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# AIMS- a Metal Additive-Hybrid Manufacturing System: System Architecture and Attributes

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## Abstract

This paper presents an integrated hybrid manufacturing approach to enhance and accelerate the adoption of metal Additive Manufacturing (AM) by adding a direct digital subtractive process to the production that is capable of improving the form, location and position tolerance of critical part features as well as improving surface finish. The hybrid system, AIMS (Additive systems Integrated with subtractive MethodS) can be integrated with existing metal AM systems without any significant modifications. The intent of this paper is to: 1) detail the system architecture, 2) highlight the process requirements, and 3) illustrate the sequential functions from development of CAD models through AM processing, to subtractive post-processing and corresponding process monitoring. Attributes of individual components such as physical and computational requirements associated with each discrete step of the overall process is presented. Advantages and current limitations of AIMS are also noted. The developed models provide insight into how the overall process-flow could be affected by errors (variability) due to both physical and data transfer across multiple systems. This paper also presents a generalized use of AIMS-for a variety of part geometries, noting materials and processing efficiencies associated with this unique hybrid method.

**Keywords:** Hybrid manufacturing, CNC-RP, AIMS, Performance Metrics and Additive manufacturing.

## 1 Introduction

The Society of Manufacturing Engineers (SME) defines this Direct Digital Manufacturing as “The process of going directly from an electronic, digital representation of a part to the final product via additive manufacturing” (SME, 2013). Since the advent of Computer Aided Manufacturing (CAM) systems, researchers have pursued the development of a Make Button process, where a Computer Aided Design (CAD) model of the desired part would be synthesized and a product would be fabricated in a few hours directly from a CAD model without the need of fixtures, molds or special

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machining stock. For many years, the emergence of rapid prototyping (RP) or Additive Manufacturing (AM) technologies was viewed as the basis of the elusive Make Button process, and there was a renewed optimism with the arrival of functionalized metal processes such as Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). Unfortunately, the high precision requirements/specifications of today's engineering components have not yet been achieved with any additive process. The reason for the lack of 5 – 20 micron precision is that the current surface morphology due to the nature of the processes for most materials prohibits the required accuracy. Currently one of the most accurate processes, Stereo Lithography Apparatus (SLA) which uses light sensitive (photo-curable) polymer comes close to these tolerances because the process does not require any melt pool while processing. For metal parts, additional post-processes like machining (milling, grinding and polishing techniques) are necessary to attain the desired functional part accuracy and surface finish. Unfortunately, there has been no direct method of integrating a part from an additive manufacturing (AM) process into a subtractive manufacturing (SM) process directly without significant human intervention (custom fixturing and multiple orientation set-ups) and lots of part programming. More importantly, the set-ups can require several days and in many cases, several weeks particularly in the case of sophisticated contours and high precision components (which are typical of commercial aerospace and biomedical parts).

In this paper, the attributes of current additive and subtractive manufacturing processes are outlined and the motivation for a hybrid manufacturing process is provided. The need for AIMS hybrid system is also presented upon review of existing hybrid methods. The principle for AIMS as we envision it is a standard process flow using existing manufacturing hardware integrated by using corresponding generic physical and process models so that the part requirements can be (semi)automatically achieved. Finally, the proposed AIMS is demonstrated through two case studies highlighting the performance metrics (material utilization and production time) of AIMS are presented to show the effectiveness of AIMS once fully automated.

# 2 Background

## 2.1 Additive Processes

Three primary methods of metal additive manufacturing exist and can be broadly categorized into powder bed, directed energy deposition and binder jetting processes per ASTM F2792-12a. The binder jetting processes are similar in nature to casting processes and will not be discussed further, however it is noted that parts produced through any of the AM processes can be candidates for the AIMS process. The interested reader is further invited to review approaches to categorizing methods (Pham, 1998; Pegna, 1997; Kruth, 1998; Williams, 2011), applications (Gibson and et.al, 2010; Frazier, 2010; Harrysson, 2008; Horn and Harrysson, 2012; Petrovic, 2011), advantages (Chiu and Yu, 2008; Czajkiewicz, 2008; Petrick and Simpson, 2013) and material properties (Bauefeld, 2009; Santos, 2006) of AM.

The principle of additive manufacturing lies in fabricating a part layer-by-layer through a bottom-to-top approach by the addition of material. The CAD file of the required part is sliced across each layer along the direction of fabrication and upon generating process files for the machine, the file is transferred to the machine and built layer-by-layer. The part is then removed from the AM machine for post-processing such as removal of sacrificial supports for any overhanging edges. Figure 1 below shows an example of such sacrificial support structures. Figure 2 shows examples of complexity possible in metal AM.

