WIRE ARC ADDITIVE MANUFACTURING WITH ROBOTIC GMAW

INTRODUCTION

Wire Arc Additive manufacturing (WAAM) is an alternative to traditional metal manufacturing methods such as casting or the machining of raw billets to produce a desired shape. One option for this ‘3D-printing’ of metallic products using the WAAM process is to apply the metal using the GMAW (gas-metal arc welding) process delivered by a standard 6-axis welding robot.

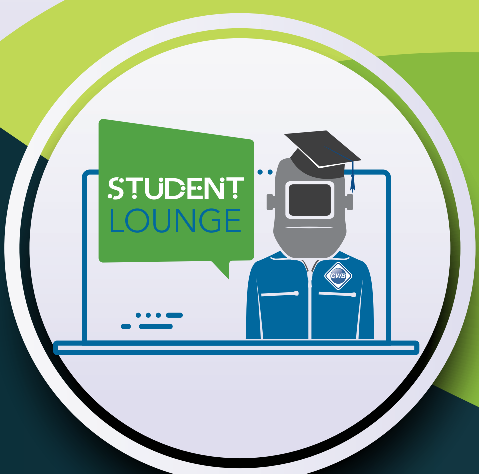
As part of a 3-rd year capstone project in the Manufacturing Engineering Technology – Welding and Robotics program at Conestoga College in Cambridge, ON, a series of thin-walled blocks, where the thickness is less than 10% of the height, were created using three common steel alloy welding electrode wires as the feedstock. This project builds upon previous studies by students at Conestoga in this area.[1] The ultimate purpose of these walls is for a separate study where their integrity and mechanical properties will be evaluated.

PROJECT OBJECTIVES & APPROACH

The project's objective was to develop a WAAM technique to create thin structural steel walls with a stable dimensional shape and to compare the performance of three types of common electrode wires for the application. In a follow-up phase of the project, the components were to be subjected to various standardized destructive mechanical tests such as Charpy impact, guided bend, and tensile tests, the walls were specified to have a minimum nominal thickness of >16mm. Walls of up to 300 mm in height and 300 mm in width were requested to suit destructive testing in both the longitudinal and transverse direction with respect to the weld layering.

Three steel-alloy filler metal classifications meeting CSA-W48 & AWS A5.18/A5.28 requirements were selected for the project. The classifications selected for un-alloyed applications were ER49S-3 and ER49S-6. The S3 classification was compared to the S6 classification with higher levels of deoxidizers such as manganese and silicon. With the automated and continuous nature of the WAAM process there is no practical opportunity for inter-pass removal of silicate (oxide) deposits, and the S3 electrode wire was expected to produce lower levels of these surface deposits than the S6 classification. In addition, the ER55S-Ni1 classification was selected for applications requiring compatibility with various atmospheric corrosion-resistant high-strength, low-alloy steels such as ASTM A242 or CSA G40.21 Grade 400A. All three electrode wires for the project were selected in the 1.14 mm (0.045 in) diameter.

The delivery system chosen for this project was a Fanuc Arc Mate 100-7L/Arc Mate 100iC 6 axis robot with a Lincoln Powerwave R350 power source, see Figure 1. A GMAW pulsed-current process variation commercially known as RapidArc®, which is designed to produce lower spatter levels, a short-arc length with relatively high-travel speeds and a lower heat input, was selected.The shielding gas chosen for the project was a 92% Ar + 8% CO_2 mixture.



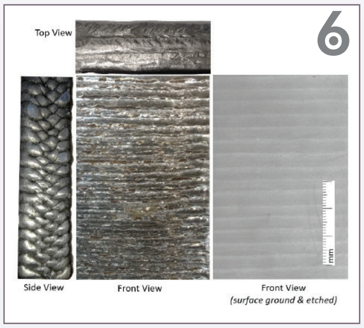


Fig. 1: Fanuc ArcMate 100-7L 6-axis Robotic Arm & Lincoln PowerWave R350 power source. **Fig. 2**: Water Cooled Steel Base Plate. **Fig. 3**: Experimental Weld Layers (length ~100 mm x ~ 16 mm wide). **Fig. 4**: Completed Tall and Wide Walls (300 x 100 x 16 mm) before removal from the base plate. **Fig. 5**: Typical Wall Straightness (less than ~2 mm per 300 mm height or width); Tall Wall shown on its side. **Fig. 6**: Close-up Views of a Typical Wall. **Image 7**: Welding Action Shot.

