Chapter

Advanced Manufacturing Using Linked Processes: Hybrid Manufacturing

Katie Basinger, Caroline Webster, Carter Keough,
Richard Wysk and Ola Harrysson

Abstract

Hybrid Manufacturing Processes (HMP) can significantly reduce time to customer, waste, and tooling costs per part, while increasing possible part geometric complexity for small batch parts. In the following chapter, HMP is defined by the production of parts produced first with a near-net shape process using methods including: additive manufacturing, casting, injection molding, etc., which is then coupled with multi-axis computer numerical control (CNC) subtractive machining or some other secondary material removal process. Creating process plans for such hybrid manufacturing processes typically takes weeks rather than hours or days. This chapter outlines several hybrid manufacturing processes and the intricacies required to develop process plans for these complex linked processes. A feature-based advanced hybrid manufacturing process planning system (FAH-PS) uses feature-specific geometric, tolerance, and material data inputs to generate automated process plans based on user-specified feature precedence for additive-subtractive hybrid manufacturing. Plans generated by FAH-PS can optimize process plans to minimize tool changes, orientation changes, etc., to improve process times. A case study of additive-subtractive methods for a patient-specific bone plate, demonstrates system capabilities and processing time reductions as compared to the current manual process planning for hybrid manufacturing methodologies. Using the generated FAH-PS process plan resulted in a 35% reduction in machining time from the current hybrid manufacturing strategy.

Keywords: hybrid manufacturing process (HMP), process planning, subtractive manufacturing, additive manufacturing

1. Introduction

Additive manufacturing (AM) can significantly reduce the development time for small batch parts or parts with complicated geometries, especially for polymer components [1]. Today, many polymer components are produced on a single AM machine, where the parts are manufactured directly to meet engineering requirements (e.g. geometric dimensions and mechanical properties). Producing a product on a single production resource yields significant benefits such as reducing material handling and in-process control. However, the most significant benefit associated with producing a product on a single production resource could be the reduction in process engineering time. For many of these polymer components, the mechanical properties come directly from the combination of the polymer material and the processing parameters. The geometric shape and dimensions comes from a combination of the computer-aided design (CAD) model developed during Product Engineering and the dimensional capabilities of the AM machine used.

Unfortunately, polymers have a limited use for only certain products. As better mechanical properties and finer geometric tolerances are required, the use of metals becomes necessary. Although metal AM has been around for two decades, the geometric accuracy of metal AM frequently falls short of the engineering specifications and the mechanical properties of AM produced metal parts are often highly dependent on the surface conditions. The result of these specifics is that metal AM production typically requires multiple post-production processes and machines. Metal AM machines have typically been used to create "near net-shape" components that require additional processes to enhance both the tolerances and surfaces as well as the mechanical properties of the AM printed component. This has slowed the adoption of metal AM for many high-performance components, especially those requiring certification.

To increase the performance of engineered parts with complex geometries which use processes such as metal AM, Hybrid Manufacturing Processes (HMP) are used which incorporate a secondary post process. HMP can significantly reduce time to customer, waste, and tooling costs per part while increasing possible part geometries and material availability for small batch parts. Examples of hybrid manufacturing for this chapter include Casting-Subtractive, Injection-Molding-Subtractive, and Additive-Subtractive processes. HMP usually have accurate results but require extra layers of complexity including process plan development.

This chapter outlines several hybrid manufacturing processes and the intricacies required to design parts and develop process plans for the complex processes. Although HMP is largely comprised of an additive process followed by a subtractive process, two other manufacturing methods are discussed since they have similar complexities in the process planning phase. Finally, a feature-based advanced hybrid manufacturing process planning system (FAH-PS) is discussed. This framework uses feature-specific geometric, tolerance, and material data input to generate automated process plans based on user-specified feature precedence for additive-subtractive hybrid manufacturing, a hybrid manufacturing process. Plans generated by FAH-PS can optimize process plans to minimize tool changes, orientation changes, etc., to improve process times. A case study of a patient-specific bone plate is described at the end of the chapter for proof of concept of the framework. Imploring a strategy of minimizing tool and orientation changes generated a process plan that demonstrated automation of an optimized process plan.

2. Hybrid manufacturing processes (HMP)

2.1 Casting - subtractive

While the modern definition of HMP focuses on the collection of production processes integrated together using computer-assisted systems engineering tools, the first instances of 'hybrid manufacturing' were originally much more sequential in nature. From literature, some of the first reported instances of using a sequential 'hybrid' approach were found in the finish machining of cast components (a.k.a. castings) [2, 3]. When combined together, casting and subsequent machining provides numerous advantages including: reduced material waste, tighter achievable tolerancing, and increased overall geometric complexity. This is because this unique combination takes advantage of the capabilities of both processes. However, the material properties can be sacrificed compared to just machining.