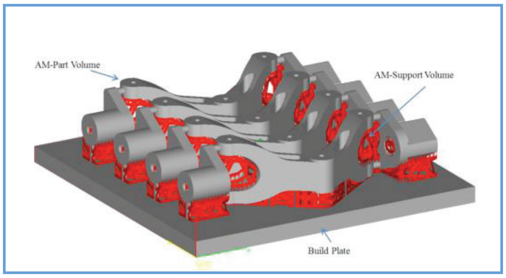

**Figure 1 Part Volume and Sacrificial Support Volume**

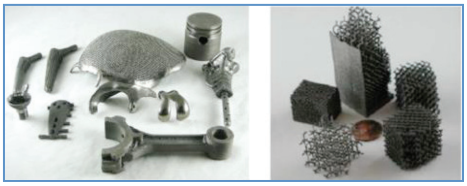

**Figure 2: Metal-AM Part Design Complexities**

While part complexity is considered inexpensive, current metal-AM methods suffer from poor surface finish and part inaccuracies when compared to subtractive manufacturing methods (Manogharan, 2012). In the case of powder-bed fusion processes (such as DMLS, SLM and EBM), metallurgical (and often mechanical) bonding of unprocessed metal powders with the processed surface occurs leading to surfaces similar to 'as-cast' parts. In the case of directed energy deposition methods such as EBF[3] (without any subtractive elements), the layer thickness is relatively high, leading to loss of finer part features. Hence it is apparent that while metal-AM has several unique advantages over other manufacturing approaches, they require significant secondary processing to generate parts within the tolerances of the required specification and surface finish (two critical aspects when the part is involved in assemblies).

## 2.2 Subtractive Processes

In the case of subtractive manufacturing, material is removed from a stock using several techniques such as machining (using a CNC machine tool), laser cutting, Electric Discharge Machining (EDM), etc. Contrary to the AM principle, subtractive manufacturing has a 'top-to-bottom' feature-based approach.

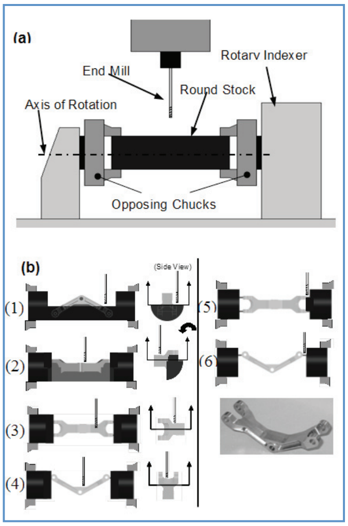

**Figure 3: CNC-RP Process; (a) Setup (b) Example**

While there are several such methods, this research focuses on a recently developed subtractive process called CNC-RP, which is analogous to the 'layer approach' found in AM processes and requires no special tooling or any part programming (Frank, 2004). Further, as in the 'freeform' aspect of AM, CNC-RP provides a comparable yet unique aspect of generating a part directly from a CAD file without any custom fixtures, tooling or part programming through machining. Similarly, a single-setup approach of CNC-RP has been extended to ‘subtract’ material through EDM (Craeghs, 2014)). CNC-RP produces accurate functional parts directly from a CAD model and available tool library (of the machine tool) without any human intervention or specialized fixtures (similar to AM) by using a 4-axis CNC setup and sacrificial fixturing techniques (similar to AM) as shown in Figure 3 (Frank, 2004).A CAD file of the desired part is analyzed by the CNC-RP software using visibility analysis to identify if the part can be machined and then determines the machining sequence and minimum number of orientations required to produce the part from a round bar stock (Yang, 2009 and Yang, 2011). Sacrificial fixtures or struts are automatically added to the original STL model to support the finished part within the stock and for it to remain in place for the duration of the manufacturing process. The size of the sacrificial fixturing is a function of the material properties of the stock and is determined based on an allowable deflection during milling. Upon determining the sequence and machining orientations from the visibility analysis, the sacrificial fixtures are integrated into the STL model automatically.

When compared to AM methods, CNC-RP provides superior part accuracy and a surface finish (similar to conventional machining methods) and the automated aspect of CNC-RP requires minimal expertise, similar to commonly used AM methods. However, due to geometric limitations similar to traditional manufacturing, CNC-RP is limited to the part design complexities that can be created using face milling. For instance, part geometries like lattice structures cannot be produced through CNC-RP. From a sustainability standpoint, the raw material-part volume (so-called “buy-to-fly”) ratio is often very high for subtractive processes since the majority of the material can end up as scrap and chips. Additionally, CNC-RP trades process planning for machining time, resulting in longer machining times and increased tool requirements.

