SS410 Process Development and Characterization

D. M. Vaughan*, A. Nycz*, M. W. Noakes*, C. Masuo*

*Manufacturing Demonstration Facility, Oak Ridge National Laboratory, Oak Ridge, TN 37831

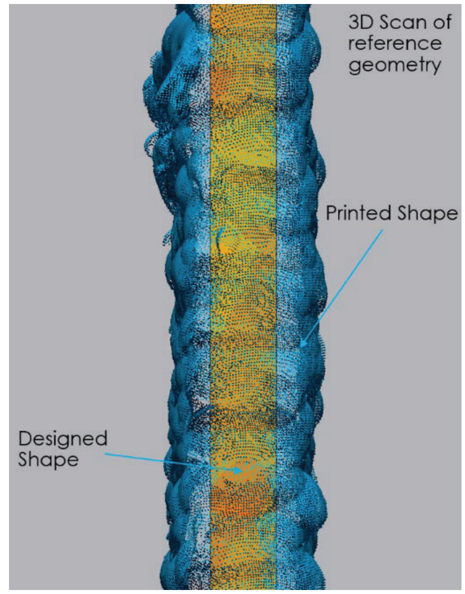
Abstract

Wire-fed stainless-steel additive manufacturing provides the potential for an alternative to traditional stainless-steel tool making processes. 410 stainless steel provides the necessary hardness for long term tool use and its corrosion resistances negates the need for post processing of non-critical faces. 410 has unique characteristics that require different design and welding parameters from other materials. This paper will look at the parameters and characteristics to expect when using wire-arc deposition for 410 stainless steel. Individual weld beads and simple geometric features were printed using the mBAAM wire-arc system at ORNL to determine effective wire-arc parameters for SS410. Once parameters were chosen, additional features were printed to determine the geometric characteristics of printed SS410 as well as compare the differences between designed geometries and printed geometries. These results allow for the formulation of smarter design rules when designing parts for SS410 additive manufacturing.

Introduction

Typical powder-based metal additive manufacturing utilizes metal powders coupled with a laser or electron beam to input the required energy to melt the powder and build a shape within each layer of metal powder [1]. Wire-arc additive manufacturing uses a metal wire as the feed material. The energy to melt the wire can be achieved from several methods. Tungsten Inert Gas (TIG) or Metal Inert Gas (MIG) are common methods. Plasma arc welding and laser systems are also used [2, 3]. The ability to use standard welding wire in wire-arc processes represents a significant advantage of these systems due its low cost, high deposition rate, and safety [4]. Wire-arc systems can also be scaled up easily allowing much larger build areas to be achieved [7].

On the other hand, wire-arc additive manufacturing systems typically have a much lower resolution for printed parts. Resolution on a wire-arc system might be on the order of several millimeters [5]. Because of this, it is important to properly characterize how materials perform when printed using wire-arc systems. Understanding geometric characteristics of a material will enable smarter designs to be developed improving near net shape qualities to reduce or eliminate post processing requirements. This paper will look at the geometric characteristics of printed 410 stainless steel using a MIG wire-arc system. Compared to printed ER70S-6 with a hardness of 150 HVN [8], 410 stainless steels corrosion resistance and hardness of 446 HVN make it an effective material for the tool and die industry. Therefore, being able to accurately design parts for printing with 410 stainless steel is extremely useful in large scale metal additive manufacturing. To develop the design rules for printing walls of 1, 2, and 4 bead thicknesses and tubes of varying diameter were printed to develop predictions on as-designed vs as-printed stainless-steel part geometries.



Overview of Experiment Setup

The work in this paper was performed at the Manufacturing Demonstration Facility (MDF); a part of Oak Ridge National Laboratory. The MDFs mBAAM wire-arc system consists of a Lincoln Electric Powerwave R500 welder with an ABB IRB2600 6 degree of freedom manipulator. Wire is fed using a traditional spool through a Lincoln Electric Autodrive 4R220 wire feeder. The wire used for these experiments was 0.045mm Blue Max ER410. The system is shown in the figure below with a dual torch heads enabling multiple materials to be printed in a single part. This feature was not used for the experiments in this paper. Parts are printed on 1” or ¼” plates depending on requirements to avoid warpage in the part.

