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Oak Ridge National Laboratory
Development and Evaluation of Hybrid Manufacturing Toolpaths

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OAK RIDGE NATIONAL LABORATORY
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MANUFACTURING DEMONSTRATION FACILITY: DEVELOPMENT AND EVALUATION OF HYBRID MANUFACTURING TOOLPATHS

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This Cooperative Research and Development Agreement (CRADA) No. NFE-19-07874 was conducted as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for MDF technical collaborations are listed in the announcement "Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies" posted at http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf. The goal of technical collaborations is to engage industry partners to participate in short-term, collaborative projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

EXECUTIVE SUMMARY

The integration of additive manufacturing (AM) capabilities on Computer Numerical Control (CNC) systems allows for the expansion of additive manufacturing to a wide range of part and tool repair operations. This multi-tasking integration, termed hybrid manufacturing, has been researched by others in the past, and Autodesk has been critical in developing process planning and toolpath algorithms for hybrid systems.

Objectives and Tasks:
Hybrid manufacturing systems enable both additive and subtractive capabilities in a single manufacturing workcell. These systems have the potential to impact a variety of industries, including the tool and die industry due to their repair, refurbishment, and complex geometry manufacturing capabilities. While there has been significant development of toolpath planning for both subtractive and additive processes independently, there has been little, if any, development of hybrid toolpath planning to integrate both processes during the manufacturing design and toolpath generation stage of a product's lifecycle. Furthermore, additive toolpath planning has been limited to planar manufacturing, but this limitation could be overcome as hybrid CNC machines have multi-axis control. The objectives of this research include:

- Development and demonstration of independent three-, four-, and five-axis toolpath generation algorithms for both additive and subtractive processes, and
- Development, demonstration, and integration of three-, four-, and five-axis hybrid process planning and toolpath generation algorithms for hybrid additive and subtractive processes.

The team will leverage the widely used Autodesk Fusion 360 product design and manufacturing (CAD/CAM) platform to achieve these objectives. Autodesk will provide the expertise in CAD tools, as well as access to their new CAD/CAM manufacturing tools (3-, 4-, and 5-axis milling, additive toolpath generation). ORNL will provide expertise in additive manufacturing toolpath generation, process planning, and manufacturing validation. By the end of the program, the team will have developed and validated multi-axis milling, additive manufacturing, and hybrid manufacturing on an industrial hybrid CNC system (Mazak 500-VC).

To verify completion of the objectives, the following tasks will be completed during this project.

Task 1: Perform machining toolpath verification (ORNL/Autodesk)

- Identify three target geometries, one each for 3-, 4-, and 5-axis machining. (ORNL)
- Develop toolpath strategies for each of these types of machining. (Autodesk)

- Manufacture each target geometry to (1) quantify manufacturing time (Autodesk/ORNL) and (2) quantify geometric accuracy using a Zeiss laser line scanner and a coordinate measurement machine (CMM) (ORNL).

Task 2: Perform additive toolpath verification (ORNL/Autodesk)

- Identify three target geometries, one each for 3-, 4-, and 5-axis additive manufacturing. (ORNL)
- Develop BeAM printer settings for Autodesk Fusion 360. (Autodesk)
- Manufacture each target geometry to (1) quantify manufacturing time (Autodesk/ORNL) and (2) quantify geometric accuracy using a Zeiss laser line scanner and a coordinate measurement machine (CMM) (ORNL).

End of phase goal: Develop and validate both additive and subtractive toolpath generation for 3-axis, 4-axis and 5-axis processes.

Results and Conclusions:

ORNL has collaborated with Autodesk to evaluate Autodesk Fusion 360 for both additive and subtractive manufacturing. Multiple components were generated using various techniques that require a varying number of degrees of freedom. This work provides a baseline understanding of the state of the art for hybrid manufacturing toolpath planning and gives direction to future research in this field. Since the completion of this project, the development on Autodesk Fusion 360 has continued. Thus, these results may not accurately reflect the current capabilities of Autodesk Fusion 360.

1. PROJECT OBJECTIVE

Hybrid manufacturing (integrated additive and subtractive processes) has the potential to significantly increase the efficiency of manufacturing through more efficient energy and material utilization in part repair and part refurbishment. The expansion of the additive manufacturing industry has catalyzed conventional machine tool manufacturers to explore hybrid manufacturing systems. By leveraging the massive CNC industrial base, production of hybrid manufacturing systems could rapidly exceed that of additive manufacturing systems by more than an order of magnitude. There are numerous examples of hybrid manufacturing reducing process energy consumption, reducing waste material, increasing cost savings, and enabling new markets:

- Part repair: Numerous industries, including construction, agriculture, defense, and oil and gas, have legacy equipment with no inventory of replacement parts. Hybrid manufacturing can enable direct part repair through the integration of additive, subtractive, and onboard inspection processes. Repair will reduce energy, cost, and time associated with complete new part production.
- Tool repair: Tooling wear can lead to loss in productivity. Production of replacement tooling can take months and cost hundreds of thousands of dollars. Tool repair, much like part repair, can significantly reduce down-time, as well as tooling cost and lead-time.
- Repurposed tooling: Rather than building new tooling from scratch, hybrid processes enable repurposed tooling: an old tool or die that is no longer in service can be reshaped for a new product, reducing tooling cost and lead time.
- Reduction in post processing time: A significant misunderstanding regarding additive manufacturing is that one simply presses the “print” button and obtains finished, end-use parts. In reality, there is significant post processing that must be done on virtually all AM parts. Such processing for metal parts typically requires significant time and energy. Hybrid operations have the potential to dramatically reduce, if not eliminate entirely, the need for post processing.