## 2.3 Hybrid Processes

In order to economically produce a part with required accuracy and specifications, it is often necessary to use several manufacturing processes sequentially. These are often referred to as ‘hybrid processes’. Such an integrated approach eliminates the limitations of individual processes while aggregating their advantages. There have been several studies that have compared different definitions and classifications of hybrid processes (Zhu, 2013; Klocke, 2010 and Nau, 2011). Researchers have extensively focused on ‘hybrid machining’ where more than one distinct machining process (e.g., milling, boring, drilling, etc.) has been employed to remove material and generate the required part (Rajurkar, 1999; Aspinwall, 2001 and Menzines, 2008). The definition of a ‘hybrid process’ has varied based on the material used (such as composite products) (Roderburg, 2011), the combination of more than one ‘active principle’ (such as laser assisted turning/ milling) (Zhu 2013 and Dandekar, 2010), the combination of different energy forms (Menzines, 2008), etc. In the case of hybrid additive manufacturing, there is a comprehensive review of multiple techniques such as melting of deposited material at different heat conditions, mixing of different materials during deposition, deposition of discrete materials, etc. (Zhu, 2013). In the context of this paper, the hybrid process is a systems view and refers to the “combination of an additive and subtractive process, sequential or integrated, including planning for fixturing and orientation in the quest of a final, usable part.” Much of the work in this area has focused on directed energy metal deposition processes such as wire welding using metal inert gas, metal active gas (Akula and Karunakaran, 2006; Karunakaran and et al., 2010) and laser melting due to the relative ease of integration (Jeng and Lin, 2001, Amine, et al.,2011). These hybrid systems are formulated by typically retrofitting 3-axis platforms (ball screw/ lead screw, etc.) in a CNC machining center by adding the deposition head into the machine volume. Another study presented a powder-plasma based system that utilizes 3-axis contour milling to finish machine near-net shape parts (Xiong and et al., 2009). In such processes, hybrid manufacturing is achieved by alternating between additive and subtractive methods after every few layers. Machining is performed after deposition or formation of relatively thick layers followed by subsequent addition and subtraction steps until the final part is created. Other hybrid process employs additional rotary axes based laser-aided deposition process in which the deposition table is rotated to accommodate overhanging surfaces by depositing material from multiple directions followed by machining (Liou and et al., 2007). Some sheet lamination additive manufacturing processes, such as the ultrasonic consolidation of metal foils utilize in-situ machining steps (Janaki Ram and et al., 2006).

The major collective attributes of the existing hybrid systems (within the realm of additive-subtractive hybrid processes) include:

- Advantage of Constant/Fixed part coordinate system to seamlessly switch between additive and subtractive operations; and uses various CNC machine cutting tools,
- Multiple machining operations such as milling, drilling, grinding etc. can be pursued along with the additive approach;
- The requirement of significant process planning to identify the sequence of AM deposition and SM machining, since 'inference/gauge check' is indispensable to ensure that the deposition element (weld or laser heads, powder feed) and the machine tool do not collide with each other or with the part
- Down-time associated with constant tool changes caused by switching between deposition and milling is a non-value adding step
- Concerns about the microstructure associated with the irregular heat distribution cycles (e.g., machining every 2 layers vs. machining after 10 layers of deposition)
- The post-processing heat treatment requirement
- Use of coolant during machining is not feasible because of the use of laser (optics) and welding heads
- Weldability of superalloys is inferior to that of other commonly used alloys (Tillack, 2007) and
- Complex part designs with non-uniformly varying cross-sections are a challenge to produce using such processes due to the infeasibility of incorporating support structures for overhanging edges.
- In addition to these attributes, it should be noted that the current hybrid processes are applicable only to direct energy deposition processes.
- The major challenge of integrating AM and subtractive machining in the current hybrid methods is the need for a 'hybrid process-planning' protocol for post-processing of AM that accounts for the varying processing nature of AM (material shrinkage, layer thickness, orientation, etc.), machining (tool design, machining allowance, etc.) and part-specific attributes (critical features and tolerance requirements).