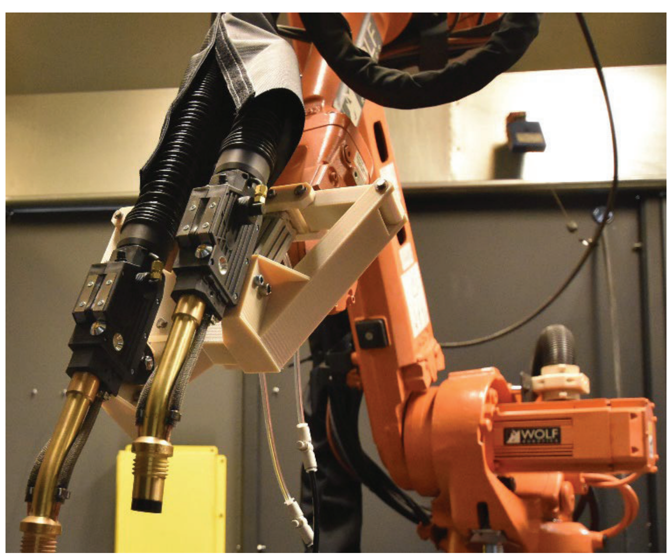


Figure 1: mBAAM Wire-Arc System with Dual Torch Setup

When printing using wire-arc deposition processes. The resulting print is near net shape, but still has noticeable geometric variations from CAD models. When designing parts to be printed using wire-arc deposition process, it is important to be aware of the differences between the geometry of the part as-designed and as-printed. Depending on the material being used for printing, these geometric differences will vary. Different materials will also have different properties when used in overhang scenarios and can add additional constraints to design.

To determine the printing characteristics of 410 stainless steel walls of varying thickness were printed to quantify the printed vs designed widths and heights differences. Due to the complexity of simulating additive welding conditions, it was decided to be more practical to obtain geometric characteristics experimentally [9]. Walls serve as a base geometry for printing as walls are typically used to make up more complex geometries. cylinders were also printed for comparison as cylinders tend to have different printing characteristics from walls and are useful as internal features. The results from these prints could then be used to develop guidelines that would enable smarter design when creating parts using wire-arc deposition processes.

Initial Parameter Development

Prior to experiments to determine geometric characteristics, single beads were deposited to obtain welder and slicer settings that would provide clean welding processes and effective bead fusion. Welder settings such as weld power, wire feed speed, and Z axis tracking gains were adjusted using Lincoln Electric Power Mode [6]. These setting were adjusted primarily through observation of the deposition process as well as checking for porosity and bead fusion after deposition. Bead spacing was adjusted to improve bead to bead fusion. 3.2mm was found to provide little to no porosity between beads. In order to implement this bead spacing, the Oak Ridge National Laboratory slicer would require that walls and other features be designed in increments of 3.2mm in order to achieve this bead spacing.

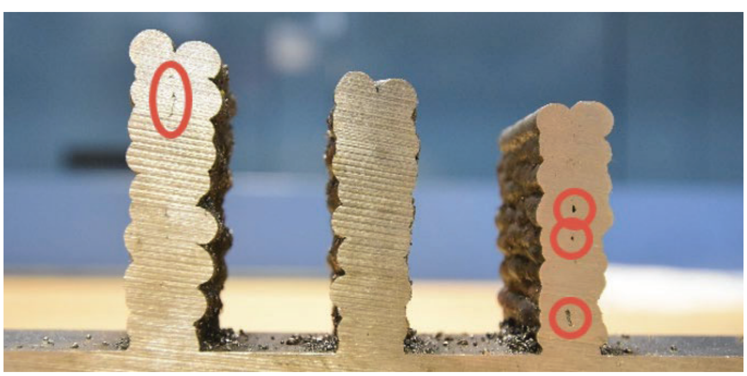


Figure 2: Incorrect bead spacing showing porosity between beads.

Single Bead Wall Geometry

A single bead wall represents the thinnest geometry that the system is currently set up to print. In order to slice the wall properly, a single bead wall was designed as 3.2mm wide. Each bead was also designed as 3.2mm high. 20 layers were printed to achieve a designed height of 64mm.

