manufacturing, metal 3D-printing, topology optimisation, lattices, lattice structures, complex geometry, additive manufacturing, rapid prototyping, powder bed fusion (PBF).

1. INTRODUCTION

Manufacturing metal parts with complex geometries using conventional methods has proven to be almost impossible due to tooling constraints. Additive Manufacturing (AM) or 3D printing has proven to be a solution for manufacturing such parts since the constraints imposed by traditional manufacturing are not applicable to AM. Additive manufacturing (AM) produces digital models layer by layer into physical parts by joining the layers of material into the desired shape (ASTM Standard, 2012; Zhang et al., 2019).

The research objective is to demonstrate the workflow of designing and manufacturing complex geometry parts using Metal Additive Manufacturing (MAM). The research utilised the Selective Laser Melting (SLM) process as a manufacturing method. A case study of manufacturing topology optimised bicycle parts was carried out at the University of Vaasa, Finland using the Print Sharp 250 SLM machine that is based on Powder Bed Fusion (PBF) process. Print Sharp250 is a product of Prima Additive, a dynamic division of Prima Industrie.

AM provides possibilities to manufacture complex parts as compared to traditional manufacturing that is more suitable for simple parts using tooling, moulding, and casting (D'Aveni, 2015; Weller, et al., 2015). AM proposes several advantages over traditional manufacturing because of the flexibility and possibilities of fabricating functional and geometrically complicated 3D parts with lattice structures integration using a broad range of materials without modifying or replacing the processing tool (Vaezi et al., 2013; Zhang et al., 2019). AM can also be used to complement traditional manufacturing methods to revolutionise it and achieve a hybrid type of manufacturing process (Holmström et al., 2016; Sasson and Johnson, 2016). Locally manufactured parts using AM makes parts closer to the point of usage and equally improves supply chain flexibility and performance (Delic and Eyers, 2020).

There are different AM processes, and they differ from each other in terms of the nature of the material (e.g., metal powder, plastics filaments, ceramics, etc), utilised, deposition technology, formation mechanism of the layers, and the characteristics of the final part (e.g., final net shape, finished surface, texture, geometrical shape, and mechanical properties). According to ASTM, there are seven categories of AM technologies based on the AM processes. These categories are material extrusion, sheet lamination, material jetting, powder bed fusion, vat photopolymerisation, binder jetting, and directed energy deposition (Madla et al., 2018).

This article is structured as follows; section 2 discusses metal 3d printing and its technologies, section 3 covers the basics of topology optimisation for generating complex geometries and topology optimisation workflow for the bicycle parts, section 4 investigates support and lattice structures for metal 3D

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printing and design for additive manufacturing to minimise support structures. Section 5 covers the results and learning points and the last part section 6 presents the conclusions of this research.

2. METAL 3D PRINTING

Metal 3D printing also commonly referred to as metal additive manufacturing (MAM) is a process used to produce metal parts using metal alloys and metal 3D printing technologies. MAM gives several possibilities in terms of part manufacturing without any tooling which includes but is not limited to less waste of raw material, design freedom, manufacturing of near-net-shape parts, manufacturing of topology optimised complex geometries, lattice structure, and mass customisation (Bourell et al., 2009; Wohlers and Caffrey, 2010). Berman (2012) posit that MAM is becoming the next industrial revolution.

MAM can produce fully dense metallic parts from different kinds of metal alloys such as stainless steel, titanium alloy, nickel-based superalloy (Inconel), cobalt-chrome alloy, aluminum alloy, and tool steels (Thomas, 2009). Common applications of MAM include but are not limited to the manufacturing of specialised jigs and fixtures, moulds, medical implants, manufacturing spare parts for automotive industries, and aerospace spare parts (Bhavar et al., 2017). Most of the parts mentioned typically have complex geometries that are difficult to manufacture using conventional methods or when manufactured with conventional methods, the parts can only have limited functionalities. For example, Garden and Schneider (2015) presented in their research how it was not possible to manufacture the required functionalities of a complex hip joint interior pores with conventional methods but with AM, they could manufacture the complex hip joint implant interior pores that make it possible for bone and cells to grow through the porous implants.