It is important to develop a 'universal' hybrid approach that can be integrated with other types of metal additive manufacturing methods such as the binder jetting and powder-bed fusion processes. The processing capability (range of materials and applications) are ever-growing in AM processes such as EBM, SLM, SLS, etc. It is therefore necessary to develop a hybrid process that can be integrated to combine advantages from such methods. For instance, existing hybrid approaches of deposition-machining are not feasible for powder-bed fusion processes as they would damage the non-processed powders and any support, making it impossible to proceed with subsequent layers. Further, in some AM process such as EBM, it is not feasible to operate/possess the machine tool in the same build environment because the EBM operates under high vacuum conditions. Because of the nature of such AM processes (hot-bed temperature with slow cooling in inert atmosphere), they are preferred to process superalloys and have better metallurgical conditions. In conclusion, a novel hybrid process is desired such that it is not linked to a specific category of AM techniques but can cater to any AM process. This can be used to produce parts made of tough-to-process alloys with minimal machining so as to achieve precision tolerance and surface finish. Similar to the 'click-to-print' approach of AM, the hybrid process should not require custom fixtures and tools based on part design and should be able to operate with minimal human intervention and expertise. The hybrid process should be applicable without any modifications to existing AM methods.

Several key improvements over other existing hybrid systems are summarized as:

- Existing, in-place additive manufacturing systems can be integrated into this approach,
    - Includes established and accepted industry processes,
    - Large varieties of materials available,
- Internal stresses, which are necessarily introduced via other hybrid approaches cause geometric distortions which are challenging or impossible to deal with *in situ*, can be eliminated before the machining operation,
- Process planning is simplified eliminating one bottleneck in the manufacturing process.

# 3 AIMS Process Outline

This research is motivated by the need for integrating additive and subtractive processes to produce complex part geometries directly from a CAD model with minimal machining to achieve precision part-feature accuracy and fine surface finish. In the case of lot sizes of 'one-to-few', it is extremely expensive to fabricate custom fixtures and special workholding devices that may be necessary to secure and locate complex part geometries. In many of these cases, the cost of the fixture can be significantly higher than that of the part being produced, especially since the fixture generally requires an accuracy of ten-times that of the part being produced. Further, there is a design and fabrication time associated with creating custom fixtures that will extend the time to actually make a final part. Therefore, the overall unit cost increases tremendously. Such approaches are preferable for mass production (e.g., sand casted engine blocks), where relatively large batch sizes of a single part design undergo secondary and/or finishing operation. In the proposed hybrid manufacturing process, sacrificial fixtures required to secure the part during the subtractive process are added to the desired part prior to 'near-net' manufacturing. In order to characterize this process, it is important to define the hybrid approach and develop an architecture that details the flow of material (physical) and information (algorithmic) through the system. However, it should be noted that the concept of creating linkage through integrated sacrificial fixtures between these two discrete stages can be employed with any additive process (e.g., LENS, DMLS) and subtractive process (e.g., wire-EDM, CNC grinding, etc.) using a similar approach.

## 3.1 AIMS Process Flow

A unique integration between direct metal additive manufacturing and subtractive machining in CNC-RP is formulated through this novel AIMS technique. This system brings together process capabilities of two different state-of-the-art manufacturing approaches (e.g., EBM and rapid CNC machining). The concept is to use an additive direct metal process such as EBM or DMLS to create complex geometries to near net-shape geometries. Further, in a precisely controlled manner, it employs a secondary advanced subtractive rapid machining method to create critical surfaces and dimensions within the requirements. Integrating these two advanced technologies yields a hybrid system with capabilities to produce functional metal parts and prototypes with precision accuracy and good surface finish. More importantly, this hybrid technology will further the feasibility and cost-effectiveness for functional parts with complex geometries, which are desired to be made from expensive and high performance metal alloys that are often difficult to process through conventional methods such as casting. Figure 4 illustrates the basic concept behind the AIMS system, showing the creation of a metal linkage via AM (EBM) and SM (CNC-RP). With a higher degree of integration and efficient process planning for AIMS, parts with complex features and accurate dimensions can be easily manufactured. In a limited sense, this research is analogous to the casting process, wherein a formative process creates a near-net shape geometry, and a machining process is used to satisfy tight tolerances on geometric and surface characteristics except without significant process planning and requirement for human expertise. However, no casting process has the capabilities to produce complex geometries of superalloys similar to direct metal systems. As shown in Figure 4, the process is hybrid in nature, utilizing a direct metal process like EBM to first manufacture a near-net shape of the desired part, with attached fixture elements designed for a subsequent rapid machining processing.

