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TOOL PATH GENERATION FOR HYBRID ADDITIVE MANUFACTURING

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Abstract

This paper presents a new approach to tool path generation for a hybrid additive-subtractive manufacturing apparatus. The goal is the development of an integrated hybrid process, based on additive and subtractive manufacturing, to produce complex geometries with continuous fiber reinforced thermoplastics.

The authors propose a novel system that can handle two heads: a filament deposition head and a milling head. The system allows for additive, subtractive, additive followed by subtractive and additive and subtractive at each layer.

Due to the use of continuous fiber reinforced thermoplastics the tool path trajectories will be different depending on part geometry to accrue mechanical properties. To evaluate the proposed strategies, one example with different features is provided on how to take an *.stl* file with a final geometry and generate the necessary adjustments to enable the subtractive process.

Introduction

As direct part fabrication is a major driver in the additive manufacturing (AM) industry, the requirements for this type of parts are more restrictive. Two of the major issues are the volumetric errors and the known staircase effect [1]. Also, the use of different technology families will render different errors and, in some cases, even for the same family the vast number of materials carries diversity to the process. This paper considers the 3D printing and surface finishing via milling of continuous fiber reinforced thermoplastics.

Nassehi et al. (2011) [2] proposes a classification of manufacturing technologies by separating them into five categories, namely joining, dividing, subtractive, additive and transformative. Subtractive technologies imply material removal from a work piece resulting in a new one. In additive technologies material is added where the mass and volume of the finished work piece is greater than the previous layer [2,3]. Considering the lack of consensus on the definition of a hybrid manufacturing process, the scope of this document it encompasses two types of processes, the subtractive, understood by researchers and well established in the manufacturing industry, and a relatively new in research fields and commercial endeavors, the additive. Researchers converge on the possible gains of studying a hybrid manufacturing process. The objectives can be the improvement of surface integrity, reducing tool wear, reducing production time and cost and extending application areas [2–11]. It is expected that such a new approach to manufacturing will influence design for manufacturing (DFM) strategies.

It is recognized that hybrid manufacturing is a vague term, the International Academy for Production Engineering (CIRP) suggests an open definition for a better common understanding. A hybrid manufacturing process combines two or more established processes into a new combined set-up where processing principles are executed in the same processing zone whereby the advantages of each discrete process can be exploited synergistically [10]

Hybrid processes conceptualization aims to enhance production capabilities while minimizing their weaknesses. In computer numerical control (CNC) machining, difficulties may come from complex shapes and tool accessibility. In a layer based additive process there is a certain compromise between time and surface quality [3,6]. The combination of the two enhances manufacturing flexibility providing high accuracy and machining speed while allowing the part complexity and design freedom that was unveiled by the additive process, but also create new problems that need to be addressed.

The operations are performed using the additive process to build a near-net shape which will be machined to its final geometry, the machining procedure is implemented to ensure accuracy, eliminate staircase effects while allowing manufacturing flexibility with no detrimental effect on surface finish [3,4,6]. Therefore, the resulting surface quality depends mostly on the subtractive process.

The process planning to integrate multiple manufacturing processes presents a key issue. Due to the design process, different surfaces of a final component may need different surface finishing, and therefore, only selected surface should be machined. To allow this, the software responsible for making the link between a stereolithography (STL) file and the necessary G-code file that carries tool paths instructions must have this information. A study carried out on a hybrid SLS milling process indicated positive results on surface finishing and process control when the subtractive process was actuated every 10 layers of 40 microns each, i. e., every 0.4 mm. The study also states that the time interval to suppress tool wear needs further investigation [9].

One possible solution pointed out in the literature could be to conceive parts, considering a DFM methodology application, with modular and hybrid points of view in which parts are 3-D puzzles with modules realized separately and further assembled. This allows each module to have an appointed manufacturing process and to be produced simultaneously and independently [5]. This conception would rely on a design for hybrid manufacturing (DfHM) strategy, which would mean that parts with a defined geometry would have a redesign necessity. To avoid DfHM, the tool paths generated for the additive process should account for the extra volume of material needed for the near net part to be produced. Since one usual problem in 3D printing is the fixing of the part to the deposition table, sacrificial fixtures are added so that the subtractive process can be executed without compromising final part geometry [7],.