There are broadly six main categories of metal 3D printing technologies. However, different manufacturers have developed their own proprietary variations of existing technologies and labelled them under their own registered business names. The six categories are Powder Bed Fusion (PBF), Direct Energy Deposition (DED), Metal resin 3D printing, Lamination, Metal Material Jetting (MJ), or Binding Jetting (BJ), and Metal Filament extrusion/Fused Filament Fabrication (FFF). The Powder Bed Fusion (PBF) technology was utilised for this research using Print Sharp 250 Prima Additive SLM Machine at the University of Vaasa, Finland because it can produce very dense complex parts with higher accuracy (Berger, 2013).

2.1 Metal 3D printing technologies

Metal AM processes are generally classified into two major groups which are Powder Bed Fusion (PBF) based technologies and Directed Energy Deposition (DED) technologies. PBF based technologies uses thermal energy to selectively fuse/melt regions of powder bed and produce metal parts while DED uses focused thermal energy to fuse/melt materials (powder or wire form) as they are being deposited. Bhavar et al., (2017) argued that these two technologies can be further classified based on the type of energy source and the raw material used in their processes. The main metal AM processes used by machines based on PBF technologies are Direct Metal Laser Sintering (DMLS)/Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Laser cusing, and Electron Beam Melting (EBM) (Serin et al. 2016; Bhavar et al., 2017).

2.2 Powder Bed Fusion (PBF)

PBF process uses metal a powder and a high-power laser to sinter or melt metal powder to produce metallic parts following a layer-by-layer pattern. Fig. 1 below shows the basic working principle of a PBF-based metal 3D printing machine. First, the printing area is made into a powder bed via the powder roller/recoater spreading powder from the nearby powder delivery unit. A high energy source of laser is used to scan each layer of a metal powder bed to sinter/melt the only required surface based on the tool path generated by the slicing software and using process parameters specified from the hatching software. Subsequent layers are printed by lowering the printing area and pushing up the powder feeding unit to allow for more powder to be fed in. The cycle is repeated until the complete part has been built. The entire sintering/melting process is conducted in an inert atmosphere using argon or nitrogen depending on the material being printed.

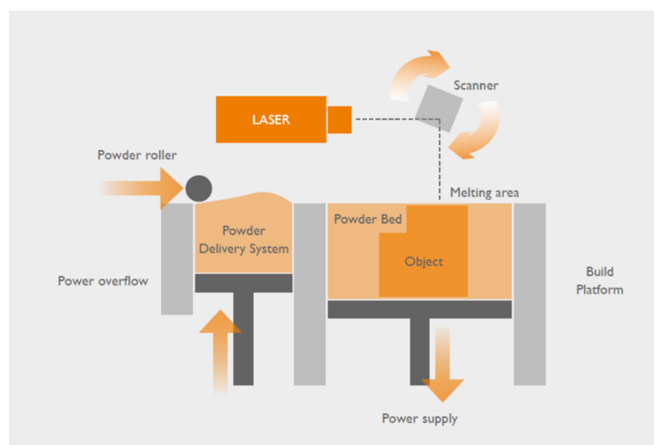


Figure 1. Basic working schematic of a PBLF based metal 3D printing machine.

3. TOPOLGY OPTIMISATION

In order to achieve a more reliable result in terms of demonstrating the capabilities of using MAM for printing complex geometries, topology optimisation has become a necessity to generate organic-looking parts with complex geometric configurations. Gebisa and Lemu (2017) proved that using topology optimisation to redesign a jet engine bracket generated a complex part that can only be produced using AM. A similar proposition was also established by Aliyi and Lemu (2019) where a triangular bracket was redesigned with topology optimisation to achieve lighter weight, the optimised part also appears naturally complex after the process and AM was considered a viable solution to manufacture it.

Topology optimisation harnesses mathematical methods to achieve an optimised material distribution for a part within a design space for specific loading and boundary conditions. The design space will undergo design optimisation and is continuously refined over a number of iterations in order to achieve the desirable volume/optimisation objectives considering certain boundaries and constraints such as load and stress. The non-design space will not be touched during the topology optimisation process, but it has certain boundary conditions like loads/tensions which are will be applied. There are different topology optimisation approaches which include the set level approach, homogenization method, BESO, SIMP method, and density approach (Rozvany 2009; Huang and Xie, 2010; Sigmund and Maute, 2013; Aliyi and Lemu, 2019).

