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Reviewed Paper

USING NON-GRAVITY ALIGNED WELDING IN LARGE SCALE ADDITIVE METALS MANUFACTURING FOR BUILDING COMPLEX PARTS

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Abstract

One of the most difficult aspects of printing large, complex metal parts is building large overhangs without the use of support structures. When using typical gas metal arc welding techniques, the torch is kept aligned with the gravitational direction. It has been shown that the maximum overhang angle that can be achieved is roughly 25°. This maximum can be increased by using part positioner, but this adds extra system complexity, especially for creating the robot paths. It is desirable then to develop a method of printing with the torch in a Non-Gravity Aligned (NGA) direction, such that the weld pool is supported and will produce the desired weld bead. This work focuses on the development of a control scheme based on sensor feedback of the state of the weld pool to maintain a stable, desired weld pool shape and thus print more complex parts using the gas metal arc welding process.

Introduction

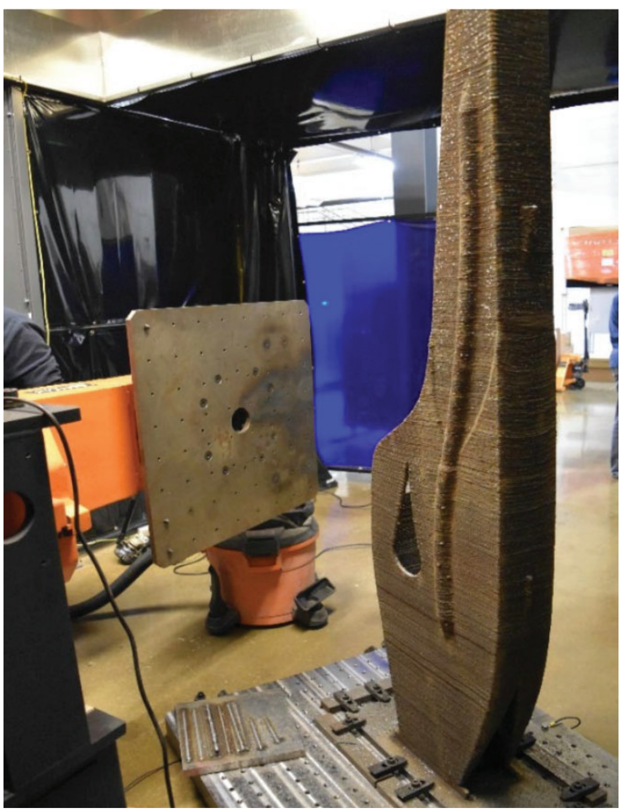

Figure 1: Example of a large part created using a WAAM process from [4].

Additive Manufacturing (AM) has continued to grow as a technique for constructing parts out of both plastic and metal for prototyping and actual industrial use. Particularly for metal AM, the most widely used commercial platforms (typically powder bed printers that utilize a laser or electron beam) are quite limited in the size of part that can be produced [1, 2]. More recently, standard Gas Metal Arc Welding (GMAW) systems have been used to build larger parts in a new process called Wire Arc Additive Manufacturing (WAAM) [3]. This process typically uses a 6-axis robotic manipulator to position and orient a standard GMAW torch which is controlled using a standard GMAW power supply. It has been shown that WAAM can be used to build very large parts quite quickly when the correct welding parameters are used [4]. An example of the type of large structures possible with WAAM can be seen in Figure 1.

One of the main issues with the current WAAM process is the lack of support material and thus the inability to create large overhanging features without reorienting the whole part using a tilt table or robotic part positioner. In [5], Xiong et al. state that in the flat deposition orientation (where the torch is aligned vertically), it is possible to reach quite large overhang angles, but it relies upon using a very slow wire feed speed, which results in a very slow deposition rate that is not practical for production. According to [6], the maximum possible overhang can be increased by setting the torch angle equal to the desired angle between the substrate and the wall to be built.