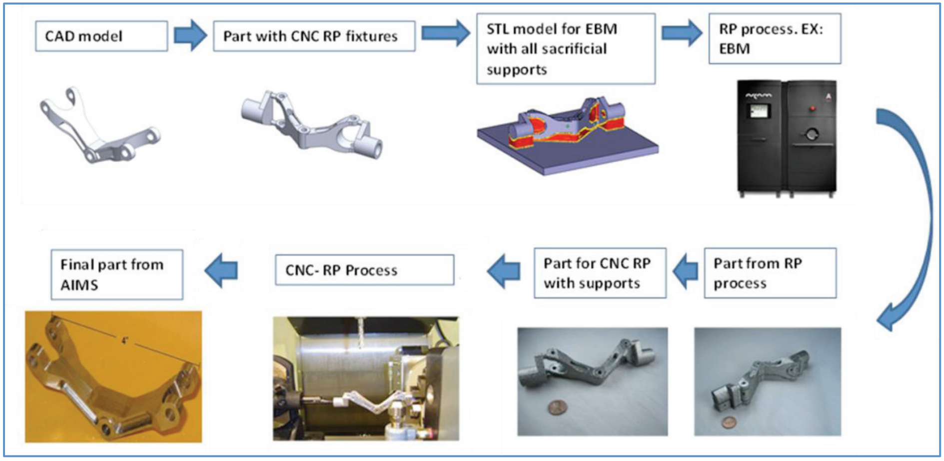

**Figure 4: The AIMS process**

The AIMS process requires the use of two kinds of sacrificial supports; 1) to support overhangs in the layer based additive process and 2) to support the part in a CNC machine fixture like a fixed structural beam. In addition to the planning of support location and geometry, it is important to identify the critical features of the part. The identified features (e.g. mating surfaces, a contour of a protruding feature, etc.) should be taken into account during process planning for both EBM or CNC-RP or a combination of the two. The ultimate goal is a push button process planning software interface that will process the CAD model of a desired part and then generate two build files/models; one for additive and one for subtractive process.

The overall process flow of the proposed AIMS system after development is detailed in Figure 5. It highlights the vital steps involved in the integration of AM and a subtractive process namely, CNC-RP. Upon receiving the CAD file, the process planning should consider the information from the file and analyze the strategies for CNC-RP based on visibility analysis, tool library, etc. and also consider the limitations of the 'specific' AM machine such as maximum build volume, part accuracy, surface finish, etc.

