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FEASIBILITY ANALYSIS OF UTILIZING MARAGING STEEL IN A WIRE ARC ADDITIVE PROCESS FOR HIGH-STRENGTH TOOLING APPLICATIONS

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Abstract

Traditional tool and die development require skilled labor, long lead time, and is highly expensive to produce. Metal Big Area Additive Manufacturing (mBAAM) is a wire-arc additive process that utilizes a metal inert gas (MIG) welding robot to print large-scale parts layer-by-layer. By using mBAAM, tooling can be manufactured rapidly with low costs. For cold work tooling applications, a high hardness level is desired to increase the life-time of the tool. A promising material that can achieve this is maraging steel. Maraging steel is known to have good weldability; however, further testing must be conducted to ensure it is feasible for printing using mBAAM. In this paper, initial process parameters were obtained by printing single bead welds. Multi-bead walls were then printed with some refinement of process parameters to construct homogenous outer features of the walls. Lastly, the walls were heat-treated, and hardness data was gathered through Rockwell Hardness tests.

Introduction

Metal Big Area Additive Manufacturing (mBAAM) utilizes a robotic welding arm to print metal layer-by-layer, similar to Fused Filament Fabrication (FFF). Unlike traditional robotic welding, welded beads are used to form complex geometry. In mBAAM, medium- to large-scale metal objects are additively produced using a Direct Energy Deposition (DED) process. Large-scale additive systems are considered to have a print envelope of one to two meters on its longest axis [1]. The challenges that arise when printing in large-scale are uneven layer height error accumulation and warp distortion caused by heat. This relies on a closed-loop control [2] that tracks the height of the layer in real-time to ensure the printed part is near-net shape. The mBAAM system developed by Wolf Robotics and Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF) is a gas metal arc welding (GMAW) robotic system that incorporates this closed-loop control feature and has successfully printed metal parts used for tooling and other industrial applications (e.g., excavator stick, propeller). This system is also equipped with two welding torches for multi-material metal printing. Currently, metals used for printing with this system are mild steel and 410 stainless steel. This means that tools and dies printed with the mBAAM system comprised of these metals.

When developing high performance tooling for metal forming, a high hardness level is necessary for the tool to maintain long production cycles. This is important in cold work tooling applications as the materials for forming can be particularly hard, which leads to deforming and wearing of the tool [3]. When dealing with steel sheet metal, a Hardness Rockwell C (HRC) above 50 is the minimum preferred hardness. This introduces some difficulties when using mild steel and stainless steel, as they have an HRC below 50. For printed mild steel, Shassere et al.

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determined that mild steel has an HVN of 170 [4], which is below the value of HRC. Printed 410 stainless steel has an HRC of 41; however, it is at least 10 values below the recommended hardness. The advantage of mBAAM is that these tools and dies can be printed in a matter of days. These parts can be quickly replaced; however, they would have to undergo post-process machining to get the proper surface finishes and tolerances required. Increasing the tool-life of these parts would decrease the need to produce these tools and dies, thus effectively decreasing cost.

When considering an HRC above 50, machining becomes a concern, as high hardness would result in wearing out the machine tool quickly. In contemplation of this situation, the material should have the characteristics of a soft metal for machining but have the capability of post-process hardening. Due to the process used in the mBAAM system, materials used for printing should have weldable characteristics while in the form of a filler wire. For this reason, the material selected to achieve these characteristics is maraging steel.

Maraging steel is known as a high-strength steel, having a tensile strength ranging from 1000 MPa to 3000 MPa [5]. It also has a hardness value of HRC 52-54 [6]. These properties occur when heat treating the metal to 480-500°C for 4 to 12 hours [6, 7]. Prior to heat treatment, maraging steel is rather ductile and soft allowing it to be easily machined. These characteristics make this material highly applicable for tooling purposes. Other applications of maraging steel are seen in the aerospace industry [7], as it is used for landing gears and rocket motor cases. Maraging steel also comes in different grades of filler wire. MAR 250 filler wire was selected as the material used in this paper.

