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CHALLENGES IN MAKING COMPLEX METAL LARGE-SCALE PARTS FOR ADDITIVE MANUFACTURING: A CASE STUDY BASED ON THE ADDITIVE MANUFACTURING EXCAVATOR

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Abstract

The Additive Manufacturing Excavator (AME) contained several key components that were 3D printed at The Manufacturing Demonstration Facility (MDF) of Oak Ridge National Laboratory (ORNL); it was presented at and performed a live demonstration for the CONEXPO 2017 exhibition in Las Vegas, Nevada in March of 2017. This paper presents challenges in building functional, large-scale metal parts based on a case study of the excavator. The excavator's metal arm was 3D printed using a modified Wolf Robotics automated metal inert gas (MIG) welding cell. Tasks included designing a new type of slicer for the metal additive manufacturing (AM) process, integrating the slicing software with the Wolf Robotics system, developing the deposition process, characterizing geometric features and material properties, managing heat, designing mechanical components for metal AM, and developing a machining approach to achieve the final part. Two fully functional excavator arms were printed and machined. Integrated hydraulics passageways that also served as structural stiffeners were included in the build for demonstration purposes. As a direct result of this project, Wolf Robotics is now working towards a commercially available large-scale metal AM system.

Introduction

The purpose of this project was to demonstrate the feasibility of implementing large printed metal components on machinery for the construction industry. The main challenges during system development and implementation included deposition process development, geometric feature characterization, robotic path integration and execution, heat management, process appropriate slicing, material properties, mechanical design oriented toward the needs of the AM process, and post-machining to reach necessary interface tolerances. A substantial development effort was required in a short period of time to ensure success.

Arc-based wire feed metal AM was chosen as the best process to produce large metal parts [1]. While metal powder bed printers are available commercially, they are not currently capable of producing large-scale metal parts [2, 3]. Welding-based systems are not as precise as powder bed in terms of print resolution, but there are no inherent limitations to the size of the part that can be printed. Post-process machining of either print technology is typically required for the final product. Therefore, arc-based wire feed technology provided the most cost-effective solution.

The development timeline was governed by the CONEXPO exhibition beginning in Las Vegas, Nevada on March 7th, 2017. The Wolf Robotics welding equipment was installed at ORNL's MDF at the end September 2016. During this short amount of time, equipment was setup, safety of the system was assessed, processes were developed, staff members were trained, and the ORNL slicer was adapted to suit the needs of the printing process. A series of smaller parts were printed to establish process parameters such as quality, shape, overlap, adhesion of the weld bead, and print resolution in various Cartesian axes. In order to meet schedule requirements, the printing of the excavator had to begin mid-January 2017 at the latest. During this time, at least two arms needed to be fabricated while leaving enough time for post-process machining, installation, testing, and shipping to Las Vegas.

The numerous technical challenges were addressed through extensive literature survey [2, 4]. Significant prior MDF experience in welding and large-scale AM as well as substantial experimental work conducted at the MDF in tungsten inert gas (TIG) and MIG welding-based AM processes was explored. Wolf Robotics and parent company Lincoln Electric provided substantial systems, welding, and materials expertise. The established base of work provided a foundation for successful completion of this project.

Challenges

Print Time

The expected print time was an important factor throughout the project. Considering the expected weight of the printed arm to be in the 300-400lb range and the maximum rate of deposition of approximately 5lb/h, the expected time of print was in the range of 90-130 hours of continuous deposition. This in conjunction with the timeline affected the design and decision-making process. Any proposed solutions had to address process print time and the available schedule. These considerations are similar to what would be required for an industrial implementation of the system [5-7].

Deposition Process Development

The hardware was originally designed for an automated welding process. Therefore, systematic analysis was required to develop a way to additively manufacture large-scale metal parts.

One of the first questions to answer is the orientation of the print. The long axis of the part can be vertical (Fig. 1) or horizontal with advantages and disadvantages in both cases. Horizontal orientation significantly decreases the number of layers and causes the bead to become longer. This results in shorter print time and limits the accumulation of the z-direction error. The downside is, considering the process and print table, decreased temperature of the build, which is far from optimal. It may result in brittleness. The other issue is warping of the build plate causing deformation of the first layers of the part. The vertical orientation increases the print time, but the thermal conditions are closer to optimal. The deformation coming from the base warping was the main factor in deciding to choose the

