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Characterization of Additively Manufactured Metals from ADDERE Printing

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ABSTRACT

Midwest Engineered Systems Inc. has created a novel laser wire metal deposition process, ADDere manufacturing. ADDere has a much higher deposition rate than powder bed fusion, making it ideal for large components. In this project, the mechanical properties of ADDere printed materials were tested and compared to typical values found in ASM publications to show the quality of materials manufactured by the ADDere printing process. A detailed material analysis was performed on samples made from Ti-6Al-4V and 17-4 PH stainless steel. This work builds upon an earlier study of samples made from 17-4 PH that were produced using a single direction pattern. In this project, the 17-4 PH samples were printed in a cross hatched pattern, and testing results were compared to existing data from single direction samples of the previous research. The Ti-6Al-4V samples were created in two builds. One using the uni-directional method and the other with the crossed pattern. Testing specimens were removed from the samples using a water jet cutter and further machined into ASTM tensile bars and metallurgic mounts to perform a thorough material evaluation. The Ti-6Al-4V sample met the expected values in the ASM literature, and the cross hatched 17-4 PH exhibited a higher hardness and better microstructure than the single direction samples from the previous work. It was also observed that when the Ti64 samples were manufactured in the cross hatched pattern, the properties indicated slight improvement and more homogeneity than those printed in single layer direction. The obtained results indicate that ADDere's printing process can produce highly refined materials that are customizable with their expected uses. This work showcases an excellent industry collaboration of an undergraduate research experience.

INTRODUCTION

Additive Manufacturing (AM)[1] is a process where material is placed layer by layer to form a part, allowing more complex and customizable parts to be made at a lower cost. The AM industry has grown leaps and bounds and currently many standards[2-3] have been established. Design for AM (DfAM) has touched many sectors such as aerospace and healthcare providing enhanced efficiency and sustainability[4]. The most common metal additive manufacturing processes involve very thin layers of powdered metal being melted by a laser to form the part. Although these methods allow for granular control and customization on a small scale, their primary drawback is they entail much longer print times for larger parts[5]. Midwest Engineered Systems Inc. (MWES) has created a laser-wire metal deposition process, called ADDere printing, which allows for much faster builds, making larger components feasible. In 2019, Dr. Subha Kumpaty from Milwaukee School of Engineering (MSOE) led research with MWES to test the material properties of 316 and 17-4 PH stainless steel which was fabricated through ADDere printing. They found that both stainless steels met expected values of ASM materials properties[6].

In continued collaboration of the Industry-University partnership, Research Experience for Undergraduates (REU) program sponsored by the National Science Foundation (NSF) the first author was able to conduct further laser wire metal deposition research furthering the prior studies on 17-4 PH Stainless Steel and embarking on the manufacture and material characterization of titanium alloy, Ti-6Al-4V. This titanium alloy is well known for it's high strength, low density, and biocompatibility, which makes it useful for aerospace and biomedical applications[7]. 17-4 PH stainless steel is a high strength precipitation hardening martensitic stainless steel capable of maintaining its mechanical properties at temperatures up to 600ºF that is also used in the aerospace and in metalworking industry[8].

ADDERE PRINTING: LASER WIRE METAL DEPOSITION

The samples evaluated in this research were manufactured through ADDere Printing[9], which involves a 5-axis industrial robot, shown in Figure 1. It has a 2-axis coordinated motion feature that is used while extruding a wire of the material that a laser melts to form the layers. The samples for this project were printed on an ADDere System III, which has a 20-kW laser, a 500 A hotwire package, and the ability to print in a completely inert atmosphere to avoid oxidation between the layers of the build.

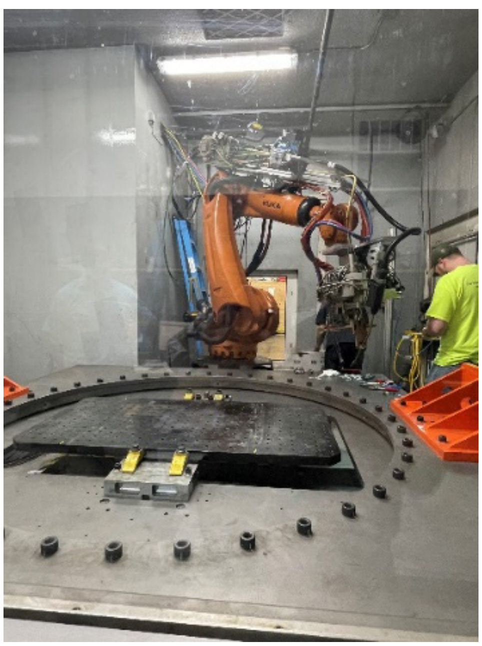

Figure 1: 5-axis robot arm used in ADDERE III

The ADDere manufacturing systems allow several parameters to be modified to customize the building material and also has remote imaging capabilities to monitor the process in real time, including the temperature and condition of the melt pool. The print parameters for each sample build studied in this paper are shown in Table 1.