The objective of this paper is to determine if MAR 250 can be used for mBAAM and maintain a similar hardness level seen in pure maraging steel. The methodology used to analyze this material began with observing the weldability of MAR 250 and developing process parameters that were used to test its printability. After printing samples, they underwent a Vickers Hardness test to obtain the HRC of this material. Results were shown for weldability, printability, and hardness, and the paper concluded with future experiments and applications.

Methodology

A. Weldability

The purpose of testing weldability is to understand the characteristics of a welded bead made of MAR 250. In addition to finding the characteristics of the bead, initial welding parameters were developed and used as a baseline for the printability test. The welder equipped in the mBAAM system was an R500 Lincoln electric welder. This welder consisted of hundreds of weld modes that changed the welding waveform. For welding parameters, Lincoln Electric's Power Mode Waveform was used for its ability to use any metal and gas type [8]. In Power Mode, welding power and pinch current can be controlled. For all waveforms, wire feed speed and welding speed (i.e., travel speed of the robot) are necessary variables for welding parameter development.

In this experiment, 203.2 mm long weld beads were printed on a 203.2mm x 609.6mm x 6.35mm (l x w x t) low-carbon steel plate shown in Figure 1. Wire feed speed and pinch current were held constant. Weld speed, power, and shielding gas were variables that were changed throughout the experiment. The beads were grouped by the welding speed used. The shielding gases used were Ar-CO_2 and Trimix (90% He-7.5% Ar-2.5% CO_2).

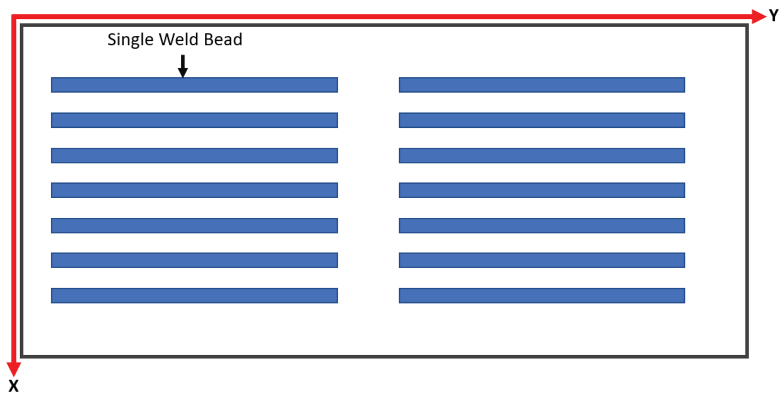

Figure 1. Welded bead test setup

B. Printability

This test consisted of printing one- and two-bead thick walls. The reason for printing walls was for simplicity and their correlation to the geometry seen in a complex part. Figure 2 shows the comparison between a wall and a more complex part in terms of print path. Walls are considered a perimeter and inset feature seen in complex parts, and thus are beneficial for the conduction of these experiments.

