

VIBRATION ASSISTED ROBOTIC HOT-WIRE GAS TUNGSTEN ARC WELDING (GTAW) FOR ADDITIVE MANUFACTURING OF LARGE METALLIC PARTS

Michael Santangelo¹, Bishal Silwal^{1*}, Alexander Purdy¹

¹ Department of Mechanical Engineering, Georgia Southern University, Statesboro, GA 30460

*Corresponding author: bsilwal@georgiasouthern.edu, (912)478-0542

Abstract

Most of the metal additive manufacturing technologies are focused on high cost and high end applications. There is in need, a low cost additive manufacturing technology suitable for low and high end metallic applications. Robotic automated welding can be considered as an alternative to manufactured large scale metal parts with layer by layer approach. However, many obstacles have to be overcome to make it viable technology in additive manufacturing industry. A Robotic hot-wire Gas Tungsten Arc Welding (GTAW) with low frequency vibrating filler wire has been used to deposit a metallic alloy. Different trials of weld-on-bead experiments were performed to obtain the desired envelop of the melt pool shape for build parts with low manufacturing costs and low build times.

Keywords: *Additive manufacturing, wire feed, hot-wire GTAW, ABAM*

Introduction

Additive manufacturing is a term which describes the building of three dimensional parts using an iterative layer-by-layer build approach. Today, 3-dimensional computer aided design (CAD) models are directly processed into build patterns, which directs the additive manufacturing equipment. Additive manufacturing machines can build a three dimensional parts with a wide variety of material types in their raw form, such as wires, powders, and sheets. These are categorized based on raw material types and the power source used (Figure 1). Additive manufacturing allows for flexibility in part design, especially over subtractive manufacturing methods, where parts must be designed in a way that allows the cutting tool to access all areas of the part. Additive manufacturing also allows for prototyping development at a much faster rate than any other type of manufacturing, allowing for designs to be visualized at much lower cost and faster turnaround time. Another benefit of additive manufacturing is for the reduction of complexity in assemblies. Because of the higher design freedom seen in additively built parts, components can be fully eliminated in some cases, by incorporating them into an additively manufactured structure.

Metal additive manufacturing technologies have existed since the 1990s (Sames, et al. 2016), when Manriquez-Frayre and Bourell used selective laser sintering techniques to print single layers of copper and tin (Manriquez-Frayre and Bourell 1990). Other types of metal additive manufacturing have emerged into the marketplace since then, most using a laser, electron beam, or plasma as the form of melting or sintering the metal into a freeform shape. Typically, as the energy density of the power source increases, the resolution and geometrical accuracy, when compared to the CAD model, increases as well. However, the deposition rate of the material is also largely dependent on the desired accuracy of the part, and when deposition rates are low, part accuracy tends to be higher. These two factors, deposition rate and part accuracy, largely dictate which metal additive manufacturing process is suitable for each application. To increase the productivity rate of metal additive manufacturing systems, hybrid manufacturing is being developed. Hybrid manufacturing combines the deposition and subtractive machining into a single machine tool.