Material	Laser Power (kW)	Wire Current (A)	Robot Speed (mm/s)	Wire Speed (mm/s)	Print Atmosphere
17-4 PH Single Direction prior work	4	500	10	40	Argon shield gas
17-4 PH Cross-hatched	13	187	13	90	Argon 500-1000 PPM O2
Ti-6Al-4V (both Single Direction & Cross-hatched)	9.5	152	13	90	Argon 100-500 PPM O2

Table 1: Print parameters of samples studied in this paper

For each material and layering direction, bulk samples were printed that measured approximately 300 mm X 300 mm X 150 mm. A representative example of one of the builds as completed can be seen in Figure 2.

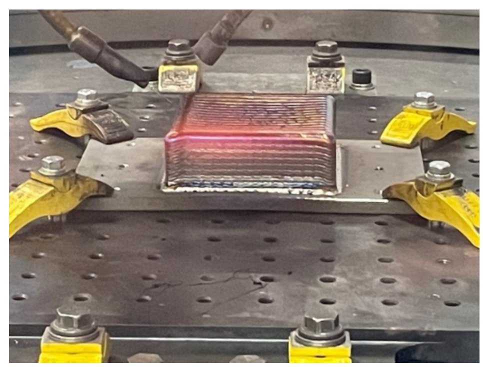

Figure 2. Completed Ti-6Al-4V plate

The cherry-red coloring on the upper portion of the as-built sample shown in Figure 2 also demonstrates some of the inherent thermal, that also results in residual tension and compression stresses, that needs to be considered in any of the AM processes utilizing laser fusion. In order to address this condition a post build heat treatment is required to refine the mechanical properties. The 17-4 PH samples were treated to the H 1025 condition while the Ti-6Al-4V samples followed a process developed by ADDere with their heat treater.

METHODOLOGY AND TESTING

The 17-4 PH stainless steel was printed in the cross hatched pattern. The cross-hatched printing is characterized by printing each layer perpendicular to the previous one. The goal of this research is to compare the material properties of each sample with the ASM values for each material, as well as the differences between the print method for 17-4 PH stainless steel. The cross-hatched samples are expected to have a higher Ultimate Tensile Strength than their single direction counterparts. Tensile tests, Vickers Microhardness tests, and microstructure analysis were performed to investigate these material properties. Previous data on 17-4 PH stainless steel (single direction, also argon as only shield gas and not) was used to compare to the data for the cross hatched sample. The Ti-6Al-4V samples were printed in both single layer direction as well as cross-hatched pattern in inert atmosphere. Figure 2 shows a completed Ti-6Al-4V plate. It is important that the chamber is maintained at inert conditions to avoid oxidation between layers.

The photograph in Figure 3 is a representative example of the 290 mm X 290 mm X 50 mm test plate machined from the build showing the locations of where the tensile and metallurgic specimens were extracted with a water jet cutter.

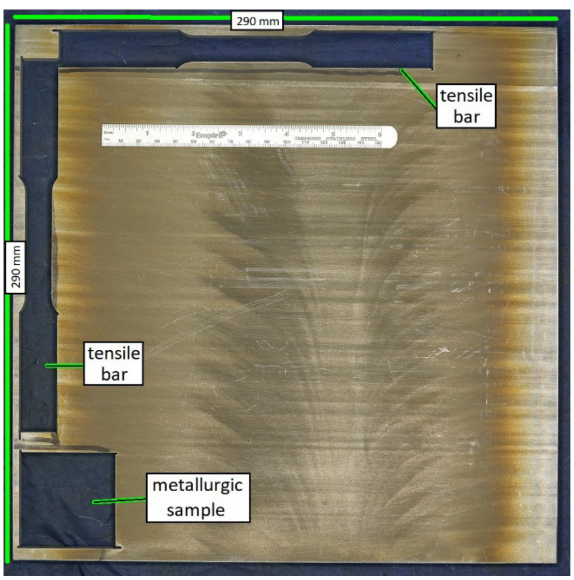

Figure 3: Test plate machined from 3D build (17-4 PH sample shown)

As can be seen in the test plate, the tensile bars were extracted in an orientation that allows for the exploration of directionality of properties. These samples were further machined into dog bone style tensile bars according to ASTM standards (ASTM E8-01).