These applications, and many more, have the potential to transform the manufacturing industry and reduce manufacturing time, material utilization, and energy. However, there are still several limitations that must be overcome before the full potential of hybrid manufacturing can be achieved. One of the key limiting factors today is the integrated process planning and toolpath generation for hybrid manufacturing systems.

2. PROJECT BACKGROUND

Autodesk, Inc. is an American multinational software corporation that makes software services for the architecture, engineering, construction, manufacturing, media, education, and entertainment industries. AutoCAD, which is the company's flagship computer-aided design (CAD) software, and Revit software are primarily used by architects, engineers, and structural designers to design, draft, and model buildings and other structures. Autodesk software has been used in many fields, and on projects ranging from the One World Trade Center to Tesla electric cars.

Autodesk is perhaps best known for AutoCAD, but now develops a broad range of software for design, engineering, and entertainment, as well as a line of software for consumers. The manufacturing industry uses Autodesk's digital design and manufacturing software, including Autodesk Inventor, Autodesk Fusion 360, and the Autodesk Product Design Suite, to visualize, simulate, and analyze real-world performance using digital models during the design process.

Autodesk released a new integrated CAD/CAM software tool, Autodesk Fusion 360, in 2013. Autodesk Fusion 360 is a departure from previous CAD software tools for two main reasons. First, it is integrated: the software contains all of the tools to support the entire design-to-manufacture process, including conventional and generative design, optimization, simulation, and computer integrated manufacturing (CAM), as well as integrated 3D printing tools. Second, it's connected: cloud-based resources enable running computationally intensive tasks in the cloud to best take advantage of both the available local hardware and scalability through cloud computing.

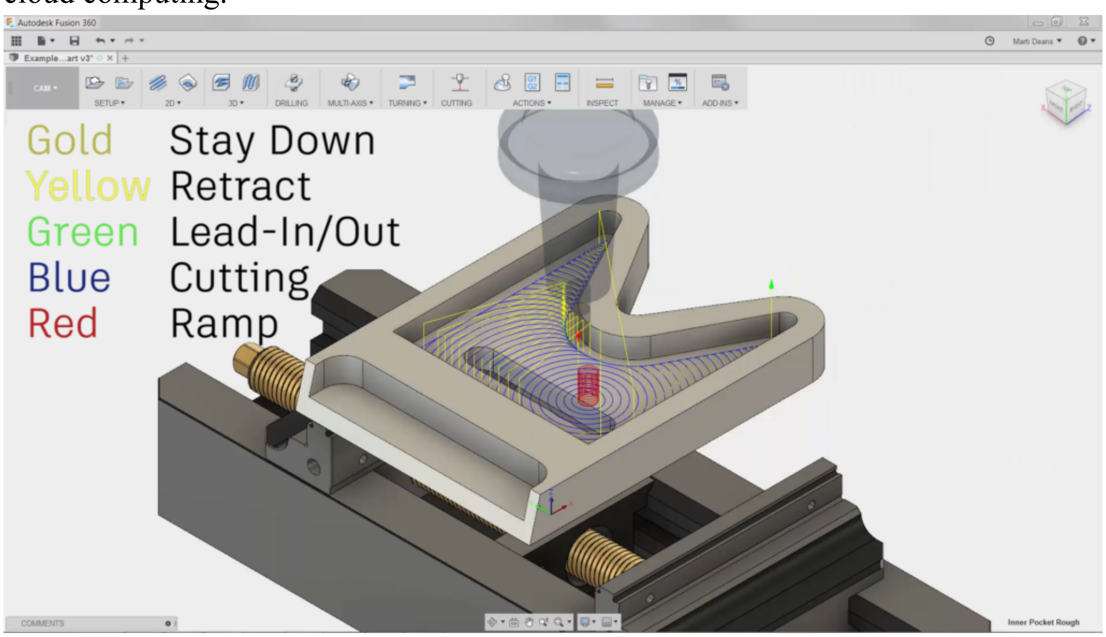

Figure 1: Autodesk Fusion 360 machining simulation

ORNL's Manufacturing Demonstration Facility has established critical partnerships with a broad spectrum of machine tool manufacturers, including Mazak, Cincinnati Inc., Arcam, and Wolf Robotics, and material suppliers, including Lincoln Electric and Techmer. These strategic partnerships position ORNL as an excellent resource in establishing and validating, as a white hat organization, software tools necessary to be effective at utilization of advanced manufacturing tools.

The strategic partnership between ORNL and Autodesk will combine both organizations' resources to enable consideration of the full manufacturing supply chain, including CAD/CAM software tools, materials, machines, and applications. The first phase efforts will focus on validation of Autodesk Fusion 360's existing CAD/CAM tools for additive and subtractive processes. The team will evaluate 3-, 4- and 5-axis milling on a Mazak CNC and 3-, 4- and 5-axis additive manufacturing on the BeAM direct energy deposition system. While there are multiple commercial solutions for five axis machining and five axis additive manufacturing, there has been no software tool that has demonstrated the ability to be effective at both processes, and the partnership with Autodesk seeks to meet that need. Therefore, once these processes are validated independently, the team will work collaboratively on developing an integrated hybrid manufacturing toolset that integrates inspection, additive, and subtractive processes. The efforts will lead to a new hybrid manufacturing tool supported by Autodesk and validated on Mazak's VC-500A/5X AM HWD hybrid CNC machine.