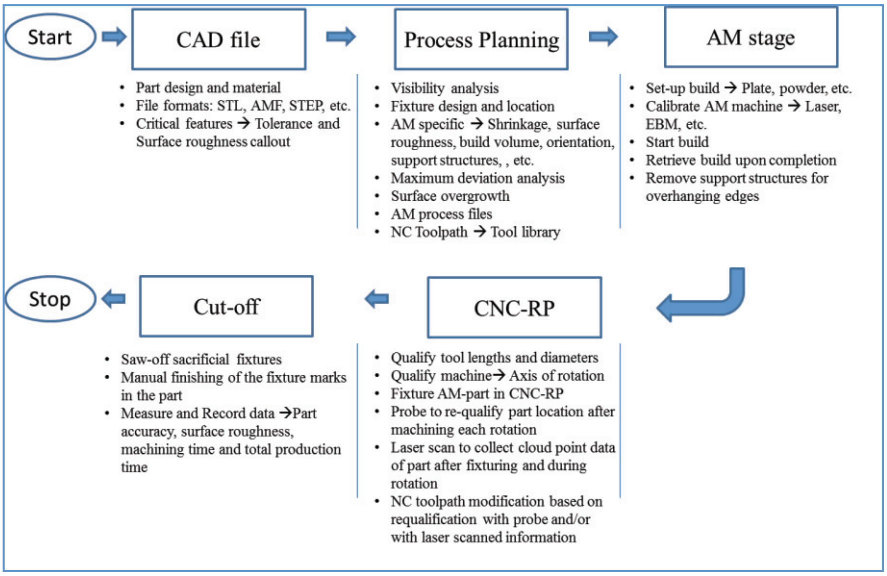

**Figure 5: AIMS process flow**

After executing the process planning, the AM stage creates the part based on the build files generated. The part, including sacrificial fixtures and supports, is manually removed from the AM system and any post AM heat treatments or hot isostatic pressing is performed. The part is then presented to the CNC-RP set up, currently performed by an operator, in the expected orientation. In CNC-RP, the AM-part is finish machined after qualifying the tools, part location using machine tool accessories such as touch-probe and/or laser scanner. Finally, the part is realized by removing the sacrificial fixtures. As can be identified from the process flow, there is a flow of information throughout the process based on the part design, the physical build, CNC-RP volume, tool path generation, etc. In order to more completely develop AIMS, there are two fundamentally different aspects associated: (1) Physical architecture defining material, AM process and CNC-RP, and (2) Software architecture which will define the individual components that need to be considered during process planning and operation of AIMS to achieve automation of all the steps involved in AIMS. It is important to identify these components to develop a seamless system because they are interrelated. For instance, processing a part design of a specific alloy through two varied AM processes such as DMLS and EBM will result in different part accuracy and surface roughness (which are physical components). As a result, part misalignment during CNC-RP will not be uniform and hence, toolpath generation using a CAD-CAM system (which is a computational component) has to account for the dissimilarities across AM technologies. Another example will be the influence of available build volume in the AM system. This will impact both the build orientation (which affects part accuracy and surface roughness) and the fixture design depending on the part volume. Hence, the computational component should consider this while determining the appropriate part offset and orientation in order to create the required final part.

## 3.2 Physical Components of AIMS

The major physical components associated with AIMS are noted in Figure 6 namely: material, AM process (equipment) and the CNC-RP setup. At this stage of development of AIMS, specific part design attributes such as thin walls, and the incorporation of lattice structures are not considered, thereby maintaining the generality associated with existing AM (CAD file additive manufacturing). The influence of material is significant since the shrinkage characteristics of each material vary for individual AM processes, which affects part accuracies. Further, fixture design is dependent upon the material properties and part geometry such that the fixtures can withstand the cutting forces for specified machining parameters.

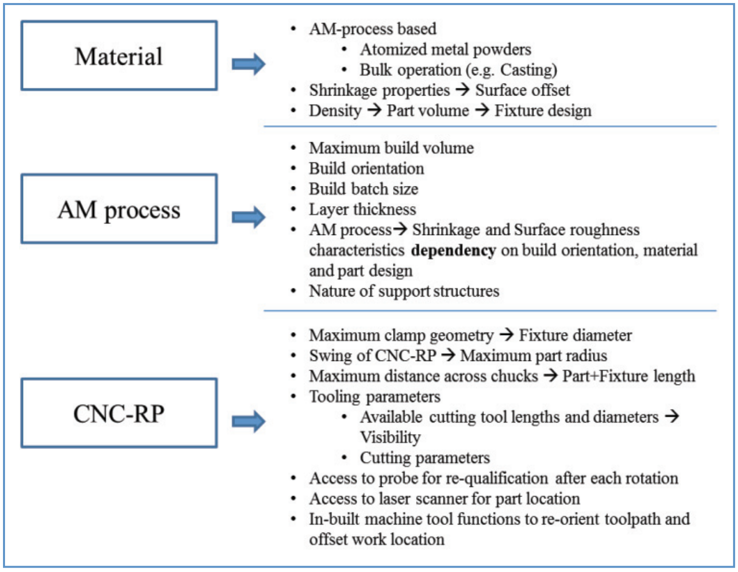

**Figure 6: AIMS physical component**

Furthermore, depending on the specific AM process used, process planning has to consider the maximum build volume and orientation to appropriately design fixtures for the specific part volume. More importantly, the part accuracy and surface roughness characteristics of each unique AM technique need to be registered in order to gauge the maximum deviation that can be predicted. Regarding CNC-RP, in-addition to information on the maximum machining volume and accessibility, part and tool qualification methods also need to be defined.

## 3.3 Computational Components of AIMS

The major software building blocks associated with AIMS are noted in Figure 7. After visibility analysis in-conjunction with physical components (maximum build volume, orientation, etc.), analysis for sacrificial fixture design should be conducted such that the fixtures can support machining forces in CNC-RP. Based on the specific AM process accuracy, fixture/part deviation analysis (in CNC-RP) should be predicted and corresponding part overgrowth should be compensated. Finally, process files for AM and CNC-RP should be generated and transferred to the machines.

