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Hybrid Additive Manufacturing for Assembly and Postprocessing Solutions

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Abstract

The paper discusses hybrid additive manufacturing (HAM) technologies to produce 3D-printed metal components and their post-processing solutions. This research demonstrates how HAM can increase the design and manufacturability of a product solution. The manufacturing techniques applied in the cases are laser powder bed fusion (LPBF), with computer numeric control (CNC), metal inert gas (MIG) welding, fusion deposition modeling (FDM), and adhesives. All these examples present different requirements; therefore, we can see how versatile and productive HAM can be by offering ways to fabricate a final part. This study highlights the possibility for HAM to transform and enable alternative routes in various sectors. However, disadvantages related to advanced material compatibility, integration of these processes, and good quality remain to be addressed for a greater HAM adoption. Four case examples suggest that re-engineering, effectively choosing the correct materials, and dealing with design limitations may be necessary to maintain the quality, functionality, and efficiency of the components presented in this study.

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1. Introduction

Manufacturing processes are moving towards efficiency. Thus, creative ways to produce a final part require combining traditional manufacturing techniques with additive manufacturing methods. For example, CNC machining is constrained by the work area of the tool and possible subsequent steps in production. By comparison, many additive manufacturing methods produce a rough surface [1]. With hybrid manufacturing methods, multiple approaches to treating parts or surfaces for assemblies are considered. The solution lies in how a process can take advantage of other processes. By bringing these methods together, industrial manufacturers can do more, be more productive, and overcome the limitations that a manufacturing approach may have. [1-3].

Hybrid manufacturing techniques are altering the situation. In general terms, the benefits of integration can be summarised by saying that they will enable us to design and build intricate components with high tolerance, aiding the manufacturer in speeding up production and materials savings better than conventional manufacturing methods [3]. This research focuses on the hybrid workflows that Metal 3D printed components must undergo to be integrated with components manufactured with traditional techniques, such as welding, gluing, machining, milling, and surface treatment in assembly processes. Through four case studies, we present various workflows for hybrid applications and describe how a particular selection of methods and setting parameters can be used to manage the associated tasks [4, 5].

2. Theoretical perspective in existing research

The ISO/ASTM 52900:2015 standard defines additive manufacturing as joining materials to create components from 3D model data, usually layer by layer [5]. Additive manufacturing differs from subtractive processes (such as milling, turning, drilling, and grinding), which often focus on removing material to drill or grind objects toward the desired shape. Lauwers, Bert, et al. [6] proposed the classification of hybrid manufacturing in two groups. Group I has processes where more than one energy sources or tool are combined. This group is divided into two subgroups. Subgroup I. A includes processes in which a secondary process assists a primary process in situ. Subgroup I.B includes mixed processes; those processes are employed at the same time. Group II includes processes that act separately to create components efficiently. This group is divided into two subgroups: II. A includes traditional manufacturing techniques, such as the combination of rolling and hardening. Pragana, J. P. M [1] mentions the subgroup II.B. This subgroup includes a hybrid additive manufacturing concept, where additive manufacturing is combined with traditional manufacturing processes. [1, 6-8]

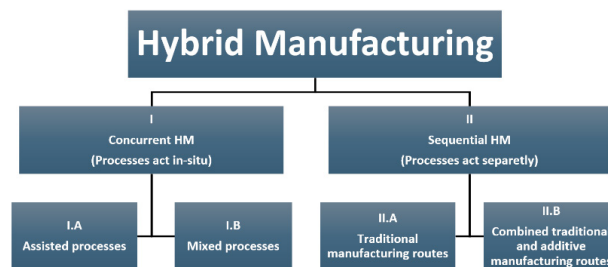


Figure 1 Classification of hybrid processes [1].

2.1. Considerations in Additive Manufacturing

The demands of manufacturing systems are also subject to geometric complexity, movement platforms, and multi-material integral parts. In additive manufacturing processes, requirements engineering aims to discover reliable combinations of process and material parameters. Process interfaces must identify and analyze the technical/economic limitations of process chain design. The starting point for evaluating capability is the hardware parameters. Processing tools and motion systems will define the strategy for gas and powder supplying. Laser power, scanning velocity,

powder rate allows for the identification of component properties. All these parameters will influence material properties. The result on microstructure, dimensional tolerances, surface and mechanical properties will affect the quality, productivity, material efficiency and economy of the production, and probable post processing steps are required [7,13,14], see Figure 2 [14].