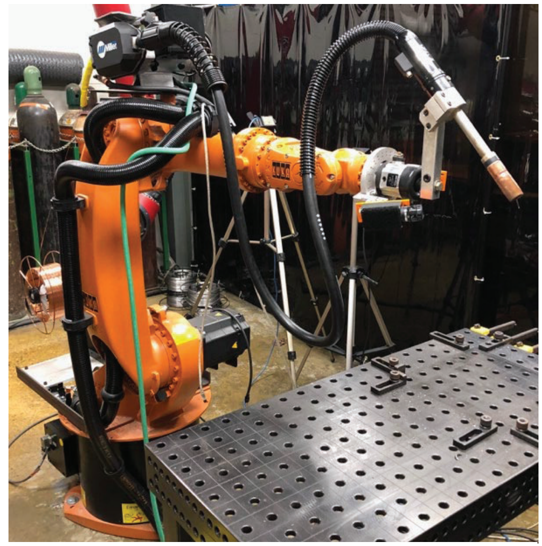

Figure 2: KUKA KR6-2 robot used in WAAM cell

In this paper, the setup of a WAAM system designed for NGA printing will be shown. The development of heuristic rules for successfully printing parts in an NGA orientation are discussed and parts with large overhangs printed using the NGA orientation method are shown. Finally, several conclusions are drawn about the feasibility of printing parts with large overhangs using NGA printing.

Experimental Setup

To perform this research, a standard weld cell was constructed using a KUKA KR6-2 6-axis robot manipulator (see Figure 2) with KR-C4 controller and a Miller AutoAxcess E450 Digital GMA power supply. A Tregaskiss straight welding torch is used and is mounted to the end effector of the KUKA robot. For all of the experiments described in this paper, the shielding gas is 92% Ar 2% CO_2, and the wire electrode is Hobart Quantum Arc 3 with a diameter of 0.035in. To perform the welds, Miller's Regulated Metal Deposition (RMD) is used. This was chosen due to its low heat input and fine bead size compared to other more standard GMAW processes.

To capture data about the weld pool and the overall part during construction, several sensors are used on and around the robot. The shape of the weld pool is monitored using a filtered CCD camera mounted behind the welding torch on the robot (see Figure 3). This allows for the camera

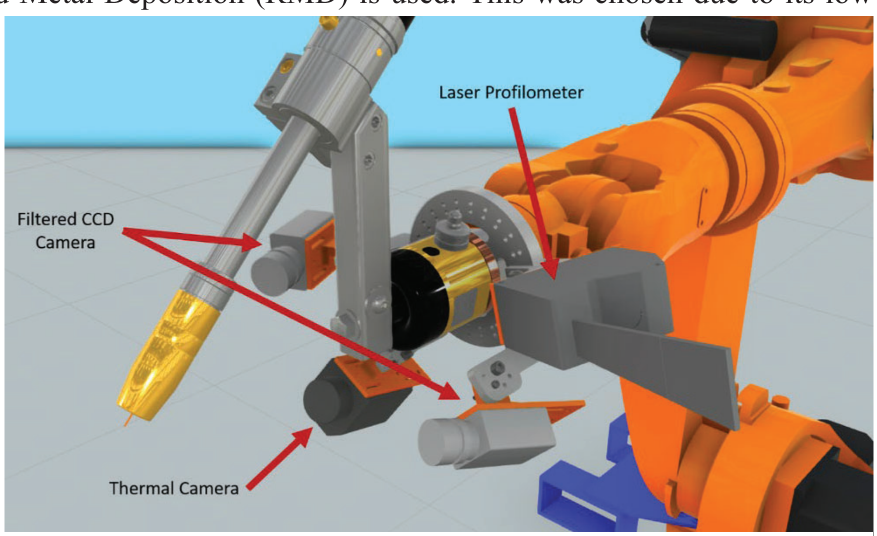

Figure 3: Sensor configuration on KUKA KR6-2 robot used for monitoring the LSAMM process

