ADDITIVE MANUFACTURING WITH ROBOTIC GMAW

Additive manufacturing (AM) is an alternative to traditional reductive manufacturing processes. Reductive manufacturing processes start with a billet of raw material and remove excess material through processes such as thermal cutting and machining to achieve the desired final shape. A key objective of AM is to minimize the amount of material used by precisely depositing only material that is required, layer by layer, and building a component from the base up as a near net shape. Prototype, complex, or replacement/ repair components can be rapidly produced in a variety of materials from a 3D model created using computer-aided design software and AM technology.

As part of a 3-rd year capstone project in the Manufacturing Engineering Technology – Welding & Robotics program at Conestoga College in Cambridge, ON, the challenge was issued to demonstrate the viability of using AM to create relatively thin-walled (<5 mm thick) metallic shapes by adopting existing gas-metal arc welding (GMAW) technology, standard welding consumables, and delivering the process using a 6-axis robot programmed from the teach pendant. This paper documents the process of welding procedure development, programming, production, and finishing, culminating in the creation of an item that any student of welding technology would appreciate: a stainless-steel beverage container.

PROJECT BACKGROUND & OBJECTIVES

Additive manufacturing is the industrial application of 3D printing. Since AM involves the part being built up, layer by layer, this method minimizes material waste throughout the manufacturing process. In the creation of metallic components AM applies the desired alloy in either powder or wire form and fuses the material to preceding layers using a heat source (e.g., a laser or an electric arc). In addition, using welding technology multiple shapes can be joined together to make a fabricated monolithic assembly.

With the many advances in AM technology, there is specialized equipment available capable of producing very complex shapes. For simpler shapes, more readily available equipment can be used. The option explored in this project was to employ a 6-axis welding robot and a standard welding process (GMAW) in a method also known as Wire and Arc AM (WAAM). [1]

While other welding methods such as gas-tungsten arc welding (GTAW), plasma-arc welding (PAW), or laser beam welding (LBW) offer distinct advantages over GMAW for an application such as AM, they typically do not offer the ease of operation, simplicity, and high deposition rates. One key disadvantage of GMAW for this application is that the delivery of the filler metal is very closely tied to the energy input of the arc, whereas in GTAW, PAW, and LBW there is typically much greater control precision over energy input, and the filler metal delivery is completely independent. With these restrictions the first step in creating a successful thin-walled AM component with GMAW was to develop a suitable low heat input welding procedure using the available equipment and welding consumables. Once the welding process parameters were established, the next steps were to program the robotic system to achieve the desired shapes, and deal with the practical problems such as smooth arc starts and stops, the position of weld beads in relation to the preceding layers, and the steadily increasing inter-pass temperature in the component.

The primary objective of this technical project was to create several different concentric and simple 3D shapes using a GMAW welding robot with standard welding consumables. The welding was performed using a 0.9 mm (0.035 in.) diameter electrode wires. For mild steel articles a CSA W48-14 ER49S-6 (AWS A5.18 ER70S-6) electrode wire was used with an 85% Ar + 15% CO_2 shielding gas; for austenitic stainless steel parts an AWS A5.9 ER308L filler metal and a 98% Ar + 2% O shielding gas was selected. The desired shapes were all programmed point-to-point from the teach pendant using touch-sensing and built-in offset commands.

WELDING PROCEDURE DEVELOPMENT

While there are a variety of welding power source technology paired with 6-axis robots at the college, the system chosen for this work was a Fanuc ArcMate 100-7L with a Lincoln R350 power source (see Figures 1 & 2). The PowerWave R350 power source includes a proprietary GMAW output waveform known as Power Mode™ which is designed to produce a stable arc at relatively low-energy levels using the short-circuiting transfer mode. This system is designed to promote arc stability through high-speed responses to arc conditions and to regulate the arc length