Topology optimisation is a product design technique that uses high-end simulation software to achieve optimised structures to generate a conceptual design with reduced weight and the resulting structures usually appear more organic and complex than CAD modelled parts. Such topology optimised structures cannot be easily manufactured using traditional methods (Bendsøe and Sigmund, 2004; Brackett et al., 2011). Considering the design rules of a traditional/conventional manufacturing process, the possibilities that topology optimization has to offer are limited. On the contrary, AM gives almost unlimited design freedoms that ensure the maximum potential benefits of topology optimisation are fully utilised. The flexibility and possibility that AM provides without any tooling make AM and topology optimisation an ideal couple (Gebisa and Lemu, 2017).

In order to achieve an efficient result with topology optimisation, it is important to understand the general overview of topology optimisation-based workflow. Arora (2004) proposes five stages that should be followed before formulating a topology optimisation-based design workflow. The five steps are i) developing the optimization problem statement, ii) collecting data and information, iii) identifying and defining design variables, iv) identifying the optimisation criterion and, v) identifying constraints. The problem statement formulation is an important step in this workflow.

3.1 Topology optimisation workflow for the metal 3D printed bicycle parts

After clarifying the general topology optimisation workflow, a problem statement definition for this case study was also formulated. The problem statement is to achieve a complex geometric structure with a certain load-bearing capacity using a topology optimisation workflow in Fig. 2 below. Using Finite Element Analysis (FEA), the stress and displacement distribution across a part is understood. Then a topology optimization tool uses this information to remove materials from a part where it is not essential to support any form of load or bear stress. Typically, topology optimisation steps start with a basic 3D model, then a set of loading and boundary conditions are specified for the 3D model, then the topology optimization software optimises the model based on the specified constraints. The software will remove areas not needed for load or stress bearing and leave only the area that meets the mechanical and design specification. The optimised part mesh is cleaned and checked for requirement specification or remodelling if needed. A second round of FEA might be carried out to verify that the optimised part meets the requirements specifications. In order to get a topology optimised part, several iterations and fine-tuning are usually required. Some of the popular topology optimisation software are Ansys, nTopology, Flow-3D, Dassault Systèmes Simulia, Amphyon, Autodesk Netfabb, Simufact Additive, and so on (Orme et al., 2018; Aliyi and Lemu, 2019). Fig. 2 below shows a typical workflow for topology optimization of a 3D model.

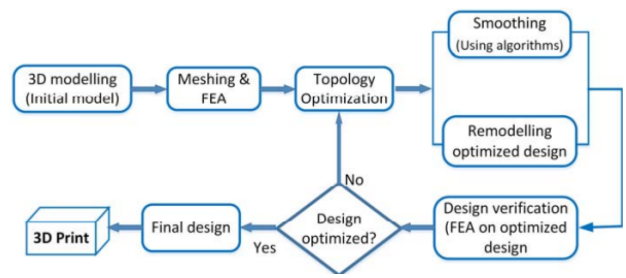


Figure 2. Topology optimization-based design process (Aliyi, and Lemu, 2019).

Following a similar workflow above, the bicycle parts were designed using CAD software and in this case, Ansys was used to specify the forces and load conditions. The part below has an original weight of 2.60kg and after several iterations including cleaning and remeshing the surface, a topology optimised part of 1.31kg was achieved resulting in an over 50% lighter part with a complex geometric structure. The material used for the simulation and metal 3D printing is stainless steel 316L. The entire workflow for the topology optimisation of the seat area of the bicycle is shown in Fig. 3 below

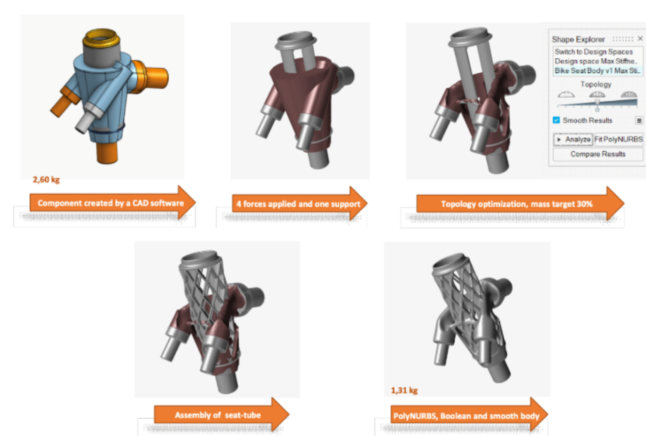


Figure 3. Workflow for topology optimization of seat area for the bicycle part for metal 3D printing.