Since the material flows into a mold cavity, casting enables the production of complex internal and external geometries that are net- or near-net shape. Parts fabricated using casting are often limited in other ways. For example, the surface roughness of castings is directly correlated to the roughness of the mold cavity walls, which in the case of sand casting is the roughness of the sand. Additionally, consideration must be given to process inherent defects that affect the mechanical performance and geometrical and dimensional accuracy of the casting such as shrinkage cavities, inclusions of air or foreign matter due to turbulence from pouring, etc. Machining can allow users to manufacture parts with increased accuracies as compared to casting alone. For example, parts often exhibit better flatness and smaller radiused corners when machined. Machining using computer numerical control (CNC), means that the process is highly repeatable and easily scalable due to the incorporation of computer-guided automation. While the accuracy is better for machined components, there is a sharp reduction of the geometric complexity possible, particularly with internal features, when compared to cast parts. This is because machining is limited to a straight line of sight from the cutting tool, which limits the features that are accessible for finishing. Additionally, unless combined with another process, machining is associated with larger amounts of material waste from transforming rectangular or cylindrical billets into final geometries.

Combined, these two processes can produce parts that are better able to meet the final part specifications in an economical way as outlined by the advantages mentioned previously. In this category of HMP, there are special considerations that must be given to the incorporation of machining after casting. For example, engineers should decide if small holes in the casting should be filled (i.e. not produced in the casting) to ensure drills would be able to accurately finish holes without tool walking. Another possible consideration is the method for fixturing cast parts to a milling machine, since each individual castings' defects (flash, shrinkage, pores, etc.) could impact this. Additional factors and where they should be addressed in the casting-subtractive category of HMP are outlined in **Figure 1**.

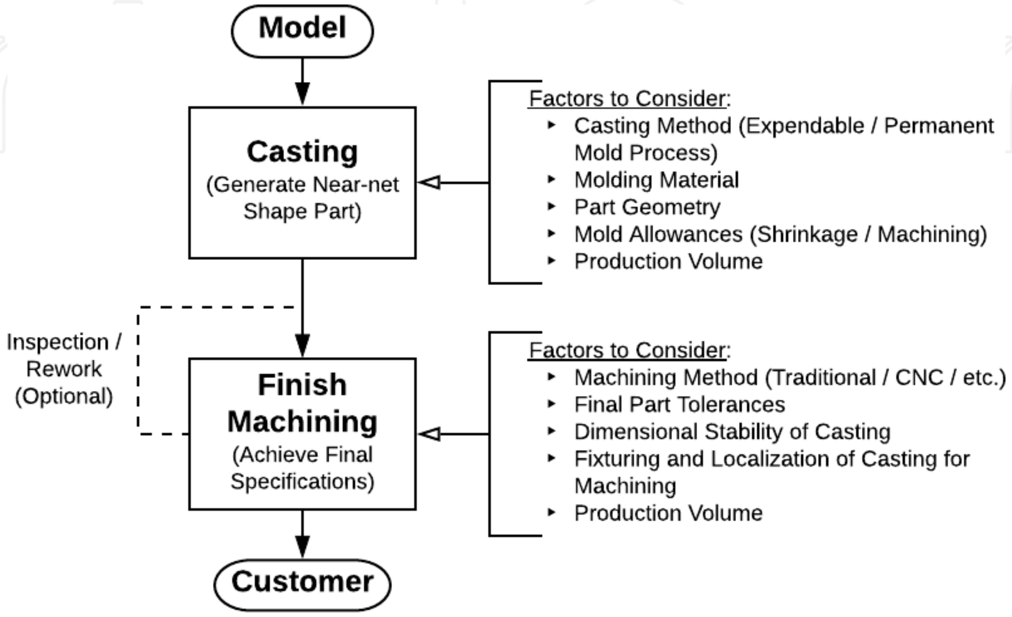


Figure 1.
Process flow of casting-subtractive category of HMP.

2.2 Injection molding - subtractive

Injection molding is most commonly used to create small to large sized polymer, and in some cases metal, parts in large batches. The parts themselves are typically ready to use, once injection parameters have been optimized to reduce; voids, shrinkage, warping, short shots, burn marks, and flash. However, the most complex, expensive, and time-consuming part of the injection molding process lies in manufacturing the mold itself. There are many methods used to fabricate injection molds, including traditional machining, casting, and additive manufacturing methods. It is imperative for injection molds to maintain extremely tight tolerances and be manufactured of materials which can withstand the repeated pressures and temperature cycles from the injection molding process of large batch size parts. Traditionally machined molds satisfy these requirements but because machining is a line-of-sight finishing method there is often an inability for intricate or complex cooling geometries within the mold. Therefore, a more modern approach is to use additively manufactured molds with complex cooling features for large batches of parts. This approach is best suited for production of smaller batch sizes where lengthy mold manufacturing times are not cost effective on a per part basis. Both of these methods require post processing, usually machining, to achieve tolerance and surface finish requirements of an injection mold.

Although injection molds are typically made from metal, molds can be created from other materials such as UV cured polymer manufactured via vat photopolymerization processes or material jetting processes. These parts will need the appropriate post curing time and conditions. This recipe of post curing will directly affect the life of the mold and the accuracy of the parts [4].

Injection molding typically requires several large investments in machinery. Specifically, the process of creating the mold, although this is typically outsourced, have their own mold fabrication shop to cut down on costs. These fabrication shops require several milling and turning machines, tools to assist in fixturing and precise measuring, as well as experienced and competent operators to design and maintain the molds. Also required for injection molding is the injection molding machine itself. Injection molding machines are typically very large, even for small parts.

