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Procedia CIRP 121 (2024) 210–215

www.elsevier.com/locate/procedia

11th CIRP Global Web Conference (CIRPe 2023)

Hybrid metal manufacturing of large freeform geometries

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Abstract

An integrated, multi-system research platform has been developed to explore the fabrication of large-scale metal components though hybrid manufacturing. The resulting research cell is highly flexible as it incorporates multiple robot stations, a multi-axis part transfer system and a five-axis CNC machine tool. Current process capabilities include multi-material wire-arc additive manufacturing, fringe projection scanning metrology, robotic part handling and finish machining. A geometric digital twin is used to establish and transfer part positions, datums and coordinate axes across these processes. Mechanical and electrical system integration is complete and a sequential process flow has been demonstrated by fabricating a monolithic, single wall part geometry.

Keywords: Hybrid manufacturing, wire-arc additive manufacturing, fringe projection scanning, multi-axis machining

1. Introduction

The timely fabrication of large, complex metallic structures is a persistent challenge for American industry. A shrinking domestic manufacturing base has resulted in delivery schedules for large parts and preforms, i.e., 0.5m cube and larger, that are routinely defined in months and years, introducing unacceptable risk and cost for many products and applications. Further, bulk feedstocks require extensive machining for complex part geometries, producing the undesirable waste of material, time and money. While additive manufacturing (AM) provides numerous opportunities to reduce material waste and improve process throughput, functional requirements for part form accuracy and surface finish typically require final finishing [1]. Thus, the majority of AM workflows demand a hybrid process wherein additive and subtractive processes are combined to deliver final products.

While hybrid processes are utilized extensively across manufacturing sectors, integrated additive-subtractive workflows and systems are relatively scarce in their deployment. Many AM service providers rely on manual workflows where parts are printed and post-finished using different machines, operators, setups and fixturing. This is particularly true for wire-based deposition processes since as-deposited geometries and surfaces typically exceed functional requirements for dimensional accuracy and surface finish [2]. Wire-based deposition processes are ideally suited for fabrication of large metal parts; they are also relatively easy to deploy. Thus, they have been researched in hybrid additive-subtractive equipment and processes for almost two decades [2-3]. Many of these implementations have mounted a gas metal arc welding (GMAW) torch [2-4], a gas tungsten arc welding (GTAW) torch [5] or a laser-wire torch [6] directly into CNC machine tools. Subsequently, commercial machine tool vendors and service bureaus [7-9] have adopted these architectures over the past decade since they rely on existing

10.1016/j.procir.2023.09.250

CNC products and can readily produce parts on the order of 0.5m.

Robots have also been explored for hybrid additive-subtractive workflows where they serve as the manipulator for both deposition and machining processes [10-12]. In each of these instantiations, parts remained fixtured relative to the machine tool or robot and retain their locations during process transitions from deposition to machining. This co-locating of processes, however, reduces throughput by requiring one or more processes to idle during other cycle(s).

De-coupling of deposition and machining is straightforward for simple shapes and represents a “traditional” sequential hybrid workflow where a complete deposition cycle of the near net part shape is followed by a complete machining cycle [13]. Complex part geometries such as topology optimized freeforms, internal features, high aspect geometries and/or multi-material constructs, however, require iterative processes whereby deposition and machining occur incrementally in some repetitive order for differing sections of the part geometry. Such iterations in a decoupled system face challenges in the loss of part location and coordinate frames with each process transition. One approach to maintaining part position is to rely solely on the positioning accuracy of a mechanical pallet system [14]. This approach is unable to adjust either machining or deposition to the previous process step and so each cycle must be conservative, resulting in overbuilt material during printing and air cutting during machining.