4. SUPPORT AND LATTICE STRUCTURES FOR THE METAL 3D PRINTED BICYCLE PARTS

Support structures and generation is a critical step in preparing parts for metal 3D printing using powder bed fusion technology. This is because metal parts that are not self-supporting and not redesigned or optimised using Design for Additive Manufacturing (DfAM) must be supported if they have overhangs less than 45 degrees (Inconel and Stainless steel), downward facing features, large round holes greater than 6mm, or tall triangular features. Such supports can help with heat dissipation as well. Topologized optimised parts usually have complex geometries that require several types of supports (solid and regular) for one or more of the reasons already mentioned above (Zeng, 2015). Due to the complex nature of topology optimised parts, the automatically generated supports by Materialise Magics, in this case, must be optimised manually.

Materialise Magics, a data preparation software for metal 3D printing, comes with an automatic support generation module which when utilised on topology optimised parts produces inaccurate surfaces with sharp contours that are not suitable for use as a support structure for metal printed parts. Irregular contour around the support structure will lead to heat and stress build-up during printing and eventually leads to parts warping and shrinking. It can lead to a huge deformation of parts and print failure from delamination from the build plate and on some occasions, it can damage the recoater blade or the part that is being printed. Hence, there is a need for manual redesign, editing, and optimisation (Zeng, 2015).

Fig. 4a below shows an automatic generated support for an optimised part. As clearly indicated, the contours are very sharp and a lot of manual work for smoothening them out must be done. Iterations of fixing and refixing the geometry for any errors must be carried out as well. Hence there is a need for an optimised workflow to achieve an efficient and first-time right build of a topology optimised parts with normal or solid support. In Fig. 4b, the jagged auto-generated edges are already cleaned and ready for a solid support generation without possible heat stress, crack, delamination, and internal crack issues while printing. Fig. 5a shows solid support already integrated into the topology optimised part for efficient heat dissipation and Fig. 5b shows the part with a regular/normal support.

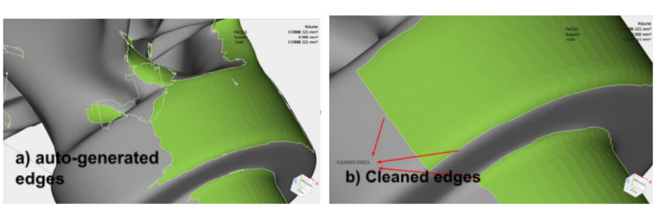


Figure 4. a) Automatic surface marking generated by Materialise Magics with sharp edges for support generation b) Cleaned edges ready for support generation.

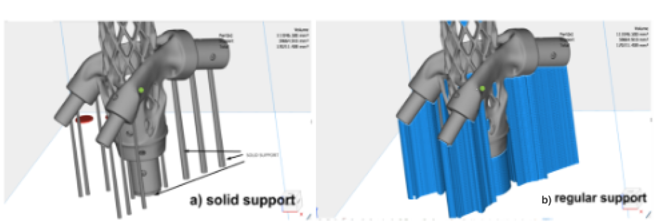


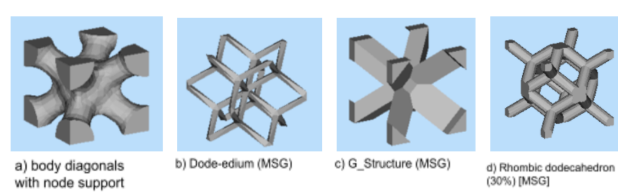
Figure 5. a) Solid support for better heat dissipation during printing b) regular support that can be easily removed after printing.