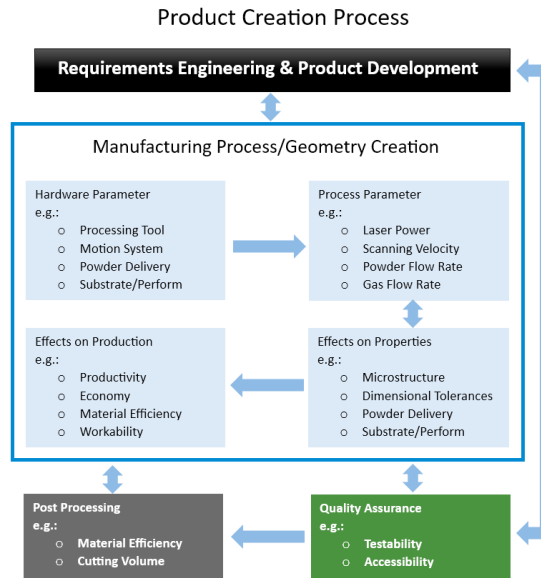


Fig. 2 Relationships within the process of creating a product [14].

2.2. Geometry considerations

Geometric The hybrid additive manufacturing (HAM) technology requires geometrical considerations. These can help identify which features should be realized by what kinds of technology or combination of different methods. Many design needs can be met by other additive manufacturing (AM) processes, such as Laser Powder Bed Fusion (LPBF), which is followed up with a specific post-processing technique or CNC milling [15, 16]. A combination of many methods Integrated systematically and effectively, these processes make up the complete HAM approach, enabling complex parts to be manufactured in an overall fashion that is not only of high quality but also economical. At the design stage, we define objective functions related to the part quantities [13, 16-18]. See Figure 3 [13].

2.3. Designing and manufacturing support structures

An essential element in metal additive manufacturing is the generation of support structures for overhangs. Supports increase the use of material, energy, and post-process time [19]. Leary, M. [20] suggests the planning of hybrid manufacturing: develop a part building with the requirements of where machining will occur (size minimums/surface finish). Post-processing issues, such as mitigating thermal warpage, can be addressed by using solid supports. They can act as the fixed points for more CNC processing. Also, support structures should be reduced to make the parts easier to assemble. Rough areas are generated at the location of support structures. Utilizing design for additive manufacturing (DfAM) is an alternative approach that should lead to lower requirements of additional support structures and post-processes [21, 22].

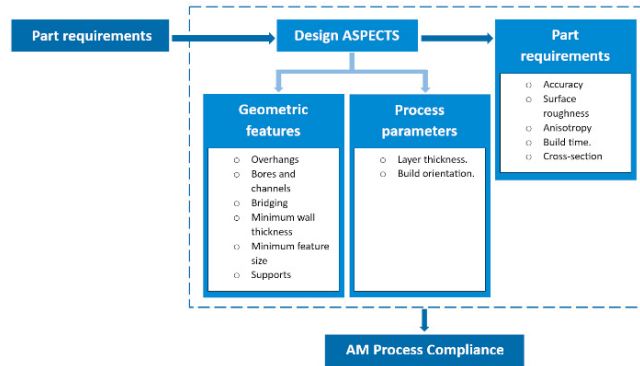


Fig. 3. Defining Aspects and Considerations for AM Design [13].

3. Materials and methods

3.1. Materials

The materials and components used in these studies were SS316L, carbon fiber rods, and aluminium tubes. Plastic prototypes were printed using FDM printers, and the materials were polyamide 6 (PA6) with carbon fibers (CR) and polylactic acid filament (PLA).

Table 1. List of materials used in all cases.

Materials
316L stainless steel atomized powder used
316L stainless steel tubes
Aluminium tubes
Carbon Fiber rods
Polyamide 6 (PA6) with carbon fiber (CR)
Polylactic acid filament (PLA)

Table 2. Chemical composition of 316L stainless steel atomized powder used in the LPBF process [23].

	Weight Percent (wt. %)						
	Fe	Cr	Ni	Mo	Mn	C	Other
MetcoAdd 316L	Balance	17.4	11.2	2.6	1.5	<0.02	<1.0

Table 3. Chemical composition of Stainless steel 316L seamless pipe

	Chemical composition in %								
	C	Mn	Si	P	S	Cr	Mo	Ni	N
316L stainless steel	0.03	2.0	0.75	0.045	0.03	16.0-18.0	2.0-3.0	10.0-14.0	0.10

Table 4. Chemical composition of rod/bar aluminium alloy EN AW-6060.

	Chemical composition in %								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
EN AW-6060	0.30–0.6	0.10–0.30	≤ 0.10	≤ 0.10	0.35–0.6	≤ 0.05	≤ 0.15	≤ 0.10	Rest

PA6+CR is a micro carbon fiber nylon with a carbon fiber reinforcement. Polylactic acid or polylactide (PLA) is a rigid thermoplastic filament with a low melting temperature of 175°C.