Although injection molding is a complex process, this chapter will focus on the methods for process planning of hybrid manufactured molds. **Figure 2** depicts the flow in which injection molded parts are developed. Note the important considerations for process planning are related to the mold design and fabrication steps.

2.3 Additive - subtractive

With growing popularity and improving resultant parts, AM is driving renewed development in process planning and optimization for hybrid manufacturing processes. Additive manufacturing is classified by the layerwise addition of material to create a near-net-shape or final part. A variety of additive manufacturing processes exist that can manufacture polymers, ceramics, or metals with varying precision. Initially, AM was considered a prototyping technology that enabled accelerating design changes due to the relatively quick turnaround from CAD model to final part. Advances in additive manufacturing and design methods have facilitated growth in the area and additive manufacturing is now being adopted as a production manufacturing technology in aerospace, medical device, and automotive manufacturing among others.

Additive manufacturing allows for components that have highly complex designs or are made from materials that are difficult to process using other methods. This often allows for the reduction in the number of components, weight reduction, or the addition of features that cannot be manufactured using any other method. However, when compared to subtractive CNC finishing the achievable tolerances of an as-built AM component are much lower [5]. These tolerances may not be acceptable and require further finishing; however, the complex designs possible with additive manufacturing can pose challenges for subtractive CNC finishing, which requires the tool to have line of sight to the region that it is finishing [6]. Design considerations for Additive - Subtractive HMP include location of

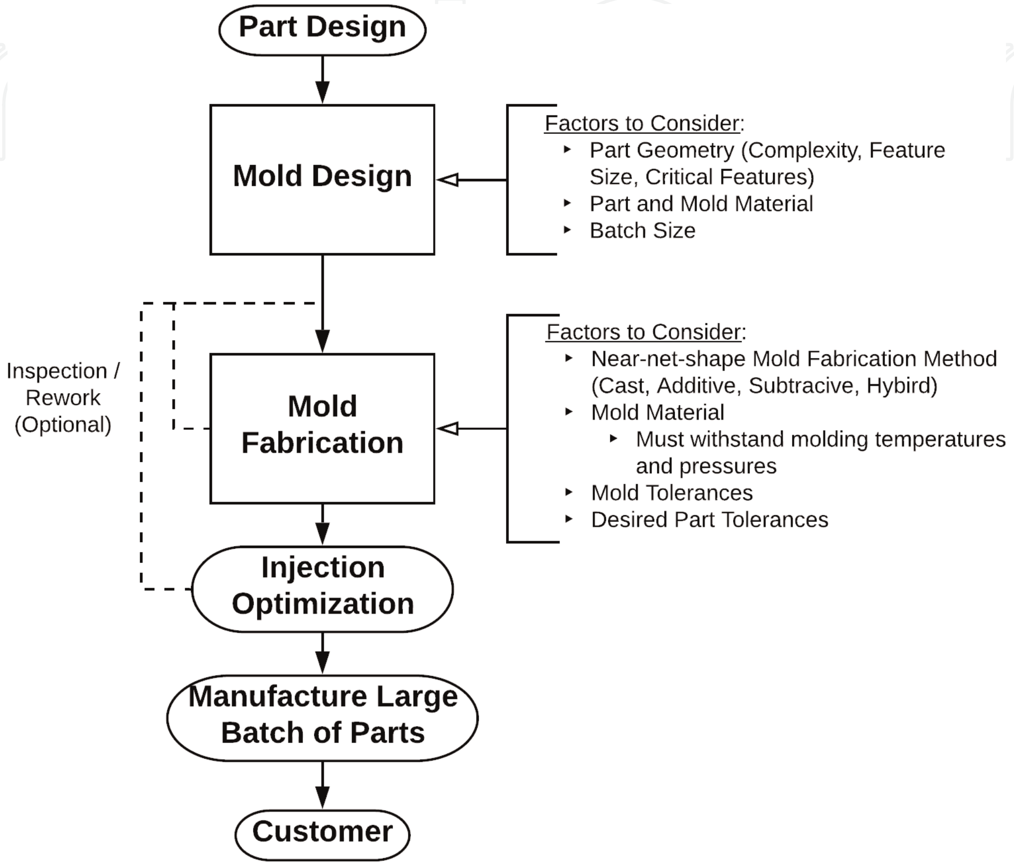


Figure 2.
Process flow for creating injection molded parts for large batch scenarios.