Table 1: Typical Welding Parameters

PARAMETER	RANGE
Wire Feed Rate ($^{mm}/_{s}$)	125 - 150
Travel Speed ($^{mm}/_{s}$)	14.5 - 15.0
Contact Tip to Work Distance (mm)	12 - 16
Arc Trim (RapidArc® Setting)	1
Current (A)	240 - 265
Arc Voltage (V)	22.0 - 23.0
Heat Input - gross ($^{J}/_{mm}$)	352 - 420
Net Heat Input ($f_i = 0.8$; $^{J}/_{mm}$)	282 - 336
Work Angle (degrees)	90
Travel Angle (degrees)	0
Z-Axis Indexing per Weld Layer (mm)	2.2
Shielding Gas Flowrate ($^{l}/_{min}$)	16 -17
Gas Nozzle Inside Diameter (mm)	16

The welding took place on a thick base steel plate (~400 x 300 x 32 mm) manufactured with internal water-cooling channels and welded to a heavy steel table, see Fig. 2. The base plate was cooled using a water cooler to help maintain a specified maximum welding inter-layer temperature of 130°C to help simulate welding larger components or built-up features on large structural members.

WAAM PROCEDURE DEVELOPMENT

Initial experimentation studied several weld positioning techniques, weld oscillation, and welding parameters to achieve dimensionally stable short walls with a nominal width of >16 mm. Examples of some of these weld trials are shown in Figure 3.

Eventually, a stringer bead technique using the parameters listed in Table 1 was selected for further development. Each layer required four weld passes, with the progression alternating from right to left and left to right with a pause between passes and a rest period at the end of the layer application to allow for a cooling period as required to achieve a maximum inter-layer temperature of 130°C. All three of the welding electrode wire classifications in the test program operated satisfactorily with these conditions.

The approach to robotic programming was online using a teach pendant. This involved teaching the robot through a point-to-point method from the base plate and using position registers to build the layers and offsets to move up in the Z-axis for subsequent layers. Programs were created for the project to build both wide (300 mm long X 100 mm tall) and tall (100 mm long x 300 mm tall) wall segments suitable for follow-up destructive testing. Additional program variations were developed to make several components concurrently to maximize the arc-on time, as shown in Figure 4.

RESULTS AND DISCUSSION

The project experimentation eventually culminated in the production of several solid walls manufactured from each of the three feedstock electrode wires in both the wide and the tall configurations. The walls were measured to be straight vertically and horizontally within less than 2 mm per 300 mm (> 1%), as shown in Figure 5.

Examination of the surface of the components showed an average visible layer spacing of 4.3 – 4.4 mm. This spacing was confirmed with an area that was surface ground and etched, as shown in Figure 6. No significant welding discontinuities were observed on the top of the welded walls; however, the sides and the front display a surface roughness to a depth of ~ 1 mm. Follow-up destructive testing on these components is expected to reveal the structural significance of these discontinuities.

Close observation of the welding performance of each of the three electrode wire classifications (ER49S-3, ER49S-6, and ER55S-Ni1) showed no significant difference in welding operations or performance. In all cases, the residual glassy silicate islands that formed on each layer were friable and spilled off to the sides in the path of subsequent weld passes. No inter-pass cleaning was performed as it was deemed to be impractical for production welding. More detailed planned destructive examination of the interiors of the components will be required to evaluate if there are significant internal differences.

The welding deposition rates in the production of the walls were calculated to be ~4.1 kg/hr (9 lb/hr). With a typical mass of ~4.25 kg (9.4 lb), the minimum time to produce one of the wall objects is approximately 62 - 63 minutes with this method and parameters using a 100% arc-on time in the cycle. Realistically, set-up times, air-cut times, and any required wait times for inter-layer cooling, the achievable production time would be significantly higher than this value, however, there are many variables in these estimates.

FINAL REMARKS

Wire arc additive manufacturing is a technology that is rapidly evolving and is being studied by research groups around the world.[2, 3, 4] While there are many methods and materials that can be used for additive manufacturing, the primary objective of this study was to utilize a standard 6-axis GMAW robot, teach pendant programming, and standard steel welding consumables to produce simple thin-walled shapes for detailed destructive analysis.

The comparison between the three steel alloy classifications used as feedstock for the process (ER49S-3, ER49S-6, and ER55S-Ni1) showed no significant differences in welding operations or performance.

Beyond the planned destructive evaluation of the components produced in this study that is already underway, recommendations for additional work include developing an off-line programming capability to produce more complex shapes using models created through computer-aided design. W

▶ **Leonardo Vidal,** graduate, Conestoga College
Farid Shigapov, student, Conestoga College
Dr. Tam Nguyen, professor, Conestoga College

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About the Authors

Leonardo Vidal is a recent graduate of the Manufacturing Engineering Technology – Welding & Robotics program at Conestoga College in Cambridge, Ontario. Mr. Vidal is currently employed as a Weld Tech at Presstran Industries., St. Thomas, Ontario. Farid Shigapov is in his final year of the Manufacturing Engineering Technology – Welding & Robotics (Co-op) program. Mr. Shigapov was a 2020 winner of the CWB Foundation's Hugh A. Krentz Exemplary Student Award, and he is continuing work in the WAAM field this year. Dr. Tam Nguyen is a Professor at Conestoga College who teaches in the Welding Engineering Technology and the Bachelor of Engineering - Mechanical Systems Engineering (MSE) programs.

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