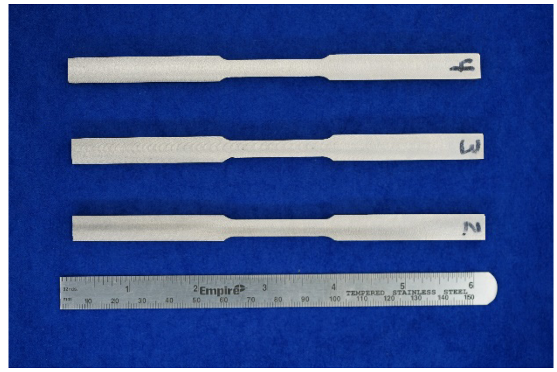

Figure 4: Prepared specimens for tensile testing (Ti-6Al-4V samples shown)

Microstructure Analysis

A sample of each material was taken using an ATM Brilliant 255 wet abrasive cut-off machine. This sample was mounted with a plastic resin in an ATM Opal 460 hot compression mounting press, which was ground with Rhaco Grit P320 at 300 rpm and 35 N until it is a flat plane. Then, it was polished with Aka-Allegran 3 and Aka-Chemal grit, each at 150 rpm for 3-5 minutes using an ATM Systemlabor automated polishing machine. Then the sample was etched with Keller's reagent for Ti-6Al-4V, and with Fry's reagent for 17-4 PH stainless steel. Then, the samples were placed under an Olympus DSX 510 optical microscope and observed at 400x and 750x.

The logic of being cognizant of the potential for anisotropic behavior was also followed in the preparation of the metallurgic samples for microstructure analysis and Vickers microhardness testing. Figure 5 illustrates the orientation method that was used to ensure the appropriate plane of evaluation was identified.

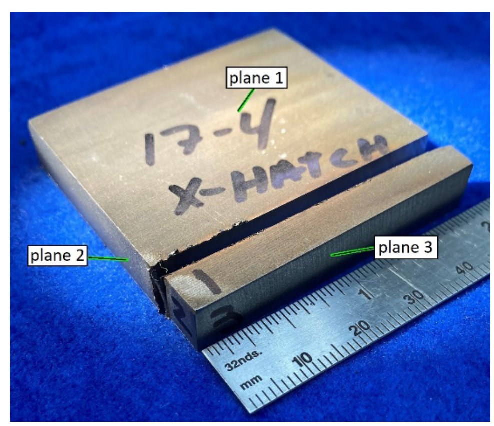

Figure 5: Metallurgic sample orientation from test plate (17-4 PH sample shown)

An example of how the method was followed on the samples for mounting can be seen in Figure 6. The arrows in the image are pointing toward the surface polished.

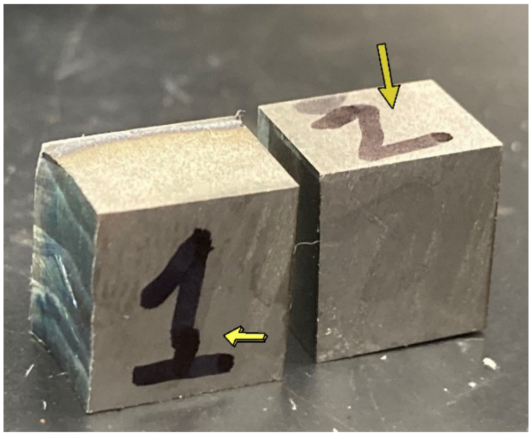

Figure 6: Orientation of polishing planes in metallurgic samples (Ti-6Al-4V sample shown)

Tensile Testing

Tensile testing was performed on Ti-6Al-4V samples using a MTS Tensile Testing machine at MSOE that is equipped with the TestWorks 4 program. Initial dimensions of the dog bone sample neck were documented with a caliper. The sample was placed into the tensile grips, and then the crosshead distance was taken. The tensile force and crosshead distance were zeroed out, and the measured lengths were put in, along with a test speed. Once all was in place, the test was run. The Testworks 4 output was a text file of data points which was taken to produce a Stress (ksi) vs. Strain % curve. The tensile testing conducted on the 17-4 PH sample was performed by an independent testing lab that is A2LA certified. An example of the curve generated is shown in Figure 7.

