HYBRID MANUFACTURING CELL DESIGN AND CONSTRUCTION

Joshua Penney[1], Aaron Cornelius[1], Ethan Vals[1], Jake Dvorak[1], Michael Buckley[1],
Leah Jacobs[1], Gregory Corson[1], William Hamel[1], Bradley Jared[1], Tony Schmitz[1,2]
[1]Mechanical, Aerospace, and Biomedical Engineering
University of Tennessee, Knoxville
Knoxville, TN 37996, USA
[2]Manufacturing Science Division
Oak Ridge National Laboratory, Oak Ridge, TN, 37830, USA

ABSTRACT

The design and construction of a hybrid manufacturing work cell is described. The intent is to enable large-scale additive metals manufacturing by combining robotic wire arc additive manufacturing (WAAM), five-axis machining, supporting metrology, and part transfer. Currently, large metal parts produced using WAAM do not generally offer the required surface finish necessary or geometric accuracy for industrial use. To provide the required dimensional accuracy and finish, the additive preforms are typically machined. Machining WAAM preforms presents several challenges, including final part containment within the preform, datum identification (if available), and coordinate system transfer from WAAM to the machining center. The work cell addresses hybrid manufacturing challenges by linking the additive and machining processes through material handling, metrology, and supervisory system control and monitoring.

KEYWORDS

Additive manufacturing, Machining, Metrology

INTRODUCTION

Recently, significant progress has been made using robotic direct energy deposition (DED) processes [1–6] to build large near net shape parts (multi-meter sizes) as much higher deposition rates than powder-bed fusion processes. Wire Arc Additive Manufacturing (WAAM) and laser hot wire DED have been demonstrated over a wide range of metal alloys with good success. DED processes can only produce near net shape parts because the material is deposited in a form analogous to weld beads which limits the part feature sizes and surface smoothness that is achievable. All additive manufacturing processes require post fabrication machining at some level, but in the case of DED, significant intermittent and post machining is essential to achieving part specifications. The combined use of additive and subtractive processes is referred to as hybrid manufacturing and is a growing area of advanced manufacturing research.

KEY REQUIREMENTS

An overview of the key work cell stations is shown in FIGURE 1. The workflow begins with the robotic WAAM process. Here, a robotic manipulator positions a gas metal arc welding (GMAW), or metal inert gas (MIG), torch to deposit material. The additive process begins on a substrate that is fixed to a pallet mounted on a three-axis workpiece positioner (two rotary, one linear). The positioner and robot arm will be kinematically linked to ensure the welding torch accurately deposits material along the designed print paths. Additionally, the welding torch selected for this system has dual wire capabilities, allowing for bi-material deposition and design choices not available in conventional additive processes. For successful deployment of the proposed additive process, *in situ* thermal and electrical monitoring and pre-process simulation will ensure the work cell performs as intended.

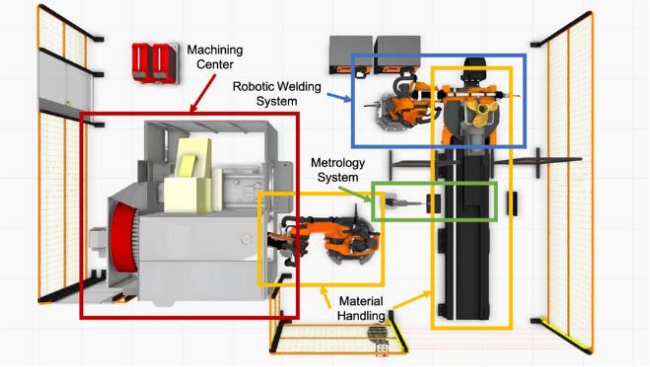


FIGURE 1. Top-down view of the hybrid manufacturing work cell showing the four key zones that comprise the system.