The single bead wall was designed as a 152.4mm by 40.64mm rectangular tube shape due to slicer limitations that prevented shapes that did not have the same start and end point from slicing properly. After printing the first bead measurements were taken of the width and height of the bead using digital calipers. After 20 layers were printed height and width measurements were taken of the wall. The part was then cut to observe the cross sections and check for porosity. As expected, there was no notable porosity in the one bead wall. Each layer fused into the previous layer relatively well and did not leave clearly defined beads in the cross sections.

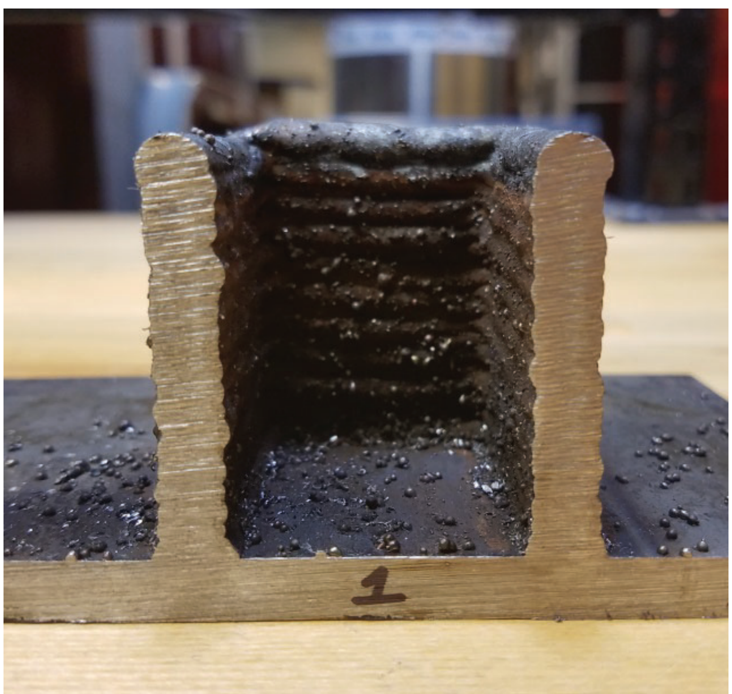


Figure 3: Cross Section Cut of One Bead Wall

The following table shows the measurements taken of the single bead wall using digital calipers.

Table 1: One Bead Wall Caliper Measurements.

Base Layer Characteristics			Layer 20 Characteristics		
Measures	Height (mm)	Width (mm)	Measures	Height (mm)	Width (mm)
1	3.3	9	1	41.23	8.77
2	3.38	9.41	2	41.89	8.42
3	3.46	9.07	3	41.96	8.08
4	3.38	9.38	4	41.77	8
5	3.42	9.23	5	41.92	7.88
Average:	3.39	9.22	Average:	41.75	8.23

Based on these measurements the as-printed dimensions are significantly different from the as-designed dimensions. Height at layer 1 was reasonably close with an error of 0.19mm. However, at layer 20 the average layer height was 2.09mm. This resulted in an overall build height error of 22.25mm. This large error in build height is likely due to the gradual increase in heat that builds up within a part during deposition. As heat increases the molten bead will flow more easily and reduce layer height once solidified.

Two Bead Wall Geometry

Two bead wall geometry is particularly important for many of the parts printed at Oak Ridge National Lab. Typically two beads are used for the perimeter shape of a part. Properly designing the perimeter ensures that the part is as close to net shape as possible. A two-bead wall serves as an effective test of the perimeter of any part.

The two-bead wall was printed as a single 152.4mm long wall. Bead spacing remained 3.2mm, so the part was designed as 6.4mm wide and remained as 64mm tall. The first layer was measured for width and height and the overall wall was measured for width and overall height with digital calipers. As shown in Figure 5 below, some sections of the two-bead wall had notably larger bead definition and increased width than appeared in the single bead test. This was particularly prevalent near the ends of the bead where the part builds up additional heat as the MIG torch moves in a U-shaped path.

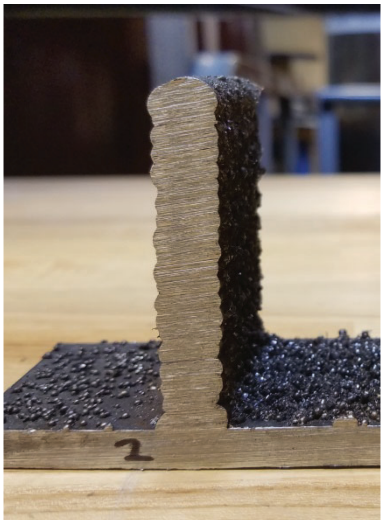


Figure 4: Two bead wall cross section.

