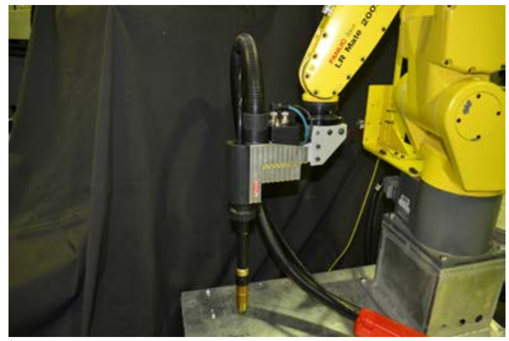
Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Wire Arc Additive Manufacturing

Project highlight. This project designs and implements a new additive manufacturing capability at Savannah River National Laboratory. Wire Arc Additive Manufacturing is an Advanced Manufacturing technology that enables materials and energy savings by producing materials that are in near net shapes to minimize material losses compared to conventional forging and machining techniques. Wire arc additive manufacturing is an evolving technology that can be used to fabricate large components with significantly less materials waste than conventional processing. This project includes an engineering model, an aspect that is largely overlooked in the Additive Manufacturing modeling work where the emphasis has been on mechanistic and microscopic modeling, to estimate the residual stresses and distortions. The Abaqus Weld Interface software coupled with user subroutines in Fortran enable the local cooling rates to be estimated to provide a coarse scale model for the secondary dendrite arm spacing, a parameter useful to estimate mechanical properties.



Wire Arc Additive Manufacturing setup with a Fronius Cold Metal Transfer Torch mounted on a Fanuc robot arm.

Awards and Recognition

No invited talks but a total of 9 presentations were provided at various venues, including Materials Science and Technology conferences, one in FY 18 and one in FY 19, and IMOGs and JOWOGs. These presentations were volunteered rather than invited.

Intellectual Property Review

This report has been reviewed by SRNL Legal Counsel for intellectual property considerations and is approved to be publicly published in its current form.

SRNL Legal Signature

Signature **Date**

Wire Arc Additive Manufacturing

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Subcontractor: A. P. Reynolds and M. A. Sutton (USC)

Thrust Area: Clean Energy and Advanced Manufacturing

Project Start Date: October 1, 2016
Project End Date: September 30, 2018

This project develops and deploys a wire arc additive manufacturing (WAAM) capability for SRNL. To better understand and predict Process-Structure-Property-Performance interrelationships, modeling was conducted a-priori with results that were consistent with the trends for cooling rate and secondary dendrite arm spacing. Two aluminum alloys, Al 2219 and Al 4043 were deposited using either a cold wire gas tungsten arc welding (GTAW) process or cold metal transfer mode of gas metal arc welding. This project positions SRNL as a technical leader in WAAM. This project redeploys a Fanuc robot arm with a state of the art aluminum welder, develops the software needed to drive the robot and weld system, and develops microstructure, thermal, and residual stress predictive tools to enable SRNL and USC to improve/optimize the manufacturing processes.

FY2018 Objectives

- Integrate CMT with Fanuc robot
- Conduct scoping studies to determine appropriate wire arc additive manufacturing space for future experiments
- Conduct statistically designed experiments to optimize microstructure and deposit shape
- Complete developing scripts to predict cooling rate and microstructure from Abaqus Weld Interface models
- Conduct instrumented experiments to facilitate correlating experimental data with models

Introduction

Additive Manufacturing has the capability to make components of almost infinite complexity using one of several different technologies. These technologies include directed energy approaches such as laser engineered net shape (LENS) or powder bed laser or electron beam processes. The powder processes work well and have dimensional limits of about 75 µm. However, the build rate is slow due to layer thicknesses of about 50 µm each, requiring over 4000 layers to build a 200 mm tall component over a time of approximately 45 hours with a single heat source. The size of the article for powder bed processes is further limited by the size of the process bed and ability of the heat source to uniformly reach the entire work area. Finally, the powder processes also have a potential fire concern, especially for reactive metals like aluminum and fine titanium. The fire hazard may be mitigated by using passivated powders, thus reducing their pyrophoric nature by slightly oxidizing the surfaces or by adding other reaction products, but this treatment degrades the powder purity which will compromise the material performance of the finished part. The reaction products could also prevent melting and inhibit the incorporation of the particles into an integral part of the component. Alternative AM methods such as the currently proposed Wire Arc Additive Manufacturing (WAAM) can alleviate these anticipated concerns.

