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Direct Additive Subtractive Hybrid Manufacturing (DASH) – An Out of Envelope Method

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Abstract:

This work addresses a critical issue affecting the adoption of metal additive manufacturing (AM) methodologies; creating a system that can produce a mechanical product to final geometric specification. To date, almost all functional metal AM parts have required secondary processing that in many cases can more than double the cost of the final part. A Direct Additive and Subtractive Hybrid (DASH) manufacturing system using both additive and then subtractive processing has been developed so that mechanical parts can be "digitally manufactured" to meet the final required geometric accuracy. The approach includes the development of a software system to link additive and subtractive manufacturing, using extensions to the AMF format, to maintain product design features along with their tolerance specifications. It also introduces the idea of sacrificial fixtures that are automatically designed into the parts to allow subsequent fixturing in the CNC mill. Once in the milling machine, a part localization system identifies the part and its location, along with capturing the geometry of any remaining AM support material left on the part. Finally, all CNC code is automatically generated and the finishing process can be executed in a lights-out operation. This work provides a drastic reduction in post processing time and cost. It further enables expansion of metal AM and uniquely addresses the challenge of out-of-envelope hybrid manufactured parts.

Introduction:

For many years, the emergence of additive manufacturing (AM) technologies was viewed as the basis of the elusive push-button manufacturing process, and there was a renewed optimism with the arrival of functionalized metal processes such as Electron Beam Melting (EBM) and Selective Laser Melting (SLM). Unfortunately, the high precision specifications of today's engineered components have not yet been achieved with metal additive processes. In most cases for metal parts, removal processes like machining (milling, grinding and polishing techniques) are inevitable to attain functional part accuracy and surface finish. In fact, most users of metal AM will regularly deploy some form of post process machining for at least a few critical features if not entire sections of critical exterior geometry. This is analogous to the day-to-day operations of the metal casting industry, and therefore, one could argue that it has been received with some undue acceptance. However, the problem with using conventional machining methods for finishing AM parts is that the economies of scale available in the metal casting industry can be used to justify the investment; whereas in AM, we need the capability to effectively produce just one or a few parts as desired. Unfortunately, there has been no plug-in method of integrating a part from an additive process into a subtractive process directly without significant human intervention (fixturing and orientation set-up). More importantly, process can require several days and in most cases, several weeks particularly in the case of sophisticated contours and high precision components (which are typical of commercial aerospace and biomedical parts). For small batch production an efficient means of meeting the geometric and surface finish requirements would decrease overall AM part costs and increase competitiveness of AM processes.

Overview of Method:

This work presents a method of integrating AM and subtractive operations into a sequential hybrid manufacturing process called Direct Additive and Subtractive Hybrid (DASH). The DASH system for use in the manufacturing of metal products can combine any direct metal additive manufacturing process with a 4-axis CNC milling system to produce high quality and high precision metal parts with limited human intervention. The system is highly software driven, using the AMF file format to represent and optimize the design for finishing by adding fixture elements and machining allowance prior to AM fabrication. This work includes development of a new software system, integration and enhancements of multiple existing technologies, optimization of a sacrificial fixturing system, and assembly into a unified operational system (Figure1).