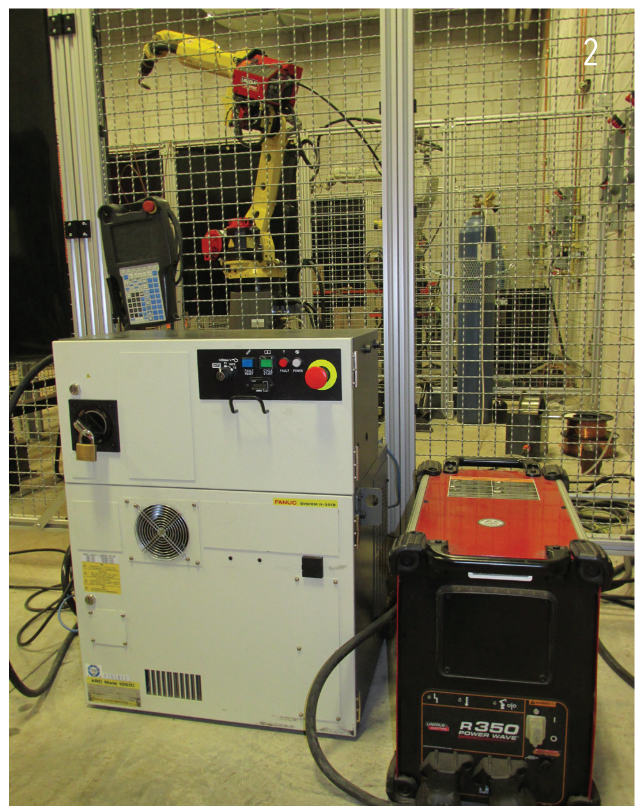

Fig. 1 - Fanuc ArcMate 100-7L 6-axis Robotic Arm
Fig. 2 - Lincoln PowerWave R350 power source and Fanuc Controller

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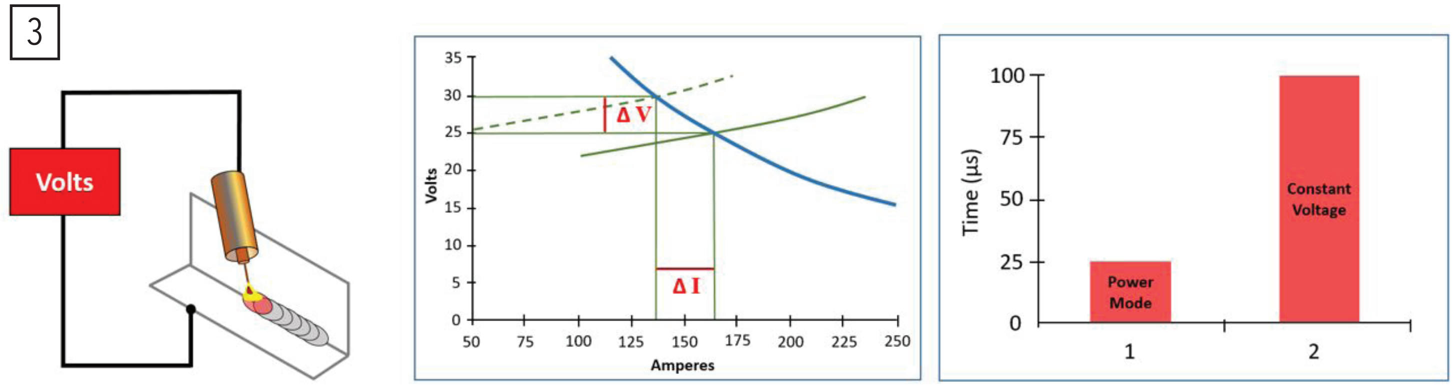

The arc voltage sensing lead reports the voltage to the power source. The voltage sensed corresponds to the arc length.

This graph represents the voltage and amperage response to increases or decreases in arc length using constant power. Here, the arc sensing lead reports approximately a 5V change (ΔV) in arc length, forcing an imbalance in the power. The current compensates slightly (25A, ΔI) to bring the power relationship balanced to the set point. Note that the current response is much less than if a typical constant voltage procedure had been used.

The Power Mode compensates for arc length fluctuations four time faster than traditional Constant Voltage or Constant Current machines. Faster response times require less drastic compensation to maintain control.

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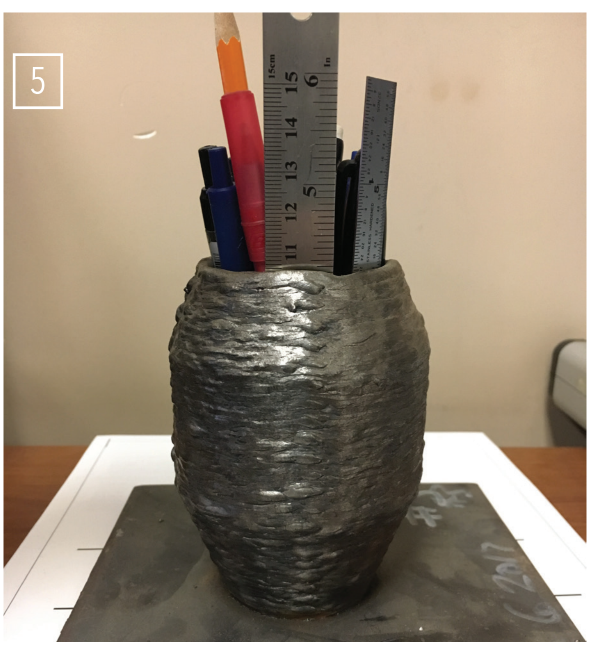

