Integration challenges with additive/subtractive in-envelope hybrid manufacturing

Matthew C. Frank, Jakob Croghan, Samantha Larson, Logan Beguhn

Industrial and Manufacturing Systems Engineering, Iowa State University of Science and Technology
Ames, Iowa, USA

Abstract

There are significant practical challenges when combining additive and subtractive manufacturing systems. The integration of AM and machining processes can be done *sequentially* or *in-envelope*. A sequential example would be where an AM part is removed from the build plate and then fixtured into a milling machine; essentially post-processing a near-net shape part. Alternately, an AM system can be added to a milling machine or a milling process can be added to an AM system, which we would refer to as *in-envelope*. This paper presents some of the practical challenges of in-envelope hybrid manufacturing; both metal and plastic AM within a CNC milling machine. In this work, a method to accomplish iterative machining in the presence of extra material allowance and limited cutting tool lengths will be described. In addition, preliminary work on accommodating multi-materials within a hybrid system will be presented.

Introduction

Driven by cost pressures, increasingly prevalent sustainability initiatives, and a desire to produce increasingly complex designs, some manufacturing firms are adopting hybrid manufacturing (HM) systems. These systems combine an additive manufacturing (AM) process with another process to create a final component geometry. An example of such a system is the combination of directed energy deposition (DED) with computer numerical control (CNC) machining. DED, as a metal AM process, enables users to selectively deposit material on a component. Due to the limitations of the process, DED is often used in combination with CNC machining to achieve the desired specification levels. The combination of these two processes into a hybrid manufacturing system has a wide variety of applications ranging from end component creation to component repair and has the ability to deposit a dissimilar material on existing geometry.

To date, applications with blown-powder DED processes have been fairly limited in their ability to create "tall" components due to CNC machine tooling limitations, particularly when it comes to tool reach and accessibility. Through the careful management of tool reach and access and, often, the use of additional machining axes, tall components have been produced using a blown powder. Tool path planning is time intensive and requires an individual to have a great deal of specialized knowledge regarding machine tooling. Five-axis toolpaths, due to their increased complexity, require even more specialized knowledge than three-axis process planning. Wire-fed DED processes often enable a simpler process-planning approach, particularly in regard to the machining stages, as the solid nature of the feedstock allows for deposition of material with minimal support structure. However, this approach cannot be readily applied to other AM processes.

The goal of this research is to take the first steps to generating an automatic process planning method for HM systems involving the combination of an AM process with CNC machining. This method will allow for the management of machining allowances to not only achieve final part tolerances, but also support subsequent AM depositions in a 3-axis configuration. This will be done by developing a method to iteratively conduct material deposition and surface machining to create tall, straight-walled geometries.

In addition, we explore the implementation of not only hybrid processes, but hybrid materials. The two most common materials in Additive Manufacturing today are metals and plastics; within each there are a multitude of options available. There has been considerable work in gradient and multi material applications within the same family, per se; metals or plastics, but not both. Obvious challenges lie in the fact that the materials are up to an order of magnitude or more different in properties, and certainly do not bond to each other. This work considers a practical approach to combining plastics and metals in a hybrid build, using a mechanical attachment that can be deployed within an additive/subtractive approach. The following sections present details on the approaches to iterative metal deposition and machining, and then a hybrid material approach to combine plastics to metals.

Iterative Additive/Subtractive Method

Directed energy deposition (DED) and computer numerical control (CNC) machining together in a hybrid manufacturing system provides the user with the unique ability to conduct "in-processing finishing of metal AM parts" [2]. According to the ASTM/ISO standard for AM terminology (ISO/ASTM 52900-15), 'DED is an additive manufacturing process in which focused thermal energy is used to fuse materials as they are being deposited.' [1]. While there is still some disagreement on which processes would fall under the DED label [3-5], this definition would include processes that utilize either a "controlled stream of powder or a wire filament" as the metal feedstock [4]. This along with the ability to produce multi-material components makes the DED approach rather attractive to users for variety of applications.