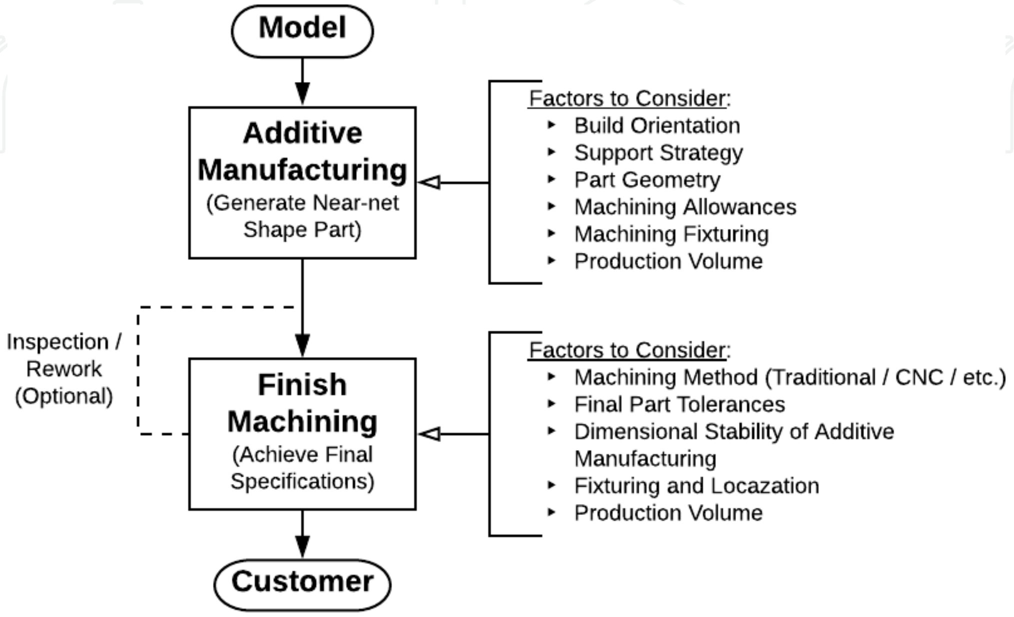


Figure 3.
Additive-subtractive HMP.

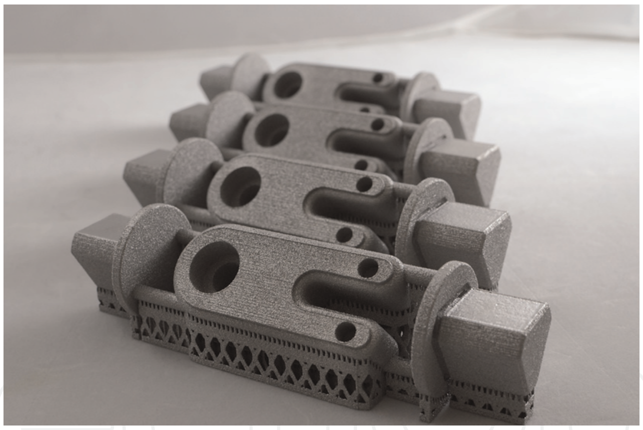


Figure 4.
Sample part which could replace multiple components and become part of an assembly after finishing (reproduced from [8]).

machining fixturing, part location in the machine due to variability in the AM processes, support structure removal, required tolerances, and required surface finish. Although there are additional considerations that must be made to accommodate the use of additive manufacturing in hybrid processes, the buy-to-fly ratio and costs can be lower than machining alone due to the material waste associated with subtractive only manufacturing [7]. **Figure 3** shows the flow chart and key considerations for additive-subtractive HMP processes.

The component shown in **Figure 4** is an excellent example of an additive manufacturing component that could be used in a functional assembly. However, the tolerances of the functional surfaces would not meet the requirements as is and would need to be finished before assembly.

3. Process planning for HMP

3.1 Process planning

Process engineering or process planning is the activity that determines how a product will be produced. That is, process engineering determines which manufacturing methods will be used in order to transform a product from one state (typically a part number) into another more valuable state (again, typically a new part number). In other words, it is the selection of the manufacturing method(s) to be used to convert a raw (or semi-finished) material into a final part requirement.

It is desirable to perform all processes at a single manufacturing station because material handling is eliminated (a non-value added process), but the use of multiple resources requires the scheduling/coordination of these resources. Unfortunately, most high-performance mechanical components are produced on a number of manufacturing resources, such as: casting processes, machining processes, heat treating processes, grinding, and other high-finishing processes. Determining which of these processes will be used, along with specifying what tooling and operating parameters will be executed, is the function of process planning. Process planning may also include defining what intermediate geometries, tolerances and material allowances are required between these processing steps. Process planning is a critical part of the engineering process because it determines the primary manufacturing cost for a product.

To illustrate this, we will use an engine block as an example. See **Figure 5**. Engine blocks are normally cast from gray iron. In order to plan a part like this

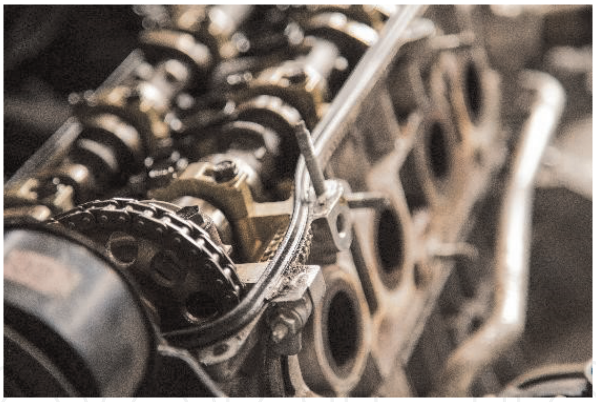


Figure 5.
Engine block with some assembled components. (reproduced from [9]. Photo by Garett Mizunaka on Unsplashed).

using traditional casting, machining, and then finishing, the process engineer would first determine how much additional material would be necessary to use in the near net-shape casting. Once this is done, the process engineer would create a "new pattern" that would be used in the green sand casting process. This pattern would allow for enough material of the critical features (faces and cylinders) for subsequent steps; this is the machining allowance. Next, the machining processes would be planned, where drilling, boring and milling operations would typically be used to create the next step in the production. Finally, finishing operations of the highly toleranced surfaces would be conducted. Planning each of these activities requires experience and a detailed understanding of the precision of each process. Tolerance stacks must be identified and used to properly sequence the operations that will be used.