3.2. Methods

A hybrid manufacturing process combines two or more types of additive and/or subtractive processes (see Figure 4). Table 5 summarizes these combinations of processes employed for various purposes and describes detailed process and strategy examples from the case studies.

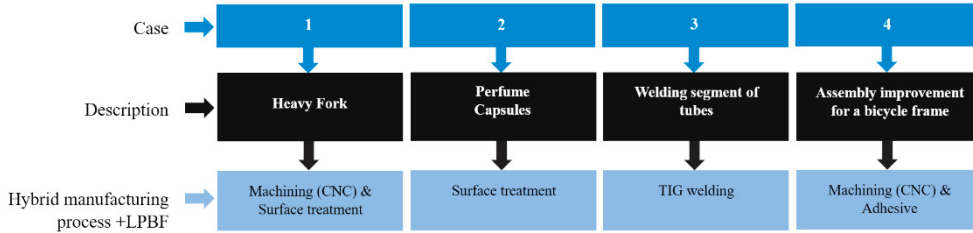


Fig.4. Combinations of manufacturing processes with Metal Additive Manufacturing process.

Table 5. Different combinations of materials and processes.

Case	Hybrid manufacturing	Reason for process selection	References
Heavy Fork, case 1 Assembly: Improvement for a bicycle frame, case 4	Additive manufacturing (LPBF) + machining (CNC)	Additive manufacturing and subtractive manufacturing have their own limitations, however by combining these manufacturing processes will overcome the limitation from each other. Irregularities, surface quality and precision of a 3D metal printed part can be achieved by a subsequent CNC manufacturing process.	[4], [11], [24], [25]
Welding segment of pipes, case 3	Additive manufacturing (LPBF) + TIG welding	Additive Manufacturing can be an alternative solution to produce segments of pipes from critical angles to complex geometry.	[23], [28], [29]
Heavy Fork, case 1	Additive Manufacturing (LPBF) + surface treatment (Polishing)	Electrochemical polishing (EP) creates surface restoration regarding micrometric smoothing and mirror-like properties. EP works on several industrial challenges, such as improving wear and corrosion resistance, creating decorative finishes (over bright-primed substrates), lowering friction, or enhancing surface preparation for coatings.	[30], [31], [32]
Perfume capsules, case 2	Additive Manufacturing (LPBF) + surface treatment (Coating)	The main problems with current metal additive manufacturing (MAM) processes are poor surface properties, accuracy, and porosity in metal parts. These problems become more critical when parts in industrial demand tight tolerances must be manufactured. A post-processing method of smoothing out the finished parts would be required as well.	[3], [35]
Improvement for a bicycle frame, case 4	Additive Manufacturing (LPBF) + adhesive	Adhesives, such as glue, allow fixing and assembling one component to another independently of the connection geometry.	[33], [34]

Heavy Fork, case 1: This case talks about the production time and surface finishing quality while discussing how changes in axial directions could be reduced. The first printing time required 44.5 hours for 7994 layers for initial prints in a vertical orientation. The second printing process in horizontal orientation took 20.5 hours for 1357 layers.

Initially, 0.5mm thickness of material is added from the CAD model; a CNC post-processing step will remove this material; the goal for this step is to get the surface quality that the customer requires. Time efficiency should be compared among various print orientations. When the process is completed, we can determine how perfect these were from the surface roughness resulting from finishing operations.

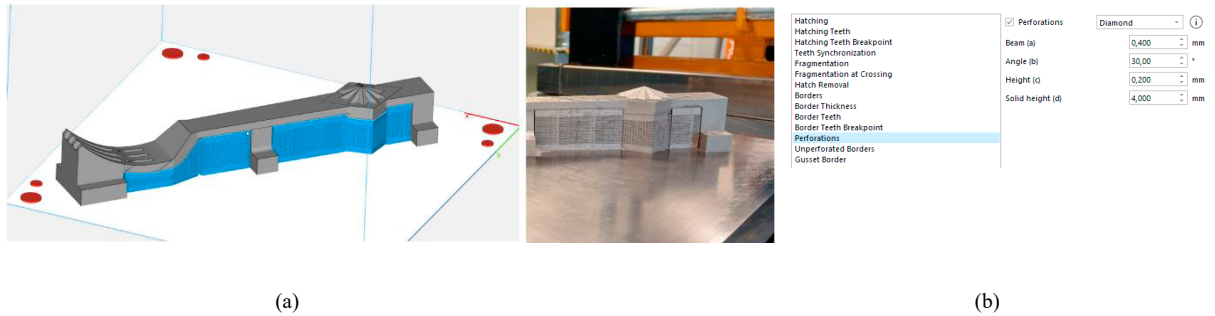


Fig. 5. The fork is 3D printed in 316L stainless steel with excess material, then CNC machined for better quality. Additional solid supports are included to facilitate fixture attachment for clamping it onto the CNC machine (a); support parameters (b)