An alternate approach is to utilize metrology to develop an in-situ digital thread [15-16] of both part position and shape, and to use this thread in an adaptive hybrid manufacturing process. This informed approach has been performed manually in prior work [17-18], has been utilized by others [19], and is demonstrated here in an integrated hybrid manufacturing platform using an automated process sequence. The hybrid cell couples multi-material wire-arc additive manufacturing (WAAM) with five-axis milling through the use of fringe projection scanning metrology and robotic part handling. Developed to examine the high throughput production of large metal parts with material and geometrical complexity, introduction of a digital thread has created a process flexible for both sequential and iterative process flows.

2. Hybrid Work Cell

The hybrid cell provides three fundamental process steps; metal deposition, metrology and machining, Fig. 1. These steps are integrated using a supervisory controller as parts can be moved between process stations at any time using a multi-axis part positioner, a six degree of freedom robot and a part pallet system.

Nomenclature

AM	additive manufacturing
CAD	computer aided design
CAM	computer aided manufacturing
CMT	cold metal transfer
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
KRL	Kuka Robotics Language
MIG	metal inert gas
PLC	programmable logic controller
RSI	robot sensor interface
WAAM	wire-arc additive manufacturing

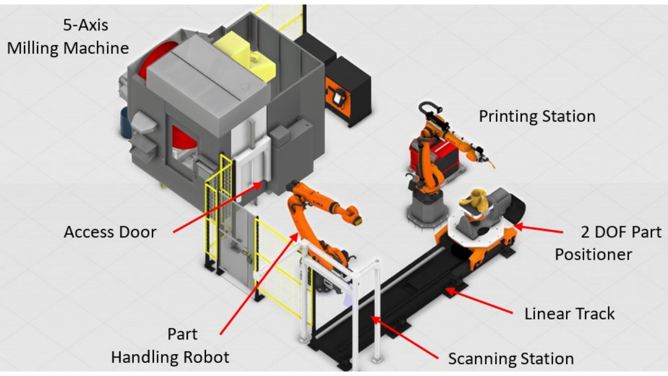


Fig. 1. Hybrid research cell layout.

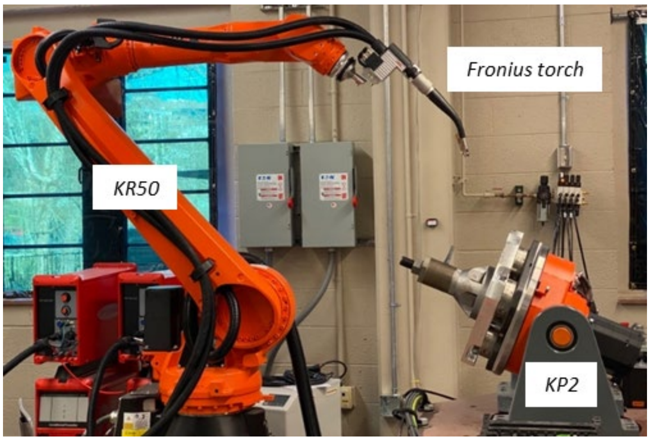


Fig. 2. Nine axis robotic printing station using a Kuka KR50 six-axis robot and a Kuka KP2 rotary-tilt positioner.

2.1. Material Deposition

Part fabrication begins at the printing station using robotically controlled wire-arc additive manufacturing. Material deposition is performed using a Fronius CMT (cold metal transfer) 4000 Advanced dual wire welding torch. The Fronius torch can function as a single or dual wire torch, and can therefore generate both single and multi-material deposits. Pre-loaded Fronius proprietary synergic lines control baseline welding profiles using two independent, Fronius CMT 4000 Advanced power supplies. Synergic lines are selected based on wire composition, wire diameter and shielding gas. Subsequent process settings are then selected based on desired bead geometry, deposition rate and heat input.

The Fronius torch and deposition baseplate are moved during printing using nine axes of coordinated motion. The welding torch is mounted to a six-axis KUKA KR50 R2500 industrial robot, Fig. 2, which is mounted on a pedestal 0.5m above the floor. Possessing a maximum payload of 50kg and a maximum reach of 2.5m, the KR50 can easily provide the

Fig. 3. HAAS UMC-750 5-axis machining center. The pneumatic entry door is partially in view, looking through the front door window.