Process planning comprehends the identification of a sequence of operations that will lead to the manufacturing of the desired part. These can be broken down into sequences of adding material, adding support material, rough subtractive operations and finishing subtractive operations. The process of adding material and sequentially subtracting it can in theory be, ad infinitum. This notion would dramatically increase the complexity of the hybrid manufacturing process and lead to great increases in production time [8].

Another developed methodology for the process planning divides it into two steps. The first step extracts information from a Computer Aided Design (CAD) file defining machining and additive features as well as the relation between them and gathers it with the technological requirements and the available resources. Based on the gathered information, in the second step, a number of heuristic manufacturing rules is defined and applied for sequencing the operations taking into account precedence constraints and tool accessibility constraints [11].

A review of the literature shows that there is a major need to establish relationships between hybrid processes and their respective control systems. Even so, there are already some commercially available machine tools with hybrid manufacturing process capabilities, that are accompanied by dedicated software. The availability and complexity of these solutions can be considerably variable and is not satisfactory [8].

Process planning methods

The approach proposed in this paper follows the research trend behind the ideas of additive systems integrated with subtractive methods (AIMS), that relies on adding a direct digital subtractive process to the additive production process. We argue that this experimental rig is not universal in the sense that all the parts will be produced by means of the hybrid system, but there are parts where both systems are needed, especially when some special features are needed, for example, the surface roughness, and where setup times are important. Some of the features presented here would also be capable to producing parts first with additive setup and then passing the near net shape part to an independent machining center, but at the expense of an extra setup time and cost.

The use of a hybrid system can then reduce this setup time and corresponding cost. This is more important when additive manufacturing parts are usually customized. This means that the setup time of machining is reduced in a hybrid system.

The point of using the FDM process is that carbon or glass reinforced thermoplastics can produce reinforced parts that can be an alternative to some metals, typically non-ferrous alloys, such as aluminum or magnesium. These materials if processed by casting are then re-processed in milling centers to get the desired roughness, dimensional and geometric tolerances. For the parts produced with reinforced thermoplastics the effect of the layered manufacturing, the staircase effect and the roughness are not competitive unless a finishing operation is also done as in the case of aluminum or another non-ferrous alloy. Figure 1 exhibits the normal finishing of a layered fused deposition modelling (FDM) with 0.1 and 0.2 mm layered height and demonstrate the need for surface finishing if necessary.

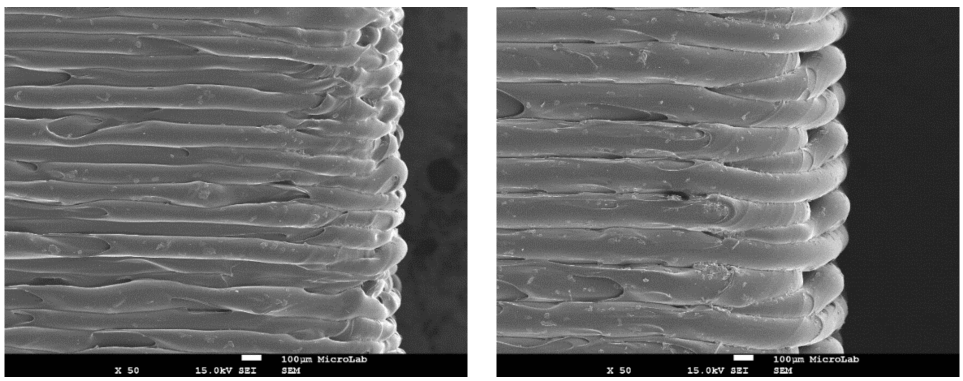

Figure 1 – SEM micrographs of 0.1 (left) and 0.2 (right) mm layer deposition using FDM.