Figure 5: Cross section near end showing additional material flow.

The table below shows the measurements taken of the two-bead wall at layer 1 and at layer 20. Caliper measurements were noted to be only the widest points at each measurement point. Solid material had a much smaller width.

Table 2: Two Bead Wall Caliper Measurements.

Base Layer Characteristics			Layer 20 Characteristics		
Measures	Height (mm)	Width (mm)	Measures	Height (mm)	Width (mm)
1	4.93	11.51	1	56.42	11.35
2	5.37	11.45	2	56.67	11.58
3	5.24	11.57	3	56	11.16
4	4.97	11.41	4	56.04	11.18
5	5.11	11.46	5	56.3	11.42
Average:	5.12	11.48	Average:	56.29	11.34

The height of the two-bead wall both at the first layer and overall was larger than the single bead wall. Average layer height overall was 2.81mm. Due to the bead spacing allowing for some overlap between each bead, this resulted in an increase in bead height which improved the build height error to 7.71mm. Width was 4.94mm wider than designed which was expected with the increased heat input.

Four Bead Wall Geometry

A four-bead wall was chosen to serve as a guide for extrapolation on larger perimeter sizes. Larger perimeters might also be needed on multi-material parts or in wall features thicker than the two-bead wall.

The four-bead wall was designed as 152.4mm long and remained 20 layers or 64mm tall. The designed width for the wall was 12.8mm. The print was again measured after the first layer and after completing 20 layers. As can be seen in Figure 4 and 5 below, the inner two beads of the wall appeared to build higher than the outer two beads. This was likely a byproduct of overlapping beads to ensure bead to bead fusion.

Figure 6: Four bead wall cross section.

Figure 7: Second four bead wall cross section.

The table below shows the measurements found on the four-bead wall. As with the two-bead wall, the width appears to increase past the first bead, but is likely due to the use of calipers only hitting the widest points of the wall.

Table 3: Four Bead Wall Caliper Measurements

Base Layer Characteristics			**Layer 20 Characteristics**		
Measures	Height (mm)	Width (mm)	Measures	Height (mm)	Width (mm)
1	8.22	17.94	1	70.6	18.34
2	7.66	17.9	2	70.01	18.55
3	7.55	17.5	3	69.62	17.57
4	7.81	17.66	4	69.85	17.89
5	7.27	17.55	5	70.42	17.95
Average:	7.70	17.71	Average:	70.10	18.06

The four-bead wall saw a further increase in build height. Average height exceeded the design height by 6.10mm. The average layer height was 3.5mm. Width of the wall was 5.26mm larger than designed which was similar to the error found in the two-bead wall.

Tube Geometry

The capability to print parts with tubes and channels built into the part represents a major advantage of additive manufacturing. For large diameters, it may be enough to simply treat tubes as walls. However, different characteristics appear for smaller tubes where heat is concentrated on a small area for the entire duration of the bead. Greater than designed width in walls can also greatly change the diameter of a printed tube. This experiment will look at the relationship between designed vs printed small tubes so that designs can be made to allow the printing of tubes much closer to net shape.

In this test six holes of varying diameter from 10mm to 20.2mm were printed to determine the characteristics of hole features when printing with stainless steel. All six holes were printed on the same 1” build plate. Each tube was printed for 15 layers. The inner diameter and height of each tube was measured in three places to determine an average. The 10mm and 12mm tubes failed to maintain a hole during printing, so are not included in the tube inner diameter table. However, their heights are still included in the tube height table. A goal of achieving an actual hole diameter of 10mm was set and is shown highlighted.