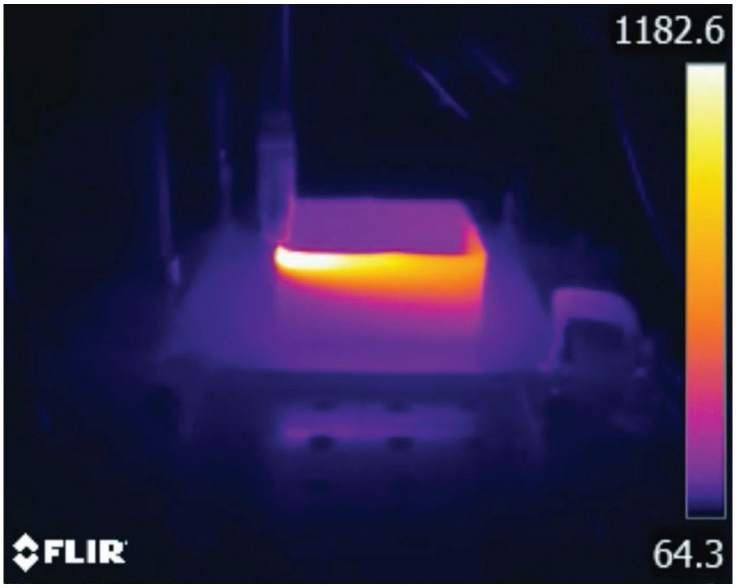

Figure 4: View from thermal camera of temperature distribution throughout a part

to maintain a constant orientation with respect to the torch tip. The exact view of the weld pool changes (whether the camera views the front or backside of the weld pool) with the welding direction, but with careful planning of a welding pass, the desired view can be seen.

In addition to the CCD camera, the power input of the welding process is monitored using a Miller LEM box which captures the real-time voltage and current so that the total heat input can be calculated for the part. This is done using (1), from [7]. To measure the profile of the part as it is being built, a laser profilometer is mounted on the end effector of the robot. It can be used to measure how a part is deviating from the desired part plan so that corrections may be made in-situ. Finally, a thermal camera is used to view the part as a whole to monitor the thermal evolution throughout the part (see Figure 4). This sensor input will eventually control the wait times between layers by monitoring the temperature of the top layer of a part and signaling the robot to begin the next layer when it reaches a desired temperature.

$$\dot{Q} = -\frac{Power\left({}^{J}/_{s} or\ W\right) \times arc\ time(s)}{Weld\ Bead\ Length\ [in.(mm)]} \quad (1)$$

In attempting to increase the maximum possible overhang possible in WAAM and determine what control action would be necessary to control the weld pool, a test part was developed (see Figure 5). This part was chosen as it provides three distinct sections in which gravity affects the weld pool differently. These zones are the horizontal sections, the vertical sections, and the corners.

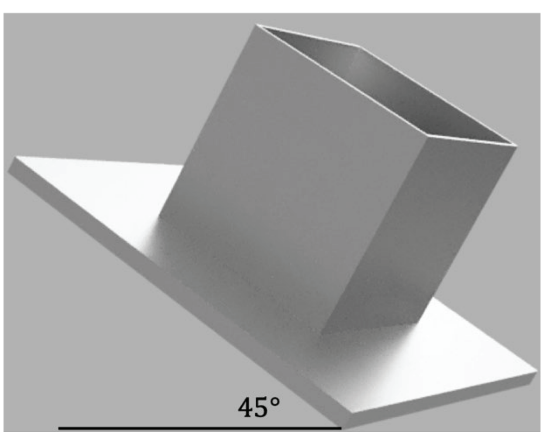

Figure 5: Part used to test non-gravity aligned welding techniques

In the horizontal sections, gravity pulls the weld pool off of the line of travel, causing the walls of the part to be non-perpendicular to the base plate, thus losing geometric conformity to the designed part. In the vertical sections, the weld pool flows downhill along (if welding downhill) or opposite to (if welding uphill) the direction of travel. This causes two possible effects on the top surface of the part. In the downhill welding case, material tends to collect at the end of the vertical section causing increased layer height in that area; in the uphill case, an uneven surface is seen that can cause long arcing issues if not corrected. Finally, the corners present an interesting challenge in that they are a transition from the horizontal sections to the vertical sections. This causes different results based on the location of the corner relative to the horizontal and vertical sections. Corners on the upper edge of the part see a decreased amount of deposited material as welding transitions from the horizontal to the vertical section, and the corners on the bottom edge see an increased amount of deposited material as welding transitions from the vertical to the horizontal section.

Figure 4: Initial build of 45º part

Results

The initial welding of this part was completed with open-loop control and the torch angled perpendicular to the base plate and can be seen in Figure 6. This part was constructed using uphill and downhill welding through starting at a midpoint of a section (top, bottom, left, right) and welding clockwise for one layer then counter-clockwise for the next layer, starting from a different midpoint. This resulted in the all of the walls of the part being perpendicular to the base plate as designed, but issues horizontal sections. It is believed that the orientation of the torch for this part did not provide enough arc force on the weld pool to compensate for the effect of gravity in the uphill and downhill welding situations. Thus, the top surface of both vertical sections is very bumpy, and these bumps ultimately caused the build to be stopped prematurely.