The planning of each of these processes can be both time consuming and expensive. For each of the three production activities illustrated in this example (casting, machining and finishing), these activities represent "fixed costs" associated with each of these activities. Planning time for each of these activities would typically be on the order of 3–10 days depending on the complexity, tolerances and experience with similar products. For very small quantities of parts, process engineering can be the dominant cost component.

The final cost of any manufactured component will be the sum of the costs at each step of the production plus the materials, holding and overhead costs. At each step, the production cost must be determined. In general, we can define the cost of a product as:

$$\text{Product Cost} = (\text{One} - \text{time Costs}) + (\text{Batch Setup Cost}) + (\text{Processing Cost}) \tag{1}$$

In order to put cost as a function of volume, we can express this as cost per part or:

$$\begin{aligned}\text{Product Cost/Part} = {} & (\text{One} - \text{time Costs})/(\text{Total Parts Produced}) \\ & + (\text{Batch Set} - \text{up Cost})/(\text{Batch Size}) + (\text{Processing Cost})\end{aligned} \tag{2}$$

Or in terms of variables:

$$C_p = \frac{C_{1-time}}{n_t} + \frac{C_{mo} t_{set-up}}{n_b} + \frac{C_{mo}}{t_p} \tag{3}$$

Where C_{1-time}, Total one-time costs; n_t, Total parts produced; C_{mo}, Cost of the machine resource and operator per unit time; t_{set-up}, Time required to set-up for a new batch; n_b, Parts per batch; t_p, Total time to process a part.

One can quickly see that to determine the production cost to plan a new product is a complex activity at each step. To make this even more difficult, the geometries and allowances at intermediate steps are also planned, and these specifics affect all downstream costs. This makes this a difficult engineering problem.

Multiple processes have been used to successfully produce mechanical parts for decades. The difference between traditional serial process planning and hybrid process planning and manufacturing is illustrated in **Figure 6**. This figure shows that in order to plan for hybrid processing, the process engineer must examine the effect of decisions made at each stage of manufacturing in order to develop the most efficient combination of processes and intermediate components.

3.2 Process planning for HMP

Process planning for hybrid manufacturing processes, is similar to that for single manufacturing method processes. Many of the key considerations are the same and include: how to minimize machining time, how to maximize tool life, how to minimize the number of tool changes, and how to minimize the number of times a part must be setup in a machine or machines. However, hybrid manufacturing processes require careful planning in design and development phases to ensure that parts and tooling are optimized for the full manufacturing flow that spans multiple manufacturing technologies.

3.2.1 Process planning for casting-subtractive

As mentioned previously, hybrid process planning is used to define how a product will be most efficiently produced by accounting for the effects of each manufacturing stage. While computer-aided process planning (CAPP) systems can be grouped into various subcategories of variants or generative approaches, such as feature-based technologies, knowledge-based systems, Petri nets (PN), agent-based technologies, internet-based technologies, neural networks, genetic algorithms (GA), or fuzzy set theory/logic, more recent interest has been shown in the development of feature-based planning approaches. Feature-based approaches are favored in many instances because large varieties of parts can be represented by individual features. Features used for plan generation are either specified manually

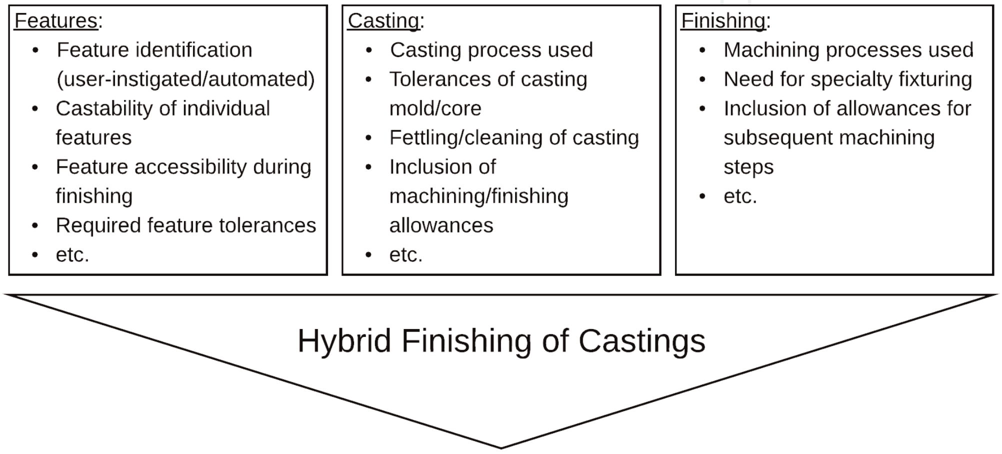


Figure 6.
Considerations for casting-subtractive HMP process planning.

or are recognized automatically using a series of rules, topology maps, or the decomposition of volumes within the part [10, 11].