Figure 1 - Motorcycle engine block with heat sinks and cooling fins

The combination of additive manufacturing (AM) with CNC machining is often the first thing considered when mentioning hybrid manufacturing. These systems have been readily adopted for a number of industrial applications, including repair applications [6], [7] and functionally-graded or multi-material applications [8]. One such application that is of particular interest to the authors is the ability to produce additional geometry on an existing geometric design. For example, heat sinks and cooling fins could be added to the main cylinder block of a motorcycle engine, see (Figure 1) [9]. As can be seen in Figure 2, the overall dimensions of the block are greatly expanded by the addition of the cooling fins. This part is likely produced via a die-casting process which utilizes high pressure to force molten metal into the mold cavity. Current limitations to the die-casting process prevent the creation of extremely tall, thin sections, which limits the designers' ability to create larger cooling fins. If this part were to be machined from raw square stock, there would be a great deal of material waste. As such, this would be an ideal part to create using a hybrid AM-CNC machining system. However, this approach would currently be limited to fin heights that are shorter than the reach of machine tool used to finish the sides.

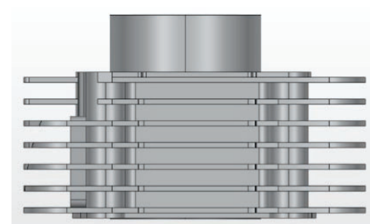

Figure 2 - Side view of motorcycle engine block

Tool reach and access problems are not limited to standalone machining; they are equally prevalent in hybrid manufacturing. Machining tall additive features requires the use of long machine tools Figure 3c. The increased deflection experienced from longer tools can be countered by increasing the diameter of the tool. However, this limits the access of the tool to the surface of part. Removal of machining allowance can be accomplished on both short features (a, b) and tall features (c, d). However, machine tool lengths can quickly become extreme. Due to hybrid manufacturing's unique ability to perform iterative deposition and machining, tall features can be broken down into several shorter features (Figure 3e).

Breaking tall features down into shorter features and performing machining in stages enables the use of shorter machine tools. Machining however being a subtractive, or material removal, process can present an issue for subsequent depositions. Figure 4 depicts how material is added in the LMD process. It should be noted that material can only be added where support exists for the deposition. Therefore, a support angle, θ, is necessary to expand beyond the bounds of the machined geometry's top plane (Figure 5). This support angle prevents the machining allowance