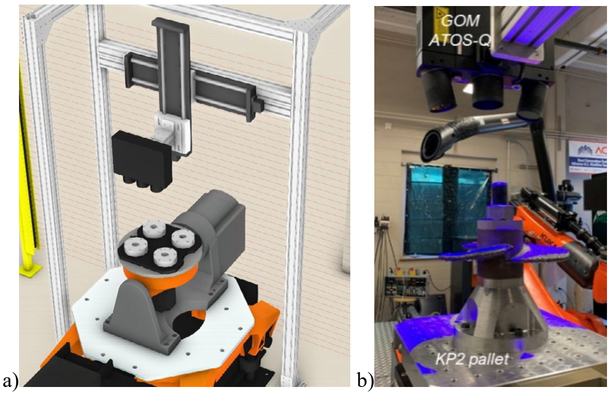


Fig. 4. a) Metrology station configuration with b) the ATOS-Q positioned vertical relative to a part surface.

motion necessary for parts up to 2m in size. Three additional axes of motion are available through the baseplate as it is fixtured to a KUKA KP2 HV500 two-axis rotary-tilt positioner mounted onto a KUKA KL4000 linear track. The KP2 provides an infinite rotation axis, and establishes the limit for printable part weight with its maximum payload of 500kg. The KL4000, with its 4000kg payload capacity and 3.4m of travel, enables part motion within the various stages of the work cell and is capable of handling any printable part.

The nine axes of motion are controlled by a single KUKA KRC4 controller using multiple coordinate frames to ensure accurate coordination of the wire and workpiece during deposition. The primary KR50 robot has a world coordinate frame located at its base. The KL4000 has a stationary coordinate frame aligned along its travel length while a moving tool frame is positioned at the top face of the KP2 rotary-tilt stage. Additional tool frames are identified at both wire tips of the Fronius torch. While redundant robot systems have been implemented by others [8, 20, 21], these systems rely on stationary six axis robots and rotary-tilt workpiece stages. Thus, kinematics and trajectory planning algorithms were developed to coordinate robot and workpiece motion using multiple static and dynamic coordinate frames [22].

To program printing motions, robotic trajectories are generated using a custom, path planning code implemented in MATLAB [23]. These path plans are converted into build files based on the KUKA Robotics Language (KRL) using Octopuz's Robot Programming software. KRL provides greater robot control than G-code, and facilitates real-time collection of robot and torch data using KUKA's Robot Sensor Interface (RSI). Control of the Fronius torch is accomplished using KUKA.ArcTech software commands generated in Octopuz that are sent to the Fronius power supplies via the KRC4 controller's DeviceNET connection. Upon generation of the entire print sequence in Octopuz, build files are uploaded to the KRC4 and the robot is prepared for printing.

2.2. Machining

A key aspect of any hybrid manufacturing process is the machining required to satisfy the form and finish specifications of industrial products. Machining in the hybrid cell is performed using a Haas UMC-750 five axis milling machine, Fig. 3. The UMC-750 is a tilting-table machine with its spindle mounted to three linear axes and its worktable mounted to two rotary axes. The UMC-750 can machine parts up to 305mm in diameter with a maximum table weight of 300kg, both smaller than the limits of printing. Parts are transferred into the machine by a KUKA KR250 handling robot thru a 690mm tall and 660mm wide pneumatic side-door. Door operation is performed manually or automatically using the supervisory controller. The UMC-750 also includes a Renishaw OMP40-2 touch trigger probe for on-machine gaging. While the probe does limit the available machining volume, it is essential in determining part location and orientation after it is transferred into the machine.