For instances of hybrid finishing of castings, where the near-net-shape component is produced using casting and later finished with machining, several factors must be taken into account during the planning stages. The numerous factors to be considered can be grouped into three categories which include those regarding: (1) which features need to be finished, (2) how cast parts are prepared for finishing, and (3) how the cast parts are finished. A general list of factors are shown in **Figure 6**.

Several scholars have attempted to address these areas primarily focusing on how to identify features for finishing stages and plan for the casting stage [12, 13]. Some have also assessed the economic costs of finishing castings, which were briefly mentioned in previous sections [14]. Few scholars however, actually attempted to address the full complexity of the entire hybrid process [15]. Kim and Wang addressed this through an algorithm that has stages for feature recognition, casting allowance recognition, and machining volume selection [15]. From the author's understanding, a complete planning system is still required to span from feature identification in a computer-aided design (CAD) model and generation of intermediate models and process selections to the output of tool paths for the finishing of the final product.

3.2.2 Process planning for injection molding-subtractive

Traditionally the process planning for injection molds has relied heavily on the experience of past mold designers and fabricators. There have been significant strides to develop computer aided process plans for traditional mold making but not with the integration of multiple processes; these models are becoming more complex and time consuming [16]. As the molds are increasingly complex so are the need for better process planning techniques.

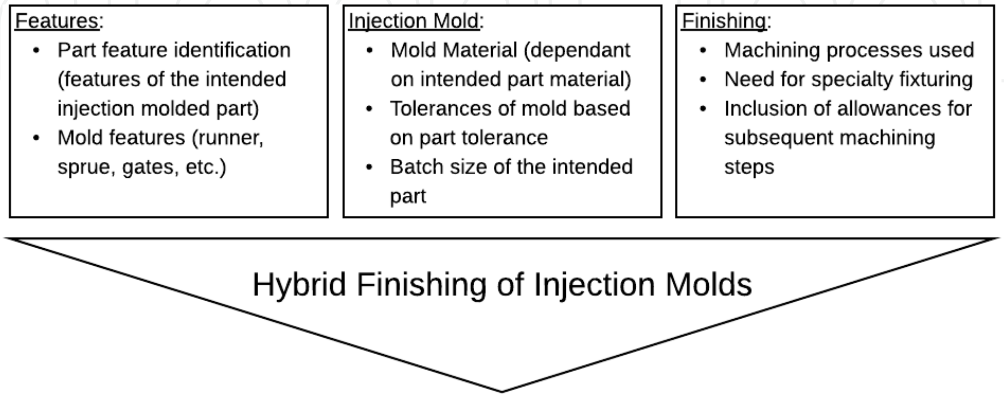
Considerations for feature based process planning are crucial in not only designing and manufacturing a mold from scratch but also repairing or refitting an injection mold. This is an iterative process in which molds are cycled through machining and testing. Many mold making facilities have an onsite injection molding machine for testing. However, some require shipment between the end customer and tool shop during this iterative process. In industry today, the most common method for process planning of injection molds is to allow experts to complete the task. However, there is a decreasing trend in qualified personnel to manufacture custom molds since the process is highly variable and requires strong problem solving skills and a high level of self-confidence [17].

The considerations specific to injection molding are similar to those mentioned previously for cast components, however there are some differences. Special factors include the identification of mold components, the development of the injection mold (including its material and tolerance specifications), and the finishing required for the mold and subsequent parts. This is further defined in **Figure 7**.

3.2.3 Process planning for additive-subtractive

Similar to the other hybrid process planning methods, process planning for additive-subtractive HMPs can either be feature-based or feature-less, and many methods utilize computer aided process planning. Utilizing CAPP methods is especially important when dealing with Additive-Subtractive HMPs due to the variability between parts manufactured both within a build and between builds. As with the other processes, the parts that are built in the first stage, must have the ability to be fixtured in the second and other subsequent stages of finishing. One such strategy is to create sacrificial supports that can be removed from the part once the components have been finished using CNC machining. **Figure 8** shows an as-built component at the back left, a finished component with the sacrificial support still in-tact in the back right, and a finished component in the front center.

Additionally, hybrid finishing of additive manufacturing requires considerations that can be grouped into three key areas: feature considerations, additive manufacturing process considerations, and finishing process considerations. **Figure 9** lists key example considerations for each area. Using the strategies



Features:
- Part feature identification (features of the intended injection molded part)
- Mold features (runner, sprue, gates, etc.)

Injection Mold:
- Mold Material (dependant on intended part material)
- Tolerances of mold based on part tolerance
- Batch size of the intended part

Finishing:
- Machining processes used
- Need for specialty fixturing
- Inclusion of allowances for subsequent machining steps

Figure 7.
Considerations for injection Mold-subtractive HMP process planning.