Wire Additive Manufacturing (WAM) uses a wire feedstock and an appropriate heat source (arc, laser, or electron beam) to melt the wire and deposit the material in a programmed consistent manner. Wire Arc Additive Manufacturing (WAAM) uses either cold or hot wire feed Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), or Gas Metal Arc Welding (GMAW) technology to deposit metal layer by layer. The use of wire as the source material enables significantly higher build rates, e.g., 1 kg/h for WAAM vs. 0.2 kg/h for powder bed processes, reported for titanium alloys (1). In contrast to fine unpassivated powders (2), wires are generally not considered pyrophoric. As a result, WAAM eliminates the fire hazard without introducing impurities (e.g., oxides) into the product. Finally, WAAM reduces the material costs, since it costs less to make wire than powder.

WAAM is being rediscovered as an approach for freeform fabrication or three-dimensional printing for large net shape components. Unlike many of the powder-based processes that produce net or near net shapes, WAAM is generally considered an additive manufacturing process that can be coupled directly with a subtractive process. The subtractive element is required due to the higher volume deposition rate and coarse deposit scale that requires machining of the excess material to meet final dimensions. This allows WAAM to produce complex parts with machined surfaces. Despite the need for subtractive manufacturing, WAAM provides tremendous cost and material savings over conventional subtractive processes. For example, the “buy-to-fly” ratio, i.e., the material required to make a component, like an airplane wing spar (Fig. 1), vs. the material remaining after final machining, can be 10:1 for conventional processing of titanium alloys while the buy-to-fly for WAAM can be as low as 1.2:1. WAAM does have the shortcoming that parts must be slightly oversized to accommodate the machining allowance; this gives rise to new design terminologies such as total wall width (TWW) and effective wall width (EWW) where TWW includes the weld bead scallops on the surface which need to be machined away and EWW is the final dimension of the post-machining wall. The difference in TWW and EWW gives rise to the buy-to-fly ratio that is attributed to WAAM. Finally, the WAAM structures can be forged to obtain improved properties over the as-fabricated microstructure.

Figure 1. Material size and scale for (a) WAAM wingspar.

Approach

This project has two primary drivers: first, establishing a WAAM capability and, second, establishing a modeling capability based on commercial software evolution. WAAM has been established as a viable technology for titanium-based alloys (3, 4, & 5) and has been suggested as a feasible technology for aluminum as well (3). Aluminum is best deposited using GMAW and either spray or dip transfer modes. The benefit of using dip transfer is that it minimizes the spatter associated with spray transfer for GMAW and the total heat input. The software and hardware will be integrated with open source code and open

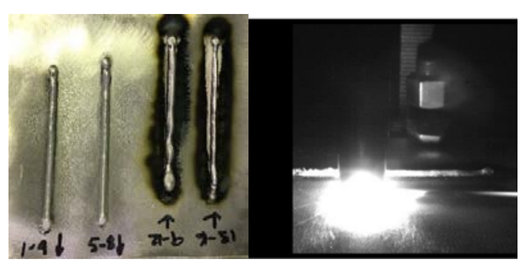

Figure 2. WAAM A4043 beads deposited on Al6061 and the CMT GMAW deposition.

architecture to allow both simple and more complex 3D shapes to be printed using GMAW torch mounted to a Fanuc Robot arm.

One major hurdle for AM is to close the gap between the as-designed and the as-manufactured configurations. For WAAM, this includes minimizing the difference between TWW and EWW (Fig. 3) as well as controlling distortion and residual stresses in the printed part. This optimization can be facilitated by computer modeling or simulation of the WAAM process. Therefore, in parallel to fabricating the SRNL WAAM system, coupled microstructural, thermal, and stress modeling was conducted. The following three-step approach is proposed. Step 1 – Simulate WAAM by predicting the as-manufactured part based on the as-designed specifications. The multi-purpose commercial finite element code Abaqus, available at SRNL, was utilized along with its welding-interface plugin. The 2017 Abaqus Welding Interface (AWI), which SRNL currently has access to in beta version, has the capability to account for gradual addition of material to the workpiece over the course of the simulation (vital for simulation of WAAM), coupled with a heat source model well-established for representing welding heat inputs. The AWI also enables specification of weld geometric features, temperature-dependent material properties, bead/chunk specification, multiple weld passes, and thermal and structural boundary conditions. The final shape of the product, distortion, and residual stress will be calculated both before and after "unclamping" of the mechanical constraints, fracture and damage can be assessed, and optimization of the WAAM process will be conducted by varying the operating parameters and the material properties. Step 2 – To close the gap between as-designed and as-manufactured configurations, it may be necessary to capture the material properties using samples with a variety of dimensions since the AM process impacts the material properties. Important metal phase transformations occur during melting and re-solidification that affect tensile strength and fracture toughness, but most currently available property data corresponds to temperatures well below the solidus temperature. This can be resolved by benchmarking the test data, or by acquiring multiscale computer software for materials modeling. Step 3 – Conduct optimization of process parameters to match the as-manufactured to the as-designed configurations (or minimize the gap between TWW and EWW, Fig. 3). The process-specific considerations include deposition path data, heat source characteristics, multi-scale scope, and the model size.

