Wire-arc additive manufacturing of reduced activation ferritic martensitic (RAFM) steel

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Abstract

RAFM steel has been considered as the candidate material for an in-vessel component of the fusion wall reactor. Known as F82H in Japan and Eurofer-97 in Europe, RAFM steel is not commercially available. The goal of this research project is to fabricate and study the technical feasibility of producing RAFM steel welding wire with wire arc AM. Metal-cored wire is a tubular electrode comprised of an outer metal sheath with alloying powdered materials inside the core. Applications of such wire include but not limited to welding, thermal spray, cladding and additive manufacturing (AM). The advantage of using the metal-cored wire is that a higher deposition rate, higher side-wall fusion, can be achieved, and more important, special alloys for special applications can be manufactured at relatively lower cost. A preliminary investigation of wire arc AM of RAFM steel was carried out using Ar-CO2 (c-25) gas. A design of experiments with GMAW based power source waveform using the metal cored wire was conducted to study the printability. The microstructure and mechanical properties (hardness and toughness) was tested, and the data were analyzed and compared with the literature.

Keywords: Additive manufacturing, wire-fed AM, RAFM steel

Introduction

In 1982, in order to meet the shallow land burial limitation, researchers attempted to develop a low-activation material for fusion reactor application [1]. Similar to Grade 91 steel (9% Chromium and 1% Molybdenum), RAFM steel was proposed as the steel offers low radio activation levels and excellent thermal properties. Moreover, the chemical composition of RAFM steel was similar to Grade 91 steel, however the high activation elements like Mo and Nb have been replaced by V, Ta and W. The main difference between the F82H and EUROFER-97 was a slight variation in the Chromium content. Tantalum has been reported to be beneficial in controlling grain size and improving toughness [2][3]. Increasing the tungsten content increased the overall mechanical properties as reported in the literature [4]. RAFM steels have been developed in many countries with different name such as F82H in Japan, EUROFER 97 in Europe, ORNL 9Cr-2WVTa in the United States [5], and IN-RAFM in India [6]. Residual high-activation elements are kept as low as possible; for example, if Ta is added, RAFM steel has <10 ppm of Nb. Similarly, aluminum (Al) is added as a deoxidizer in steel making, and <100 ppm have been observed in RAFM steel.

Now the RAFM steel has been benchmarked as a candidate material for fusion reactor components. Evidence confirms it can be joined with all the available technologies, but it is not available commercially in any form. New approaches to its fabrication are needed to develop nuclear reactor components that meet the minimum chemical composition and mechanical properties requirements. The traditional RAFM Steel making method involves melting and remelting (vacuum induction melting (VIM)+ Electro slag remelting (ESR)/ Vacuum arc remelting (VAR)) [7]. The steel is then rolled and drawn to make solid wires. The metal cored wires differs from solid cored wires, and bring advantage of controlling the chemistry with fine and pure powder particles in a low production setting. First, a metal strip is milled to form the outer sheath that houses the powder core. Using a specialized process, the powder is fed into the sheath in a precise manner. The filled wire is then rolled into a tubular shape and drawn to its final size, a diameter ranging from 0.045” to 0.125”, which is ideal for fusion welding, thermal spray, and direct energy deposition-based AM. For the equivalent heat input, metal cored wire carry higher current densities than solid wire. Thus, higher deposition rate, better penetration, and improved side wall fusion with low spatter can be achieved [8]. **Although the cost of the metal cored wire is higher than solid wire, improved productivity offsets the additional cost** [9]**. In addition, the cost could be even lower because the metal strip that will be used in metal-cored wire does not involve remelting.**

P91 alloy has been successfully welded using metal-cored wire, and improved toughness was reported when using metal-cored P91 wire for welding [10]. In another paper from the same authors, higher welding speed and deposition rate was reported using metal cored wire when thicker P91 steels was welded [11]. A recent study exploring the use of metal-cored low carbon steel wire for direct energy deposition technology (additive manufacturing) showed excellent mechanical properties [12]. A recent study exploring the use of metal-cored low carbon steel wire for direct energy deposition technology (additive manufacturing) showed excellent mechanical properties [13]. Thus there is a potential for metal cored wire to implement in direct energy deposition for the fabrication of nuclear components.