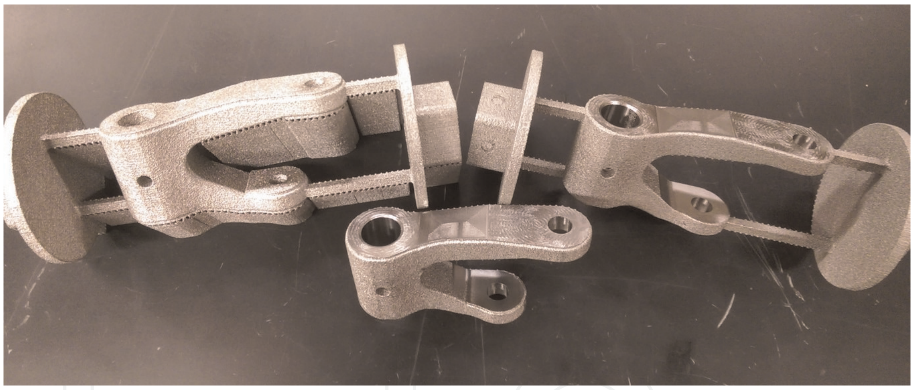
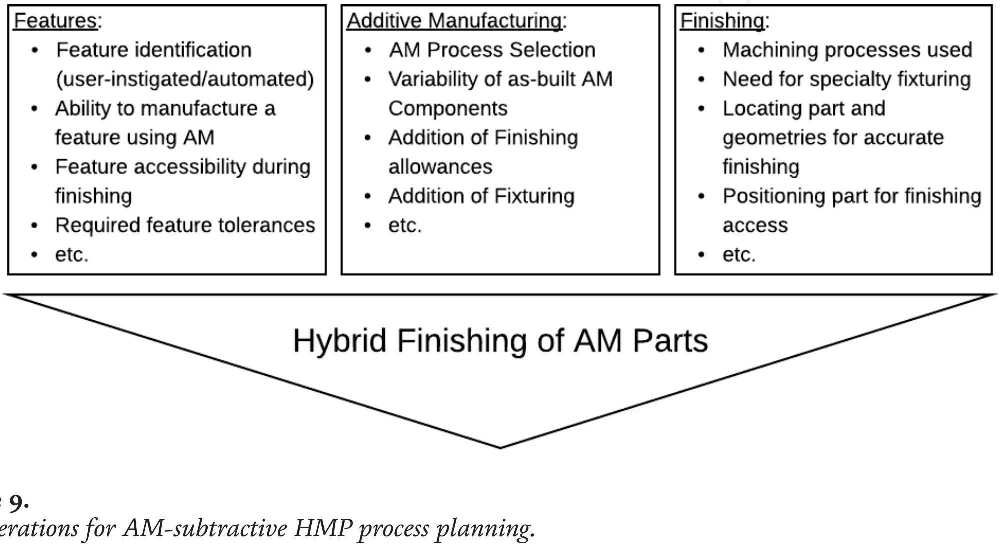


Figure 8.
Sacrificial support strategy example part (reproduced with permission from [18]).



Features:
- Feature identification (user-instigated/automated)
- Ability to manufacture a feature using AM
- Feature accessibility during finishing
- Required feature tolerances
- etc.

Additive Manufacturing:
- AM Process Selection
- Variability of as-built AM Components
- Addition of Finishing allowances
- Addition of Fixturing
- etc.

Finishing:
- Machining processes used
- Need for specialty fixturing
- Locating part and geometries for accurate finishing
- Positioning part for finishing access
- etc.

Figure 9.
Considerations for AM-subtractive HMP process planning.

described above, the production costs and product costs can be calculated to determine if additive-subtractive HMP is the appropriate manufacturing solution for a particular part.

3.3 Optimizing process planning for HMP

When developing a process plan for any manufacturing method there are many avenues in which the plan can be developed. The most intuitive process plan can be developed from the perspective of the features themselves; this is a precedence based approach where higher precedence is given to more critical features for final part function. In this situation each feature is completely manufactured before the next feature is considered. This is the most logical method for creating a process plan.

However an optimized process plan might consider is the minimization of the number of tool changes. A tool change can occur multiple times in manufacturing a single feature. This can take a significant amount of time, especially if the tool change process is manual. In this situation the process plan is developed such that each tool is used on as many features as possible before changing tools. The drawback to this method is that multiple features may be in process at any given time. If features have critical tolerances based on each other this process plan can result in a part that does not meet standards.

Another optimized process plan may consider manufacturing parts one that reduces the number of orientation changes required. In an automated 5 axis CNC machine, orientation changes are often not a problem, however in a more manual process, changing the orientation of a part can take hours to re-fixture and re-center the part. In this scenario every feature in each orientation is machined before reorienting the part. Again, multiple features are in-process at the same time.

Even further optimized process plans can be developed combining any of the three techniques: precedence, minimizing tool change, or minimizing orientation changes. Each of these methods are important especially to HMP parts since often complex or unusual features are the driving force for choosing such complex and time consuming manufacturing methods. If the process plans are then developed manually this can take days, weeks, even months to develop an initial plan delaying a project entirely. If the plan needs to be optimized for precedence, tool changes, orientation changes, or a combination of the three the process planning phase can take an extremely lengthy amount of time delaying the project even further. Therefore, there is a considerable need for computer aided process planning software which can account for the complex geometries of such HMP parts. An Excel based prototype has been developed and is described further in the next section.