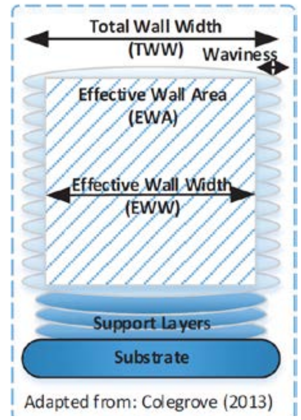

Figure 3. Definitions for TWW and EWW for WAAM processes showing the required overbuild.

Figure 4. As-printed surface condition from a full factorial DoEx conducted at USC.

Results/Discussion

Weld microstructures were improved from significantly porous structures to near full density by modifying the appropriate weld parameters. Scoping studies, Fig. 5, were used to define the initial parameter space and were optimized using statistically designed experiments. One concern for the build-up of the deposits is the incorporation of air and presence of oxides on the weld wire, but the wire could not be cleaned either prior to loading in the welder or while it was being consumed by the welder. To minimize the effects of local atmosphere on the deposit microstructure, an additively manufactured gas showerhead was produced to displace the air with argon during welding. The level of soot that was deposited on the surface of the substrate decreased in the presence of the gas showerhead, but not consistently. An unfortunate condition occurred when using the Fanuc robot in that the controller did not produce a smooth movement. This characteristic manifested itself as waves in the WAAM deposit with a periodicity of about 8 mm and a height that depended on the weld current.

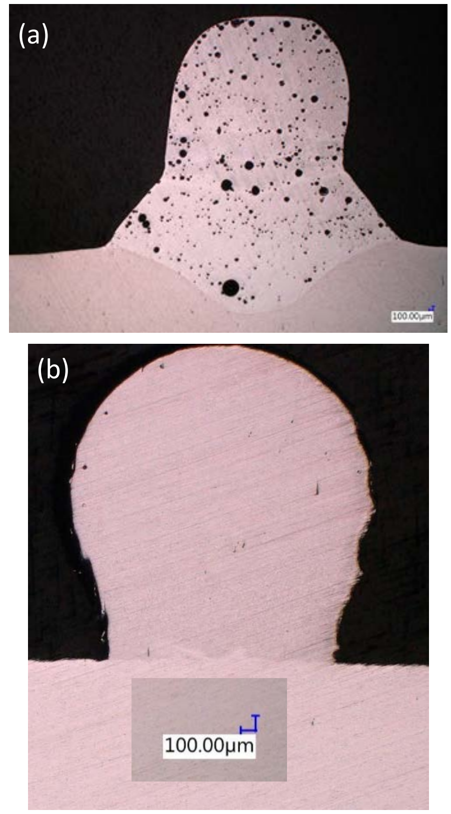

Figure 5. (a) Initial scoping study welding at high current and 90° torch angle and (b) lower current weld at 75° torch angle—note absence of porosity.

A two-level, four-variable design of experiments was conducted to determine the process window for pore-free deposits. The wire feed, torch speed, use or omission of the gas showerhead, and cup-to-plate height variables were tested. The parameter set selected did not fully eliminate the porosity, although the porosity was reduced and concentrated near the top of the weld as opposed to throughout the weld, as shown in Fig. 5a. The presence and absence of soot on the plate was not a good indicator of porosity. High wire feed rates significantly affected porosity, while the other three variables had small or no discernable effect (Fig. 6). Torch speed and wire feed affected the weld bead deposit size with high torch speed producing a smaller deposit and high wire feed producing a larger deposit. There was no discernable effect of cup height and shield gas on the response variables.