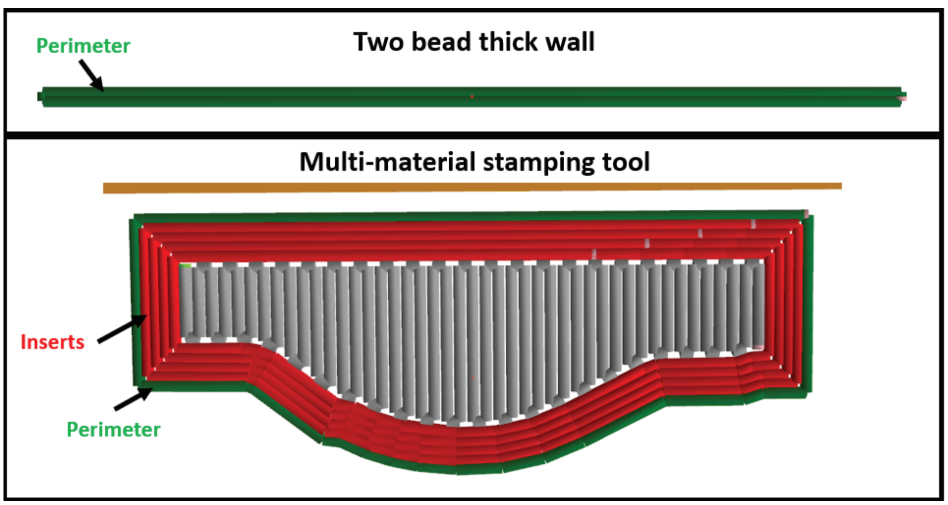

Figure 2. Print path of a wall and a stamping tool

In the printability test, surface finish and geometric conformity were the main characteristics that were observed. Parameters that affect these characteristics are bead spacing and welding parameters (e.g., weld mode, wire feed speed, weld speed). Walls were printed with the same bead spacing of 3.0mm and a constant wire feed speed of 95.25mm/sec. Weld speed and weld mode were changed for every wall printed.

C. Hardness Test

Vickers hardness tests were conducted on a two-bead thick wall printed in MAR 250. The wall was cut into sections and were hardness tested in three locations, as shown in Figure 3. Hardness was measured from sections with different heat treatment temperatures including one section without heat treatment. The temperatures ranged from 420ºC to 1115ºC. For 420ºC to 520ºC, isothermal temperatures were kept for three hours. For 815ºC to 1115ºC, the temperatures were kept for one hour and were then dropped to 420ºC for three hours.

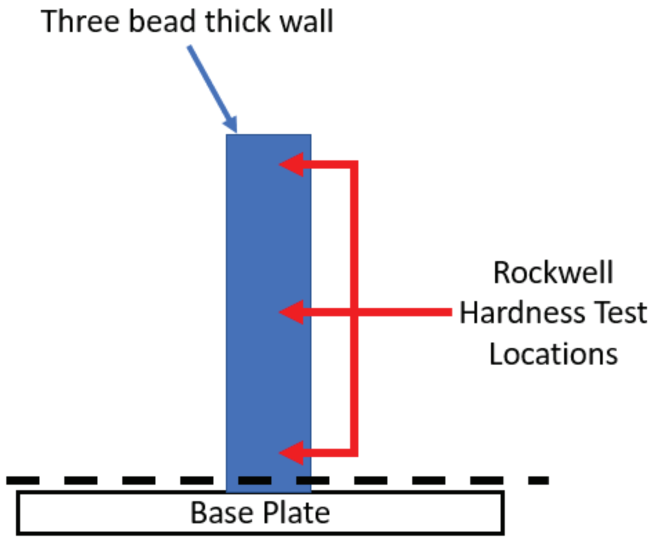

Figure 3. Hardness test locations on the three-bead thick wall

Results

Regarding the weldability test, there were no apparent issues welding with MAR 250 using the Power Mode Waveform. A wire feed speed of 95.25mm/sec was used, and a power of 3.3 kW was used. 2.5 kW was originally used for the power; however, this produced a colder weld with minimal wetting. Visible ripples in the weld and non-uniform melting of the metal droplets occurred as well. In Figure 4, it was observed that using Trimix gas improved the surface quality of the welded beads, which was caused by the additional heat added to the system. Since Trimix mainly consisted of Helium gas, it has a higher thermal conductivity than Ar-CO_2 gas mixture. Different welding speeds were used, and improvements were seen using a faster weld speed of 16 in/min (6.77 mm/sec) compared to using 10 in/min (4.23 mm/sec).