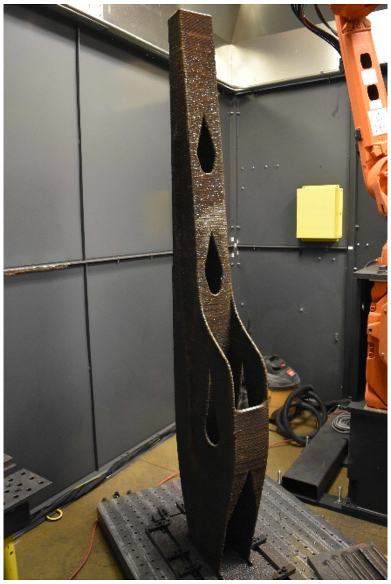

Figure 1. Vertically printed arm on a 4'x3' table.

vertical orientation. The z-error accumulation was mitigated by introducing a closed-loop control system and designing extra volume in the part.

Metal-arc printing requires adequate print table (Fig 1-2), base plate, and clamps. Due to the nature of the process, the table and the plate must be made of metal to conduct electricity and be heat resistant. The print table must accommodate the size of the base plate (function of the size of the part) and the size of the mounting solution. In addition, it should have enough thermal capacity to sink and dissipate the energy of the process. It also must be strong enough to withstand the force acting on the build plate due to deformation and warping.

The base plate (Fig. 2) must be thick enough to minimize deformation. In this case, the standard thickness was 1 inch. The surface of every plate was thoroughly cleaned to remove traces of oil and contaminants to help with the initial bead deposition and decrease any unwanted electrical resistance. The cleaning also ensured proper flatness of the plate. The material used for plates was AISI 1018 mild/low carbon steel.

The base plate was mounted to the build plate to prevent unwanted motion, ensure electrical contact, and minimize warping during the print (Fig. 2).

Gas Metal Arc Welding (GMAW) was used to build the excavator stick with Lincoln Electric Power Wave® Technology tuned for low heat input deposition, which allows metal deposits to be stacked. It used a mix of Argon and CO2 at the ratio of 96-4%.

A 0.045in diameter (ER70S6) [8] 70ksi low carbon steel wire was used for the feedstock, which provided sufficient deposition fluidity/wetting and mechanical properties. It was also widely commercially available, and the chosen diameter had a good ratio of expected deposition rate and feature resolution. It resulted in a maximum deposition rate of 5.15lb/h for the Surface Tension Transfer (STT) process. For the given process, the arm speed was 6.67mm/s, and the wire feed rate was 84.67mm/s.

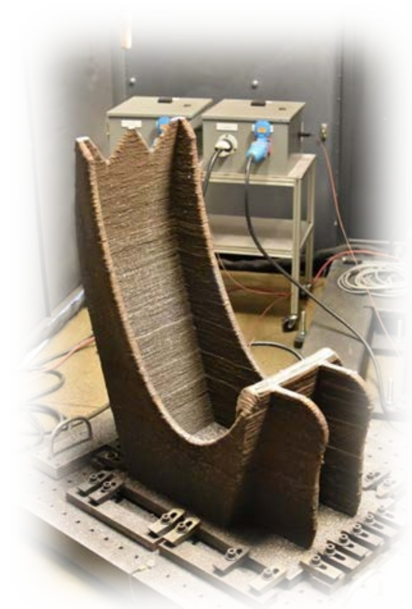

Figure 2. 3D printed bucket with base plate and mounting clamps.

The system was built with a Lincoln Power Wave® S500 welder and AutoDrive® SA servo wire feeder with a secondary push-pull servo motor at the deposition head. This type of wire feeder allows for adequate control of the length of the wire between the surface of the part and the tip of the torch throughout hours of printing.

The system was equipped with an arc tracking system, which measured impedance of the welding arc and provided corrections to maintain a specified current. The use of the arc tracking system resulted in consistent contact between the welding tip and the component being fabricated. It also allowed for automated control of the distance of the torch over the part and prevention of part torch collision. In addition, another closed loop control system was developed and implemented to control the build height of the part. This way the robotic arm was automatically correcting the build height of the part and overriding the command coming from the slicer generated G-Code commands.

Geometric Feature Characterization

In order to print arbitrary shapes, basic building blocks had to be identified along with their interaction. The process relied on layer and bead structures. Each layer is made up of beads, and beads are considered to be a continuous path of deposition.

Beads were divided into the following types: insets, skeletons, and infill. The insets are contour lines forming the external and internal edges (Fig. 3). The skeletons are a special type of inset bead that were placed where regular perimeter beads were geometrically inadequate. The purpose of the infill beads is to fill the empty space between contour beads creating solid metal structure.