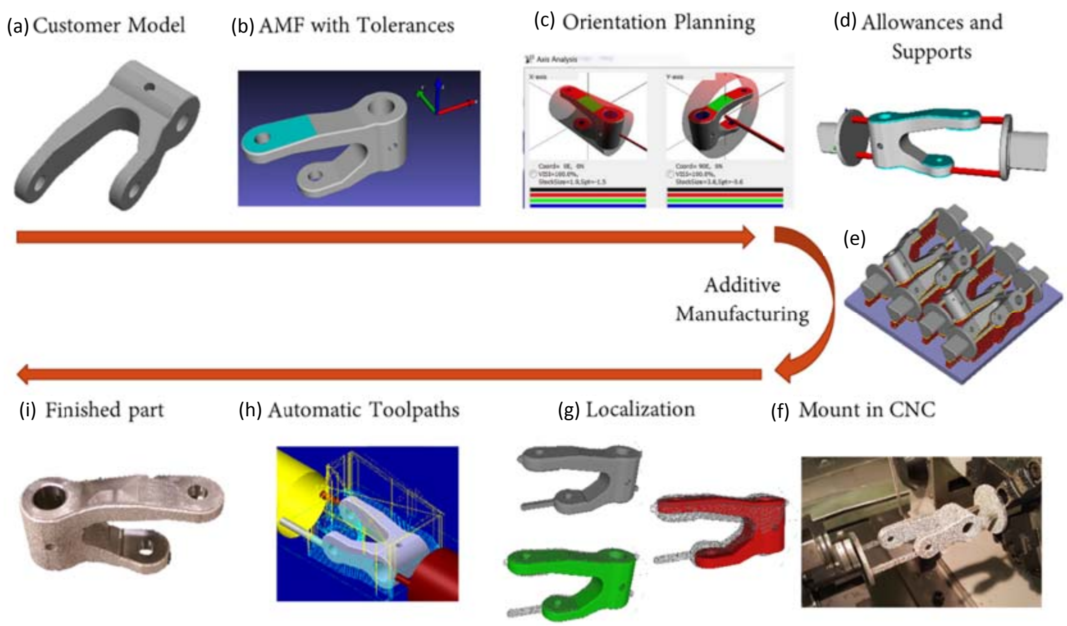

Figure1: DASH Process Flow; (a) Customer model input, (b) AMF model creation with critical features identified, (c) Machining setup orientation planning, (d), Addition of machining allowance and sacrificial fixture supports, (e) Metal AM processing, (f) clamping in CNC mill, (g) scanning and part localization, (h) automated toolpath generation, (i) finished part after support removal

Figure 1 shows a specific example part that underwent these steps and demonstrates the current capabilities of the DASH process. To start, the customer model (Figure1a) is used to generate an AMF file which is marked up digitally to identify critical part surfaces (Figure1b) in a custom program called AMFCreator (Srinivasan et al., 2015). This step is where the user is choosing surfaces that will require post processing, and providing data about the surface type and tolerance. Next, we take a forward-looking step and determine how the part will need to be machined, using that information to drive a CNC setup orientation (Figure 1c). The AMFCreator software then adds machining allowance to critical surfaces, along with sacrificial fixture elements that will secure the part during machining (Figure 1d). Finally, we reach the typical starting point in metal AM, where we have an STL file ready to process and print (Figure 1e). Upon removal from the build plate and AM support removal, the part is clamped in a CNC machine using the sacrificial fixture supports (Figure 1f) (Boonsuk and Frank, 2009). Next, the part is scanned (using laser or other) and the part orientation and stock conditions are captured (Figure 1g). In CAM, using CNC-RP (Frank et al., 2004), the part has automated toolpaths generated and executed (Figure 1h), and the machined metal AM part is delivered (Figure 1i). The following sections provide a brief review of each major step in the DASH process.

Critical feature identification:

As a part of the DASH process, one must first identify the critical features that are slated for post process machining. As such, a software package called AMFCreator' was developed to allow an operator to create and manipulate AMF Files that designate as-printed versus as-machined features. The software is used across numerous steps such as; 1) importing and exporting to and from STL and PLY files, 2) Selecting surfaces and associating them with features, 3) adding tolerance information to features, 4) Adding machining allowances, 4) computing feature parameters and finally 6) creating sacrificial support geometry for the final machining process.

AMFCreator was written in C++ with the QT ("Qt - Home," n.d.) widget toolkit and the VTK ("VTK - The Visualization Toolkit," n.d.) visualization system. XML I/O was performed with the TinyXML2 library ("TinyXML-2," n.d.). The UI consists of two sections, as seen in Figure 2. To the left is a window in which the AMF model is displayed. Models displayed in this window can