3. RESULTS AND DISCUSSION

Project results and discussion are organized by the project task. This phase I collaboration consisted of two tasks which evaluated machining and additive toolpath planning respectively. The ensuing sections outlines the results and provides relevant discussion.

3.1 PERFORM MACHINING TOOLPATH VERIFICATION

The first task of this project is to perform machining toolpath verification. The purpose of this task is to evaluate machining toolpath generation for a commercially available hybrid manufacturing system (Mazak VC-500A/5X AM HWD)

3.1.1 3-Axis Circle-Diamond-Square

A widely accepted test for machining center acceptance is a Circle-Diamond Square (CDS) as defined by ISO standard 10791-7. This test quantifies the cutting accuracy of machining centers with multiple axis of motion. To machine the various geometrical shapes, a varying number of linear axes are used to generate the required motion. The model and machining toolpath for this component requiring 3-axis of motion were both generated in Autodesk Fusion 360. Figure 2 shows the 316L stainless steel stock used, and the resulting component after machining. The cycle-time for the entire machining operation was 81 minutes.

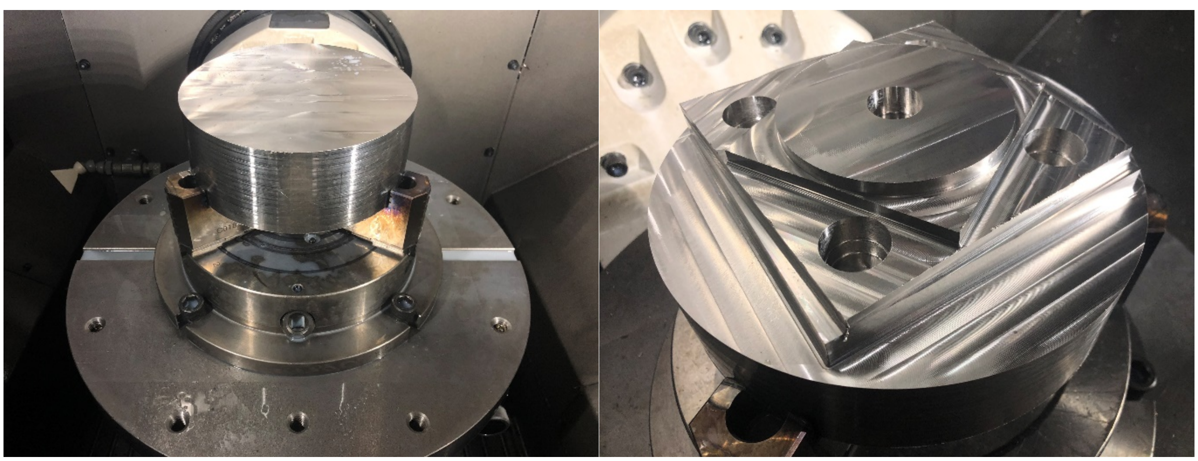

Figure 2: Left - CDS Stock, Right - Finished CDS Component

This component was evaluated using a Zeiss CMM for 44 features including roundness, concentricity, profile, and flatness. All 44 features evaluated exceeded a geometrical accuracy of 0.004”, 19 of which exceeded 0.001”.

3.1.2 4-Axis Hinge

To demonstrate machining toolpaths that require 4-axis of motion, a hinge that is used in aerospace applications was selected. The design, toolpath planning, and inspection of this component were all generated in Autodesk Fusion 360. Due to the height and internal features of the component, the rotary axes were used to reorient the component during the machining operation. This is normally referred to as "3+2 machining".