The robotic control of the welder was not optimized but the WAAM system was used to fabricate a 3-D layup that consisted of four layers, using non-optimized parameters, in the shape of a rectangle, Fig. 7. The control system was not optimized for stops and starts so craters and bulges were present. In addition to the rectangle, a single bead wide "blade" eight layers thick was also deposited as can be seen in Fig. 7.

Experiments were conducted that demonstrated the ability to generate relatively square cross-sections of weld deposit, Fig. 4. These samples were subsequently evaluated for secondary dendrite arm spacing (SDAS). The SDAS coupled with weld modeling is used to correlate cooling rates to weld parameters. These data can then be utilized for estimating deposition strengths based on literature correlations.

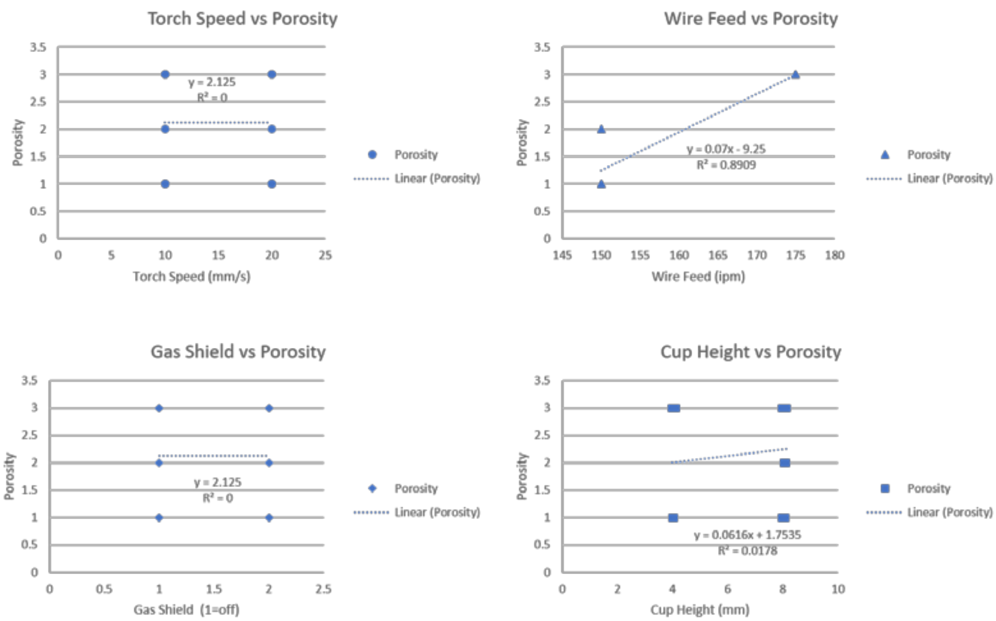

Figure 6. Effect of the variables tested, torch speed, wire feed, gas shield, and cup height on the response variable "porosity".

Figure 7. 3-D WAAM deposits using programmed torch paths to create a four-layer rectangle and an eight-layer "blade".

FY2018 Accomplishments

- Integrated Fanuc robot with Fronius welder to enable arc start and motion for simple geometries. Prior to this development, SRNL did not have the capability for robotic welding in more than two dimensions.
- Completed scoping studies that resulted in a significant improvement in process conditions to virtually eliminate porosity in the CMT GMAW WAAM deposits.
- Fabricated and tested a gas cover showerhead using polymer additive manufacturing to improve shielding to reduce deposit porosity. Conducted a DoEx and determined the effects of travel speed, wire feed, gas cover, and arc distance at two levels.
- Completed an experiment to determine the temperature and cooling rate as a function of position from the WAAM deposit and as a function of 1 to 4 layers in the presence and absence of additional cover gas.
- Completed DoEx for optimizing a square deposit using cold wire GTAW to maximize the material usage on a layer to layer basis. Developed an ImageJ script for image analysis to automate the data capture and analysis.

- Demonstrated that the predicted cooling rate from the weld modeling and the measured secondary dendrite arm spacing data had consistent trends.

Future Directions

- Obtain future funding to enable additional capabilities of the WAAM based on having a capability at SRNL.
- Incorporate additional sensors and data analytics for smart manufacturing using thermal and optical sensors for process sensors and defect detection and prevention.