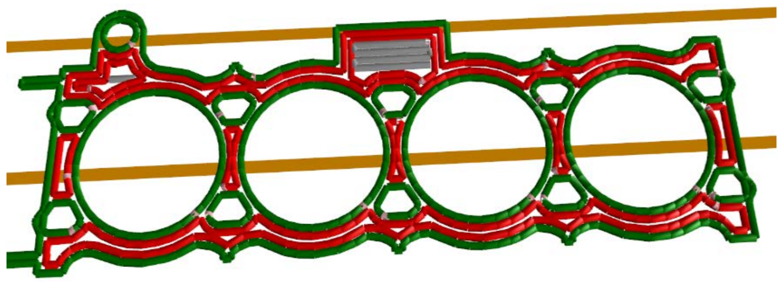

Figure 3. Bead types: green – external insets, red internal insets, grey – infill.

Unlike polymer deposition, metal AM allows and requires bead-to-bead and layer-to-layer re-melting to build structures of adequate mechanical strength that are free of voids and crack initiation artifacts. A key factor is the choice of proper bead-to-bead overlap and layer heights. The effective distance for contour beads was 4.5mm (center-to-center) resulting in 12mm width for two-bead walls. Based on the arm speed, wire feed rate, nominal process settings, nominal thermal conditions, and two-bead wall structure, the average layer height was 2.31mm.

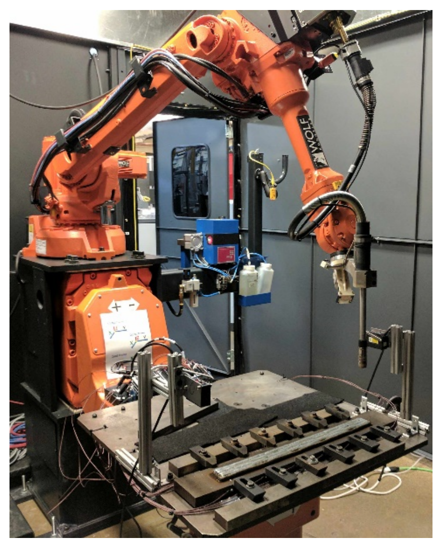

Figure 4. Metal deposition arm.

Robotic Path and Integration

This system used an ABB 2600 six degree-of-freedom arm with an IRC5 controller (Fig.4). The ABB internal path execution system is inherently incompatible with G-code syntax. Although G-code interpreters do exist [9], the complexity of the task and the level of customization required a new approach.

The system automatically performs maintenance activities. They include wire cutting, mechanical nozzle cleaning, nozzle spraying, arm parking, and re-engaging for tip replacement. The wire cut is executed before every bead and after tip change. It guarantees a proper starting process and minimizes voids related to starts and stops. Nozzle cleaning removes the weld spatter and allows for proper shield gas flow. Spraying the nozzle with a liquid agent also decreases the spatter adherence to the torch/nozzle.

To maintain proper current and tracking calibration, the current conducting tip had to be replaced every 60 minutes. This operation was done manually when the arm automatically placed itself in the maintenance window at predetermined time intervals. The print resumed after the operator restarted the system using the user interface.

Most of the process parameters could be controlled on the fly and overwritten as needed by the operator. This allowed for direct experimenting and corrections that are not present on systems executing G-Code exclusively. This included bead tracking and height corrections and could be done both automatically and manually.

The path generation system was equipped with a G-Code translation toolbox. It allowed importing G-Code generated geometries and translated them into robot native execution files. In addition, it allowed for offline program simulation and print validation

Heat Management

Based on experience and interviews conducted with welding experts, the goal was to keep the inter-pass temperatures in a range of 200-350C, optimally at about 300C. In the case of a small cross section, a fixed minimum layer time of 240 seconds was enforced to provide enough cooling time. An inter-pass temperature that is too high causes additional temperature rise in external, small areas and in overhang features. This results in melting of the previously deposited layers and may end in catastrophic failure. An inter-pass temperature that is too low affects mechanical properties and may result in brittleness, poor bead-to-bead re-melting, and void creation.

The choice of the welding process was also affected by the heat management. A modified Lincoln Electric short arc process was used offering excellent bead deposition while maintaining short arc and low energy. This is accomplished by manipulating the output voltage and current from the welding power supply to control metal droplet size and transfer rate. This resulted in a low heat input process with minimal spatter. It was accomplished through a proper current wave design.