To address this waviness in the vertical sections, the part was built again but with a steeper torch angle of 50º from the perpendicular orientation. This result can be seen in Figure 7. For this build, the part plan was updated to only weld in the downhill direction for the vertical sections.

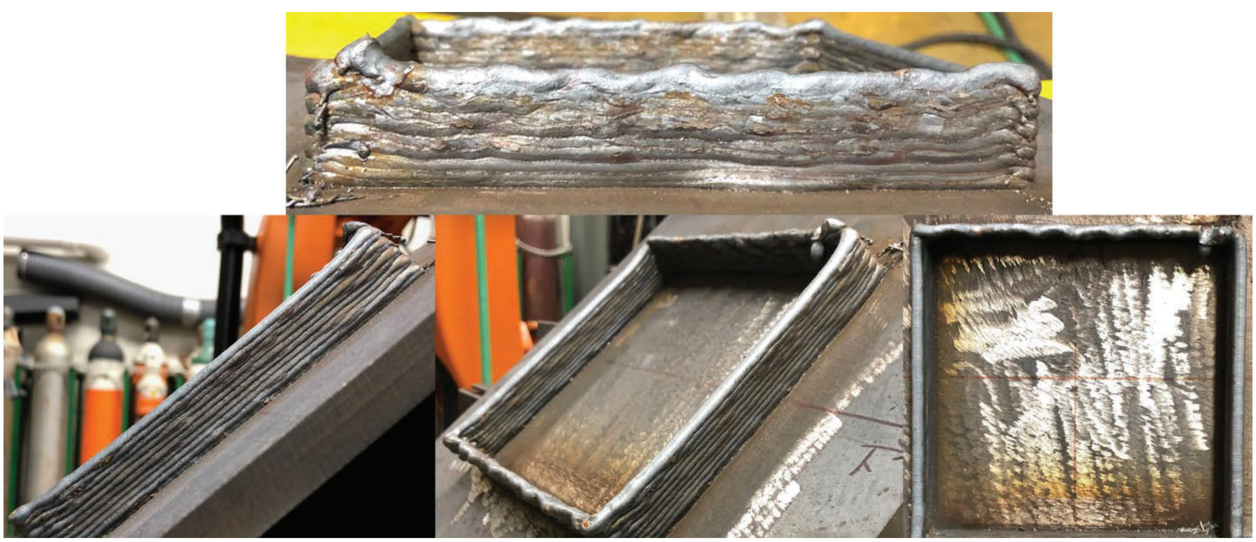

Figure 5: Result of updated 45º part using only downhill welding and angled torch orientation