FY 2018 Publications/Presentations

1. SRNL-STI-2017-00594, Development and Deployment of a Wire Arc Additive Manufacturing Capability, Anna d'Entremont, Andrew Duncan, Poh-Sang Lam, John Bobbitt, Eric Kriikku, Derek Gobin, Matthew Folsom, Paul Korinko, Anthony Reynolds (USC), presented at MS&T17, Oct. 8-12, 2017 Pittsburgh, PA.

2. SRNL-STI-2017-00688, Development of a Wire Arc Additive Manufacturing System, Paul Korinko, Andrew Duncan, J. Bobbitt, E. Kriikku, D. Gobin, PS Lam, A. d'Entremont, M. Folsom, W. Housley, & A. Reynolds* (*USC), Additive Manufacturing IMOG, Kansas City National Security Campus, Nov. 7&8, 2017

3. SRNL-STI-2018-00025, SRNL Additive Manufacturing Site Update, Paul Korinko, Welding IMOG / WAM FE, Sandia National Laboratory, Livermore, CA, Jan. 22-23, 2018

4. 2018-SRNL-STI-00167, Savannah River National Laboratory Additive Manufacturing and Metallurgy, Paul Korinko, Georgia Southern University, April 13, 2018, Statesboro, GA

5. SRNL-STI-2018-00234, Wire Arc Additive Manufacturing at SRNL, Paul Korinko, Andrew Duncan, J. Bobbitt, E. Kriikku, D. Gobin, PS Lam, A. d'Entremont, M. Folsom, W. Housley, & A. Reynolds* (*USC), Wire Additive Manufacturing Focused Exchange and Welding JOWOG, May 21-25, 2018, AWE, Reading, Berkshire, England.

6. SRNL-STI-2018-00236, SRNL Additive Manufacturing Update, Paul S. Korinko, Wire Additive Manufacturing Focused Exchange and Welding JOWOG, AWE, Reading, Berkshire, England, May 21-25, 2018

7. SRNL-STI-2018-00237, SRNL Welding and Joining Site Update, Paul Korinko, Wire Additive Manufacturing Focused Exchange and Welding JOWOG, AWE, Reading, Berkshire, England, May 21-25, 2018

8. SRNL-STI-2018-00339, Prediction of local microstructure for wire-arc additive manufacturing of aluminum alloys, Andrew Duncan, Anna d'Entremont, Poh-Sang Lam, Paul Korinko, ASME 2018 Pressure Vessels and Piping Conference, July 15-20, 2018.

9. SRNL-STI-2018-00130, Deposition of Aluminum 4043 during Wire Arc Additive Manufacturing, Paul Korinko, Eric Kriikku, William Housley, John Bobbitt, Andrew Duncan, Anna d'Entremont, Matthew Folsom, and Matthew Van Swol, to be presented at MS&T18, Oct. 15-21, 2018, Columbus, OH.

References

1. Busachi, A., et. al, "Designing a WAAM Based Manufacturing System for Defence Applications", Procedia CIRP (2015), 48-53.
2. Kwon, Y.S. et. al, "Passivation process for superfine aluminum powders obtained by electrical explosion of wires", Applied Surface Science 211 (2003) 57–67.
3. Williams, S.W, et. al "Wire + Arc Additive Manufacturing", Materials Science and Technology, 32:7, 641-647, DOI:10.1179/1743284715Y.0000000073
4. Szost, B.A., et. al, "A comparative study of additive manufacturing techniques: Residual stress and microstructural analysis of CLAD and WAAM printed Ti–6Al–4V components, Materials and Design 89 (2016) 559–567.
5. Berminham, M.J., et. al, "Controlling the Microstructure and Properties of Wire Arc Additive Manufactured Ti-6Al-4V with Trace Boron Additions", Acta Materialia 91 (2015) 289-303.

Acronyms

Al	Aluminum
Al4043	Aluminum welding alloy 4043
Al6061	Aluminum alloy 6061
AWE	Atomic Weapons Establishment
AWI	Abaqus Welding Interface
CMT	Cold Metal Transfer
DoEx	Design of Experiments
EWW	Effective Wall Width
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
MS&T	Materials Science and Technology
SDAS	Secondary Dendrite Arm Spacing
SRNL	Savannah River National Laboratory
USC	University of South Carolina
TWW	Total Wall Width
WAAM	Wire Arc Additive Manufacturing

Intellectual Property

None

Total Number of Post-Doctoral Researchers

One MS student was supported through a subcontract with University of South Carolina