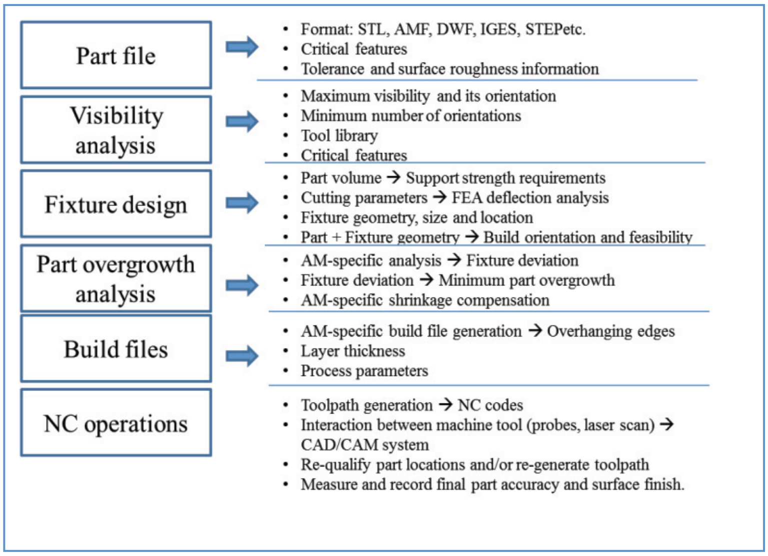

**Figure 7: AIMS computational component**

## 4 AIMS Demonstration

A case study of two parts, a hinge component from an airframe (Figures 8 and 9) and a suspension part from a bicycle (Figures 11 and 12), is presented here. Each of the parts were run through the CNC-RP ™ process planning software in MasterCAM ® 6 to generate tool paths. The CNC finishing paths for both the AIMS process as well as the traditional CNC-RP approach are assumed to be the same. Tool lengths were considered infinite in this study and no consideration was given to feasibility of a specific tool length. Tool surface speeds and feed rates were maintained constant for titanium grade 5 alloy (Ti-6Al-4V) with 0.508 m/s surface speed and .025mm per tooth-rotation for all tools. Tool selection for both parts included a 19mm four-flute carbide end mill and 12.5mm four-flute carbide end mill for roughing and a 6.3mm four-flute carbide end mill for finishing. The Z-axis step down for finishing (6.3mm four-flute end mill) was set to 0.127mm, with a maximum engagement of 2.5mm.

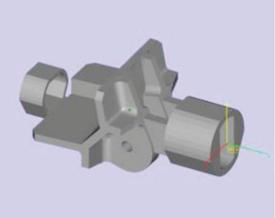

**Figure 8: CAD model for hinge part including machining allowance and sacrificial fixture**

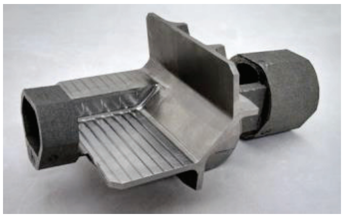

**Figure 9: Hinge part after machining prior to removing sacrificial fixtures**

**Figure 10: Suspension part with sacrificial fixtures, support structures for AM process and 1.0 mm machining allowance**

**Figure 11: Finished suspension part prior to removing sacrificial machining fixtures.**

The estimated CNC-RP machining time for the bicycle suspension part was 660 minutes for roughing and 1590 minutes for finishing. The estimated machining time for the airframe hinge was 1722 minutes for roughing and 3432 minutes for finishing. The minimum stock size for the suspension part was 163.5mm by 53.4mm and for the hinge part was 160mm by 104.14mm, length and diameter respectively. Considering the hybrid AIMS system, the material required for building the suspension part is 0.25kg including support material and sacrificial supports and 0.87kg for the hinge part. Final mass of the desired suspension part is 0.1kg and for the hinge 0.3kg. The resulting buy-to-fly ratios are calculated for the AIMS process of 2.5 and 2.9 respectively. As a comparison, a bounding cube (cylinder as defined above for CNC-RP) containing the hinge part with 6mm offset from all sides has a mass of 3.6kg (6kg) and a buy-to-fly ratio of 20 and the suspension part stock mass of 1.35kg (1.63kg) resulting in 13.5 buy-to-fly ratio. In order to understand the effects of materials, the (Ti-6Al-4V) parts used in this study were analyzed for Al 6061 (commonly used traditional material) and SS 316L (commonly used AM material). Using ASM Machining Handbook (ASM, vol. 16) and the same tool diameters, the surface speeds used were 6.5 mm/s and 1.8 mm/s for Al 6061 and SS 316 L respectively. The chip loads used were 0.13 mm/s and 0.05 mm/s for Al 6061 and SS 316 L respectively. The tool surface speeds and feed rate were kept constant throughout the machining duration. Also, the cutting tool life was estimated at 15 minutes to determine the number of cutting tools required. It should be noted that the cutting tool change time is not included in the overall machining time. Hence, the overall production time (and cost) will increase with higher tool life consumption (including the cost of the tools). The machining time and number of tools for different materials are shown in Figure 12.