RAMF steels fabricated by selective laser melting show better or similar mechanical properties [15]. **Metal-cored wire provides the same advantage to additive manufacturing community as powder bed fusion: the chemical composition can be altered and design the alloy of choice by meeting the chemical requirements**. Wire-fed AM such as plasma/electric arc, laser, or electron beam, to melt a feedstock material can take advantage of using the metal cored wire.

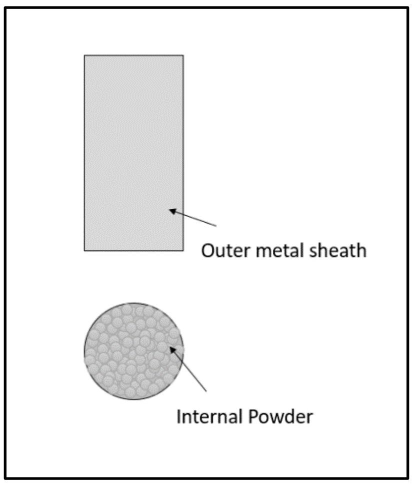

Figure 1: Overview and section of the metal cored wire

The goal of this research is to study the technical feasibility of producing RAFM steel components with wire-arc AM. In RAFM steel, the trace impurities such as Co, Cu, Ni, Mo and Nb (as they exhibit higher radio activation level) are undesirable and must be minimized. The development of metal cored wire can exclude such undesirable elements and the chemistry can be controlled. The metal cored wire as shown in Figure 1 is fabricated using a sheath made of the major element and the sheath is fed by the alloying elements in powder form using a specialized feeding process. Additive manufacturing (AM) has become the fabrication technology of choice in defense, medical, aerospace, automotive, tooling industries. AM – more specifically WAAM that uses wire as a feedstock can produce components that are within dimensional tolerances, which will improve the productivity, lowering cost and time to market. To date, no studies have focused on building parts and components using direct energy deposition because RAFM steels is not available in wire form. This project will pioneer the methodology to fabricate RAFM-cored wire for use in direct energy deposition technologies. We will study the uniformity and homogeneity of the alloying elements; test for levels of impurities; and analyze and compare mechanical properties and microstructure with the published literatures.

Experimental

Table 1: Chemical composition of RAFM metal cored steel wire (balance Fe)

C	Cr	Mn	V	W	Ta
0.1	8.8	0.4	0.2	1.2	0.06

The WAAM system is comprised of a robotic manipulator, welding power source, and automation kit to combine the power source and robot (Figure 2). The Robotic hardware consisted of a Kuka KR6 R900-sixx robot arm with a KRC4 controller, a mechanical reach of just over 1m at the mount plate which provides a large build area for production. The Arc welder used was a Lincoln Powerwave R450, with auto drive wire feeder which is adapted to the Kuka robot mount plate using a Tregaskiss CA3 Tough Gun robotic MIG welding kit. An open source software Ultimaker Cura was used to slice the CAD file and an offline programming software OCTOPUZ was used to convert the G-code into the native robotic language. A Sigma Epsilon infrared thermometer was placed to measure the interpass temperature. The standard metallographic procedure was used to prepare the specimens for optical microscope, and microhardness.