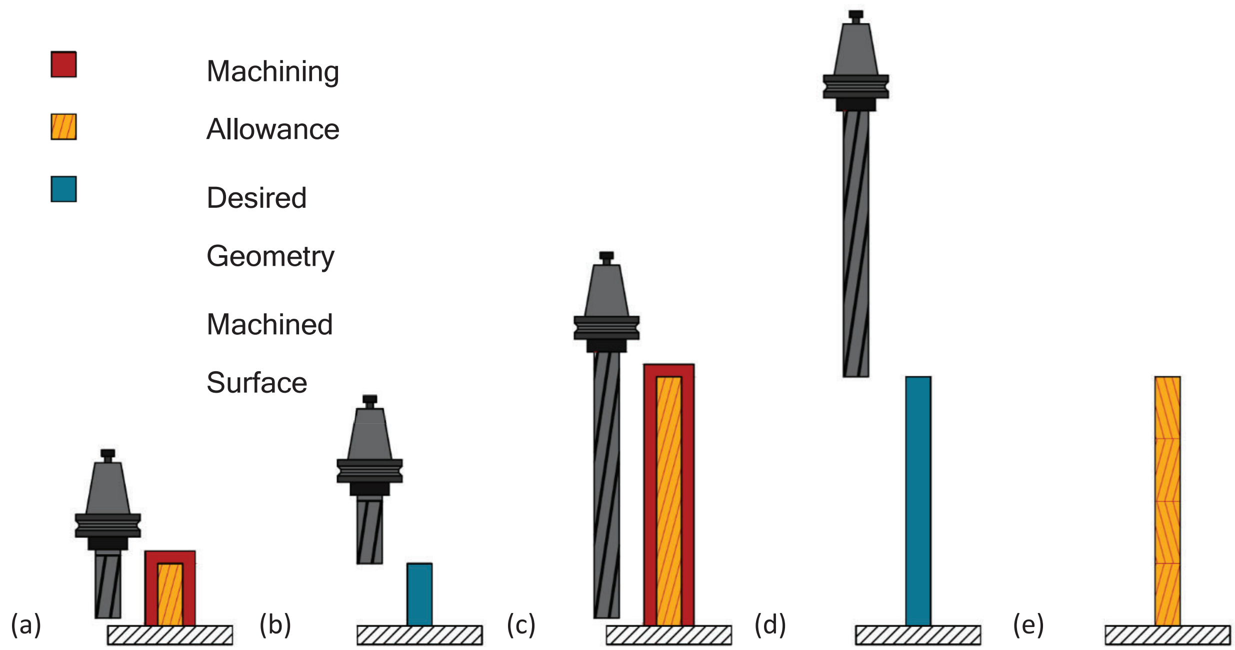

Figure 3 - Tool reach consideration within hybrid manufacturing

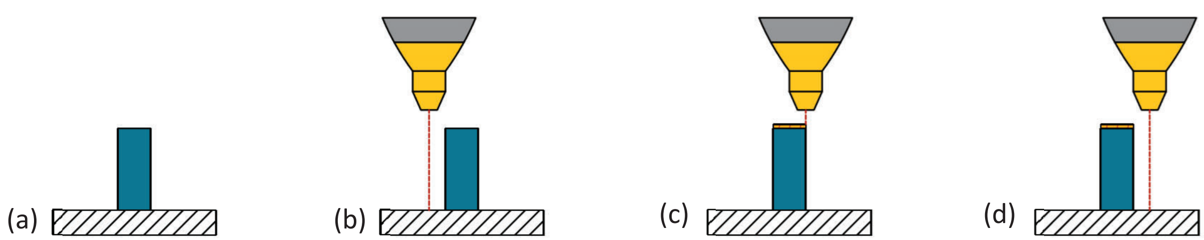

Figure 4 Metal deposition in LMD

from being fully attained on the initial layers of subsequent depositions after it has been removed. For instance, a support angle of $\theta = 45°$ would equate to a section of material with less than desired machining allowance as tall as the machining allowance is wide. This is problematic as the machining allowance is critical in attaining sufficient surface finish on the final part. A method to continuously cycle between deposition and machining without sacrificing machining allowance is necessary to progress hybrid manufacturing in the production environment.

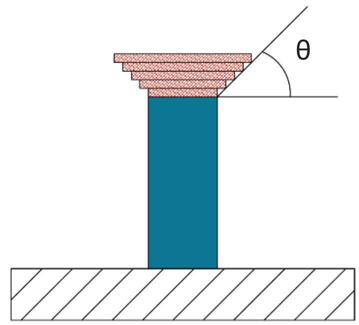

Figure 5 - Support angle

Proposed Solution

Following deposition of material via an additive process, the exact surface geometry of the part is unknown. Hybrid manufacturing often integrates post-processing in the form of machining or another finishing process to achieve final part tolerances. The following method takes this a step further, integrating machining mid-process. Face milling is conducted between deposition cycles to eliminate inconsistencies in stack up of the 2-½ D layers and provide a known flat surface. Profile milling is also conducted along the contour of the part, removing the machining allowance and any excess material. This process continues cyclically until the final height of the part is attained.

This process is unique in that profile milling is not conducted with standard flat or ball end mills, rather side or undercut machine tools are used. These cutting tools allow for material to be removed from the side rather than above, even in a simple 3-axis machine setup. Leveraging side-cutting tools, a ledge is created by selectively removing the machining allowance from the bottom up. The created ledge then acts as a support structure for additional material to be deposited in subsequent additive cycles.

Process Flow

Figure 6 depicts the flow for the iterative hybrid manufacturing process, repeatedly cycling between deposition of material via an AM process and material removal via CNC machining. The process starts with a short material deposition, oversized by an appropriate machining allowance, Figure 6a. This is followed by a two-stage machining cycle, beginning with face milling, Figure 6b, before transitioning to profile milling and creation of the ledge, Figure 6c. These three steps—1) deposition, 2) face milling, and 3) profile milling are repeated, Figure 6d-f, until the final desired height is attained, Figure 6h.