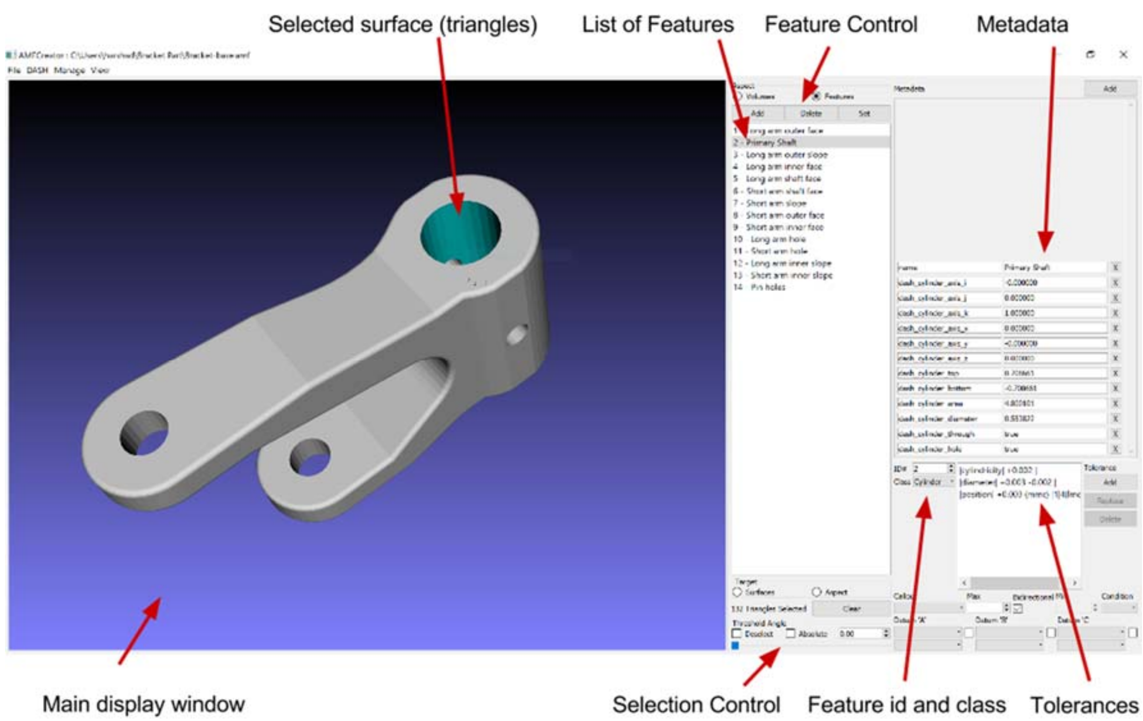

Figure 2: AMFCreator software interface

be scrolled and panned similar to any CAD package. The window is also used to demarcate surfaces for association with a feature, and as a means for selecting volumes and surfaces. To the right of the display window is a list that displays either the set of features or the set of volumes in the AMF file. In this step of the process, the user navigates across the surface of the part selecting and painting features, along with tolerance and other feature parameters. The output of this is an AMF model that is interpreted by the machining process planning software, CNC-RP, which is described next.

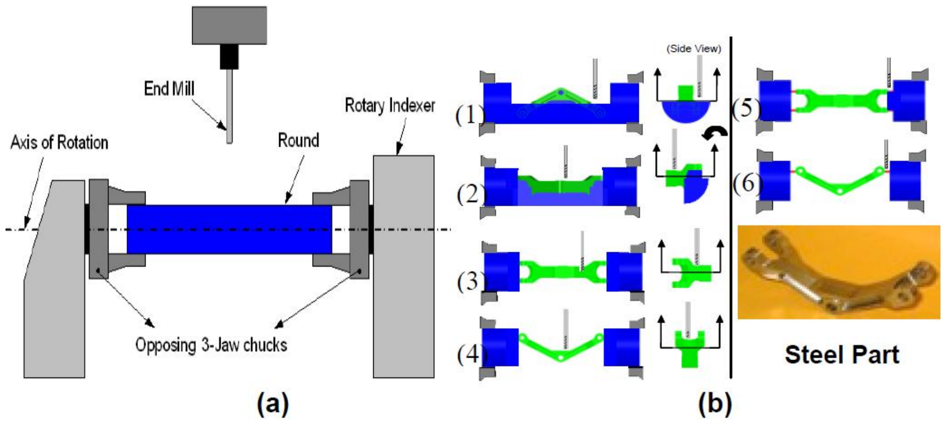

Figure 3: CNC-RP Process, (a) Rotary fixture setup; (b) Process sequence of steps (1- 6) to produce a steel component

Machining Approach:

An existing enabling technology for rapid machining, CNC-RP, was originally conceived at Penn State and further developed at Iowa State University (Frank et al, 2004, 2006; Petrzelka and Frank 2010). It is a fully automated Subtractive Rapid Prototyping process that uses a 3-axis vertical milling machine with a 4th axis indexer for multiple setup orientations. In this system, round stock material is fixed between two opposing chucks and rotated between operations using the indexer, and visibility analysis of cross sectional slice data provides a basis for automated setup planning about a single axis. This implementation uses a modified Greedy set cover algorithm to determine orientations. For each orientation, all visible surfaces are machined using simple toolpath planning while leaving a structure of “sacrificial supports” that are used to fixture the part (keeping the part attached to the remainder of the stock). The number of rotations required to machine a model is dependent upon its geometric complexity. Once all of the operations are complete, the supports are severed in a final series of operations, and the part is removed. Figure 3 illustrates the process steps for creating a typical complex part using this method. The following sections will overview a few critical steps within CNC-RP process planning, for orientation, setup, and sacrificial fixture planning. As shown, CNC-RP is a plug-in for MasterCAM software, using tool library and toolpath generation methods from the commercial software, while automating decisions and planning normally done by the NC code programmer.

Orientation and Setup Planning:

The “Axis Analysis” interface in CNC-RP is made up of nine images as shown in Figure 4, where each image denotes an orientation and the scores for this orientation given. As shown, images # 1, 2, 3 always present the three principle orientations, while images # 4, 5, 6 pick the best option according to a sole criterion, namely, the best orientations for visibility, stock diameter and support rigidity. Image #7 presents the software-suggested orientation based on a multi-criteria search, while image #8 presents the orientation that the user chose in the search space. Lastly, image #9 presents a rotatable orientation that the user can customize. The colored progress bar indicates the visibility, where the color indicates the type of the surfaces in question (flats, holes, or freeform).