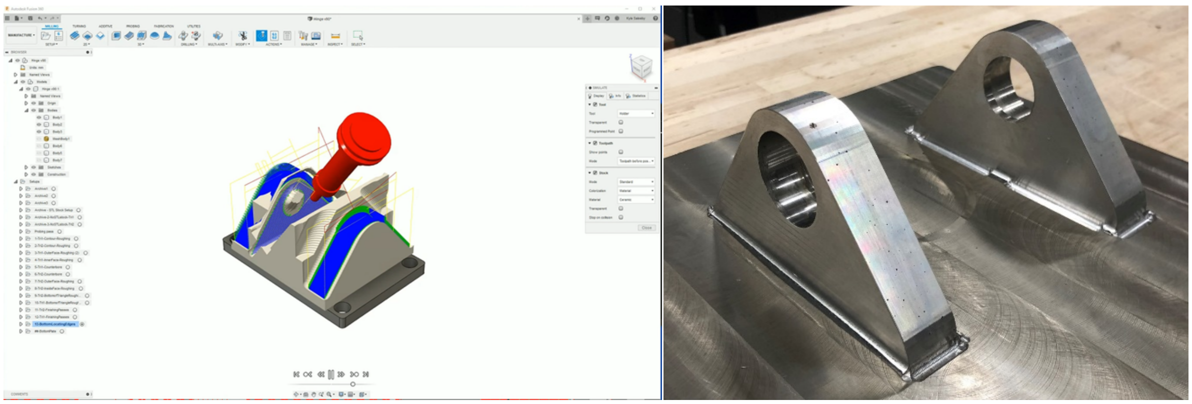

Figure 3: Left-Hinge Toolpath Simulation, Right-Finished Hinge Component

One large unknown in the machining of additive components is the amount of excess deposited material. If overestimated, machining cycle-time is wasted where pre-planned toolpaths are not removing material. On the other hand, tooling and equipment can be damaged if the overbuilt material is underestimated and toolpaths remove too much material in a single pass. To evaluate this workflow, the team developed a process to include inspection techniques in the development of subtractive toolpaths. This novel solution mitigates any guesswork that exists in the toolpath generation process. Figure 4 demonstrates this by showing how a structured light scan was used to generate the stock model of the component being machine. Furthermore, Autodesk Fusion 360 was used to generate inspection toolpaths to leverage the onboard metrology capability of the hybrid machine. This allowed the operator to precisely know dimensions of the deposited component and where it is positioned in the machining volume. Without this workflow, there is a high probability that components would be machined incorrectly. The total machining time for this component was 15:45. However, extremely conservative material removal rates were programmed for these tool paths to safely explore the novel toolpath planning method. A drastic reduction in total machining time is expected if this component was manufactured again and programmed with production-level material removal rates.

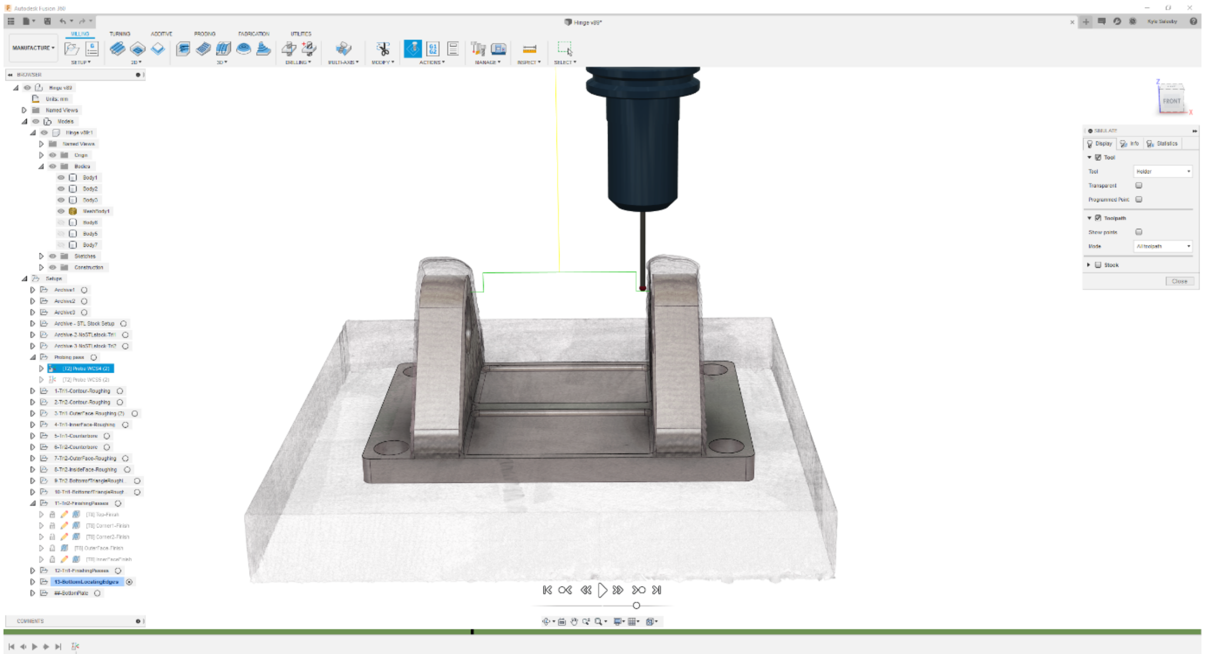

Figure 4: Inspection Based Toolpath Planning

3.1.3 5-Axis Blade

To evaluate 5-axis machining toolpaths developed by Autodesk Fusion 360, an aerospace blade was selected. The geometry of this component was carefully selected to necessitate the use of all five machine axes. This geometry is composed of two main sections; (1) A half-cylinder base measuring 4” in diameter and 4” in length, and (2) a lofted blade of 1.9” in height, measuring 0.08” at its thinnest point and 0.23” at its thickest point. Both the cylinder base and blade geometry were printed on standard stainless steel substrate before machining. The deposition development process for this component is described in Section 3.2.3.

Figure 5: Machined Aerospace Blade

Machining strategies were developed in Autodesk Fusion 360 with series of roughing and finishing passes. The printed half-cylinder base was rough machined with a parallel toolpath strategy. This strategy moves the tool in parallel lines of constant stepover following the contour of the cylinder. A final finishing pass with decreased stepover was used to prepare the surface for blade deposition. The blade component was machined with a multi-axis toolpath in four primary sections; (1) Suction side roughing, (2) pressure side roughing, (3) leading and trailing edge roughing, and (4) surface finishing. Both roughing and finishing strategies relied on point machining with a ½" diameter ball end mill, where the tip of the cutting tool is used to trace out the blade's contour. The lead and lead angles of the ball endmill (additional orientation positions enabled by B- and C-axis rotary table) were restricted between 30deg to 55deg. It is noted that not all material was removed at the blade's base due to difficulties in toolpath programming, illuminating areas of improvement for the Autodesk Fusion 360 software. Total machining time was 4:28.