The hybrid combined process requires some implications in the additive preparation of the part. Two different methods are considered and presented in Figure 2. The first one, in red deposition, shows an entire extra wall over the final dimension. The expected milling process should remove this entire extra wall and reveals the next one with the correct final dimension. This method has the worst roughness finishing as the different layers should be noticeable again. The second method, in green, shows a wall offset always inferior to 50% of a wall size, to prevent the action of ripping on wall from the other instead of cutting it. After the milling process, this should be the method that shows the better results, avoiding the space between the walls, improving significantly the roughness of the final product.

Process planning for a hybrid system with additive FDM and subtractive finishing with reinforced thermoplastics is much more complex than the one for just additive. Figure 3 shows the generic process planning and the adaptations or constraints that the hybrid system imposes. The generic process planning starts with receiving a part in a CAD format, then determining the part orientation followed by slicing the file in layers and determining support structures. In the end tool paths are generated for contours, infill and non-deposition paths.

This generic process planning is constrained with the introduction of reinforcement fibers and the subtractive system. The subtractive process constrains part orientation since the parts that are machined during the additive process must the available to the finishing tool. On the other hand, the introduction of reinforcements at certain layers to increase part strength also pose a strong constraint on the part positioning. The position of the part for the additive system impacts the time to build and the need for support material. After the part is positioned and sliced, support structures are placed, and all the sacrificial and excess material must be created. There are also constraints on the minimum radius a composite fiber can bend and that constraints the capacity to reinforce small areas of the part. In the end, the process planning delivers tool paths that generate sacrificial and excess material for subtractive, the contours and infill for the additive and the tool paths for the regions of the layers where fiber should be placed.

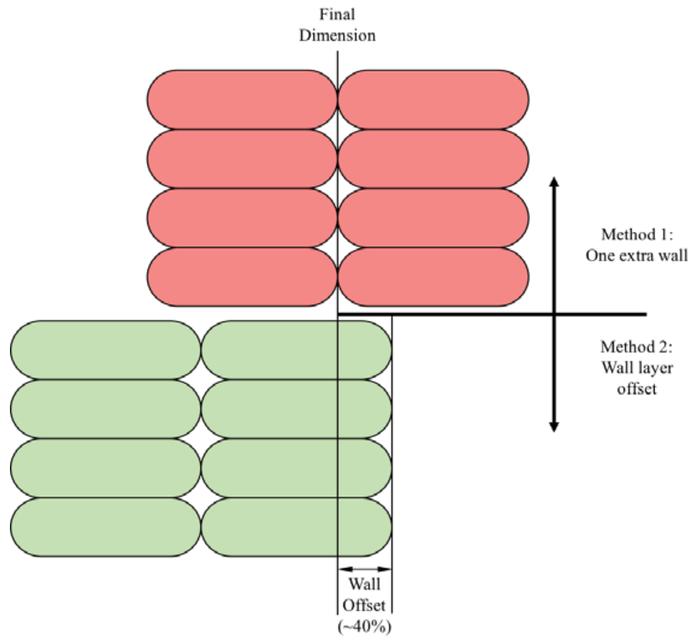

Figure 2 – Two possible methods for machining excess material

From Figure 3 a conclusion arises: the generic process is much more complex and the trade-offs between the different processes will result in much more constrained parts, meaning that the use of this hybrid system is not for all parts, but only for parts that have strong requirements on strength and surface roughness.

The slicing software generates the necessary G-code for the FDM process. The user must provide the information regarding the layers in which the subtractive tool should actuate. A key aspect of the procedure is identifying the outer and inner contours on any given layer. At this point, a given number of extra contours is added in each layer resulting in a new tool path for the additive head.

Experimental Rig

The setup of the apparatus consists of a XYZ cartesian conception in which two tool heads are present. These heads can move independently along a common X-Y plane. The additive process used is fused deposition modelling (FDM) in which layers are parallel to the mentioned plane. The first layer is deposited in a heated bed that allows for a correct fixing of the part and that can move along the Z axis while either of the processes is occurring (see Figure 4).