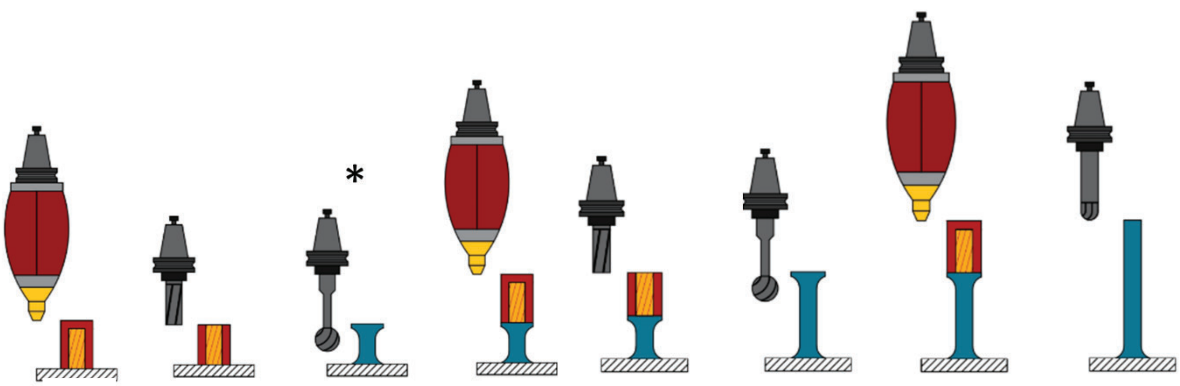

Figure 6 – Overview of iterative machining illustrating a 3 segment incremental machining process

The method was implemented using an AMBIT DED system from Hybrid Manufacturing Technologies, which is installed on a UMC 750 5-axis CNC milling machine from HAAS. The material is 316 SS deposited on a SS substrate. Figure 7 illustrates the first few steps in the prototype two-wall construction process. Figure 7a shows the first “slab” of deposition, follow by face and end milling operations in 7b and 7c, respectively. Figure 7d shows the result of side and undercut machining using the spherical ended mill to create the side profile and the “shelf” used to support subsequent depositions (Figure 7e).

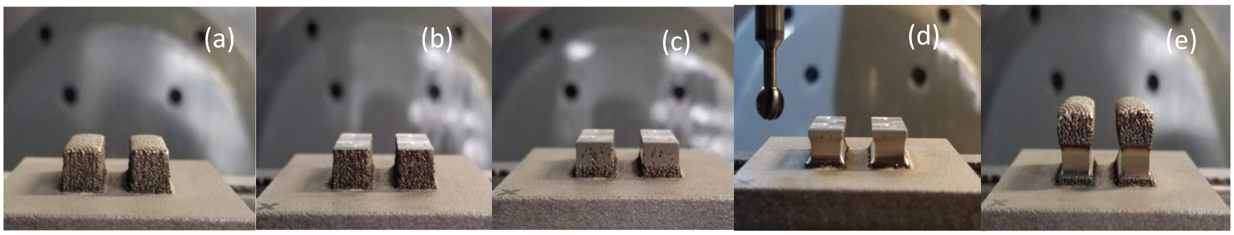

Figure 7 – Implementation of the proposed iterative method showing two segments deposited

This process was iterated 4 cycles, producing the two walled structure shown in Figure 8. As illustrated in Figure 8a, the milling of the two walls was accomplished with a tool decidedly too short to reach the entire depth without collision. It is proposed that this process could be sustained for exceedingly taller walls versus tool reach and access that is typically required.