Fig. 3 - The Operation of Lincoln Electric's Power Mode™ Waveform. [2]

Fig. 4 - Truncated Cone Structure from ER70S-6 Filler Wire

Fig. 5 - Barrel Structure from ER70S-6 Filler Wire

despite inevitable variations in contact-tip to work distance as the weld progresses. (See Fig. 3) This system uses two primary inputs, wire feed speed and power mode trim, to adjust the arc length and arc power (in watts) by adjusting both the arc voltage and amperage. [2]

To develop a stable welding process for the subsequent 3D part production a simple 2D linear object ('the Wall') was created which only required X and Z axis motion. This program for this object only consisted of 6 move commands and approximately 7 logic commands. (Logic commands are lines of code that are not used to move the robot or weld but involve counting and adding to the program registers used to index the gun position at the end of each layer). The wall object created had a length of ~100 mm, a height of ~100 mm, and a nominal thickness of ~4 mm. The primary issue encountered with this object was excessive weld build-up at the start/stop point of each pass.

The welding conditions established and used with only minor adjustments for the subsequent components are listed in Table 1.

Table 1: Typical Welding Parameters

Electrode Spec. & Class.	AWS A5.18 - ER70S-6	AWS A5.9 - ER308L
Electrode Diameter	0.9 mm (0.035 in.)	0.9 mm (0.035 in.)
Shielding Gas	85% Ar + 15% CO2	98% Ar + 2% O
Wire Feed Speed	65 - 85 mm/s	45 - 65 mm/s
Z-Axis Indexing (per weld layer)	0.8 – 1.35 mm	0.8 – 1.35 mm
Travel Speed Range	7.5 – 9.5 mm/s	6.5 – 8.0 mm/s

3D PART DEVELOPMENT AND PROGRAMMING

The two primary approaches to robotic programming for arc welding are on-line (from the system teach pendant) and off-line (using a 3D CAD model and specific off-line programming software). For the relatively simple 3D shapes in this project the on-line teach-pedant programming method was chosen for it's simplicity and accuracy. (Future projects at the college are extending these AM developments using commercially available off-line programming software with CAD to path capabilities and building upon these empirical welding results.)

Teach pendant programming involves either teaching the robot through a point-to-point method, or by using position registers and offsets. For the creating of the 3D parts in this project the programming method focused on the use of offsets to minimize the amount of code and assist in the maneuverability of the code. The primary feature of this technique is called Touch Offset (the primary function of the Touch Offset is to be used for Touch Sensing, it can also just be used to apply offsets). When implementing a Touch Offset, a 'on' and 'off' line must be used. Any move commands in-between these two lines have a specific offset applied with a position register (PR). For example, to index the height (Z-axis) for each weld layer build-up, a line of logic was used to add a set amount to the offset PR. The PR that was used for the Touch Offset had each axis cleared to 0, then it would have a second PR added to it so that it would continually index in the Z-axis. Depending on the part an offset of 0.80 mm - 1.35 mm was used in this work. This created two tiers of PR's, the first tier is the PR that is being applied as an offset and the second tier is being used to add to the first tier.

To create a cylinder from a base plate a "Move-C" (circular motion) command was used and a series of weld layers were applied around the circumference one-layer at a time by raising the Z-axis. To help minimize the effects of excessive weld build-up at the start/stops, these were programmed to index and rotate between the four quadrants of the Move-C command. Delays of 30 seconds were also programmed between weld runs to allow for a cooling period that would control inter-pass temperatures. The resulting cylinder was ~100 mm in diameter and height.

Creating a truncated-cone involved slightly altering the diameter of each weld layer, in addition to indexing the Z-axis, and rotating the start/stop locations as before. This was achieved by offsetting the four locations in the Move-C command in the X or Y axis for each weld layer as a 2nd tier of PR's. Simple trigonometry was used to calculate the X-Y axis offset value required to achieve a desired angle. The truncated cone shown in Fig. 4 has a major diameter of ~100 mm; the slope was achieved using a 0.30 mm X or Y axis offset on the 2nd tier PR's. A truncated cone is shown in Fig. 4.

The barrel shape shown in Fig. 5 was created by combining elements of the cone and cylinder programming. Since the programming complexity was increasing it became useful to introduce a third tier of PR's and to break the program into two components. The move commands were separated from the PR logic commands (including all the counters and offsets required to design the diameter, Z-axis indexing, and the X-Y offsets required to change the slope).