2.3. Metrology

Since printing and machining processes are physically isolated and therefore decoupled from one another, fringe projection scanning metrology is performed to generate a geometric digital twin which is used to establish part shape and location. Scanning is performed using a GOM ATOS-Q 8M fringe projection scanner due to its uncertainty (roughly 25µm), its image resolution (100µm in X-Y) and its ease of implementation. The scanner has a fixed working distance of 490mm, a field of view of 350 x 260mm and captures 8 million surface points per measurement scan. It is mounted to a rigid frame positioned above the KL4000 linear track, Fig. 4. The frame includes two manual linear stages and a pivoting gimbal mount for positioning the scanner relative to the part. During measurements, the scanner position is fixed with the KP2 rotary-tilt stage providing pitch and yaw part motion. This approach has proven efficient and straightforward for simple part geometries. More complex geometries, however, experience challenges with feature access and measurement time [24].

To generate the part-fixture geometric digital twin, multiple scans are performed using different part-to-scanner positions and orientations. These scans are stitched together in GOM software to produce a three- dimensional point cloud of the part that is polygonised and converted into a watertight STL model, Fig. 5. This digital representation is then used to

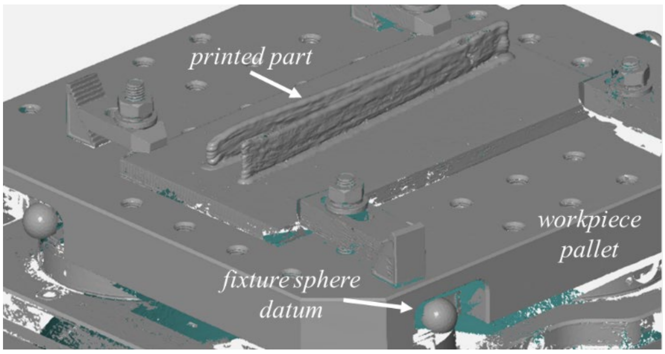
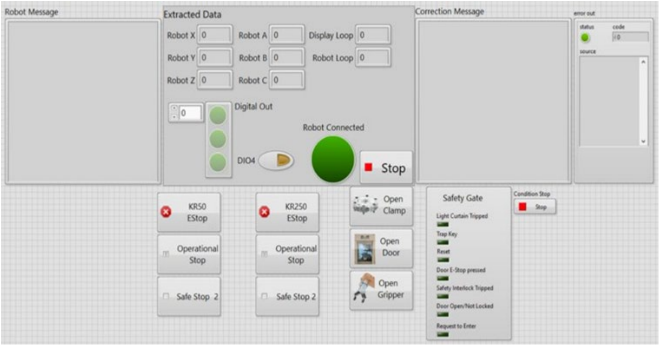


Fig. 5. Digital model of a part and fixture captured using the ATOS-Q scanner. White regions in the image represent measurement dropout.



Robot X 0
Robot Y 0
Robot Z 0
Robot A 0
Robot B 0
Robot C 0
Display Loop 0
Robot Loop 0
code 0

Fig. 6. LabVIEW operator interface for monitoring and controlling the hybrid manufacturing cell.

establish a virtual part coordinate frame in CAM software based on fixture datums more accurate than any WAAM feature or surface. This virtual coordinate frame can be transferred directly for printing since the part remains fixtured when moved from metrology to printing via the KL4000. When the part is moved to the UMC-750, however, its coordinate frame relative to the machine is established by probing the fixture datums using the Renishaw OMP40-2. Thus, part transfers can be performed without loss of the part surface geometry, location or orientation [17-18].

Creation and use of the digital part-fixture model holds additional benefits. It provides an accurate stock preform for CAM programming that can be moved and oriented virtually to optimize machining metrics such as cycle time, form accuracy or surface finish. It can also ensure that the desired part shape is contained within the preform. The identification of missing material in the preform can facilitate pre-emptive correction or repair, and subsequently eliminate wasteful process cycles. Typically, missing material can be remedied through additional deposition and occurs due to deposition underbuilds, part distortion and/or excessive machining. Such control is typically unnecessary for simple part geometries, ex. thick walls, but becomes necessary for complex or high aspect ratio parts where the location of the final part relative to the preform geometry is not easily determined. Further, metrology after each process step provides information on part evolution that is valuable to research, computational models and/or control of deposition or machining parameters.