In the scope of this paper both processes never happen simultaneously. Once the composition of a part achieves a user specified layer, the additive tool head will pause its process and the subtractive tool will then machine the intended surface. The purpose of this experimental apparatus is to create parts using additive manufacturing with continuous fiber reinforced polymer and to be able to increase the surface quality in certain predefined surfaces.

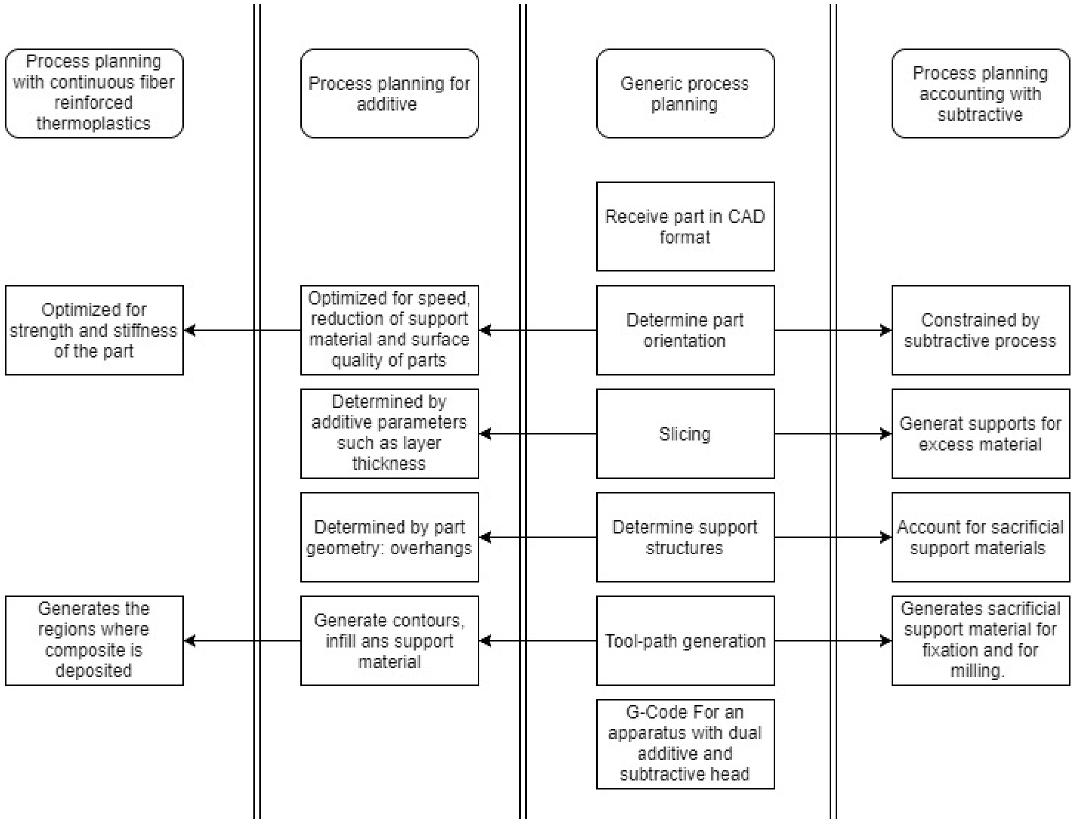

Figure 3 – Generic process planning and different adaptations for additive, subtractive and reinforced additive.