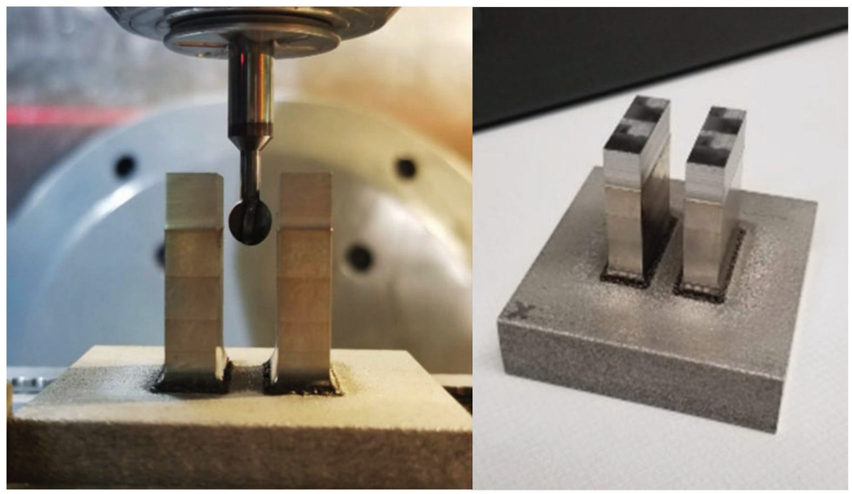

Figure 8 – Illustration of two wall, five segment stacking and machining example

Hybrid Materials – Plastics and Metals

Multi material Additive Manufacturing is an extraordinarily powerful innovation, allowing realistic application of gradient materials, assembled constructs of plastic and rubber, live hinges and a variety of new approaches to design of products. However, simple integration across material classes remains a practical challenge. Although plastic, metal, wood and composite filaments are available for FFM printing, the combination of multiple materials can be problematic (e.g. printing a solid plastic filament and a metal powder filament into one build, where the metal filament requires post process sintering). In this work, we explore the possibility of a mechanical connection between plastic and metal using a pre-machining root interface. The goal, as shown in Figure 9, is to attach representative plastic airfoils on an aluminum rod in a radial array.

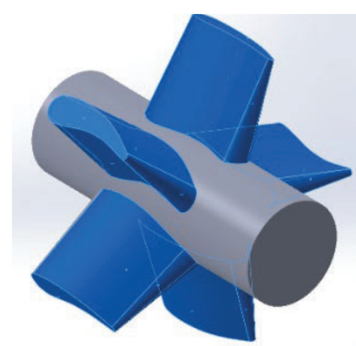

Figure 9 – two material construction goal

The proposed approach is to use a milling tool, typically called a dovetail cutter to create a root structure within the metal substrate. Plastic will then be deposited into the undercut geometry and then on top of the substrate, in an attempt to keep the plastic from pulling out of the substrate due to mechanical connection, as shown in Figure 10.

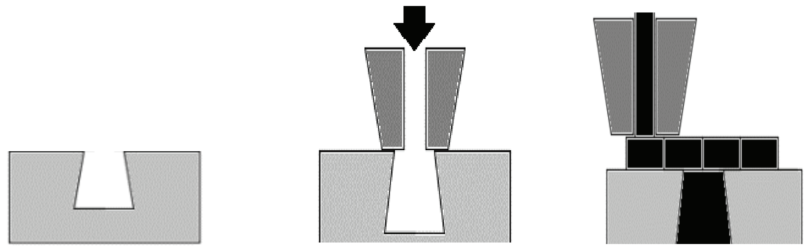

Figure 10 – Undercut (dovetail) machined for root structure

Preliminary results from early testing are mixed. In the condition where a single dovetail root is created, the plastic shrinks away uniformly causing the part to move (Figure 11a). However, when opposing roots, or better, a complete circuit of roots is machined, the subsequent layers of the part plastic shrinkage appears to improve mechanical linkage. The hypothesis is that the "layer 1" of the actual part, with significant volume compared to the root structure, draws the root plastic inward, causing the inboard edges of all root structure to drawn down even tighter (Figure 11b). This approach was tested on a sample part, shown in Figure 12. In this part, figure-8 root structures were machined into each of the three metal faces prior to deposition and subsequent ball milling of plastic. Initial results were highly successful, with all 3 airfoils securely attached to the 6061 aluminum rod.

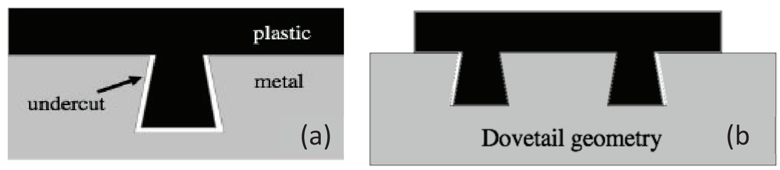

Figure 11 – Shrink conditions, (a) single root causes uniform shrink versus (b) multiple roots drawn together by part layer