2.4. Part Transfer

Robotic part transfer is a differentiating, yet crucial element of the hybrid manufacturing cell as it directly impacts part location and stability across process steps. While the KL4000 positioner moves parts between the printing and metrology stations, a KUKA KR250 R2700 six-axis industrial robot is used to move the part and its pallet system from the top of the KP2 to or from the inside of the UMC-750. The KR250 has a reach of 2.7m and a maximum payload of 250kg, the current limit to part weight for the hybrid cell.

Parts are fabricated onto build plates that are clamped to a reusable pallet system that mounts onto the KP2 or the UMC-750. The pallet interfaces to four Schunk NSL3-400 pneumatic clamps which generate 32kN of clamping force with a positioning repeatability of 5μm. The pallet interfaces to the KR250 using a Schunk NSR 160 end-of-arm pneumatic gripper. The NSR 160 has a 4kN pull-down force, and maximum moment loads of 600Nm and 1600Nm for its pitch and roll axes, respectively, when supporting the pallet in a horizontal orientation.

2.5. Supervisory Control

Integrated control of the hybrid manufacturing cell is performed using a supervisory control system [25]. System communications are performed using programmable logic controllers (PLCs), while cell operation is managed through a LabVIEW operator interface on a single host computer, Fig. 6. The operator interface oversees all printing and part handling robotic operations. It also provides monitoring and control of material handling peripherals, safety systems and shutdown procedures. Finally, the supervisory controller is responsible for monitoring and recording process sensor data.

3. Sequential Hybrid Demonstration

Operation of the integrated hybrid manufacturing platform has been demonstrated by fabricating a 50mm tall, thin-walled vee geometry. The vee consisted of two 254mm long legs, separated by a 7.4° internal angle. The part was printed using 25 single bead layers, each with a nominal layer height of 2mm and bead width of 6mm. The machined wall location was positioned at the centerline of the nominal 6mm wide bead deposit. Prior work developed a sequential process flow for a low carbon steel thick wall using independent WAAM and machining systems, and manual part transfers [18]. The same process flow was utilized here, but with the hybrid cell performing the complete cycle in an automated manner using the supervisory controller. Operators programmed and monitored each process step, with robots and the machine tool performing each operation. A notable exception was the manual control of layer starts based on manual measurements of part interpass temperature.

Images from each major process step are provided in Fig. 7, with the resulting fabricated geometry provided in Fig. 8. Material deposition required roughly 2hr and was performed using AWS A5.7/ErCuNiAl nickel aluminium bronze filler wire. Fronius CMT deposition settings used a spiral weave with a 290J/mm heat input, a 108mm/s wire feed speed and a 5.4mm/s robot speed. GOM ATOS-Q scanning was

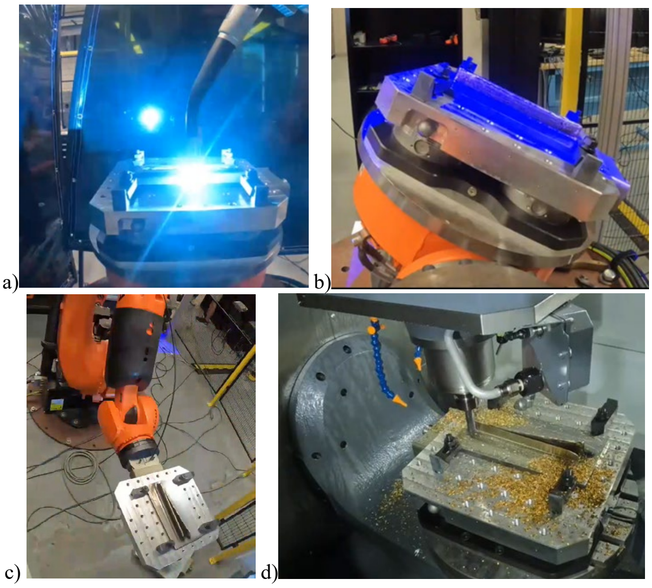


Fig. 7. Hybrid manufacturing cell in operation demonstrating a) material deposition, b) metrology, c) part transfer and d) machining.