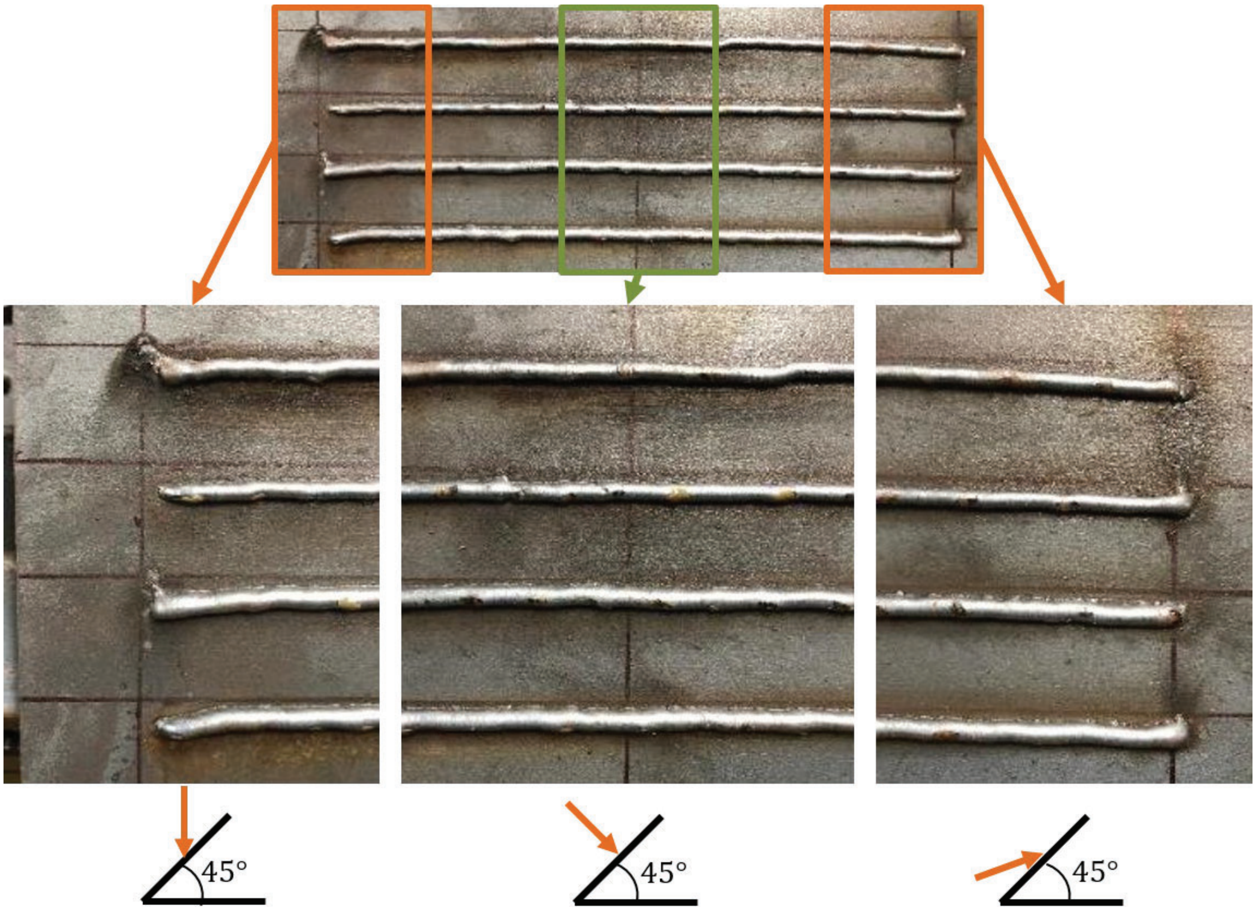

Figure 6: Result of the torch angle sweep test. The angles below show the torch angle relative to the base plate at each vertical line drawn on the plate.

This was done so that the orientation of the torch would provide the maximum support to the weld pool and guide it down the vertical sections. Two interesting observations were made during this build: first, while the vertical sections showed great improvement in the top surface topology, the horizontal sections were no longer perpendicular to the base plate. It can be seen in Figure 7 that the top and bottom sections are tilted downward due to the gravitation effect on the weld pool.

Secondly, the top surface of the horizontal sections of this part exhibit the wavy behavior seen in the vertical sections seen previously. To determine why the new torch angle caused this behavior in the horizontal sections of the test part, an experiment was developed to isolate just a single bead welded in the horizontal section. In this experiment, several beads were welded across

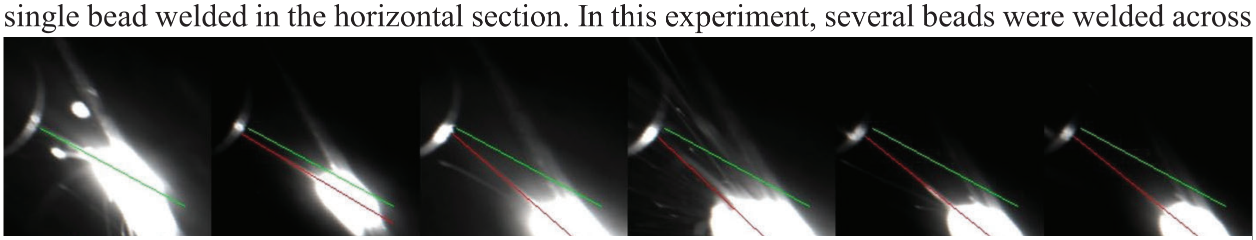

Figure 7: Images of the weld pool during the torch sweep test. The green line represents the starting position of the wire electrode while the red line shows the current position of the wire in each frame.