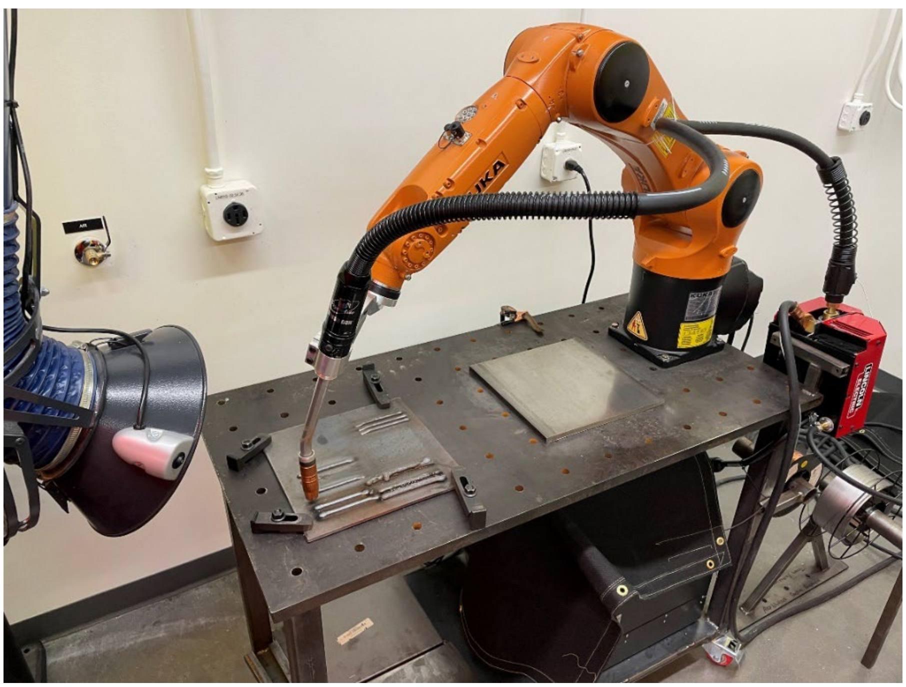

Figure 2: Wire Arc AM setup

Results

First welding trials began with near no baseline. Pulsed current was singled out to be the excellent deposition waveform. The pulses measured minimum amperage of 120 A and a peak amperage of 375 A; the wire feed speed and peak amperage pulse were directly correlated with the work point. Pulse current was the initial testing priority for its decrease in overall heat input and increase in peak amperage, lower heat assists in mitigating warpage. This is because the higher amperage at peak should change the metal transfer method to spray transfer briefly as peak amperage is hit, and then reduce after lowering the heat input. Figure 3 and Table 2 shows the design of experiments results of a single bead RAFM steel using different GMAW waveform.

Figure 3 C25 trial 1-7 using various GMAW waveform

Table 2: R1 - R7 Weld Mode Trials using various GMAW waveform

Weld #	R1	R2	R3	R4	R5	R6	R7
Bead type	Single	Single	Single	Single	Single	Single	Single
Speed (mm/s)	14	14	14	14	14	14	14
Mode	power mode	Constant Voltage	Rapid arc	Pules	Pulse	Pulse	Pulse
Power level	3.5kW	18V					
WFS (in/m)	225	400	430	375	375	375	375
Trim	-	-	1	1	1.25	0.75	1
Ultimate Arc	-	-	0	0	0	0	-5
Wire Stick out (mm)	10	10	10	10	10	10	10

bead width avg (mm)	5.00	5.64	8.28	7.67	10.77	6.08	7.60
bead height avg (mm)	3.20	5.04	5.62	3.04	2.91	4.37	3.69
Gas flow rate (L/m)	17	17	17	17	17	17	17
Gas Type	C25	C25	C25	C25	C25	C25	C25

Deposition losses can be seen in the amount of spatter surrounding the wall and the drips on the edges from where the heat buildup caused drops of metal to fall off. Figure 4 shows the 56 layers 115 mm tall double bead wall structure.

Figure 4 double bead deposition wall, 300 Amps, 115mm peak height, 56 layers tall

Microstructure

An optical microstructure is presented in Figure 5. The microstructure is a lath martensite. Some prior austenite grain boundaries and delta ferrite can be also observed on the microstructure (Figure 6).

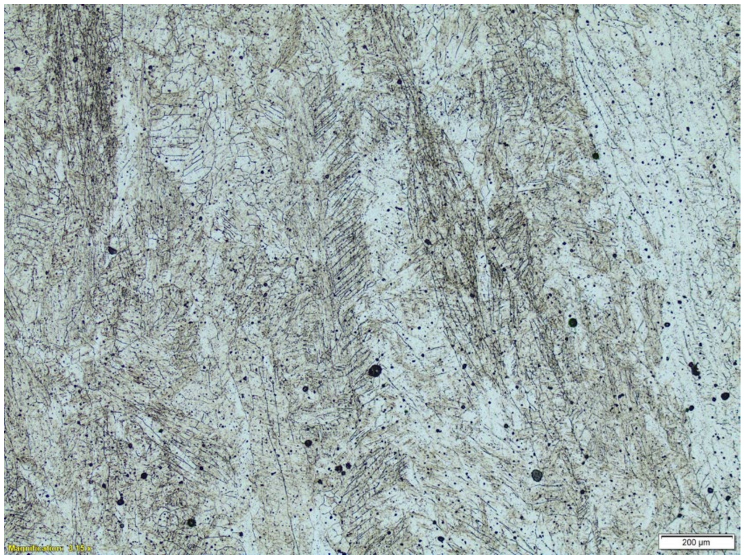

Figure 5: Microstructure of WAAM fabricated RAFM steel represents lath martensite with oxides