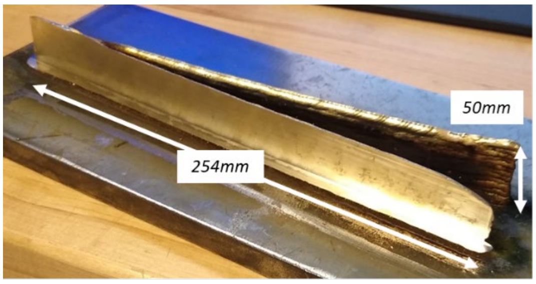


Fig. 8. Final part geometry demonstrating the integrated hybrid manufacturing research cell.

performed in 1hr, while robotic part transfer required only 3min. Finish machining was performed without coolant in 10.5min using a 4 flute, 19.05mm diameter endmill. Cuts were conservative and unoptimized, but performed using a 1528rpm spindle speed, a 543 mm/min federate and a 3mm axial stepdown per pass.

As anticipated from a hybrid additive-subtractive process, the dimensional form accuracy and surface finish of the as-printed geometry were improved dramatically after final finishing. Fig. 9 provides comparisons of the baseline design geometry with the part shapes measured by the ATOS-Q scanner. The as-printed near net shape part exhibits over 3.5mm of overbuilt material, while the finished side wall geometry is within 0.2mm of the baseline design. The errors in the opposite leg of the vee geometry are not shown, but exhibit a similar shape and dimensional error. Fig. 10 shows the as-printed and machined side surfaces measured at 12x using a Keyence VR-5200 fringe projection optical microscope. Individual bead layers are clearly visible in the as-printed surface, resulting in an areal surface roughness, S_a, of 270µm and a peak-to-valley deviation, S_z, of 2.1mm. The machined surface is improved by two orders-of-magnitude, with a S_a of 2.7µm and a S_z of 72.8µm. Again, these values are not the result of an optimal machining process, but demonstrate the generalized utility and potential of the hybrid process.

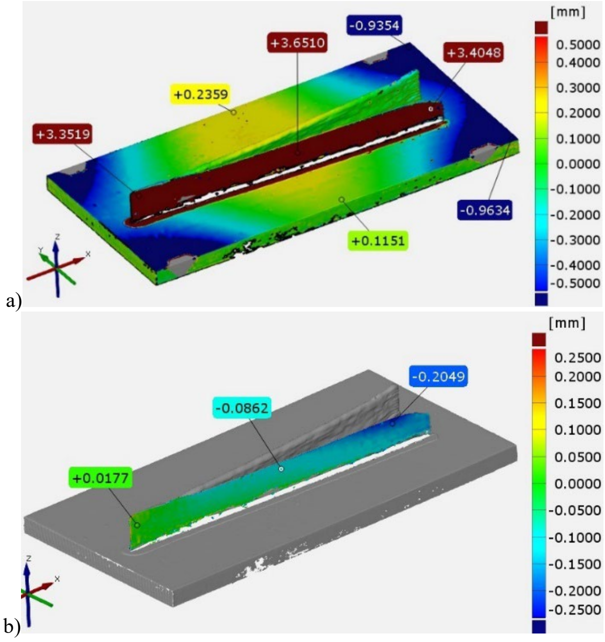


Fig. 9. Comparison of the baseline design to the a) as-printed geometry and b) final machined side wall.