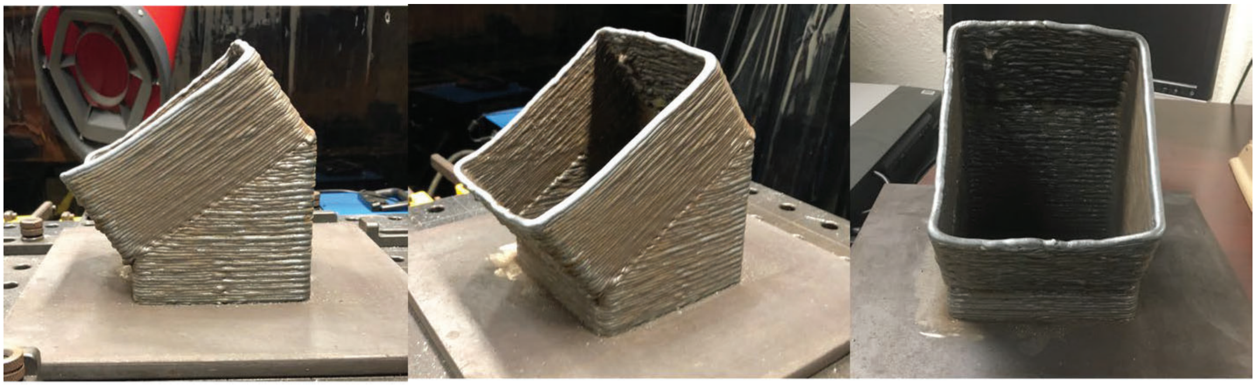

Figure 8: Complex part printed in open-loop based on previous results using different torch angles for the vertical and horizontal sections.

a base plate set at 45º and the torch angle was varied across the entire bead from being aligned with the vertical orientation at the weld start, to being perpendicular to the base plate at the midpoint, and finally ending with the torch almost parallel to the base plate (see Figure 8).

Using the filtered CCD camera pointed at the weld pool, it was seen that the wire electrode moved with the weld pool downhill at the start and end of each weld bead (see Figure 9). Each weld pass of this experiment was programmed along the line directly above the weld bead that was produced. This shows that at all torch angles, some amount of shift in the weld bead was present, with the least amount of shift occurring when the torch was perpendicular to the base plate.

This result, coupled with the result of the vertical sections when the torch was at 50º from perpendicular, led to a final, more complex part seen in Figure 10. In this part, a gravity aligned base was first built so as to reach a thermal steady state in the part. Then a transition zone was built using a stair step method to create the surface for the non-gravity aligned section of the part. Finally, in the non-gravity aligned section, the torch angle was set to be perpendicular to the base plate in the horizontal sections, and 50º from perpendicular in the vertical sections. Through the corners, a linear torch angle sweep was used to transition between the two torch angles.

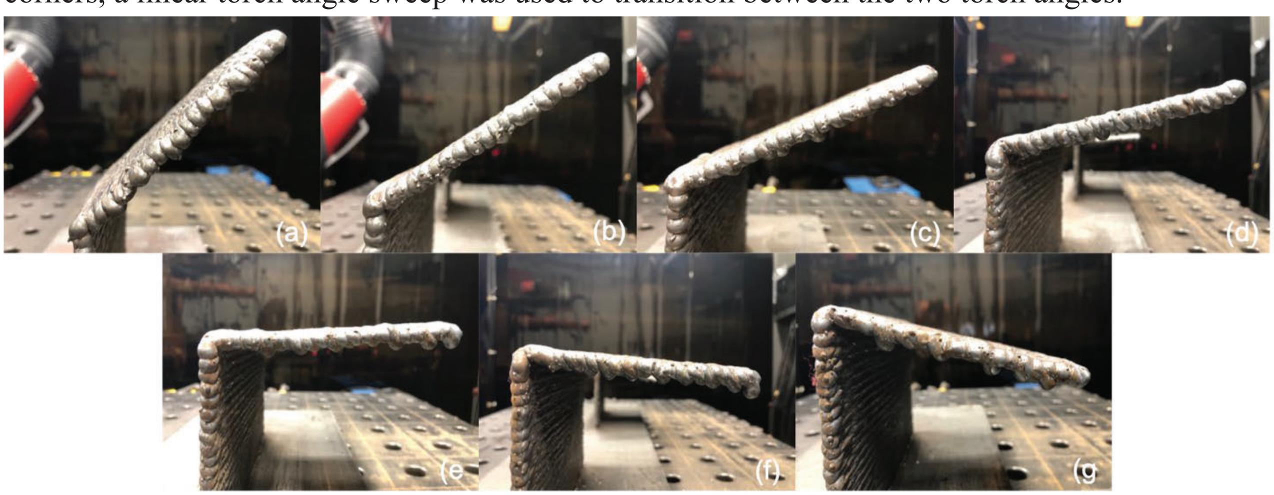

Figure 9: Overhangs printed in the horizontal welding direction with overhang angles of (a) 45°, (b) 55°, (c) 65°, (d) 75°, (e) 85°, (f) 95°, and (g) 105° measured from vertical