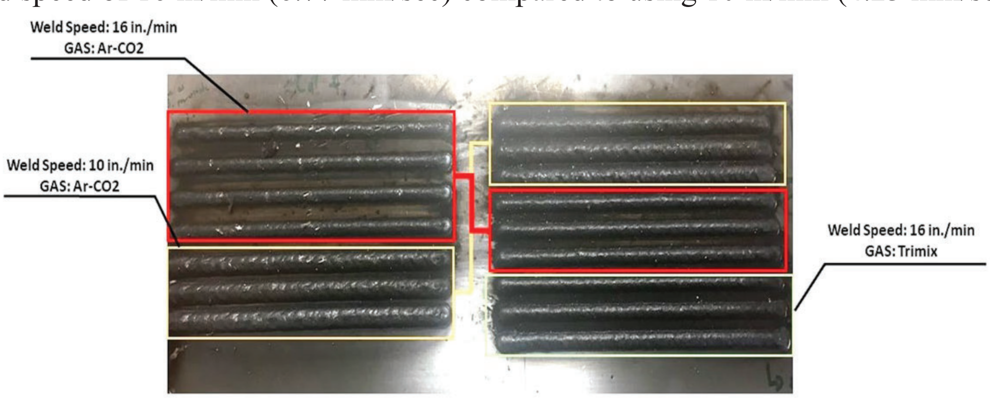

Figure 4. Single bead welds of MAR 250 with different welding speeds and shielding gas mixtures

Using the welding parameters obtained from the weldability test, a single bead wall was printed. This resulted in a large and rough surface finish. Figure 5 shows the printed one-bead thick wall. The sides of the wall have large uneven lumps. This feature in a single bead would not be suitable when printing multi-bead thick parts. This will lead to uneven melting causing visible voids in the printed part. Uneven melting of the layers would occur due to the actual geometry of the bead. Since the bead itself has uneven geometry, when the beads overlap each other, the bead-to-bead spacing (Figure 6) would differentiate throughout the build. Less spacing would cause significant overbuilding throughout the layers, and more spacing would create pockets between the beads.

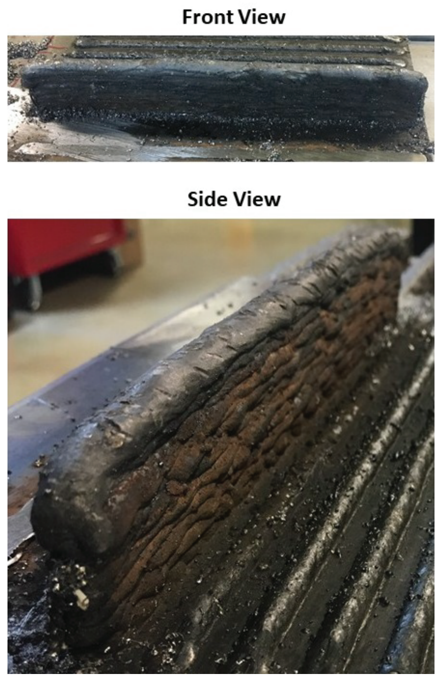

Figure 5. Single bead wall printed in MAR 250

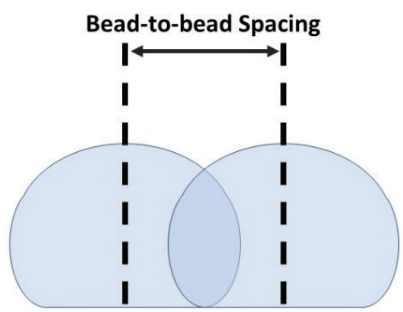

Figure 6. Bead-to-bead spacing representation

Two-bead thick walls were printed to investigate on possible defects that could occur from these geometric instabilities observed in the one-bead thick wall experiment. The first set of walls (Figure 7) were printed with the welding waveform, Power Mode. It was determined that using a welding power of 1.7kW and increasing the travel speed improved the shape of the walls. Travel speed ranged from 16 in/min (6.77 mm/sec) to 30 in/min (12.7 mm/sec). Originally, 3.3 kW of power was used; however, this increased the surface roughness. The high power added excessive amounts of heat to the wall, thus causing molten metal to droop randomly during the print. In Figure 7c, the printed wall with a travel speed of 30 in/min (12.7 mm/sec) visibly has the least surface roughness. Although there were improvements, the printed walls still encountered uneven surface geometry.