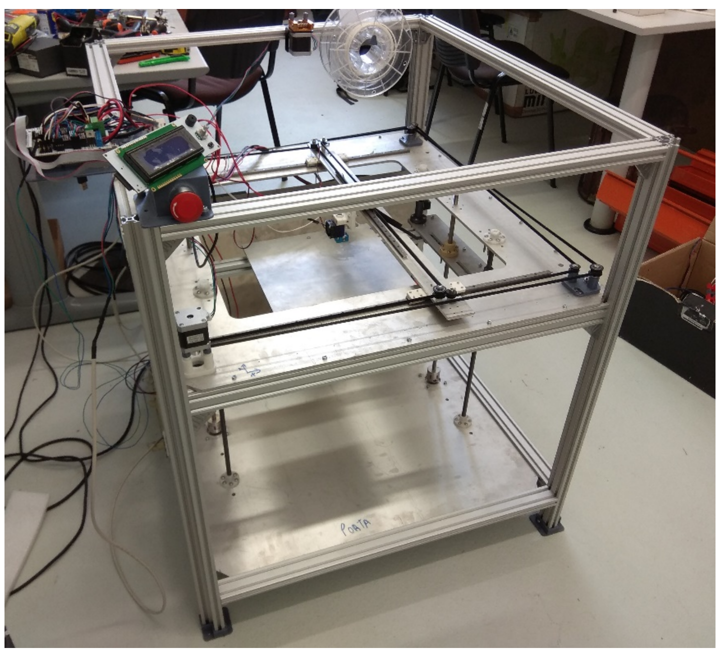

Figure 4 – Experimental rig for hybrid additive and subtractive processes

The additive process creates virtually no scrap material and load solicitation to the part behind produced. On the other hand, the subtractive process implies the existence of cutting forces that oblige the apparatus to have part fixing capabilities that exceed the techniques commonly used on FDM processes. This can be done with several techniques such as vacuum or the use of sacrificial material.

The system allows for just additive, just subtractive, first additive followed by subtractive and finally additive and subtractive intercalated along the hybrid process. To avoid the possibility of deposition material on top of scrap material left by the subtractive process, the setup must remove the machining process leftovers. This is possible by two aspiration systems, one that follows the subtractive tool head and a static one that imposes a constant air flow in the manufacturing chamber. To avoid defects on final parts from temperature cycles, the airflow entering the manufacturing chamber is heated and mixed until this chamber is at an acceptable steady temperature.

Example

In this section an example of a part that would need the introduction of continuous fibers in some layers and a subtractive process is presented. Figure 5 shows a front view of the desired part on the left and the same part with added material for the subtractive operation and support material necessary to make an overhang, on the right.

In Figure 6, a half-section of the desired part is presented. Item number 2 represented the net shape of the part to be produced. Item number 3 is a possible geometry for the support structures needed and item number1 is the base sacrificial material in which the deposition is built on. This base material can be understood as a structure to raise the part and has the function of allowing the possibility of machining surface A, without it, the subtractive tool could collide with the build plate. Another possible function for structure 1 is fixing of the part to the build plate preventing its dislocation during subtractive tasks.

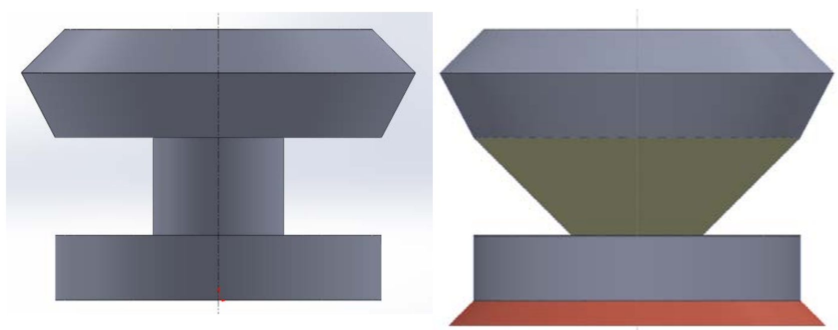

Figure 5 – Front view of the finished part example (left) and part with supports and sacrificial material (right).

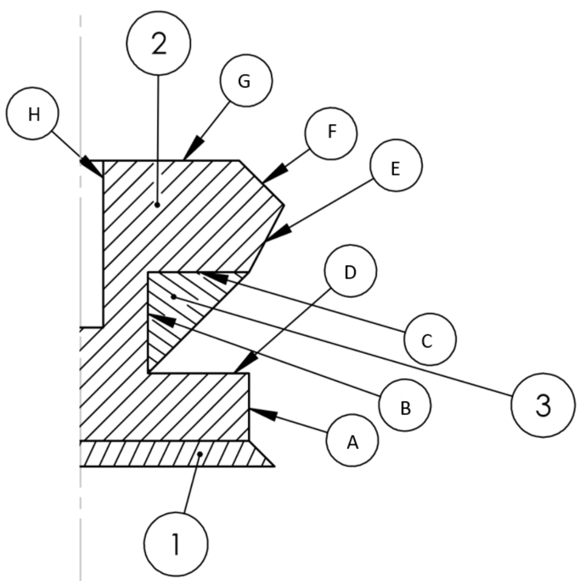

Figure 6 – Half-section of the example part with surfaces that need to be finished.