Following the WAAM process, a digital twin of the deposited material will be defined using structured light scanning. This digital twin will serve as the input stock model for the machining process computer aided manufacturing (CAM) software. The corresponding toolpaths and machining operations will provide the net design shape and surface finish for the part. A crucial aspect of this digital twin construction will be the accurate transfer of the part coordinate system from the additive to machining operations and vice versa. Through the implementation of a novel fiducial structure, coordinate alignment between the physical and digital domains is ensured. For optimal manufacturing flexibility, digital process methods are being developed to enable additive deposition on machined surfaces for a fully iterative working environment.

A central robotic arm will transfer the preform pallet from the additive process to the five-axis machining center. A supervisory control system will provide the required oversight for full work cell automation and will limit human interaction. The work cell will perform autonomous additive and machining operations while validating the geometric performance until the workflow determines that the intended design specifications have been achieved. The following sections describe the individual systems and conclude with a case study validating the hybrid manufacturing process.

WAAM SYSTEM

The WAAM system is comprised of two main components: a six-axis industrial robot and GMAW system (see FIGURE 2). The industrial robot is a KUKA KR50 R2500. It is rated for 50 kg of payload at the end effector with a reach of 2.5 m. It is capable of linear motion speeds of 2 m/s with a repeatability of ±0.05 mm.

A Fronius CMT Advanced Twin welding torch capable of depositing two different (or the same) material wires simultaneously through the Fronius Cold Metal Transfer (CMT) process will be attached at the robot end effector. CMT is a short circuit GMAW process which is ideal for additive manufacturing due to the reduced heat input compared to other GMAW processes. With the CMT Twin system, it is possible to feed two wire of different sizes or compositions, if desired, or instead feed two identical wires to increase the deposition rate. Each wire feed is fully independent, so it is possible to use each wire on its own or, if two different materials are used, mix materials at different dilution rates.

FIGURE 2. (A) KUKA KR50 industrial robot used for WAAM process (B) Dual wire CMT Advanced welding torch.

In addition to the robot WAAM, voltage and current sensors and thermal cameras will be used to add a layer of real-time control to the WAAM process. This real-time control ensures that the process is stable and producing the desired beads and, therefore, the desired geometry.

FIVE-AXIS MACHINING SYSTEM

Additively manufactured parts often require finish machining to meet surface finish and tolerance requirements. To accommodate complex parts, a Haas UMC-750 five-axis machining center was selected (see FIGURE 3). The rotary axes allow the machine to approach the part from different angles so that many designs can be machined in a single setup.

Several machining challenges are anticipated. First, the freeform geometry and large surface deviations common to additively manufactured preforms generally do not provide any clear datums for locating the part on the machine and establishing a machining coordinate system.

Second, the surface variation means that it is difficult to know where material needs to be removed to produce a finished part.

FIGURE 3. *Haas UMC-750 five-axis milling center.*

A novel coordinate transfer method incorporating the structured light scanner will help to resolve these concerns. In this approach, fiducials will be temporarily attached to the preform. These fiducials will be used to define a machining coordinate system. The machining toolpaths will then be programmed in this coordinate system, using the structured light scan as a stock model to determine where material needs to be removed.

After the part is transferred to the machining center, the fiducials will be located using the machine's spindle probe. These positions will then be used to construct the work coordinate system, ensuring that machining is performed on the correct areas of the workpiece. This process has been tested on a simple part that is discussed in the case study.

METROLOGY SYSTEM

The GOM ATOS Q is a structured light scanner that uses fringe projection to determine the geometry of the scanned object (see FIGURE 4). It is composed of a central projector and two cameras. The scanning hardware is accompanied by software, GOM Inspect Suite 2020, which enables scanning, inspection, and reporting. Reports can be produced using the measurement results, including nominal to actual comparisons, position tolerances, and volume inspection. Computer Aided Design (CAD) imports, mesh editing, and a Python interface are also provided. A custom coordinate system can be identified either from the imported CAD or from the measurement data. This coordinate system will be exported with the mesh to the machining or welding toolpath planning software to provide coordinate transfer.