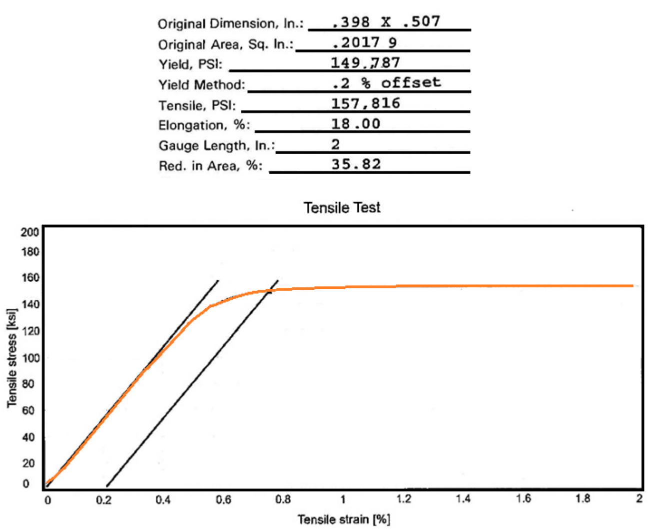

Figure 7: example of stress strain curve generated (17-4 PH sample shown)

Vickers Microhardness

Microhardness data was taken on each plane of the samples using a LECO AMH 55 using a 500 g load. In order to obtain a robust body of data, arrays of at least 40 indentations were generated. An example of one of these arrays with the indent spacing can be seen in Figure 8. After the indents were made, the Vickers microhardness was calculated based on the indent depth, and the equivalent Rockwell Hardness C is calculated based on that result with the LECO Cornerstone software package.

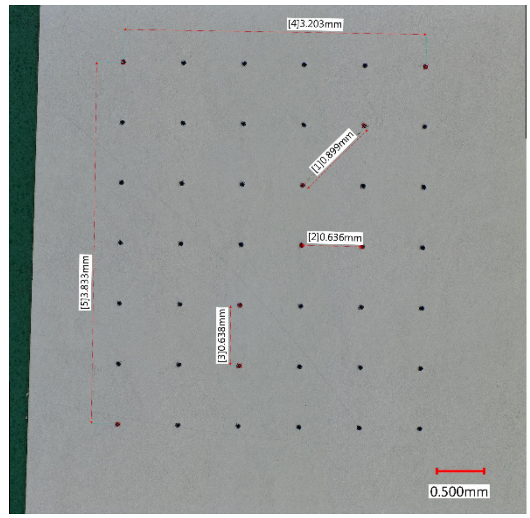

Figure 8: Example of microhardness array

Microstructure Analysis

A sample of each material was taken using an ATM Brilliant 255 wet abrasive cut-off machine. This sample was mounted with a plastic resin with an ATM Opal 460 hot compression mounting press, which was ground with Rhaco Grit P320 at 300 rpm and 35 N until it is a flat plane. Then, it was polished with Aka-Allegran 3 and Aka-Chemal grit, each at 150 rpm for 3-5 minutes using an ATM Systemlabor automated polishing machine. Then the sample was etched with Keller's reagent for Ti-6Al-4V, and with Fry's reagent for 17-4 PH stainless steel. Then, the samples were placed under an Olympus DSX 510 optical microscope and observed at 400x and 750x.

RESULTS AND DISCUSSION

Tensile Strength

17-4 PH Stainless Steel: The ASM published values for annealed 17-4 PH samples are 140ksi ultimate tensile strength, and 115ksi yield strength with percent elongation of anywhere between 5-14. The samples that were tested during prior research (single layer direction with argon gas shielding) exhibited an average ultimate tensile strength of a 145ksi, and average yield strength of 116ksi with an average percent elongation of 15. This showed that the additively manufactured samples met or exceeded each criterion. In the current cross-hatched pattern printing, the results showed further improvement with an ultimate tensile strength of 159ksi, yield strength of 147ksi and an average percent elongation of 18. Please see appendix for tensile graph. With the cross-hatched pattern easily programmable in the print selection, it has been recommended to MWES as a default option in future builds.

Ti-6Al-4V: The ASM published values for ultimate tensile strength is 950 MPa (138ksi) and for yield strength 880 MPa (128ksi). For the samples in single layered printing, the ultimate tensile strength was found to be 133ksi, which is very close to the expected value. When we tested the samples of cross-hatched pattern, the results affirmed improved ultimate tensile strength of 142ksi with yield strength of 122ksi and 10% elongation. It is clear the laser wire metal deposition process meets the expectation of ASM standards. Based on our studies on direct metal laser sintering (DMLS), the properties can be further improved but the ADDRERE laser wire deposition is much faster than DMLS and hence presents itself as a very viable choice for manufacturing.