4.1 Design for Additive Manufacturing (DfAM)

Over the years, the term "Design for Additive Manufacturing (DfAM)" has been used by many researchers. However, only a few researchers have defined the term from a technical point of view. Thompson et al., (2016) argue the need for proper education and expertise for the development of DfAM. DfAM involves a way of thinking about design that helps reduce manufacturing time, material usage, and cost and thereby helping to achieve high-performance quality products at the same time and increasing profitability. The very specific standard related to design for AM which is called ISO/ASTM DIS 20195 "Guide for Design for Additive Manufacturing" is currently under development and such standard will help achieve a universal language of design for AM (Thompson et al., 2016).

The DfAM paradigm to design practice is valid for the majority of the requirements for DfAM. However, DfAM might require more process-specific design rules and tools that are not necessarily in line with the traditional DfAM. For example, with the high level of freedom when manufacturing with AM, the need for assembly for example could possibly be eliminated and the batch sizes, production time/methods/volumes and cost drivers are completely different than in traditional manufacturing. In essence, having a proper standard for DfAM will enable AM to be considered as a viable solution for industrial manufacturing. Topology optimisation is seen as a great tool in achieving a better DfAM due to the enormous benefits it offers in terms of design freedom, minimising material usage and hence saving cost, and build time and achieving light weighing of parts with the same or even superior functional performance.

Lattice structure integration is one of the DfAM approaches that was utilised during the design of the bicycle parts for this research. Different kinds of lattice structures available in Materialise Magics such as cross-x, diamond, G-structures, and body-diagonals with nodes are shown in Fig. 6(a-d) below. Fig. 6e below shows the integration of one of the lattice structures already mentioned into the seat area of the bicycle.



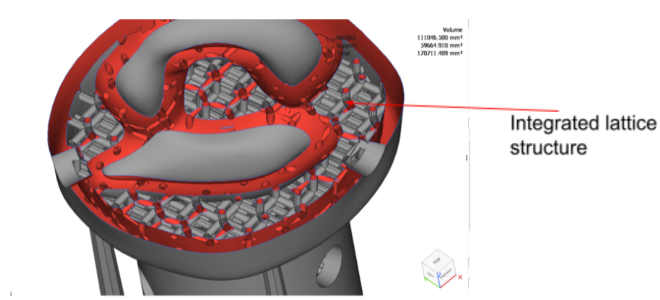


Figure 6e. Internal lattice integration for the bicycle seat area (Lattice = Rhombic dodecahedron 30% from Materialise Magics).

Another lattice generation and integration software that was also explored and utilised during the research is nTopology. nTopology is a powerful topology optimisation and lattice generation tool for light-weighting a part for metal 3D printing. Fig. 7a below shows the process of lattice generation with different parameters while Fig. 7b shows the already integrated lattice structure into the bicycle part (head tube) that was printed.

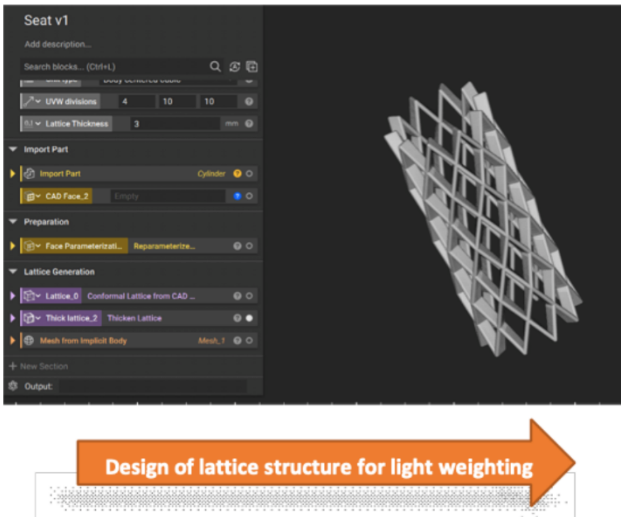


Figure 7a. Lattice generation with parameters in nTopology software.

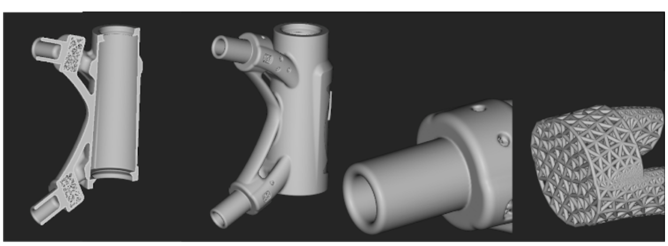


Figure 7b. Already integrated lattice structure into the head tube of the bicycle.