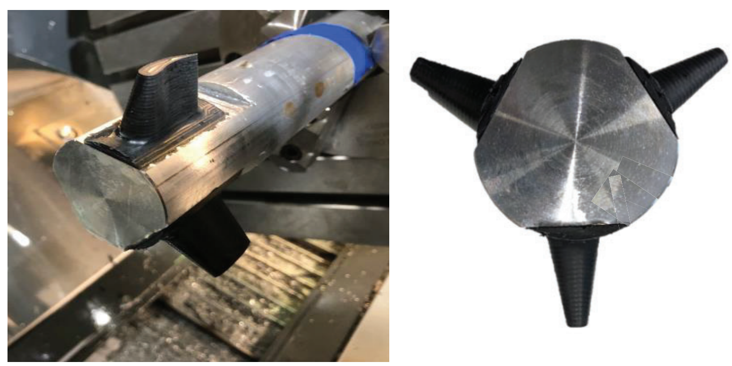

Figure 12 – Aluminum rod with ABS/CF plastic deposited and machined using dovetail root concept

Conclusion

Hybrid manufacturing using additive and subtractive methods shows promise in delivering both complex parts and integrated post process machining in one system. In addition, multiple materials within a hybrid process allow design complexities not seen in conventional manufacturing. That said, there remain seemingly fundamental challenges related to the iterations and integration of multiple processes and materials. This work presented some basic problems where machining allowance, upon removal, is not available to serve as the substrate for subsequent printing of a tall component. This paper proposes a method to avoid multi-axis machining, and common collision conditions related to tall close proximity features. The method is in early testing, and does not yet provide a clear solution for the optimal parameters of an optimal build, but early results are promising. The other method shown herein tackles a simple problem; vastly differing materials simply will not bond to each other. The dovetail cutting approach shown in this paper is seen in mechanical joints today, but usually in similar/same materials (e.g. attaching turbine blades to a rotor). However, this work shows preliminary success in using the expansion/shrink properties of the plastic to actually increase rigidity upon cooling. The process is only successful so far using a closed circuit of root structures, as any single dovetail sees significant uniform loosening.

Reference

[1] T. W. Simpson, "What Is Directed Energy Deposition?," *Modern Machine Shop*, 25 January 2019. [Online]. Available: https://www.mmsonline.com/blog/post/what-is-directed-energy-deposition. [Accessed 27 May 2019].

[2] J. B. Jones, "The synergies of hybridizing CNC and additive manufacturing," *Hybrid Manuf. Technol. Ltd*, 2014.

[3] Q. Zeng, Z. Xu, Y. Tian, and Y. Qin, "Advancement in additive manufacturing & numerical modelling considerations of direct energy deposition process," in *Proceeding of the 14th International Conference on Manufacturing Research: Advances in Manufacturing Technology*, 2016, pp. 104–109.

[4] K. A. Lorenz, J. B. Jones, D. I. Wimpenny, and M. R. Jackson, "A review of hybrid manufacturing," in *26th Solid Freeform Fabrication Symposium Conference Proceedings*, 2015, vol. 53, pp. 96–108.

[5] I. Wright, "Hybrid Manufacturing & The Future of 3D Printing for Production," *engineering.com*, 24 September 2018. [Online]. Available: https://www.engineering.com/AdvancedManufacturing/ArticleID/17717/Hybrid-Manufacturing-The-Future-of-3D-Printing-for-Production.aspx. [Accessed 25 May 2019].

[6] J. Bennett *et al.*, "Repairing Automotive Dies With Directed Energy Deposition: Industrial Application and Life Cycle Analysis," *J. Manuf. Sci. Eng.*, vol. 141, no. 2, 2019.

[7] P. Zelinski, "Metal 3D Printing in a Machine Shop? Ask the Marines," *Additive Manufacturing Magazine*, 10 April 2019. [Online]. Available: https://www.additivemanufacturing.media/blog/post/metal-3d-printing-in-a-machine-shop-ask-the-marines. [Accessed 27 May 2019].

[8] S. Flank, A. R. Nassar, T. W. Simpson, N. Valentine, and E. Elburn, "Fast Authentication of Metal Additive Manufacturing," *3D Print. Addit. Manuf.*, vol. 4, no. 3, pp. 143–148, 2017.

[9] "Air Cooled Yamaha Engine Block For Motorcycle , Wear Resistant DF 125cc," *China Good Quality Motorcycle Cylinder Supplier*, 2019. [Online]. Available: http://www.motorcycle-cylinder.com/sale-9697493-air-cooled-yamaha-engine-block-for-motorcycle-wear-resistant-df-125cc.html. [Accessed 28 May 2019].