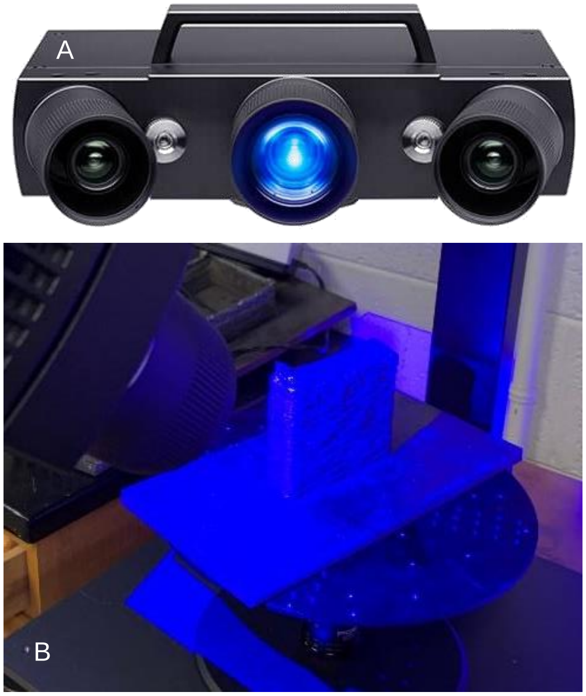


FIGURE 4. (A) GOM ATOS Q structured light scanner (B) Scanning process of an WAAM part.

MATERIAL HANDLING SYSTEM

There are three elements to the material handling system: a KUKA KL4000 linear track system, a KUKA KP2-HV500 two-axis part positioner (rotary), and a KUKA KR250 R2900 six-axis industrial robot (see FIGURE 5). The linear track system is rated for a 4000 kg payload and has a maximum travel of 3.4 m with a maximum linear speed of 1.89 m/s and positioning repeatability of ±0.02 mm. This track will be used to move the part between the WAAM, metrology, and machining cell stations.

The two-axis part positioner is used by both the WAAM and metrology stations to properly orient the part in space. Axis 1 (the tilting motion) can move ±135° with a repeatability of ±0.009°; it can complete a 180° rotation in 1.9 s. Axis 2 (the top plate rotation) has infinite rotation with a repeatability of ±0.009°; a 180° rotation takes 1.8 s. In the case of the WAAM process, the positioner is kinematically coupled with the welding robot so that motion profiles can be specified to ensure that the welding torch remains in a gravity-aligned orientation. This ensures that gravity has a minimal influence over the molten pool's geometry during deposition, thus depositing the desired bead shape. For the metrology station, the positioner is used to orient the preform and fiducials relative to the structured light scanner.

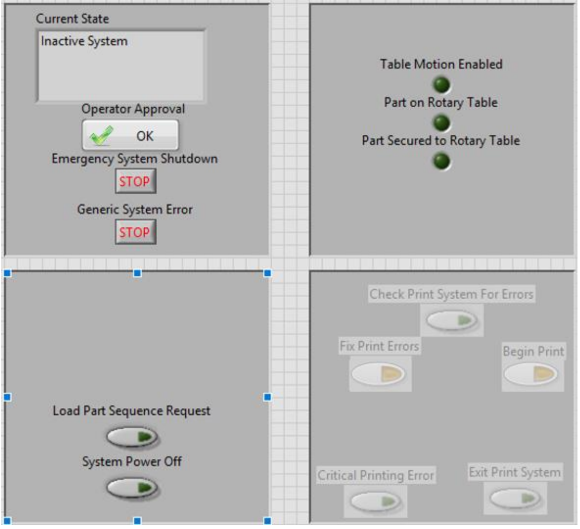
FIGURE 5. KUKA KR250 industrial robot for moving parts between the linear track and the machining center.

To repeatably transfer the part pallet from the material handling station to the machining station, a Schunk pneumatic pallet system is used. This system clamps the pallet in both locations using a semi-kinematic coupling approach.