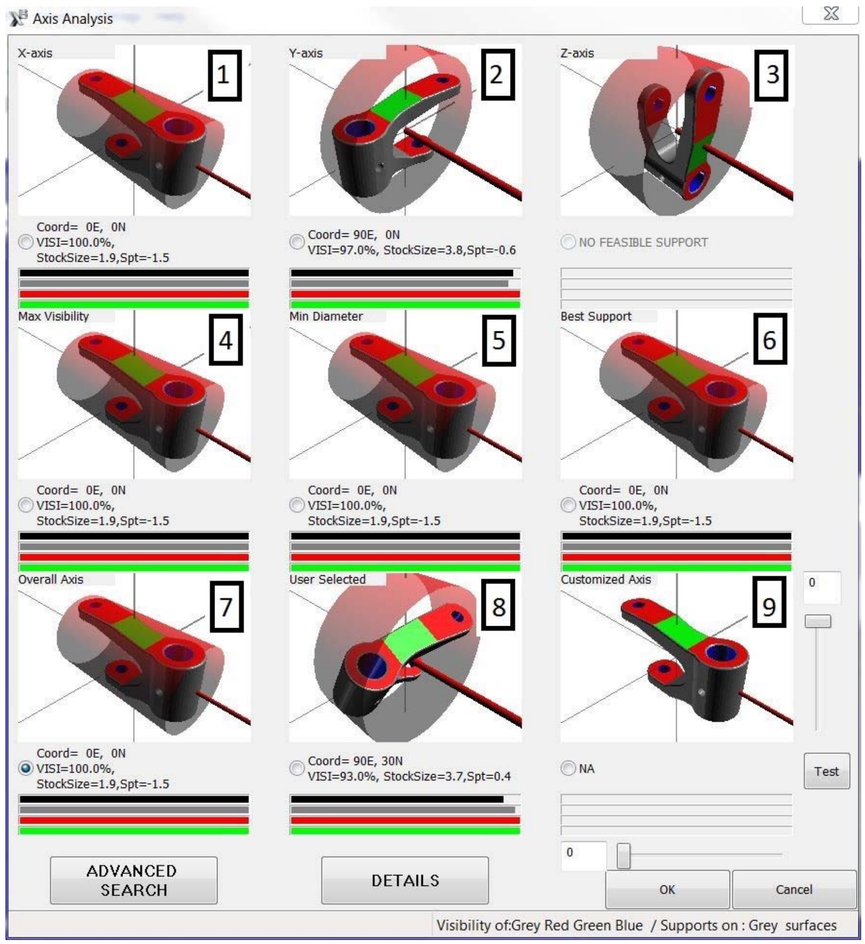

Figure 4: Axis analysis interface

Once an orientation for the rotary axis is chosen, the software aids in creating sacrificial supports that keep the part fixed to parent round stock. The user selects 1) a material type, and 2) a maximum allowable deflection (related to overall part tolerances). CNC-RP then automatically identifies the diameter, number and location of supports based on beam theory and an optimization routine. The interface shown in Figure 5 allows the user to examine sacrificial support placement based on the orientation they chose and to modify the positions and sizes of the supports. There is an approximately 2X factor of safety, allowing the user to as-much-as delete one of the supports entirely.

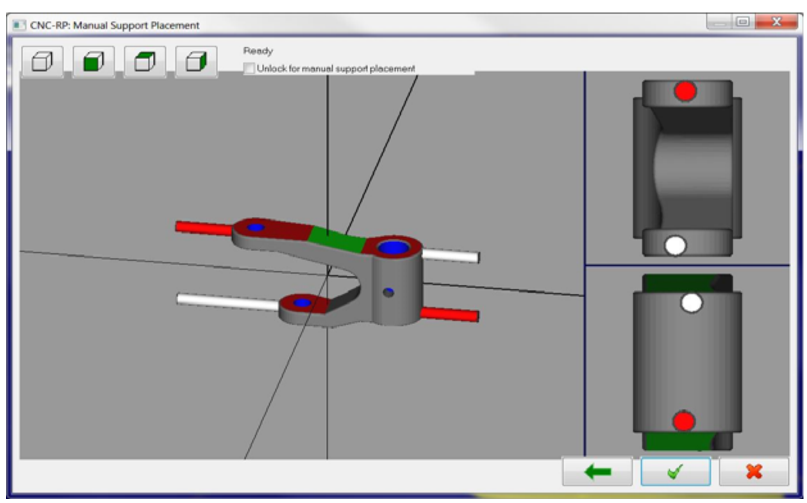

Figure 5: Sacrificial support placement interface

Allowances and Fixturing:

Up to this point along the work flow, the part's machining orientation has been chosen and support geometry is identified. Any changes to part orientation is captured in .XML data that is passed back to AMFCreator. Next, AMFCreator must add additional fixture clamping elements, along with machining allowance (padding material) on the feature surfaces that will be machined. In addition, sacrificial supports defined in CNC-RP as cylinders are converted to prismatic (square section) and oriented to minimize AM supports (based on build orientation). Finally, the part's STL model is prepared for metal printing. As shown in Figure 6, the customer's initial model in arbitrary orientation is now appended with fixture and support elements that are ready for printing. AMFCreator will eventually contain a library of fixture clamping interfaces depending on CNC machine setup; in this case, a simple 3 jaw chuck clamp-able set of triangles. An example part build from an EBM is shown in Figure7.

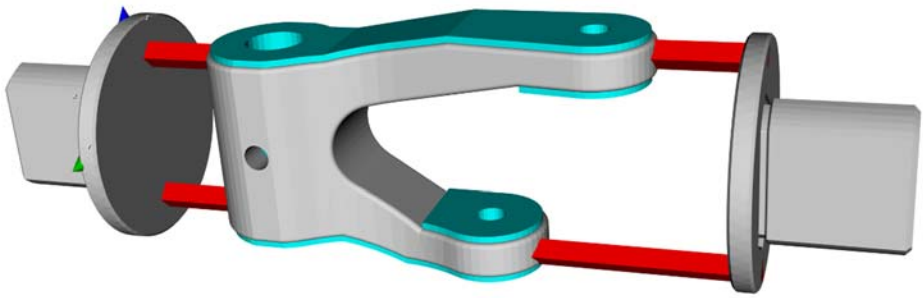

Figure 6: Part model in AMFCreator, with sacrificial supports, fixture clamping elements, and machining allowance on critical surfaces

Figure 7: Part, AM supports, and Sacrificial supports to fixture clamping elements after powder bed metal printing

Scanning and Localization:

Each part, like those shown in Figure 7, will be clamped between opposing jaw chucks of the milling machine. Of course, a combination of metal printing variability, warping, handling, placement and clamping errors have placed the part in an orientation that does not precisely coincide