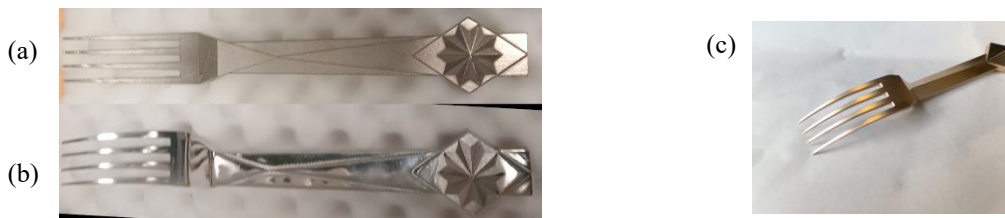


Fig. 6. After machining post-processing (a); the fork underwent electropolishing (b); final component machined in CNC (c)

Perfume capsules, case 2: The purpose of this project was to modify only the internal design while keeping the functionality of the components. The result was a reduction in the generation of support structures in critical areas for assembly, achieved by minimizing rough areas while maintaining functionality.

Table 6. PVD coating was applied to 4 components.

Component	PVD coating, cathodic arc process	
	Material	Thickness (microns)
I	Balinit A	2-3
II	Alcrona Pro	2-3
II	Durana	2-3
IV	Balinit Croma	3-8

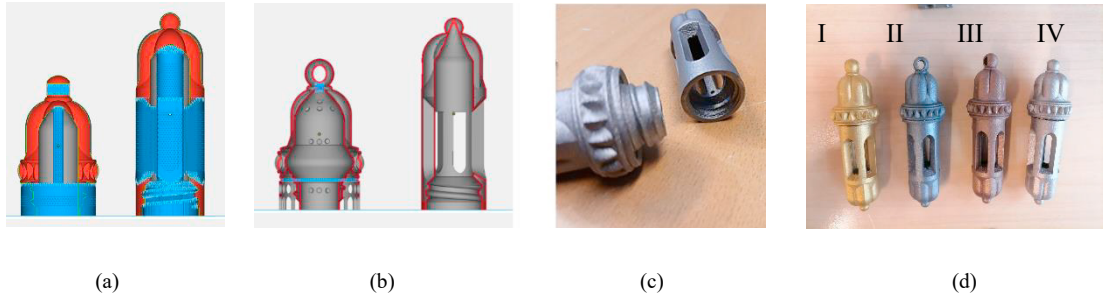


Fig. 7. Support generated in the original components prior to modification (a); support structures were generated to a minimal extent (b); printed components (c) and PVD coating (d).

Our components were PVD-coated, as shown in Figure 7d. Table 6 provides information on the PVD coating process applied. LPBF presents built-up stress caused by thermal differences between the base plate and the components. Figure 8 shows the thermal stress performance of parts and supports.

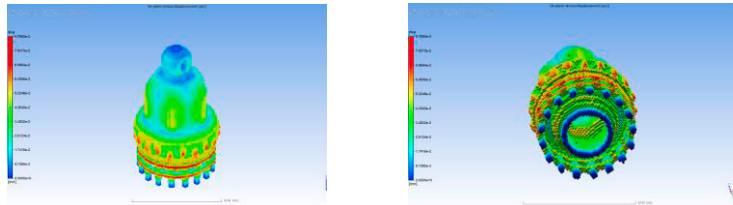


Fig. 8. Thermal stress and stress prediction.

Welding segment of tubes, case 3: The 316-L stainless steel seamless tubes and sections from 3D-printed tubes are used in this work. This experimental study is focused on the print parameters that influence quality welding properties—the performance we experienced after each of the tests, Non-destructive tests (Liquid Penetrant), and destructive tests (Hydro and tensile test). The project will improve both welding procedures and speed in hybrid manufacturing applications. Further coverage of these new changes will be in future articles.