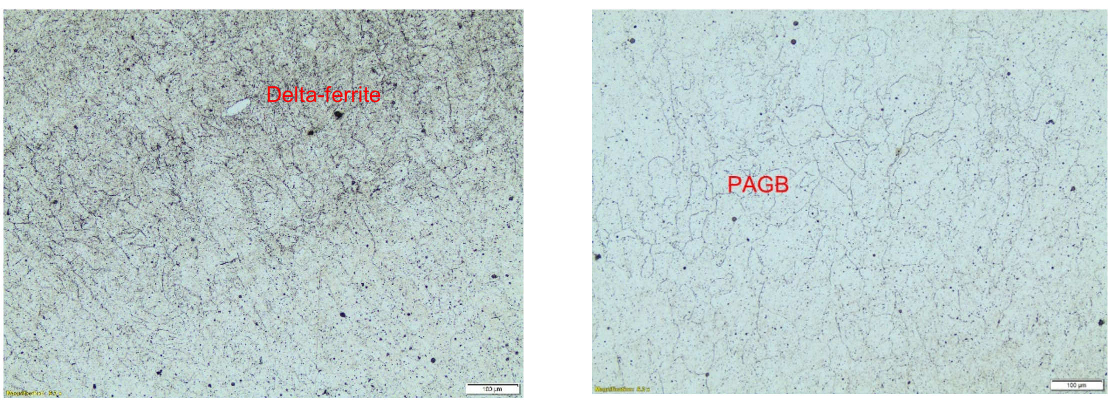

Figure 6 Microstructure of WAAM fabricated RAFM steel shows the presence of delta ferrite and prior austenite Grain boundaries

Impact Toughness testing was designed according to ASTM A370; a total of eight sub-size Charpy impact V-notch specimens were prepared. The cuts were sectioned horizontally along with the deposited layers; no vertical test specimens were cut. The testing temperatures selected are 0, 25, 50, 100, 150, and 200 ° C because high hardness steels can fail in a brittle manner even at temperatures above 0^{o}C. The Ductile to Brittle Transition Temperature is the point at which the material's ability to absorb impact energy is greatly reduced due to temperature, causing the failure mode to transition from ductile to brittle. The test results are shown in Figure 7.

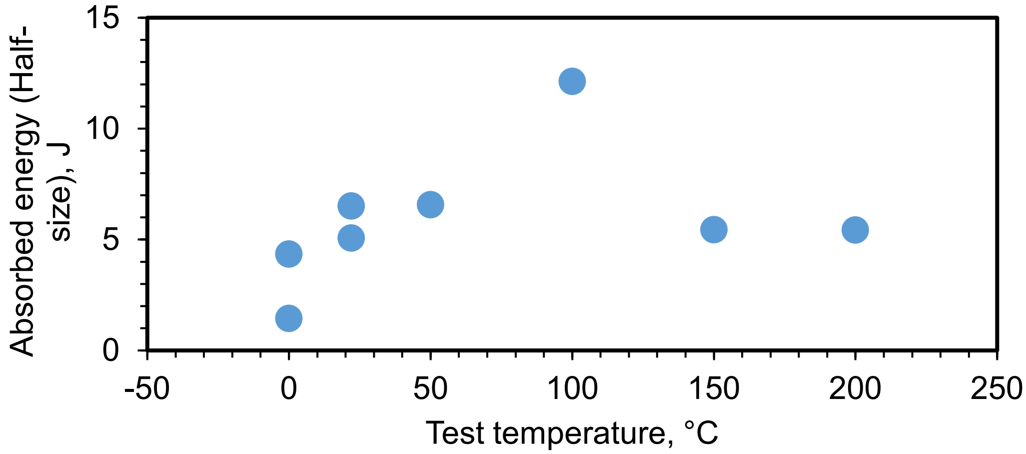

Figure 7 Charpy impact test results

When comparing the impact toughness of WAAM RAFM samples to welded CLF-1 steels [16], the average impact toughness was closest to the two lowest impact energy tests recorded, at 3.3J and 4.3J, respectively. These both had a high heat input and, therefore, large delta ferrite formation, above 2.5% [16]. The welding process examined in that study was electron beam and has a much higher power density than arc welding.