Hardness

17-4 PH Stainless Steel: The ASM values for 17-4 PH using HRC scale ranges between 29 to 40. The average value of 10 points taken on a 17-4 PH sample came out to 28HRC from prior work. With the 17-4 PH block printed in the chamber with Argon and in cross-hatched pattern, the Rockwell Hardness C was 37.2± 5. This cross-hatched pattern printing yielded superior hardness and is recommended as a preferred mode of printing. These results fully comply with standards in the ASM handbook.

Ti-6Al-4V: The ASM value for Vickers Microhardness is 349. The tested values fell within the expected ranges: for Ti-6Al-4V (single direction print), HV 332 ± 6 (HRC36) and for cross-hatched print, HV 355± 14 (HRC36).

Optical Microscopy

17-4 Stainless steel: In the prior work[6], the single direction print when performed under adequate argon gas shielding, provided the following micrograph under optical microscope with low level of cavity within the martensitic grain structure (Figure 9).

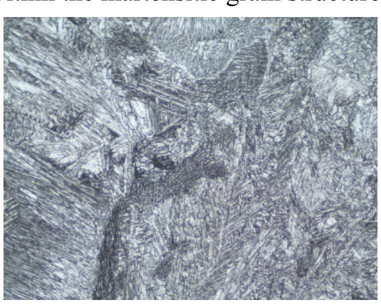

Figure 9: Microstructure of 17-4 PH stainless steel using Fry's etchant, 100x original magnification (single direction print, argon gas shielding)

The cross-hatched print was attempted in this work was also produced with an argon filled atmosphere. An example of the microstructure as viewed from plane 1 is in Figure 10. It shows that the cross hatched print had no porosity and a predominately martensitic structure.

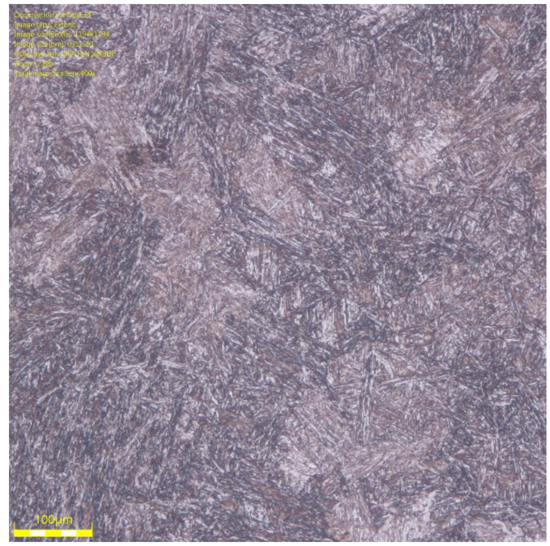

Figure 10: Cross-hatched 17-4 with Fry's etchant (view from plane 1, 400X original magnification)

Similar results were observed in the plane 2 direction as shown in Figure 11.

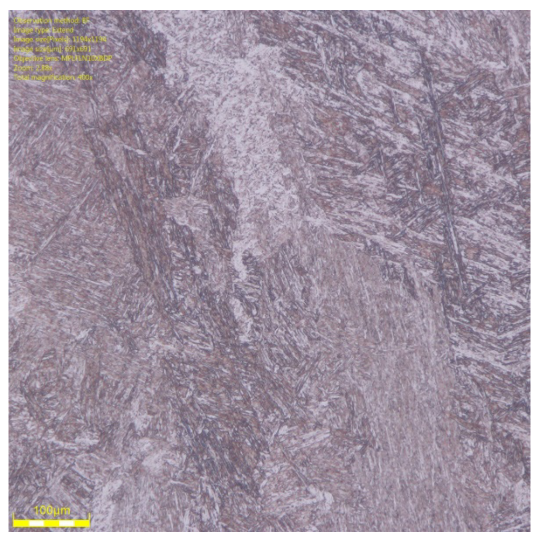

Figure 11: Cross-hatched 17-4 with Fry's etchant (view from plane 2, 400X original magnification)

Ti-6Al-4V: Both single direction and cross-hatched pattern blocks were printed in inert environment and with same print parameters. The Ti-6Al-4V microstructure was a good example of Widmanstätten Basket-Weave grain structure, which is characterized by highly dense, interwoven grains. Figure 12 shows the micrograph of single direction print sample.