4. Feature-based advanced hybrid manufacturing process planning system (FAH-PS)

The Feature-based Advanced Hybrid Manufacturing Process Planning System (FAH-PS) presented by [19] may be applied to multiple types of hybrid manufacturing processes such as casting-, injection molding-, and additive-subtractive. FAH-PS utilizes a modular and extensible software framework, which was intended to address: (1) the determination of operations final order in a process plan, (2) the types of processes supported in a hybrid process plan for holes, flats and slot features, and (3) the general extensibility of process planning systems for future program advancements [19]. The decision structure of FAH-PS uses feature specific geometric, tolerance, and material data inputs to generate automated process plans based on a user-specified critical feature precedence [19]. Individual modules are used to process machine information about specific feature types (hole, pocket, slot, etc.) and calculate required tooling and approximate machining times for each feature and part [19]. Based on user preference, FAH-PS can also generate additional process plans that aim to minimize tool changes, orientation changes, etc. to improve process times [19]. **Figure 10** shows the decision tree that FAH-PS follows in the development of process plans.

A case study was completed using the FAH-PS framework of a HMP bone plate shown below in **Figure 11**. More information regarding the specifics of this study can be found in [19]. In summary, FAH-PS produced 4 automated process plans, the results shown in **Table 1**.

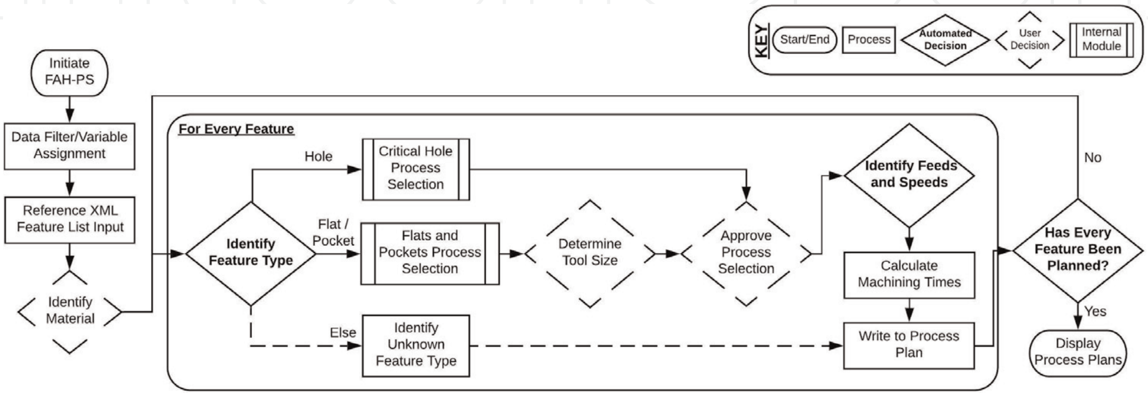


Figure 10.
FAH-PS decision structure (adapted from [19]).

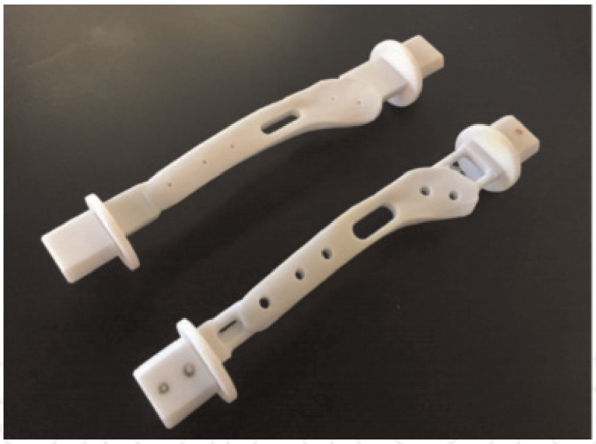


Figure 11.
Case study of using FAH-PS for finishing of a patient-specific bone plate (reproduced with permission from [16]).

Process plan	Machining Time (Min)	Time saved (Min)	Tool Changes count	Orientation Change count
Manual	17	—	2	26
Feature precedence	11	6	16	4
Orientation change	10	7	16	2
Tool change	9	8	4	12
Orientation and tool change	7	10	10	2

Table 1.
FAH-PS case study results (recreated results from [19]).

This planning system is one example of the demonstrated feasibility of automated and semi-automated process planning for hybrid manufacturing systems of small batch parts. It was shown in [19] to be a valuable tool during the design and preparation stages of production as it reduced difficulties in obtaining optimal machining strategies quickly with improved levels of accuracy. Incorporation of other features and types of processes as well as detailed assessment of costs for the auto-generated process plans are still needed, however this planning system is a good guide for future developmental efforts.

5. Conclusion

Within this chapter several hybrid manufacturing processes were outlined and an overview of factors affecting the development of process plans for these processes was given. The complexities of process planning for multi-staged processes and optimization of such process plans was also explored. Effective planning for HMPs requires a shift from manual approach to an automated process planning system. The FAH-PS system was provided as one example of a system designed to plan for such HMP.

Author details

Katie Basinger[2]*, Caroline Webster[3], Carter Keough[1], Richard Wysk[1]
and Ola Harrysson[1]

1 North Carolina State University, Raleigh, NC, United States

2 The University of Florida, Gainesville, FL, United States

3 Stryker, NJ, United States

*Address all correspondence to: katie.basinger@ufl.edu

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