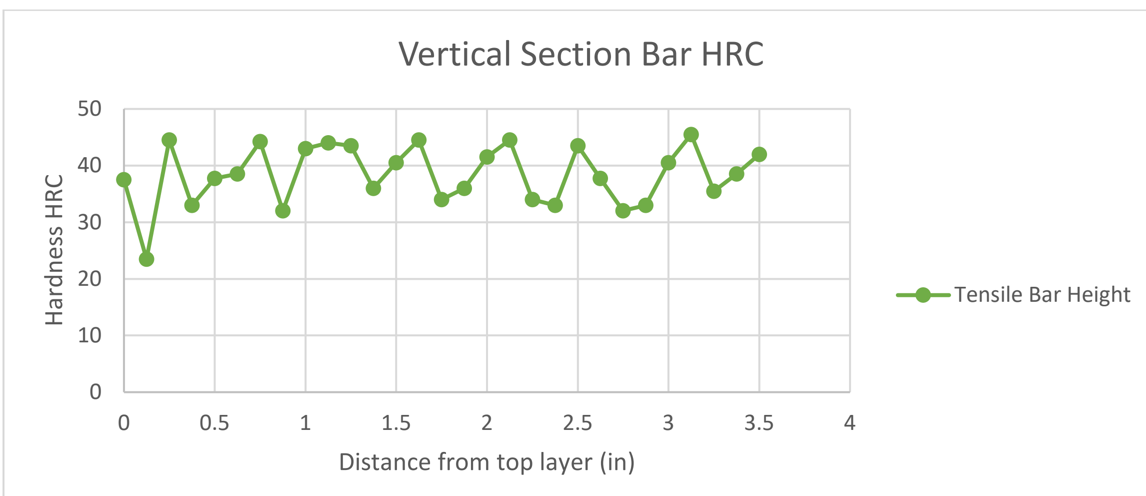

Figure 8 *Vertical section bar HRC hardness testing graph*

Rockwell Hardness tests were marked every 1/8th inch, to examine the differences in the deposited layers; this test was conducted on one side of an unused tensile specimen vertically sectioned from the 56-layer wall deposition. The test results (Figure 8) show an average Rockwell hardness of 40 HRC. The sizeable initial drop-off in hardness on the tensile bar was due to a inclusion.

Microhardness tests were conducted to study the effect of interpass temperature. Three experiments were performed; a) stopping arc between layers for 20 seconds b) 40 seconds and c) after the surface reaches temperature around 300 °C. The temperature profile and the microhardness results are shown in Figure 9 and Figure 10. The dual peaks in Figure 9 are formed by the forward and return path of the motion when performing a two-bead wall. The temperature was measured at the mid location of the print length. The peaks plateaued at 1500°C when the arc is passing across the measuring point. The interpass temperature were above 300 °C for both the 20 seconds and 40 seconds paused experiments. There is no significant change in the hardness data and the data ranges between 400 to 450 HV. This microhardness value resembles a typical RAFM steel hardness.