SUPERVISORY CONTROL SYSTEM

Due to the complex nature of this system, a supervisory control system is implemented. The Human Machine Interface (HMI) for this system is executed using a dedicated computer to provide supervisory control. The HMI is designed in LabVIEW, a graphical, system engineering software, which is connected to a programmable logic controller (PLC), through a Modbus connection that is, in turn, connected to the robots, machines, safety interlocks, and other system components. The goal of the supervisory control system is to implement a combination of Boolean control and data logging. The Boolean control portion oversees the current state of the system, allowing actions to be performed according to that system state and station operator approval. It is important to ensure that no steps are run out-of-order and that no safety protocols are violated. The data logging portion receives relevant machine messages and data from the various cell stations and stores them with the appropriate metadata for readability and future reference.

The entire system runs inside a physical safety barrier to prevent any damage to personnel or equipment. The supervisory control computer is located outside of the safety barrier and is connected to all components internal to the system. This allows operators to see the system states and other data without entering the work area. The states in the LabVIEW HMI create a digital twin of the system, which enables real-time process monitoring and comparison to anticipated performance. A subset of a preliminary HMI is shown in FIGURE 6.



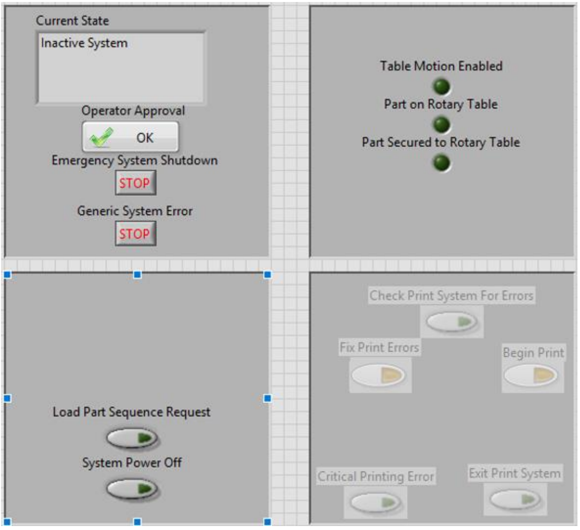


FIGURE 6. Initial HMI for controlling and monitoring the hybrid manufacturing process.

CONCLUSIONS

The hybrid manufacturing cell described in this paper offers new possibilities for coupling the capabilities of wire arc additive manufacturing, metrology, and multi-axis machining. Using the

Fronius CMT Advanced Twin welding system, multiple deposition materials will be explored, and the robotic system allows for complex geometric features to be produced. The metrology system provides part geometry throughout an iterative manufacturing process and ensures that the desired part is contained in the additive preform part before machining begins. The materials handling provides safe, automated, and accurate positioning of the preform throughout the entire cell. Finally, the desired geometry and surface finish is produced by machining the preform.

ACKNOWLEDGEMENTS

This work relates to Department of Navy award (ONR Award No. N00014-20-1-2836) 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.

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

REFERENCES

1. Greer C, Nycz A, Noakes M, Richardson B, Post B, Kurfess T, et al. Introduction to the design rules for Metal Big Area Additive Manufacturing. Additive Manufacturing 2019;27:159–66. https://doi.org/10.1016/j.addma.2019.02.016.
2. Simunovic S, Nycz A, Noakes M, Chin C, Oancea V. Metal big area additive manufacturing: Process modeling and validation. NAFEMS World Congress, vol. 2017, 2017.
3. Patrick S, Nycz A, Noakes M. MULTI-MATERIAL PROCESS PLANNING FOR ADDITIVE MANUFACTURING n.d.
4. Hassen AA, Noakes M, Nandwana P, Kim S, Kunc V, Vaidya U, et al. Scaling Up metal additive manufacturing process to fabricate molds for composite manufacturing. Additive Manufacturing 2020;32:101093.
5. Hu X, Nycz A, Lee Y, Shassere B, Simunovic S, Noakes M, et al. Towards an integrated experimental and computational framework for large-scale metal additive manufacturing. Materials Science and Engineering: A 2019;761:138057. https://doi.org/10.1016/J.MSEA.2019.138057.
6. Penney JJ, Hamel WR. Using non-gravity aligned welding in large scale additive metals manufacturing for building complex parts. Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2019, 2019.