5. RESULTS AND LEARNING POINTS

The results show that MAM is a viable solution for manufacturing topology optimised complex parts. However, it comes with some challenges. Some of the challenges are design issues, support generation issues to achieve a printable topology optimised part, and so on. Designing for MAM is entirely different from designing for a CNC or moulding machine for example. DfAM is a critical phase in achieving successful metal 3D parts. In practice, manufacturing with AM is a different approach and so is the design for AM. Designers should strive to achieve a CAD model/topology optimised parts that require little or no support during printing. A design that requires little or no post-processing due to excess support removal will make AM workflow flexible enough and ready to manufacture functional parts that can be installed directly on the lines as soon as they are printed.

The Learning point from the research shows that in addition to the design issue already mentioned above, support structure and generation is a very important aspects to consider in order to achieve a successful build free from internal stress, cracks, and deformation. Additionally, lattice integration is another important approach towards achieving even lighter weight and more optimised parts. Part orientation during printing is a major determinant of a successful print. Fig. 8, Fig. 9, and Fig. 10 show the designed CAD parts, the topology optimised parts with internal lattice structures, and the printed bicycle parts respectively.

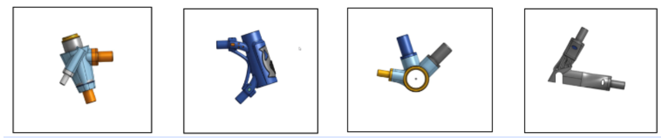


Figure 8. CAD design for bicycle parts. a) seat area b) head tube c) pedal area d) tail area.

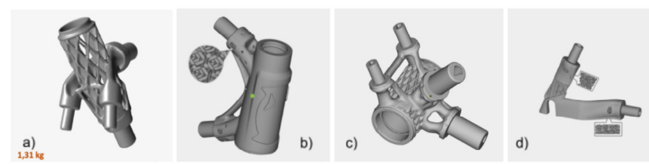


Figure 9. Topology optimised design for bicycle parts, ready for metal 3D printing. a) seat area b) head tube c) pedal area d) tail area.

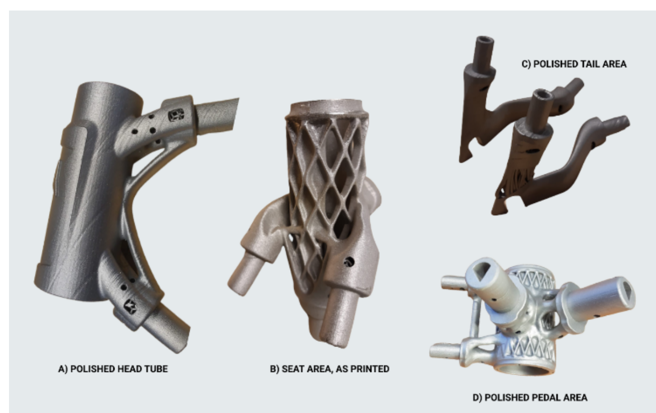


Figure 10. Metal 3D printed bicycle parts. a) head tube (polished) b) seat area (as printed) c) tail area (polished) d) pedal area (polished).

6. CONCLUSIONS

MAM is a growing field with many possibilities for manufacturing advanced/complex parts that are difficult to be manufactured using conventional methods. MAM also makes such parts closer to the point of usage and thereby contributing to a better and more flexible supply chain network. However, it requires a complete change in mindset starting right from the design phase to optimisation phase, and to the final printing phase. Designers, Engineers, and researchers alike must be willing to change their way of thinking, and understand and explore different workflows that can produce better results with less cost, time, and resources. The contribution of this research shows that the established workflow for preparing parts for metal 3D printing does not work well for topology optimised parts, further manual editing must be done. The material cost, machine cost, operator cost, machine time, and other related costs could be quite high compared to traditional manufacturing costs for a specific part and this is one of the limitations of this research and possible areas of further research. In essence, this research does not consider the cost implications of using MAM to manufacture the bicycle parts compared to using conventional methods.

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