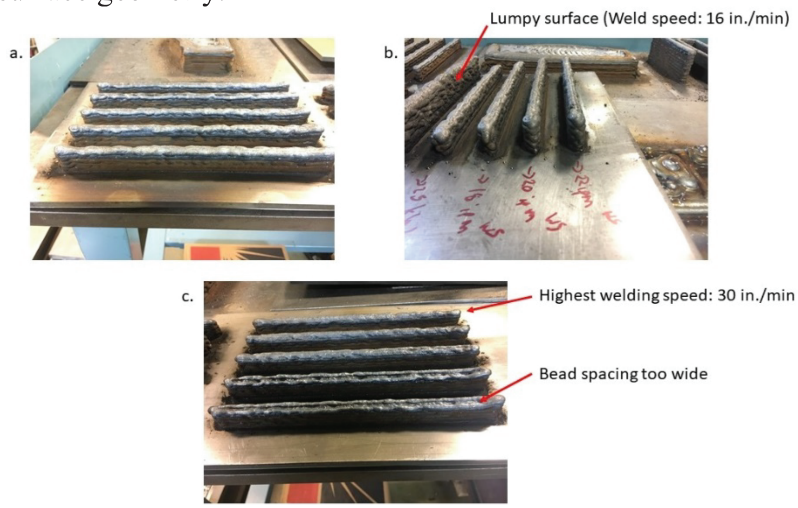

Figure 7. Two-bead thick walls printed with Power Mode. a.) front view of the walls, b.) side view of the walls, c.) wall with fastest travel speed used for this set.

A second set of two-bead thick walls (Figure 8) were printed with the welding waveform, surface tension transfer (STT). In STT, current automatically adjusts the heat without depending on the wire feed speed [9]. This minimizes the heat added to the weld, which is ideal for this material. In addition to minimizing heat, STT has more variables to control such as peak current, background current, and tail-out speed. This allows finer tuning of the welding parameters. The outcome of these walls was significantly better in surface roughness. It was evident by visual observation and was confirmed by software developed in MDF. This software (Figure 9) uses scan data to interpret surface roughness by cross-sectioning the point-cloud of a wall and analyzing each side of it. The surface roughness average data is shown in Table 1. Based on the results in Table 1, walls printed with STT have about a 30% lower surface roughness average compared to walls printed with Power Mode. The walls printed with STT had higher consistent bead geometry with less waviness at the top surface of each wall. There was no significant difference in wall surface roughness when increasing the weld speed from 24 in/min (10.16 mm/sec) to 30 in/min (12.7 mm/sec).

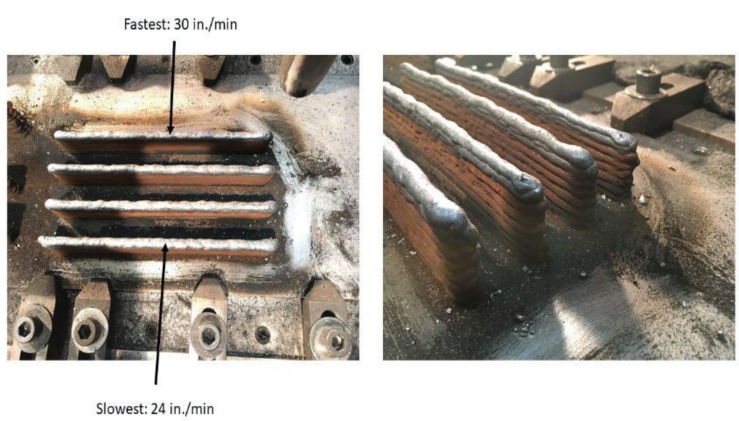

Figure 8. Two-bead thick walls printed with STT

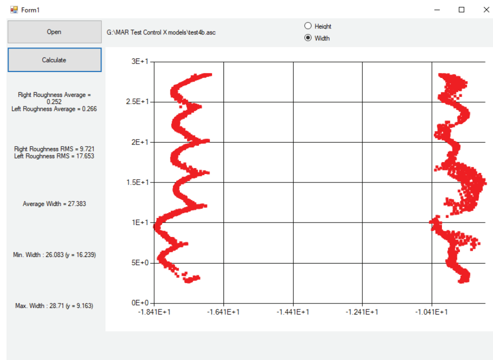

Figure 9. In-house software to find surface roughness average from point-cloud data