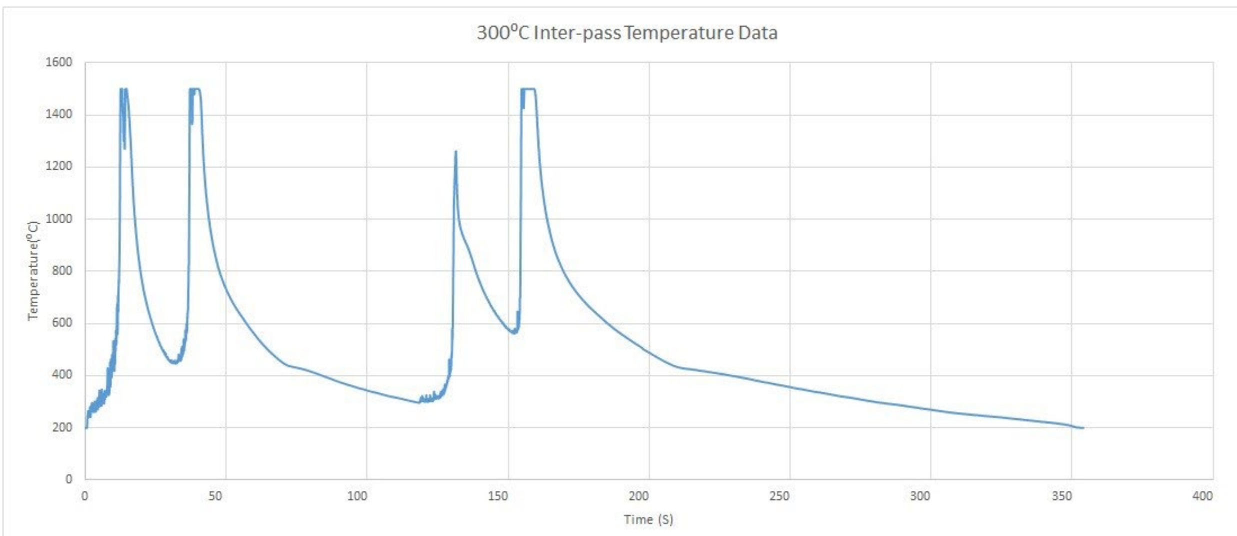

Figure 9 - 300°C Interpass time temperature curve for a two bead two layer

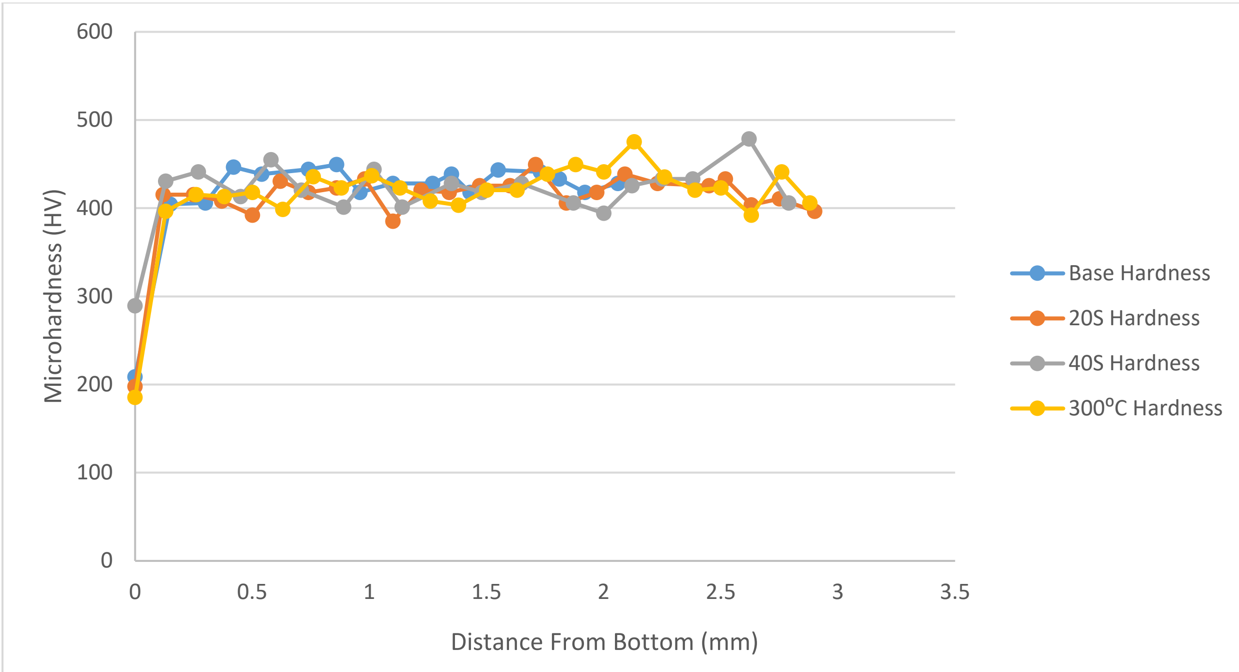

Figure 10: The comparison of microhardness values obtained from different interpass temperature and time

Conclusion

RAFM metal cored-wire were successfully printed using WAAM. Pulsed current deposition is the ideal waveform for the GMAW process. The testing showing that even cooling to below 300 ºC caused no significant difference in the grain reformation was very beneficial to the eventual success of larger-scale deposition tests. The metallographic testing showed a majority martensitic morphology and the presence of delta ferrite. When comparing the composition of the deposited material to that of cast samples, the morphology looks as expected, which helps to confirm the fusion of the powdered components in the wire to create the RAFM chemistry. The average resistance of 6.25J from the impact testing indicates low toughness, which, compared to previous studies, was anticipated, and correlated to a more significant delta ferrite volume percent. Future work involves heat treatment and high temperature material testing and EDX analysis.

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