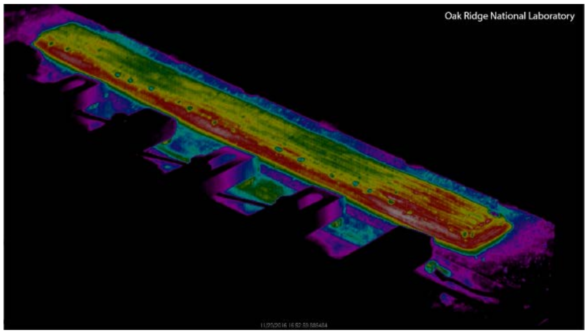

Figure 5. Path simulation and post processor virtual environment

To better understand the thermodynamics of large-scale printing using arc welding, IR images (Fig. 5) were taken and temperatures of the part throughout the build history were analyzed. In addition, thermocouples in the based plate and table as well as pyrometers were used to analyze the thermodynamics of printed parts.

Slicing

While working on the Big Area Additive Manufacturing (BAAM) development, the MDF team also developed their own slicing software called *ORNL Slicer*. The Metal BAAM has a similar structure, but not identical, to BAAM. Therefore, a version of the *ORNL Slicer* meeting the specific needs of metal arc deposition was created. The output of the slicer is G-Code. G-Code is a set of instructions that tells the machine how to build the part. It includes all the necessary commands for completing the print. This can include temperatures, speeds, moves, and turning devices on and off. (Fig. 6)

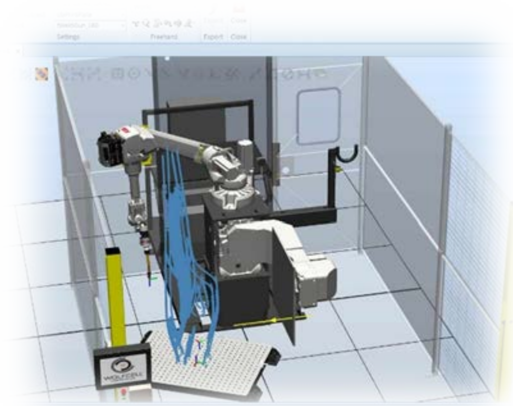

Figure 6. Path simulation and post processor virtual environment

The main differences in the metal AM version of *ORNL Slicer* were the scale of the parts used, complexity, bead definition, start and stop actions, tip wipes, use of bead types, order of print, heating and cooling conditions, curve smoothing tolerance, first layer settings, and direction of printing.

Material Properties

One of the main concerns of the metal arc technology is the presence of voids and porosity in the build. To test for voids and porosity, several large parts were printed, and their surfaces were machined. The largest part was a 4ft section replica of the excavator arm. Over the area of roughly three-square feet, there were no large voids and only a few small (~1mm in diameter) artifacts. Throughout the development process and extensive testing, no cracking was observed. It was credited to the properties of the mild steel ER70S6 wire in conjunction with the chosen process.

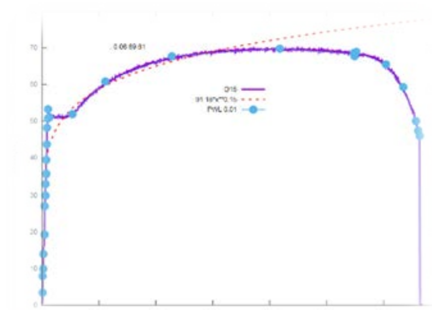

Figure 7. Sample tensile test result

The ER70S6 wire is rated at 70 ksi for yield strength [10]. Based on the feedback from the manufacturer, Lincoln Electric, the expected AM yield strength should fall in the 50-60 ksi range. The initial X (printing) and Z (vertical, perpendicular to print) direction tests showed 52 ksi strength (Fig. 7). The strength can be affected by heat management or path planning resulting in harder or softer metal.

Mechanical Design

Large-scale metal AM using a MIG process lacks definitive design guidelines in its initial phase. Therefore, based on empirical studies and suggestions from welding experts, in-house rules were defined. The excavator overhang angles were limited to 15 degrees. Single, solid features were limited to one inch in length. Most walls were modeled as two-beads that were 9mm wide with 4.5mmm center-to-center distance. The effective, as printed, distance resulted in 12mm width. This was directed by the necessity of bead overlapping.

One of the requirements of the project was to print embedded high pressure hydraulic channels within the structure. The standard cross section is circular; however, AM allows for relative freedom in defining shape. Therefore, an oval shape was chosen. In addition, the channels were directly integrated into load bearing walls, which minimally increased weight and provided additional stiffness.

Figure 8. 4ft test segment arm.

To account for the transient phase of the process and any initial layer deformations, an extra inch of height was added to bottom of the build. An additional two inches of height were added to the top of the part in case of unexpected height error accumulation.