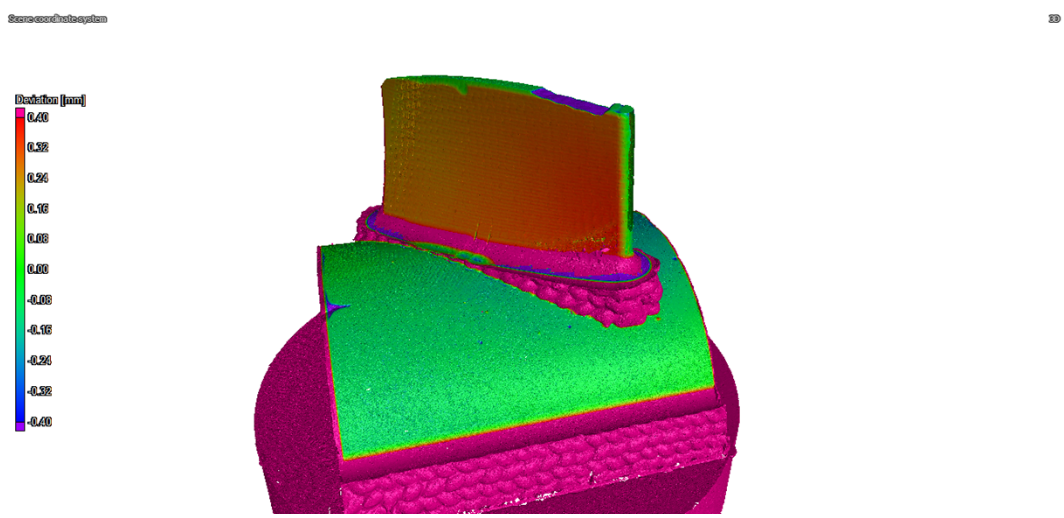

Figure 6: Scanned Aerospace Blade

3.2 PERFORM ADDITIVE TOOLPATH VERIFICATION

3.2.1 3-Axis Circle-Diamond-Square

The CDS geometry defined by ISO standard 10791-7 and presented in section 3.1.1 was also used to test and verify additive toolpath generation in Autodesk Fusion 360. A cylinder measuring 8.1” in diameter and 1.4” in length fully encapsulates the CDS geometry. Additive toolpaths to print the bounding cylinder were generated in Autodesk Fusion 360. The total simulated deposition volume is 663 cm^3.

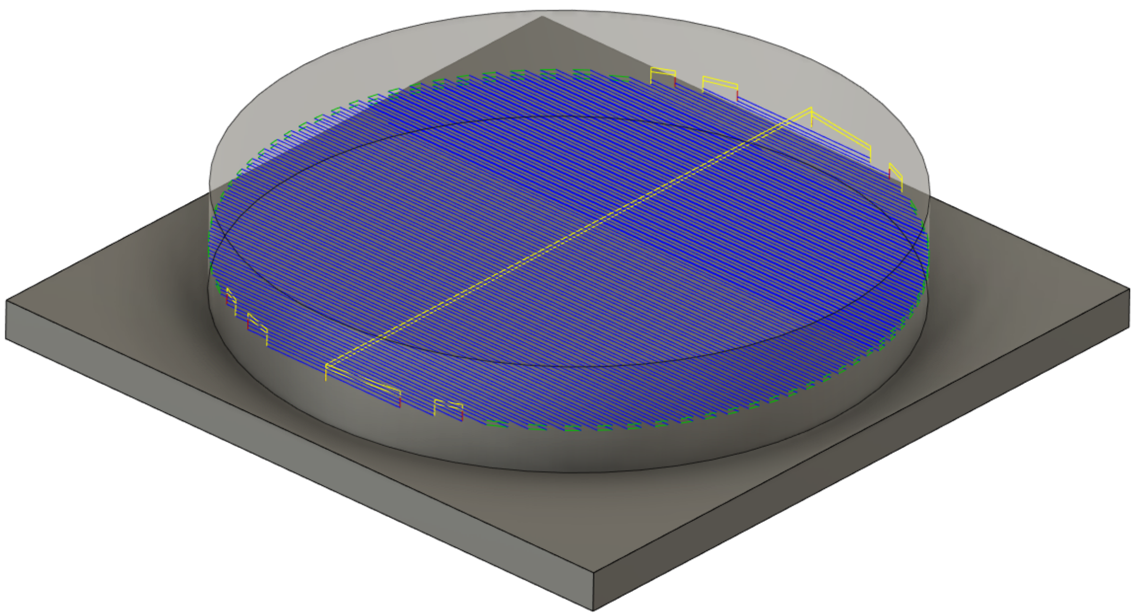

Figure 7: Circle-Diamond-Square Printed Stock

Additive toolpaths were validated on a Mazak VC-500A/5X AM HWD. A total of 24 layers were deposited, and a dwell time of 32 seconds was used between deposition of each layer. Total deposition time for this geometry was 3:56.