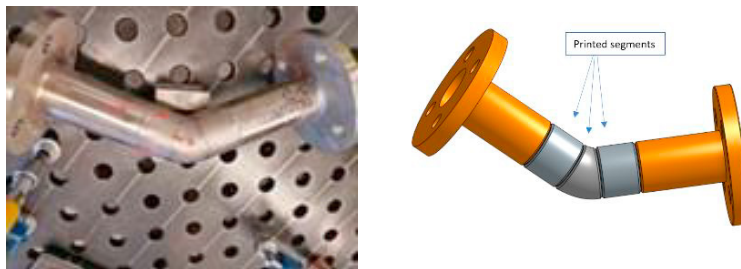


Fig. 9. Welding stainless steel seamless pipe pipes and 3D-printed pipes made from 316L stainless steel.

Assembly improvement for a bicycle frame, case 4: This case study focuses on using AM to design and optimize a complete road bike frame. We aim to solve the issue of bonding the 316L metal components with the carbon fiber

rods. We look forward to seeing this study led to a lighter and stronger frame. The bicycle frame comprises five printed parts and seven carbon fiber rods from Kevra, Finland.



Fig. 10. Components from the bicycle frame.
(Part 1) Seat tube; (Part 2) Head tube; (Part 3) Bottom Bracket Joint. (Part 4) Two stay unions.

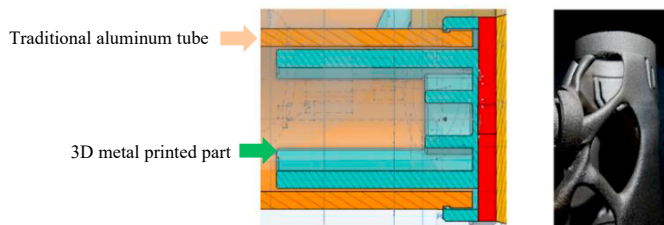


Fig. 11. Design of the interlocking in a Head-tube of a bicycle; the grooves are intended for assembly interlocking the aluminum tubing with the printed parts.

Rigid Interlocks

A rigid interlock is a connector or joint that results in multiple elements that restrict motion freedom. Once one part gets in the right place, it becomes difficult to disassemble. In the present work, we use these connectors to constrain rigid body motion without bonding agents or locks, such as glues, bolts, and nails [9–12]. A few of the chained structures to be discussed include:

- Interlocking mechanisms: Pieces are put together without the need to be screwed or glued together.
- Snap-Fit Connections-Parts snap together easily. It makes assembly easier and eliminates rotation.
- Threaded design printed joints: 3D Print threads directly onto parts, which can further simplify the assembly process.
- Press-Fits Connectors: Because of precision manufacturing, parts that stick one part design onto the other (no additional need for fastening).

The components of a frame were topology optimized, and embedding lattice structures were applied to reduce mass and weight. The interlock mechanism is in the design of the printed parts and the aluminium tubes; these needed to be machined. As a result, it is not necessary to use screws or bolts; only press fit by hand to assembly. The design or redesign can improve strength and make one-man assembly more convenient and efficient.

4. Conclusions

In the study regarding the 3D printing of a fork, case 1, the printing orientation and nesting can decrease production time and enhance surface quality. The results also emphasize the importance of optimal printing parameters (Scanning speed, laser power, support settings), demonstrating that surface finish and post-processing can be minimized while reducing efficiency.

In the case regarding perfume capsule, case 2, the modification to the internal design significantly reduced support structures; and less support structures improve surface quality in critical areas and reduce post processing time. The PVD-coated process also enhanced surface quality, which resulted in a better fit for the assemblies.

On the other hand, although traditional subtractive manufacturing offers a more significant variation of material choice, precision, and surface finish, other methods provide opportunities for complex geometries and even cost-effective, lightweight solutions such as additive methods. The need to produce components that can satisfy the customer with quality and efficiency is going to be met by hybrid manufacturing processes. The printing parameters (scanning speed, laser power) in case 3 were considered essential aspects that might affect the performance of the join between a segment of 316 stainless steel seamless tubes to 316L stainless steel printed tubes.

Topology optimization and lattice structure geometries are so complex that additive manufacturing has become the solution for their fabrication. However, in case 4, we have to optimize the assembling aspect. During the first couple of iterations, we assembled carbon fibre rods and metal-printed components using adhesives. Then, we revised the components for weight reduction. The interlocks used in the second version of the bicycle frame assembly have enabled these parts to be assembled onto the aluminium tubes without bolts, screws, or adhesives. We modified the aluminium tubes using CNC. The aim is to make the bike assembly easy for customers to carry without needing extra equipment.

All four cases indicate that efficiency and performance improvements can be achieved for the product by combining different manufacturing techniques. However, there is still a long way to go before we make the additive manufacture and hybrid processes ideal for manufacturing.

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