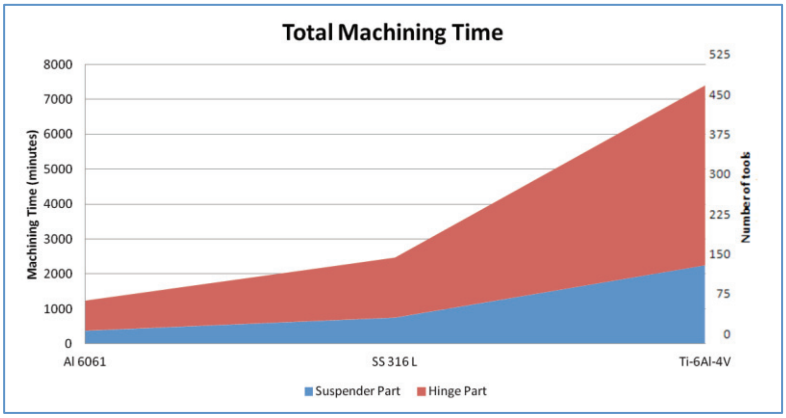

**Figure 12: Influence of Material Selection on Machining time.**

Any situation that increases the pre-finishing time i.e., machining time and cutting tool usage of roughing or hogging tooling, or stock costs will favor the hybrid process and 'near-net' shaping using additive processes. This is intuitive and explains why significant research thrusts in the additive manufacturing arena are towards nickel based super alloys and other difficult to machine materials. It is also somewhat instructive as to why aluminum research in these processes is somewhat muted, as the machinability of aluminum is much greater than that of cobalt chrome and titanium alloys. Other situations may not be as intuitive. Parts that require relatively little hogging or roughing time, such as parts where part volume approaches that of the rough stock size in CNC-RP will favor CNC-RP, and parts where the majority of the material removal is done by the relatively large and rigid hogging tool will again favor CNC-RP.

# 5 Conclusion

Based on the major advantages and limitations of additive and subtractive manufacturing principles presented earlier in this paper, an argument for integrating the additive with subtractive manufacturing approaches was presented. It was noted that poor surface finish and lack of high part tolerance were the main drawbacks of current AM methods. On the other hand, subtractive methods required custom tooling and fixtures. Developing a hybrid process that does not inhibit developments and use of existing AM and SM processes, and can be implemented across all AM processes is the key to successfully developing a rapid 'high precision' hybrid process. Furthermore, based on the AIMS process model an overarching scope of research and a desired automated process flow required detailed.

From this study, it is observed that machining duration of CNC-RP only production is significantly longer than AIMS, (only the finishing stage of CNC-RP). This could be attributed to the machining parameters such as feed and depth of cut employed for milling alloys such as Ti-6Al-4V. For instance, machining time would be drastically lower in the case of processing relatively softer materials such as Aluminum or Brass. However, material utilization in terms of part-stock volume of expensive tough to machine materials could become a critical factor based on part geometry while processing solely in CNC-RP. This is important in the case of expensive superalloys used in aerospace and mechanical applications. On the other hand, the hybrid process demonstrated higher material utilization of expensive alloys in EBM along with the ability to 'finish' machine through CNC-RP.

The benefits were three-fold: (1) addition of sacrificial fixture for CNC-RP in the near-net part eliminated the need for any additional fixtures, (2) employing only 'finish' CNC-RP reduced total machining time (as compared to CNC-RP) and also, lower tooling cost and (3) higher material utilization by using only 'near-net' volume of material (as compared to bar stock in CNC-RP). It is also somewhat instructive as to why (again neglecting any geometric constraints) aluminum research in these processes is somewhat muted, as the machinability of aluminum is much greater than that of cobalt chrome and titanium alloys. For future research, the characterization models that were developed in this model can be adapted to other metal-AM methods such as ExOne systems to estimate fixturing inaccuracies. Also, algorithms can be developed to automate the fixture design using recorded data on different fixture inaccuracies, machining forces based on part geometry and tool parameters. In addition, using a textured or labeled CAD file format can be implemented to identify the critical surfaces to identify fixture locations. Finally, AIMS could be enhanced by developing hybrid-centric visibility analysis that could be adapted for 'minimum-tool length' and 'critical surfaces' since unlike conventional CNC-RP bulk of the roughing operations does not exist.

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