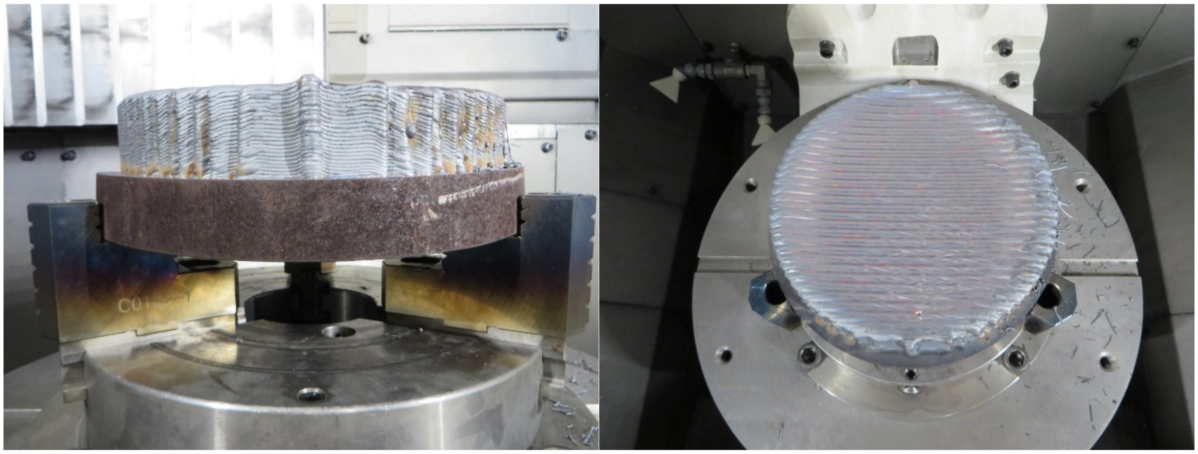

Figure 8: Circle-Diamond-Square Deposited Geometry

Significant underbuilding was found near the center of the CDS printed geometry. This is common effect caused in part by thermal overheating and static process parameters. Additionally, small bead segments tangent to the cylinder were generated at either end of the geometry. These points were significantly overbuilt, demonstrating an area for improvement in Autodesk Fusion 360's additive toolpath strategy.

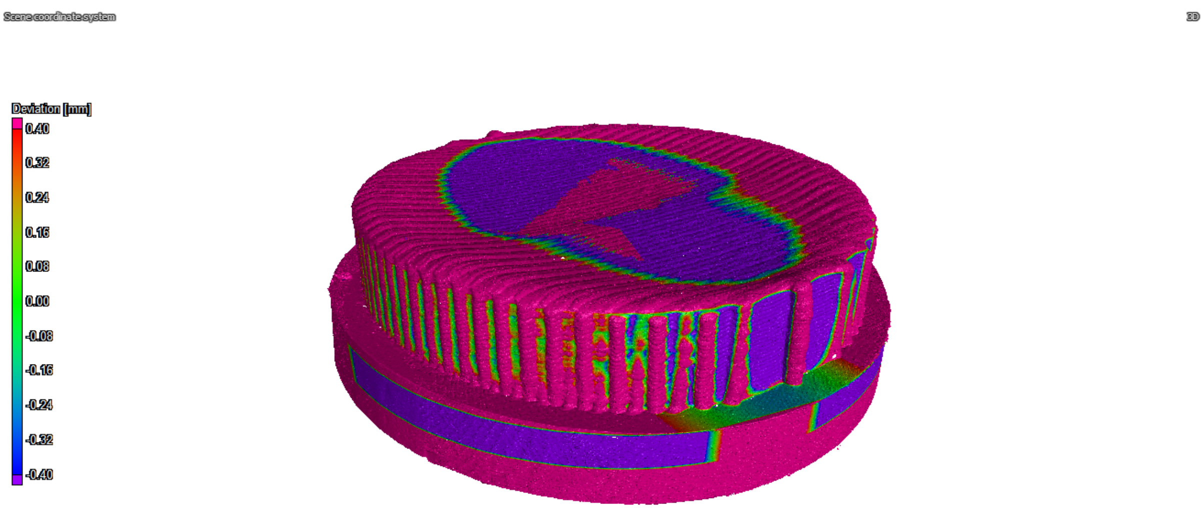

Figure 9: Circle-Diamond-Square Scan

Significant warping of the substrate resulted after the CDS printed geometry cooled. Deviations up to 0.20" were measured from previously machined surfaces. Warped geometry was closely matched with areas of non-uniform printing, such as the ends of the geometry with significant overbuilt geometry.

3.2.2 4-Axis Pyramid

A five-sided pyramid geometry was chosen to validate 4-axis deposition tool paths in Autodesk Fusion 360. It was intended that the geometry would be printed at a fixed B-axis orientation while the C-axis rotated, providing primary motion for circular tool paths. However, Autodesk Fusion 360 was unable to generate a correct strategy for this configuration. Autodesk Fusion 360 was able to generate fixed 3-axis and full 5-axis deposition toolpaths, but additional development is needed for deposition with 4^{th} axis rotational configurations. The geometry and deposition strategy were modified to use a standard 3-axis deposition strategy and a 3+2 machining strategy. This part provided an additional benefit of exploring correct bead stepover and height parameters for non-vertical geometry in Autodesk Fusion 360.