Table 1. Roughness averages of the two-bead thick walls printed with Power Mode and STT

	Power Mode			STT	
Cross Sections	Right Ra (mm)	Left Ra (mm)		Right Ra (mm)	Left Ra (mm)
1	0.279	0.383		0.303	0.213
2	0.401	0.319		0.252	0.266
3	0.381	0.419		0.202	0.198
4	0.312	0.344		0.189	0.258
5	0.309	0.319		0.222	0.346
Average Ra	0.3364	0.3568		0.2336	0.2562

In Figure 10, hardness values are shown for each heat treatment temperature used. As expected from maraging steel, the HRC values for no heat treatment were below 32. For heat treatment temperatures ranging from 420ºC to 520ºC, hardness was higher near the bottom of the wall. However, for 815ºC and 1115ºC, hardness was at its highest in the center of the wall. This was most likely caused by the weld dilution caused by welding on the base plate for the bottom portion. This area would be less pure in maraging steel as it has mixed some composition with the base plate. In the top layers of the wall, hardness was at its lowest. This was also seen in mild steel [4], which was caused by the less refined microstructures seen in this region.

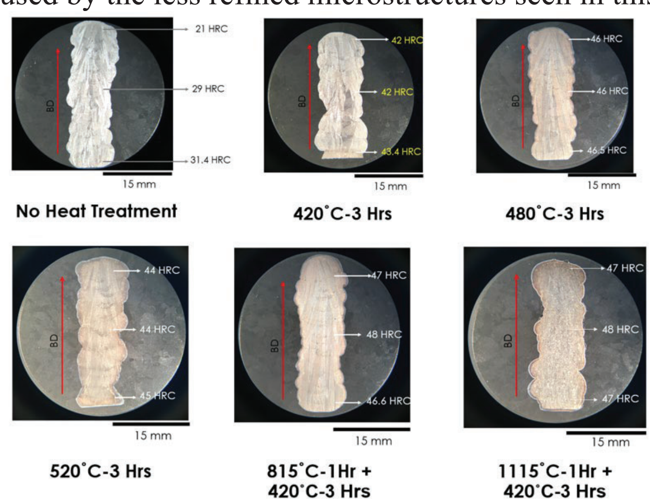

Figure 10. Hardness values taken from three locations of a two-bead thick wall as well as different heat treatment temperatures

Conclusion

Maraging steel shows promise in providing the desired hardness of an HRC above 50. By using MAR 250 welding wire, weldability was tested and shown to be weldable. Different shielding gases were tested with Trimix gas producing the best results. Using the starting welding parameters from the weldability test, walls were printed to observe how the material bonds together. Results show that one-bead and two-bead thick walls were successfully printed; however, the geometric features of the walls were rough, with large waviness. Using another welding mode, STT, surface roughness of the beads improved with more homogenous layers.

Overall, process parameters for MAR 250 will need further adjustments to produce similar results shown in printing mild and stainless steel. On the other hand, its printability success makes it a feasible material for mBAAM. MAR 250 did result in a slightly lower hardness than the desired 50 HRC; however, it is significantly better compared to mild and stainless steel. Future tests will be conducted with MAR 350 welding wire to observe if the hardness has increased with the higher strength material. Ultimately, maraging steel will be used for multi-material prints (Figure 11) to develop high strength tools and dies with low costs. This can be achieved by printing an outer perimeter of maraging steel and an inner core of mild steel.

Figure 11. Multi-material stamping tool with an outer surface of stainless steel and an inner core of mild steel

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