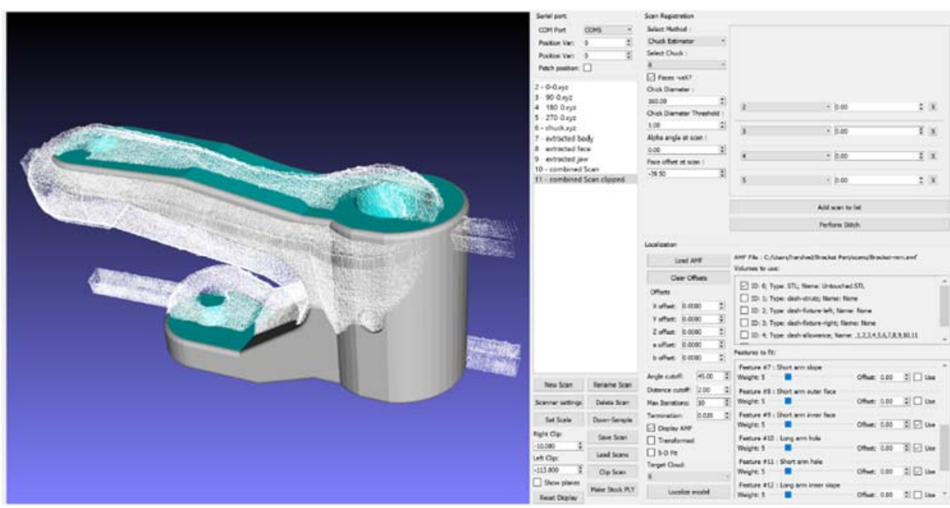

Figure 8: Laser scanning interface for DASH

with the part model in the CAM software. We now desire the answer to two questions; 1) where is the part geometry located? and 2) how much material represents the "stock surfaces" after printing, now for machining? With respect to the second question, after printing we might anticipate some AM supports have been removal, but not all; therefore scanning yields the as-printed stock conditions. One would actually anticipate that a DASH-processed part would not technically require any AM support removal per se; but it would reduce machining time if AM supports can nominally be broken away before machining. The method chosen to find the part location and model its stock condition is laser scanning. Figure 8 presents the scanning software interface for DASH. In this process, the point cloud data from scanning is used to do two things. First, we identify a set of critical surfaces on the part, and calculate the transformation matrix that would align this as-fixtured part orientation to the CAD model's location in the CAM (MasterCAM) environment. As such, the part is translated and rotated in CAM, using the CNC-RP software plug-in. In addition, a slightly oversized STL mesh of the entire part, support, etc. geometry is passed to CNC-RP, where MasterCAM can utilize it as a stock model. In the following step, CNC-RP will have all information necessary to generate NC code for critical surfaces.

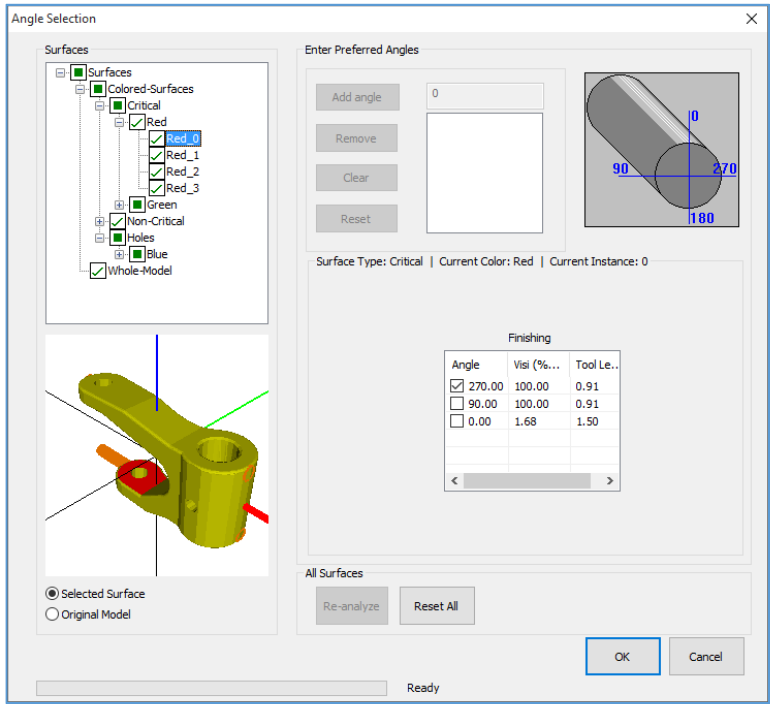

Figure 9: CNC-RP toolpath planning interface

Toolpath Generation:

The details of all surface-based automated toolpath planning is neglected here for lack of space. In brief, each critical part surface previously identified in the AMF model is used to create a set of feature-specific toolpaths. As shown in Figure 9, a flat surface (red) on a part has been identified and machining angles are chosen automatically (Frank et al., 2006). The subsequent steps choose tools, machining strategy, cut parameters, and automatically define containment boundaries.

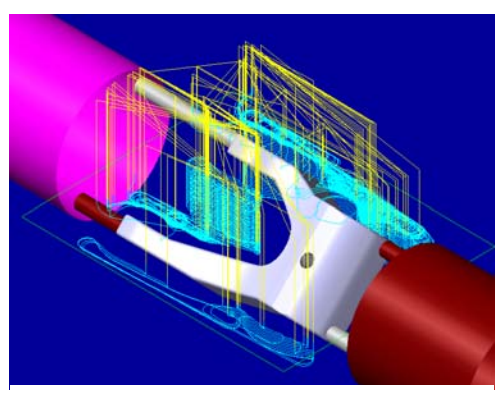
Figure 10: Roughing toolpath calculation

Once all critical surfaces are identified, CNC-RP additionally calculates toolpaths for rouging operations that remove all remaining AM supports first (Figure 10), before launching into feature-specific toolpaths. Total process planning time for NC code generation is measured in minutes.

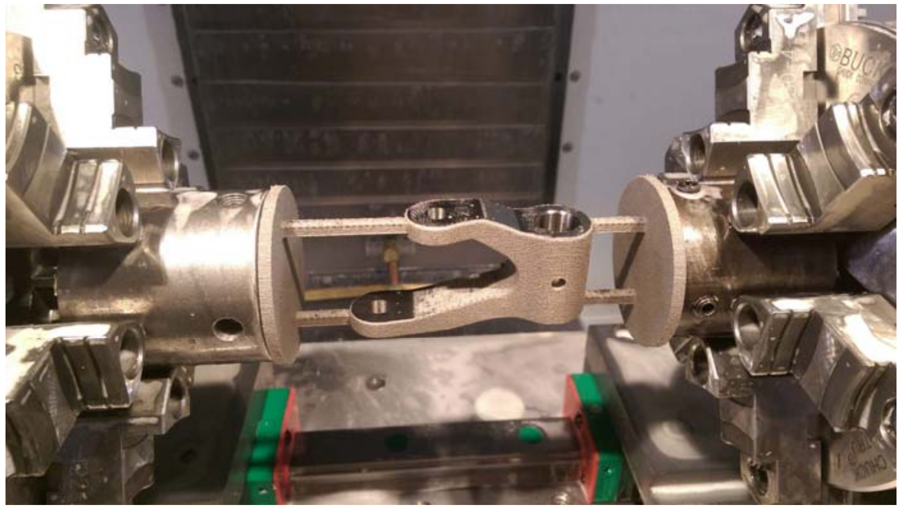

Figure 11: DASH processed part immediately after machining

Implementation:

The DASH process has been executed on sample linkage components using both steel and titanium alloys. The titanium alloy was printed using an Arcam EBM while the steel parts were made on an EOS DMLS system. Critical features were originally overgrown 2mm for the first builds in steel and titanium, and then a second set of trials in titanium used a smaller allowance of 1.25mm with no negative effects. Figure 11 shows the part in the milling machine while Figure 12a shows the progression of the part, from as printed in the EBM, to as-fixtured and machined in a HAAS VF2ss, to final part upon sacrificial support removal. In addition, CMM measurement data (Figure 12b) shows dimensional accuracy well within 0.1mm (0.002”). These and numerous other trials have shown the effectiveness of the DASH process at integrating Additive and Subtractive Manufacturing and providing high-quality finished metal components.