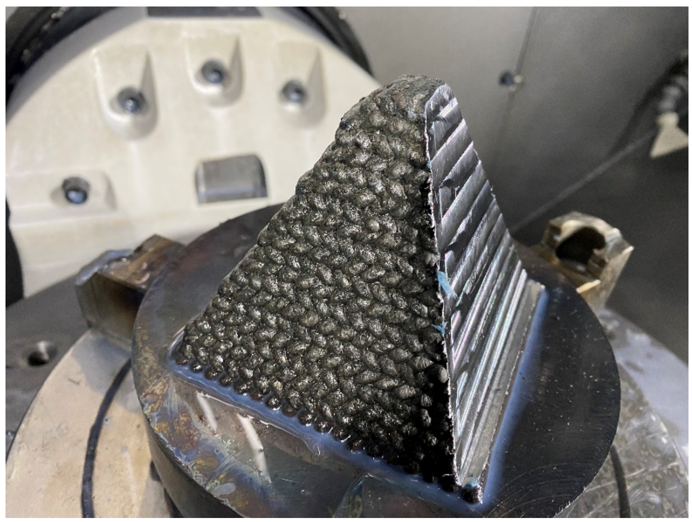

Figure 10: Pyramid Deposited Geometry

Total deposition time for the pyramid geometry was 0:40. A 30 second dwell was used between each layer. Uniform rastering strategies for this component resulted in little, if any, unintended underbuilding. After deposition paths were validated, machining paths were used to create functional surfaces. The part was oriented at fixed B- and C-axis orientations to position the face orthogonal to the cutting tool. A parallel machining strategy with a ½" flat endmill was used to finish the pyramid surfaces. A constant 0.5mm stepdown and 7mm stepover was programmed to create even chip loads. Total machining time was 1:07.

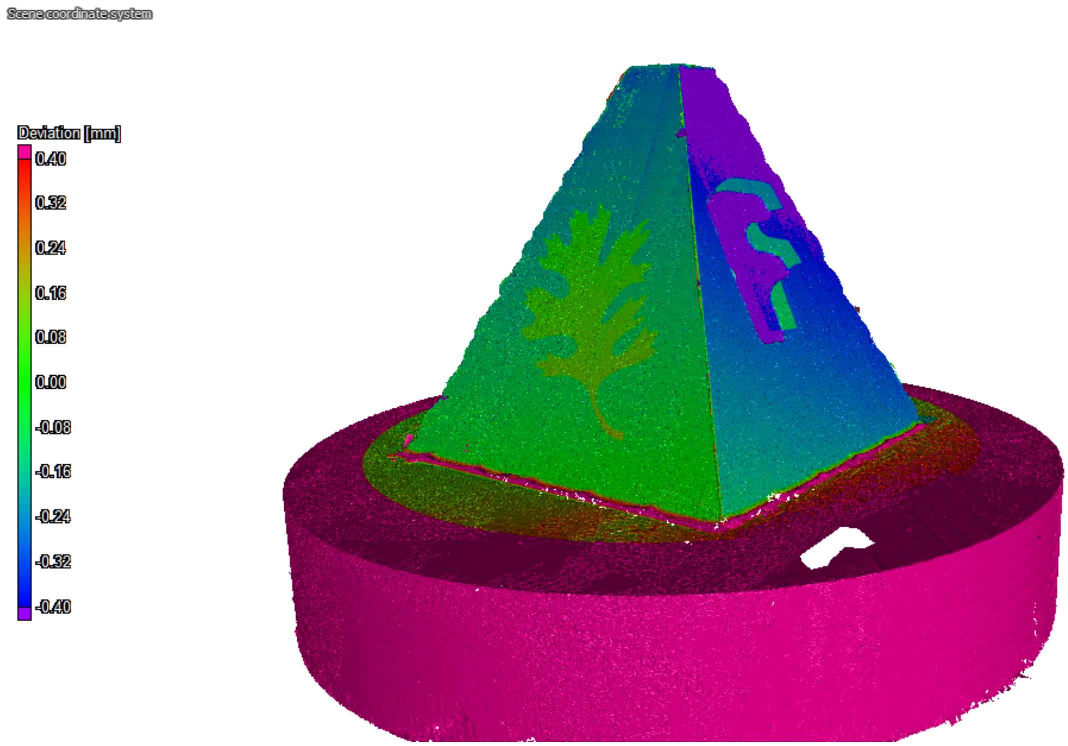

Figure 11: Pyramid Machined Scan

3.2.3 5-Axis Blade

A blade geometry 1.9” in height, resting on a 4” half-cylinder was selected for 5-axis deposition strategies using Autodesk Fusion 360. The geometry is described in depth in section 3.1.3. The 4” diameter half cylinder was printed with a 0.06” radial overbuild and 0.12” axial overbuild. A 30 second dwell was used between deposition layers to reduce thermal overheating. Total deposition time was 1:35. The printed half-cylinder was machined to provide a curved base for the blade.

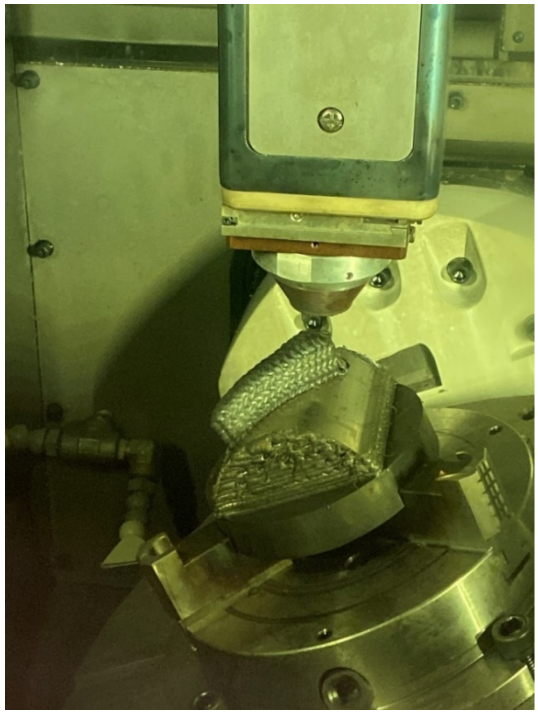

Figure 12: Aerospace Blade Deposition

Deposition of the blade geometry necessitated the use of all 5 machine axes to keep the deposition head orthogonal to the curved half-cylinder base. The print orientation was programmed at a 45 deg angle to the X-axis, rastering across the width of the blade. Due to the orientation of the blade on the curved surface, the B-axis was used for primary rotary motion, ranging from -35 to 35 degrees. The C-axis was primarily used for smaller positioning increments, ranging from -15 to 15 degrees.