The possibility of machining specific surfaces during the print and after the print is, of course, subjected to normal machining restrictions of tool geometry, dimension and availability. Considering so, a hybrid approach applicability could perform the subtractive process in the manufacturing steps described in Table 1. Note that support material (item 1) must always be removed after the print and all the machining is complete.

From Table 1 there are some surfaces that can be machined when the user wants, some are possible during print and other are possible after the additive manufacturing printing is done. For example, Surface D can be machined after the deposition of the last layer that defines it or once the additive process is finished. The existing C surface imposes a need for support structures, therefore the machining process of surface D should not be executed once the deposition of support material starts.

Surface B can be machined after the additive process is finished, which would mean the destruction of the support structures. If the support structures (3) would be constructed in a way that they wouldn't need to be connected to surface B (as shown in Figure 7), the additive and subtractive processes could be intercalated. Even so, this approach could possibly not affect the surface rugosity since the staircase effect could still be present.

Table 1 – Machining strategies possible

Surface	Machining when?		
	Anytime	During print	After print is complete
A	yes	yes	yes
B	no	yes	yes
C	no	no	yes
D	no	yes	yes
E	yes	yes	yes
F	yes	yes	yes
G	yes	yes	yes
H	yes	yes	yes

If support structures are as shown in Figure 7, the machining of surface D should only be performed after the last layer that defines it if the support structures are composed of soluble (or equivalent) material, otherwise the rugosity of this surface will depend on the process of removing the supports and not on the machining parameters as intended.

This theoretical example aims to demonstrate that the sequence of additive and subtractive tasks is highly dependent on part geometry adding complexity to the process planning. Machinability could be performed in the future as the need for support structures is performed presently. Even if software can anticipate its need, predict its applicability and propose a solution there is probably a different possibility for the process execution.

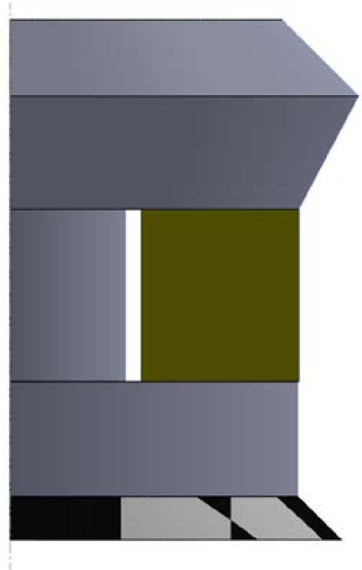

Figure 7 – Half-section with different support structure strategy

Discussion and conclusion

The lack of metrics to quantify sacrificial fixtures shortens the prospects and future of a hybrid additive-subtractive process. Metrics need to be developed regarding parameters as process time, material usage, accuracy of features, tool head dimensions. The accurate decision behind the timeframe of actuation of the subtractive process is also key to the success of a hybrid manufacturing path. A well-defined sequence of operation will depend deeply on machine configurations and part geometry. This can mean that a totally automated hybrid process is for now far from reality.

Therefore, a future optimization of the process regarding the amount of excess material needed to be added for machining purposes and closer look at the milling process of layer should be conducted. One obvious advantage foreseen with the use of an apparatus such as the one proposed in this work is the reduction of setup times and costs in comparison with independent additive and subtractive systems, along with the reduction of accumulated errors emerging from the reduction of setups needed. Combined, these factors are of the most importance for the industry and will, ultimately, impose the thrust for further investigation.

ACKNOWLEDGMENTS

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