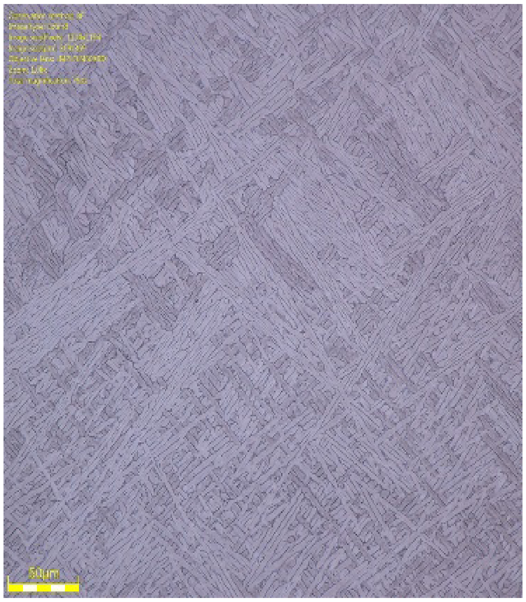

Figure 12: Ti-6Al-4V microstructure with Keller's etchant (Single direction print, 750X original magnification)

The microstructure from the cross-hatched print was similar in that there was no porosity and it had the characteristic basket weave pattern, but this view shows a slightly more random distribution of the acicular martensitic structure features.

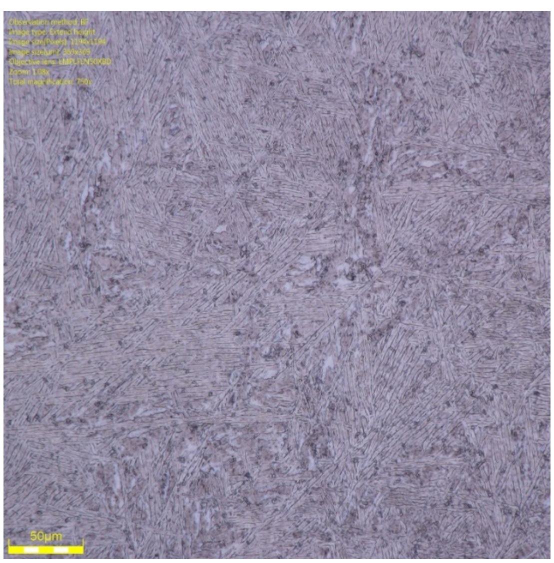

Figure 13: Ti-6Al-4V microstructure with Keller's etchant (cross-hatched print, 750X original magnification)

SUMMARY AND CONCLUDING REMARKS

This research is part of an ongoing University-Industry collaboration between Milwaukee School of Engineering and Midwest Engineered Systems. The first author is an REU participant who joined the team in summer 2021 under NSF grant. He has grown in handling research challenges, finding solutions, and presenting before a variety of audiences. This research affirmed the manufacturing process and the build parameters based on the material characterization studies that were conducted with an overarching goal of producing parts that would comply with ASTM standards. The importance of this work is apparent even as the newest volume of ASM Handbook on AM processes[10] was released in 2020.

The results of this research indicated excellent compliance with ASM standards for the ADDere printed Ti-6Al-4V and 17-4 PH Stainless Steel. Also, the quality of the microstructure reflects well on the ADDere printing process. The clarity of the microstructure is due the control over the laser power and the melt pool in the printing process. MWES has optimized the process to make sure that the laser power is not only enough to melt the top layer, but also penetrates a few layers down, which creates a homogeneous melt pool, allowing to microstructure to also be homogenous, without any indication of the print layers. Another notable result is that the cross hatched direction outperformed the single direction samples in both hardness and microstructure. With 17-4 PH results, it must be reiterated that the difference in microstructure is more due to the print atmosphere. The single direction sample was printed with an argon shield gas, which still allowed some porosity to develop. The cross hatched sample was printed with a fully inert argon atmosphere with 500-1000 PPM O2, and produced a clear, martensitic microstructure with little to no porosity. The cost of maintaining an inert chamber must be taken into consideration when designing for additive manufacturing of various metal blocks.

MWES continues to work with MSOE on characterization studies of materials. This work also brought other industries (Perkins Engineering and Innio Waukesha Gas Engines and its principal scientists) to contribute intellectually and to provide critical facilities for successful completion of the project. This collaboration is proving to be a good model for implementing REU and other research projects.

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