It was decided to post machine the arm and add conventional parts where the benefits of AM would be marginal. The conventional parts included sleeves, bearings, and pins. Those areas were designed as solid surfaces.

A requirement from the machining team was to provide two axes of reference. The horizontal one was the cut line parallel to the build plate, and the vertical one was a printed feature.

In order to test all requirements and assumptions, a four feet section of the excavator arm (in scale 1:1) was printed (Fig. 8).

Machining

One of the advantages of AM is that one can design parts that cannot be produced with traditional machining. On the other hand, one of the disadvantages is that one can design parts with shapes that lack references and are difficult to setup for finish machining operations. Understanding how one is going to machine a part and the needed references is an important step in designing the part.

The short test link (Fig. 8) was printed and used as a test article in the workshop. The part was cut off from the base plate, and one side was milled to achieve flat surfaces and to test for voids. Then, the joint areas were cut out, and the fit of pre-machined sleeves was tested. In addition, the test link was used to verify the weldability of the different alloy sleeves to the 3D printed part. No major issues and no cracking susceptibility was observed.

The "as printed part" lacked adequate flat surfaces that could be used as reference lines for CNC machining configurations. Therefore, the cut line resulting from removing the base plate was used as a horizontal line for initial setup. The vertical reference line was obtained by manually fitting the part into

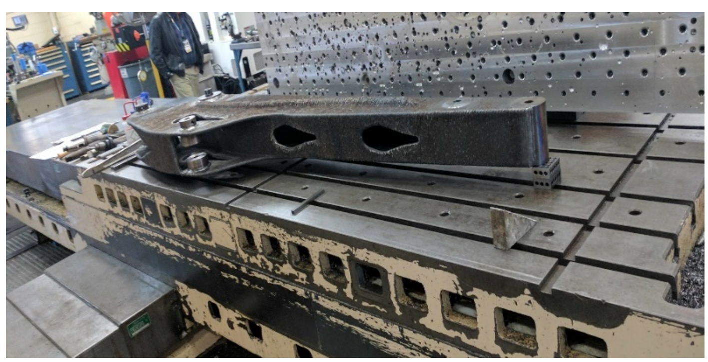

Figure 9. Arm on CNC table.

the digital model CNC path. Proper setup required realigning the parts multiple times because of the lack of adequate references and added time to the machining process.

The lessons learned by using the short test link helped to facilitate the machining of the two full-sized excavator links. Fig. 9 shows one of the links set up on the CNC machine.

Results

Two identical metal arms were manufactured and post-processed (Fig. 10). One was installed on the excavator and performed a three-day live demonstration during the 2017 CONEXPO Las Vegas show (Fig 10). No mechanical failures were observed. Both the excavator and the extra arm are now located at ORNL's MDF and are occasionally used for demonstration purposes.

Each arm took about five days of nonstop printing; each arm consists of 927 layers and weighs about 400lbs as printed. Arms were over 7ft tall, and the final height error was close to 1mm. Each arm used approximately 14 miles of wire. The approximated cost of electricity was $20.

Figure 10. 3D printed excavator during CONEXPO 2017 demo tests.

Figure 11. Additively manufactured arm on a deposition table.

In addition to the excavator, several other parts were manufactured to demonstrate new AM capabilities. They included a 3ft tall trenching bucket and two 1ft tall bucket teeth.

Since then, a variety of other complex parts have been printed. These include a four-cylinder, full-size engine block, boring disc drill bits for a large-scale hole boring machine, water pump impellers, and complex test geometries.

The ongoing efforts include metal characterization of printed parts, modeling, and further enhanced control and sensing. The modeling efforts are focused on thermal, distortion, stress, and metallography prediction conducted with the Simulia (ABACUS) team of Dassault Systems.

Conclusions

This work successfully demonstrated the feasibility of building large-scale metal parts with an arc-based wire feed process. The entire development, analysis, and manufacturing cycle for the excavator arm was completed in four months. Two identical arms were produced. One was mounted on an excavator, and one was mounted in a display stand for inspection and discussion during the trade show. The excavator was successfully demonstrated with nearly three days of continuous digging at CONEXPO.

During the initial development process, the need for accurate z-height build control was noted, and a novel closed-loop method for controlling z-height was implemented. The closed-loop method maintained accuracy to 1mm even during large builds. Parts did require post machining to remove "support structure" and material near the base layer where weld quality was not ideal. Post machining generally included only those areas necessary required to interface with other, conventional parts in the system. All aspects of development and fabrication were successfully completed. The conclusion of this work was a prototype for a new AM machine and possibly another step toward creation of a main stream economic sector based on large-scale metal AM.

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