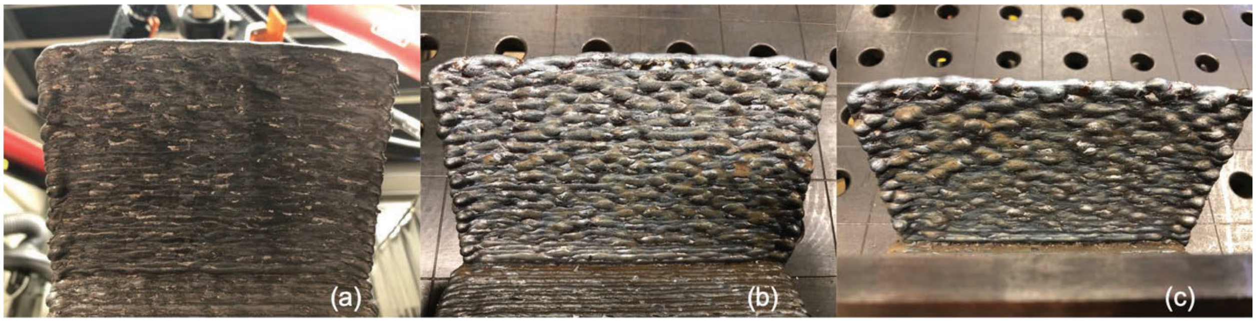

Figure 10: Undersides of the overhang sections for the (a) 45° , (b) 75° , and (c) 105° overhang parts

In further testing the limits of NGA printing, further tests in an isolated horizontal welding direction were performed. In each of these tests, a 4-inch vertical wall was built with a 4-inch section of overhang stemming from the top of the vertical wall. Each part was built using the knowledge gained from the previous experiments, particularly that for the horizontal welding direction, it is ideal to keep the welding torch perpendicular to the overhang angle.

The results of this series of tests can be seen in Figure 11. This clearly shows the capabilities of NGA printing in building large in the horizontal direction. It was seen that as the overhang angle increased, the surface waviness of the underside of the overhang section did increase (see Figure 12). It is believed that this occurred due to some minor drooping of the weld pool. As these parts were built in open loop control, it is believed that by closing the loop on controlling the shape and drooping of the weld pool in the NGA orientation, that this surface waviness may be minimized.

Conclusions

Throughout these builds, several key issues have been identified as elements of the WAAM process that need to be controlled to produce good quality, near-net shape parts. The first is the layer height throughout the part. It has been observed that there are two distinct stages of the build between which, if not controlled, the height of the weld bead changes. These two stages are an initial transient stage which lasts for approximately the first 10-15 layers of the part (depending on its size) and a steady state stage, as shown in Figure 5. In the initial transient stage, the layer height is typically higher than that of the steady state stage due to a lower overall temperature of the total part. When the part reaches steady state, the temperature of the previous layer remains higher than during the initial transient stage, which causes the weld pool to flow more than in the initial transient stage which results in a slightly flatter, wider bead.

The issue of layer height also indicates another important issue that should be controlled during the WAAM process, the overall thermal evolution of the part. By monitoring and controlling the overall thermal evolution of the part, the efficiency of the WAAM process increases as, rather than relying on a experimentally determined amount of time to elapse before starting the next layer, the surface temperature of the part can be used to trigger the start of the next layer. This allows for more consistency in the height of the layers and will prevent part meltdown.

Finally, the geometric state of the weld pool must be controlled to ensure the creation of a near-net shape part for parts that include a large overhang. As seen in the test parts built at 45º, different welding directions require different torch angles to effectively create the desired geometry. The horizontal overhang parts further demonstrate the capabilities of NGA printing as well as the need for closed loop control to mitigate the surface waviness seen on the underside of the overhanging surfaces.

Through the experimentation already performed, some initial heuristic rules have been developed to assist in the part planning process. But these rules are not fully sufficient as the open-loop parts produces above are close to near-net shape, but not fully acceptable. By closing the loop on these three issues, these parts can be produced with higher geometric tolerance and increasing the level of part complexity possible with WAAM technology.

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