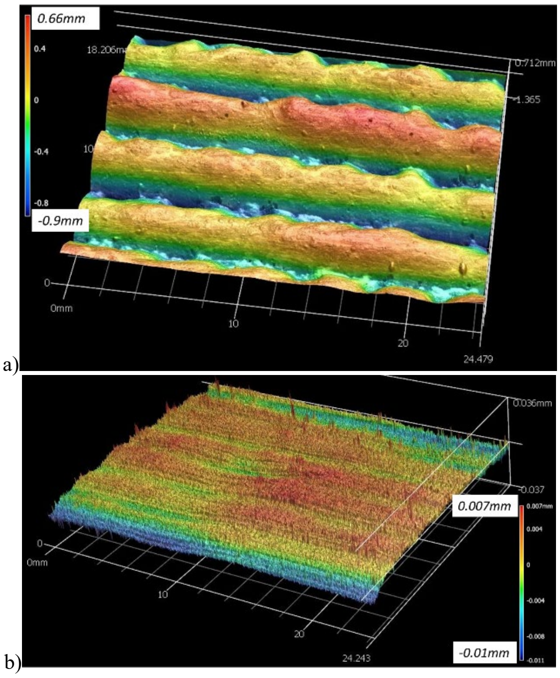


Fig. 10. Comparison of the a) as-printed part side wall surface and b) final machined side wall surface.

4. Research Outlook

On-going research continues on the hybrid manufacturing research platform. System operation has been demonstrated by generating a relatively simple part geometry using a sequential hybrid workflow. Additional work is occurring to apply this capability to larger and more complex part geometries, and to quantify process and part performance relative to material integrity, process accuracy, part deformation and process bounds. Further, an iterative process sequence is being explored whereby more complex part geometries can be produced. Process details are being developed regarding part-to-robot positioning, robot path planning, corrections for missing material, multi-material deposition and process settings. As with sequential processing, part and process outcomes will be explored and quantified.

Extending process automation is required at multiple levels. The need to capture interpass temperature and control layer start times represents one current automation task under development. The deployment of other process sensing and control modalities is also underway. A more difficult, yet compelling vision is to advance automation throughout process planning and execution. The existing flow relies on an "*a priori*" approach whereby process programs are developed manually prior to and outside of process sequences. Instead, an "*in-situ*" approach is desired whereby process sensors inform control decisions in real time throughout material deposition, metrology, machining, and any of their intersections. Such an approach would start with an initial process plan, but would adjust each process step to improve part and process performance. While extensive work is required to implement such a framework, the research platform demonstrated here represents an ideal environment in which to explore and develop this ability.

5. Conclusions

The design, construction, integration and initial demonstration of a hybrid manufacturing research cell for the production of complex metal geometries has been discussed. A foundational deposition-metrology-machining sequential workflow has been demonstrated on a single material exemplar. In-process metrology and the generation of a geometric digital twin have proven critical to the successful coupling of printing and machining. On-going work is focused on increasing process complexity and implementing in-situ process monitoring, with the future objective of developing an intelligent and adaptive hybrid manufacturing process capability for large metal parts.

Acknowledgements

This work relates to Department of Navy award (Award Number N00014-20-1-2836 in collaboration with Oregon State University) issued by the Office of Naval Research. The United States Government has a royalty-free license throughout the world in all copyrightable material contained herein. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research.

References

[1] Dutta B, Babu S, Jared B. Science. Technology and Applications of Metals in Additive Manufacturing. Elsevier; 2019.

[2] Song YA, Park S, Choi D, Jee H. 3D welding and milling: Part I - a direct approach for freeform fabrication of metallic prototypes. Int J Mach Tool Manu; 2005.

[3] Sreenathbabu A, Karunakaran KP, Amarnath C. Statistical process design for hybrid adaptive layer manufacturing. Rapid Prototyping Journal; 2005.

[4] González J, Rodríguez I, Prado-Cerqueira JL, Diéguez JL, Pereira A. Additive manufacturing with GMAW welding and CMT technology. Procedia Manufacturing; 2017.