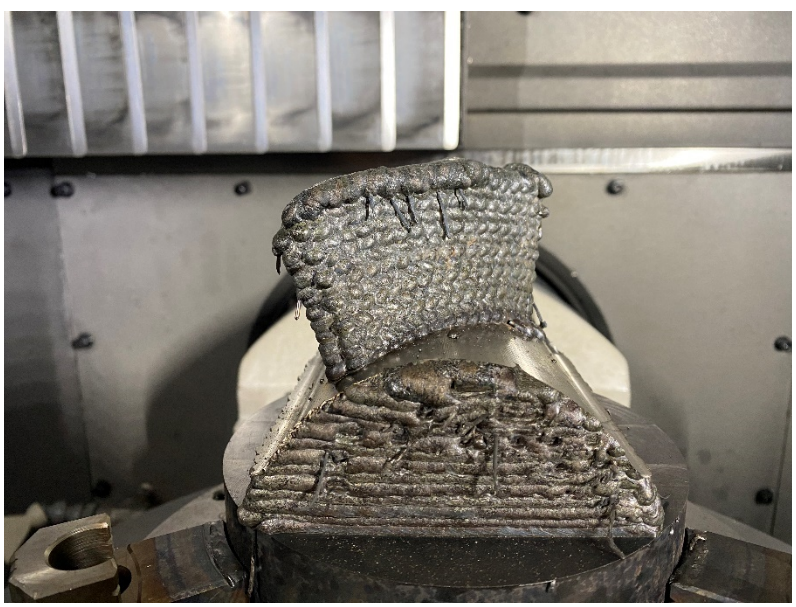

Figure 13: Deposited Aerospace Blade

Toolpaths for the blade geometry resulted no significant underbuilding in the geometry. A constant stepdown height of 0.5mm over 5 subtractive passes was used to machine the printed geometry. Tool engagement was consistent across the blade's face, demonstrating a uniform build in most locations. However, there was significant overbuilding of the leading and trailing edges of the blade. This is primarily due to decreased feed rate when the print head attempts to accelerate around small fillet contours. Additionally, high frequency motion was found during deposition near the leading and training edge of the blade. It became clear that greater B- and C-axis rotary motion would be needed to smoothly position the deposition head in a full 5-axis configuration. This is an area of improvement identified for future development.

4. CONCLUSIONS

During this project, Autodesk provided expertise in CAD tools, as well as access to their new CAD/CAM manufacturing tools (3-, 4-, and 5-axis milling, additive toolpath generation), and ORNL provided expertise in additive manufacturing toolpath generation, process planning, and manufacturing validation to develop and validated multi-axis milling, additive manufacturing, and hybrid manufacturing on an industrial hybrid CNC system (Mazak VC500 HWD.)

During the completion of this work, significant collaboration with the Autodesk Fusion 360 deposition development team was required to generate and validate deposition toolpaths. Multiple technologies and toolpath strategies in the Autodesk Fusion 360 environment were identified for continued development, such as the inclusion of 4-axis deposition strategies and refinement of 5-axis smoothing capabilities for deposition on non-planar surfaces. These capabilities are essential for CAD/CAM manufacturing tool, necessitating future development and validation. The Autodesk Fusion 360 platform, widely distributed in small-medium business machine shops across the country, is uniquely positioned to support the adoption of hybrid technologies, decreasing material waste and increasing energy efficiency. Since the completion of this project, the development on Autodesk Fusion 360 has continued. Thus, these results may not accurately reflect the current capabilities of Autodesk Fusion 360.

4.1 PUBLICATIONS AND PRESENTATIONS

T. A. Feldhausen. “Hot-Wire Deposition Development”. Conference Presentation. Discover 2019. November 2019

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T. A. Feldhausen. “Distortion Monitoring and Control for Directed Energy Deposition”. Conference Presentation. American Society for Precision Engineering. July 2020

T. R. Kurfess, T. A. Feldhausen, K. S. Saleeby, V. C. Paquit. “Leveraging the Digital Thread to Integrate Next Generation Manufacturing Processes”. Presentation. DOD I-DREAM4D. July 2020

K. S. Saleeby, T. A. Feldhausen, T. R. Kurfess, L. J. Love. “Feedback Control of Hybrid Manufacturing Processes with Infrared Thermal Measurements and Low-Cost Sensors”. Conference Presentation. International Symposium on Flexible Automation. July 2020

T. R. Kurfess, T. A. Feldhausen, K. S. Saleeby, V. C. Paquit. "Integrating Hybrid Manufacturing Processes via the Digital Thread". Conference Presentation. International Symposium on Flexible Automation. July 2020

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K. S. Saleeby, T. A. Feldhausen, T. R. Kurfess, L. J. Love. "Production of Medium-Scaled Metal Additive Geometry with Hybrid Manufacturing Technology". Proceedings of the ASME 2020 15th International Manufacturing Science and Engineering Conference. January 2021

K. S. Saleeby, T. A. Feldhausen, L. J. Love, T. R. Kurfess. "Rapid Re-Tooling for Emergency Response with Hybrid Manufacturing". Smart and Sustainable Manufacturing Systems. November 2020