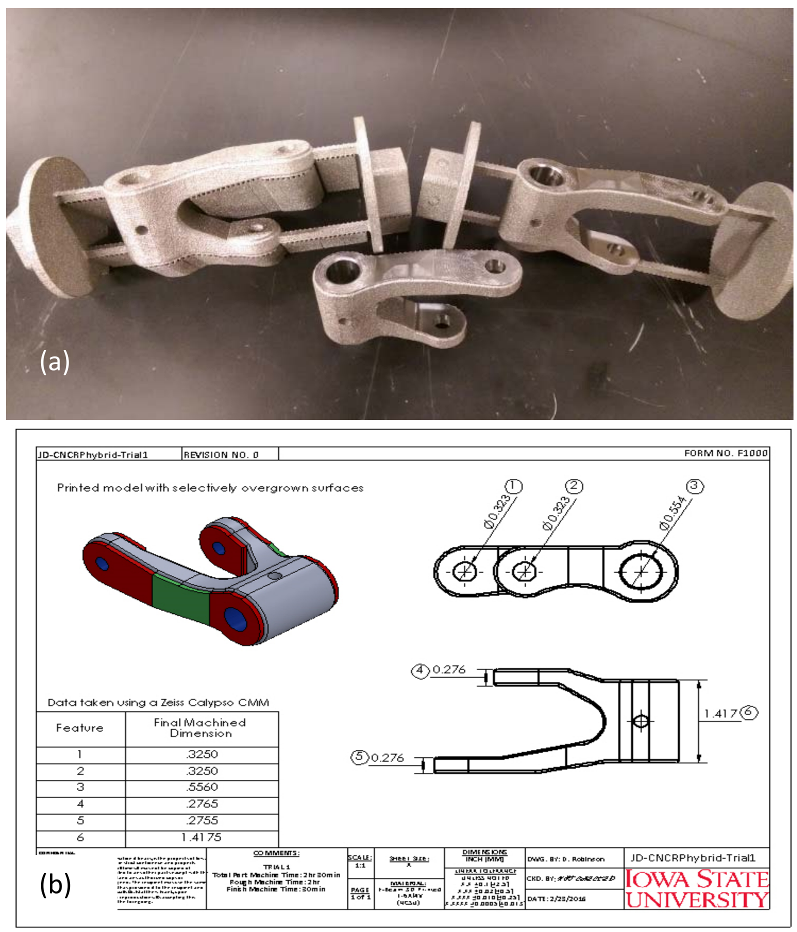

Figure 12: Titanium part sample; (a) progression across the process, and (b) CMM analysis data on nominal dimensions

Conclusions:

The proposed DASH process is focused on integrating additive manufacturing (AM) with a subtractive manufacturing (SM) process for the production of precision metal components. The concept for finishing metal additive manufacturing (AM) parts using a traditional subtractive manufacturing process appears to work well for test components to date and is providing high quality parts at remarkable levels of automated process planning. However, the process is not a simple "turnkey system" and requires human intervention across the stages. It does not, however, require days or weeks from a machine shop nor does it take the level of skill of a typical CNC programmer. In closure, DASH shows promise for significant reductions in both cycle time and skill required to get a functional, post-processed part from metal additive manufacturing.

Reference:

Boonsuk, W. and Frank, M.C., "Automated fixturing for a rapid machining system", Rapid Prototyping Journal Vol. 15, No. 2, pp. 111-125, 2009

Frank, M.C., Wysk, R.A., and Joshi, S.B., "Rapid Planning for CNC Machining – A New Approach to Rapid Prototyping", Journal of Manufacturing Systems, SME, Volume 23, No. 3, pp. 242-255, 2004

Frank, M.C., Wysk, R.A., and Joshi, S.B., "Determining Setup Orientations from the Visibility of Slice Geometry for Rapid CNC Machining", Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol. 128,
No. 1, pp. 228-238, 2006

Petrzelka, J.E., Frank, M.C., "Advanced Process Planning for Subtractive Rapid Prototyping", Rapid Prototyping Journal, Vol. 16, No. 3, pp. 216-224, 2010

Srinivasan, H., Harrysson, O. L. A., & Wysk, R. A. (2015). Features and tolerances in additive manufacturing - An extension to the AMF file format. In American Society for Precision Engineering, ASPE.