[5] Kapil S, Legesse F, Kulkarni P, Joshi P, Desai A, Karunakaran KP. Hybrid-layered manufacturing using tungsten inert gas cladding. Prog Addit Manuf; 2016.

[6] Feldhausen T, Raghavan N, Saleeby K, Love L, Kurfess T. Mechanical properties and microstructure of 316L stainless steel produced by hybrid manufacturing. Journal of Materials Processing Technology; 2021.

[7] Mazak VC-500A/5X AM HWD. https://www.mazakusa.com/machines/vc-500a-5x-am-hwd. Visited August 1, 2023.

[8] 3DMP process - The industrial WAAM solution, GEFERTEC GmbH. https://www.gefertec.de/en/3dmp-process. Visited on August 1, 2023.

[9] Big Metal Additive. https://bigmetaladditive.com. Visited August 1, 2023.

[10] Li F, Chen S, Shi J, Tian H, Zhao Y. Evaluation and Optimization of a Hybrid Manufacturing Process Combining Wire Arc Additive Manufacturing with Milling for the Fabrication of Stiffened Panels. Applied Sciences; 2017.

[11] Zhang S, Zhang Y, Gao M, Wang F, Li Q, Zeng X. Effects of milling thickness on wire deposition accuracy of hybrid additive/subtractive manufacturing. Science and Technology of Welding and Joining; 2019.

[12] Massive Hybrid Manufacturing Machine in Europe Pushes Boundaries of 3D Printing. Available from: https://redshift.autodesk.com/articles/hybrid-manufacturing. Visited on August 1, 2023.

[13] Lopes JG, Machado CM, Duarte VR, Rodrigues TA, Santos TG, Oliveira JP. Effect of milling parameters on HSLA steel parts produced by Wire and Arc Additive Manufacturing (WAAM). Journal of Manufacturing Processes; 2020.

[14] Honeycutt A, Mhatre P, Gibson B, Smith S, Richardson B. Iterative hybrid manufacture of a titanium alloy component. Manufacturing Letters; 2021.

[15] Jones D, Snider C, Nassehi A, Yon J, Hicks B. Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology; 2020.

[16] Uhlemann THJ, Lehmann C, Steinhilper R. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. Procedia CIRP; 2017.

[17] Cornelius A, Dvorak J, Jacobs L, Penney J, Schmitz T. Combination of structured light scanning and external fiducials for coordinate system transfer in hybrid manufacturing. Journal of Manufacturing Processes; 2021.

[18] Dvorak J, Cornelius A, Corson G, Zameroski R, Jacobs L, Penney J, et al. A machining digital twin for hybrid manufacturing. Manufacturing Letters; 2022.

[19] Chernovol N, Sharma A, Tjahjowidodo T, Lauwers B, Van Rymenant P. Machinability of wire and arc additive manufactured components. CIRP Journal of Manufacturing Science and Technology; 2021.

[20] Large Scale 3D Metal Printing, AML3D. Available from: https://aml3d.com. Visited on August 10, 2023.

[21] Large Format Metal Additive Manufacturing Parts, Additive Solutions. Available from: https://additive.lincolnelectric.com. Visited August 12, 2023.

[22] Vals E. Redundant Kinematics Solution for a Combined 6DOF Robotic Manipulator and 2DOF Part Positioner in a WAAM Application. MS Thesis. University of Tennessee, Knoxville; 2022.

[23] McNeil J, Hamel W, Penney J, Nycz A, Noakes M. Framework for CAD to Part of Large Scale Additive Manufacturing of Metal (LSAMM) in Arbitrary Directions. Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium; 2019.

[24] Quigley TP. Path Planning For Additive Manufacturing of Wire Arc Additive Manufacturing and Blue Light Fringe Projection Scanning. MS Thesis. University of Tennessee, Knoxville; 2022.

[25] Buckley M. Design and Simulation of a Supervisory Control System for Hybrid Manufacturing. MS Thesis. University of Tennessee, Knoxville; 2021.