Figure 8: 18.2, 18.7, 19.2, and 20.2mm Tubes

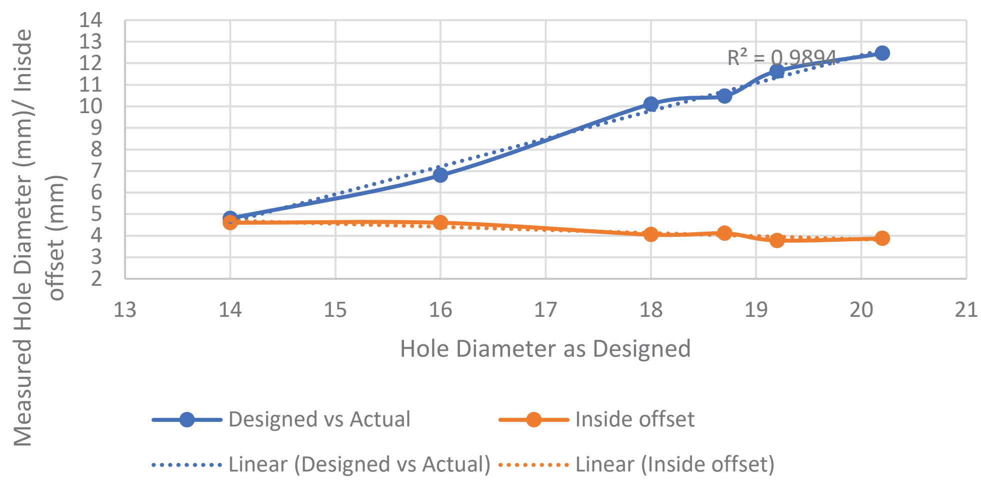
Figure 9: 10, 12, 14, and 16mm Tubes

Table 4: Measured Tube Diameters

Designed	14mm	16mm	18.2mm	18.7mm	19.2mm	20.2mm
Measured	Hole D (mm)	Hole D (mm)	Hole D (mm)	Hole D (mm)	Hole D (mm)	Hole D (mm)
1	5.1	6.99	10.08	10.79	11.63	12.44
2	4.66	6.46	10.16	10.33	11.69	12.18
3	4.64	6.96	10.08	10.32	11.59	12.75
Average:	4.8	6.80	10.11	10.48	11.64	12.46
Inside offset	4.6	4.60	4.05	4.11	3.78	3.87

Based on the results found measuring each of the printed tubes, a relationship was plotted to compare the as-designed and as-printed tube sizes. This relationship could then be used to improve part design to allow interior tubes to be designed to achieve the correct diameter as-printed.

Figure 10: Circular Hole Diameter: Designed vs Actual



<u>Design Rules Based on Experiments</u>

Using the results found from the four different printed geometries a set of design rules can be developed to aid in designing for wire-arc additive processes. The table below shows the combined results of the 3 printed walls for their as-designed vs as-printed dimensions.

Table 5: Comparison of Printed vs Designed Geometry

	One Bead Wall		Two Bead Wall		Four Bead Wall	
	Designed	Printed	Designed	Printed	Designed	Printed
Width	3.2mm	8.23mm	6.4mm	11.34mm	12.8mm	18.06mm
Height	64mm	41.75mm	64mm	56.29mm	64mm	70.1mm

	One Bead Wall	Two Bead Wall	Four Bead Wall
Designed Distance from Bead Center	1.6	3.2	6.4
Printed Distance from Bead Center	4.115	5.67	9.03
Excess Material on Each Side of Wall	2.515	2.47	2.63

Based on the above table, each wall had on average 2.54mm of excess material on each side. Therefore, when designing parts of stainless-steel wire-arc systems excess material extending 2.54mm beyond what is designed should be expected. However, this excess material is not necessarily solid. Due to the rough texture of the printed walls, the material on the side of each wall will likely not extend this distance in all positions.

For the tube geometry, it can be inferred from Figure 10 that the tube diameter will follow a roughly linear relation:

$$D_{printed} = 1.2894 * D_{designed} - 13.419$$

This relation can then be used to size printed tubes for the as-printed geometry. As with the printed walls, these values would estimate a minimum diameter for the tube. Variations in surface geometry would likely create points where the inner diameter was larger.

Conclusion

The increased deposition rate and build volume that wire-arc additive manufacturing provides also bring a decrease in print accuracy. However, smarter design rules such as the ones in this paper can be developed that take into consideration the characteristics of a printing method and material characteristics. Using these design rules will help take full advantage of the benefits of wire-arc additive manufacturing while minimizing the drawbacks of decreased accuracy.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, under contract number DE-AC05-00OR22725.

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