Further experimentation on conical shapes determined that a maximum X or Y axis offset of ~0.50 mm could be used with the welding gun oriented perpendicular to the base plate surface and applying filler metal on previously deposited layers at an accumulating angle of ~60° from the horizonal. Creating flatter angles in shapes with these welding conditions will require either programming the work-angle of the welding gun to suit the desired slope (and dealing with the inevitable gravitational effects) or incorporating a tilt-turn positioner and coordinated motion to maintain the layer stacking perpendicular to gravity.

STAINLESS STEEL BEVERAGE CUPS

The project experimentation eventually culminated in the production of a number of austenitic stainless-steel beverage cups, each with a total height of ~180 mm and a nominal

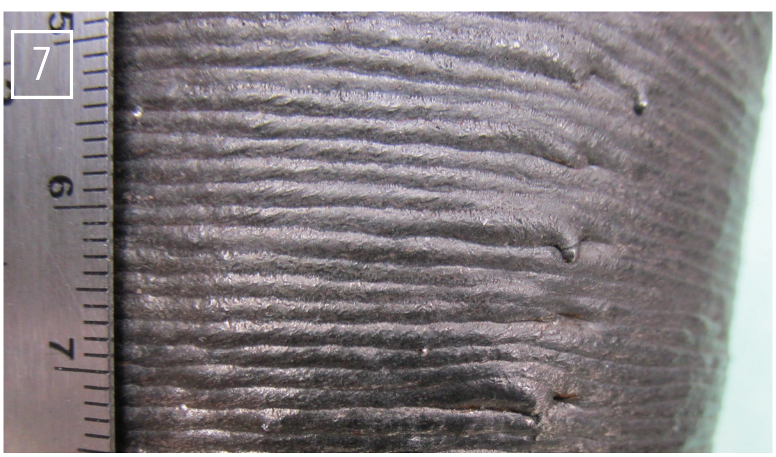

Fig. 6 -Beverage Cup from ER308L Filler Wire

Fig. 7 -Outer Surface of the Beverage Cup (scale in mm)

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wall thickness of ~4 mm. An example of one of these cups is shown in Fig. 6 (post finishing). To maximize the productivity multiple cups were welded in an array to best utilize the cycle times and still allowing the required cooling periods to reduce the inter-pass temperatures, improving the surface quality of the products. (Fig. 7 is a macroscopic image of the post-weld outer side-wall surface.) While one layer was applied to a cup, other cups in the array were cooling, but welding proceeded essentially non-stop (minus the air-cut times). The accumulated 'arc-on' time to produce one of these cups was ~70 minutes.

Although the final surface finish of these cups was quite appealing (to those of us who appreciate a nice-looking weld at least!), the surface of walls is oxidized, and it does contain the occasional burr. For this reason, the interior surface and the lip of the of the cups was machined on a lathe to a smooth finish.

FINAL REMARKS

Additive manufacturing is a technology that is rapidly evolving. While there are many methods and materials that can be used for AM, the primary objective of this study of employing a standard 6-axis GMAW robot, teach pendant programming, and standard welding consumables, to produce simple thin-walled shapes was achieved.

Welding conditions and techniques were developed for the future application of AM technology to produce more complex shapes using offline programming and commercially available off-line programming software with CAD to path capabilities (OCTOPUZ® Offline Robotic Programming Software). These projects are currently underway.

Recommendations for additional work include experimenting with arc starting and stopping routines to minimize the excessive weld build-up and spatter, extending the process to non-ferrous alloys (e.g., aluminum or nickel based), and including a tilt/turn positioner with coordinated motion to achieve more complex shapes without the problems of gravitational effects. W

▶ **Aaron DeJong, Len Frejlich, and Tam Nguyen**

Acknowledgment

The authors would like to acknowledge the invaluable assistance of Professor Joe Barnes for with his consultations on robotic programming and Mike DeWeerd of the Industrial Maintenance program for assistance in the machining of the cups. This project was conducted as a final year engineering technology capstone project and was supported by Conestoga College.

About the Authors

Aaron DeJong and Len Frejlich are both recent graduates of the Manufacturing Engineering Technology – Welding & Robotics program at Conestoga College in Cambridge, Ontario. Mr. DeJong is currently employed as the Fabrication/Welding Technologist at Accumetal Manufacturing Inc., Stratford, Ontario. Mr. Frejlich is working as a Joining & Automation Engineer at R&E Automated Systems in Macomb County, Michigan. Dr. Tam Nguyen is a Professor at Conestoga College.

References

[1] S. W. Williams, et al, "Wire + Arc Additive Manufacturing," Materials Science and Technology, vol. 32, no. 7, pp. 641-647, 2016.

[2] Lincoln Electric, "Wave Form Control Technology - Power Mode," Available Online: http://www.lincolnelectric.com/assets/US/EN/literature/NX260.pdf, 2011.