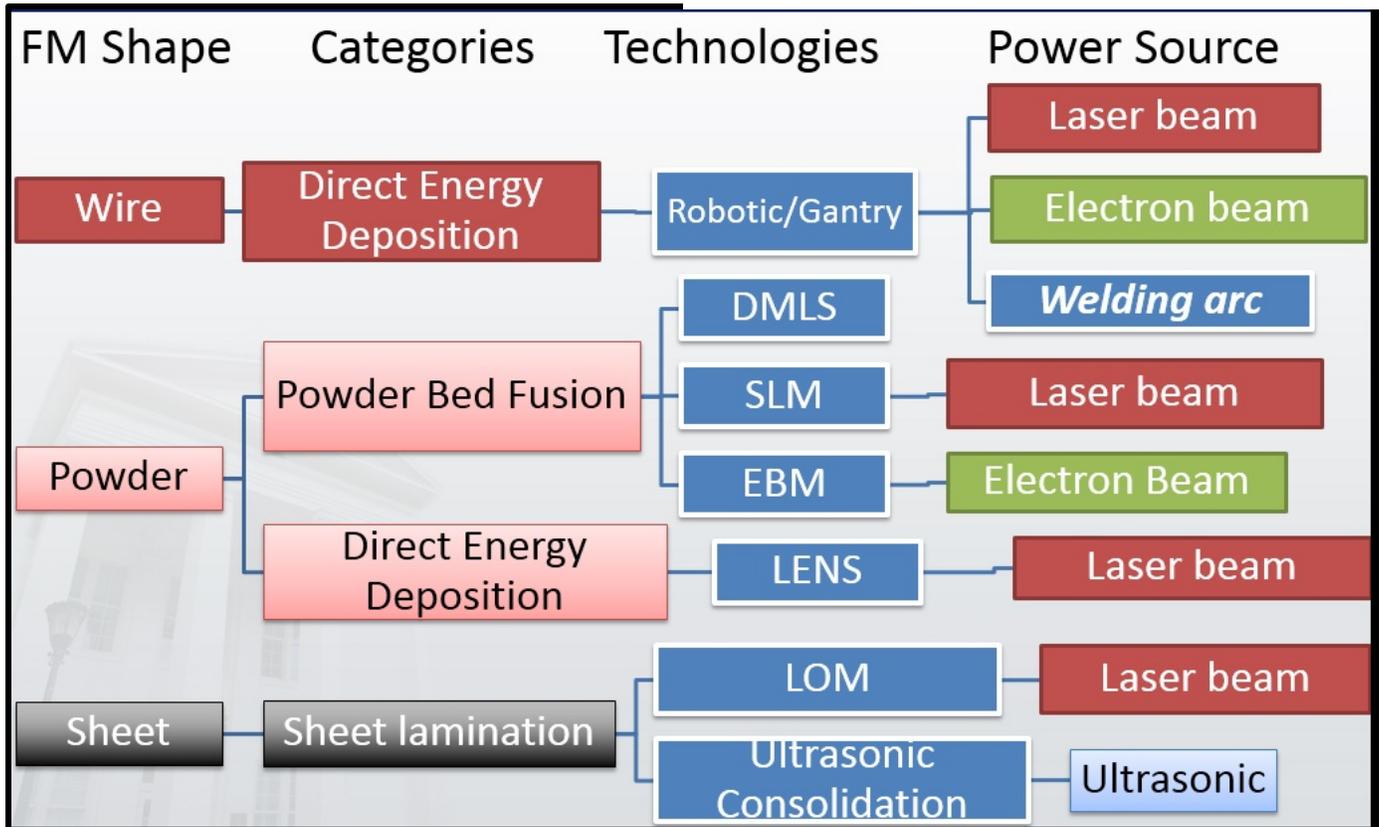


Figure 1 - Current metal additive manufacturing technologies

While all the forms of metal additive manufacturing technologies shown in Figure 1 have their own niche in the industry, most of them require the use of expensive and sensitive equipment, most notably the laser and electron beam systems. In addition, the powder systems have a low material deposition rate: 0.22 - 0.44 lbs/hr (Lathabai, Glenn and Ritchie 2014), very high part accuracy, making them ideal for prototyping small, yet highly complex parts.

Background

The arc based additive manufacturing (ABAM) process uses an electric arc welding equipment to melt an automatically fed wire or powder. As the wire melts it enters into the molten pool, it will eventually solidify and form the layers of the part. A computer controlled gantry or robotic arm guides the motion of the welding torch, building iterative layers, similar to current 3D printers. The key advantage of the wire and arc based systems is the much higher deposition rates, compared to powder additive manufacturing. In addition, the electron beam and laser systems have larger capital costs. Furthermore, the build environments are much more sensitive to contaminants. The ABAM process offers a low-cost alternative to the more expensive and exotic manufacturing methods already in place for metal additive manufacturing (Uziel 2016). It has a high deposition rate, and while the parts require post-process machining, the benefit of using ABAM over traditional methods can increase productivity rates while reducing manufacturing costs significantly. Although the ABAM offer many advantages, it also imposes challenges that have to be overcome to make this technology viable, as depicted in the fish-bone diagram (Figure 2).

Many arc welding technologies such as Gas metal arc welding (GMAW), Gas tungsten arc welding (GTAW), Plasma arc welding (PAW) etc. have been used as a rapid prototyping technique. Ouyang et al. used variable polarity GTAW to fabricate 5356 aluminum alloy part (Ouyang 2002). Colegrove et al. used high pressure rolling to minimize residual stress in the wire and GMAW additively manufacturing parts (Colegrove 2013). When comparing GTAW to gas metal arc welding (GMAW), the process parameters for the GMAW system, such as shielding gas, droplet detachment method, pulse frequency and other parameters must be varied for each metal, whereas the GTAW system requires significantly less change to switch between the various

metals. To increase the flexibility of the system and widen the process's scope of work, a gas-tungsten arc welding (GTAW) heat source has been used in this study.

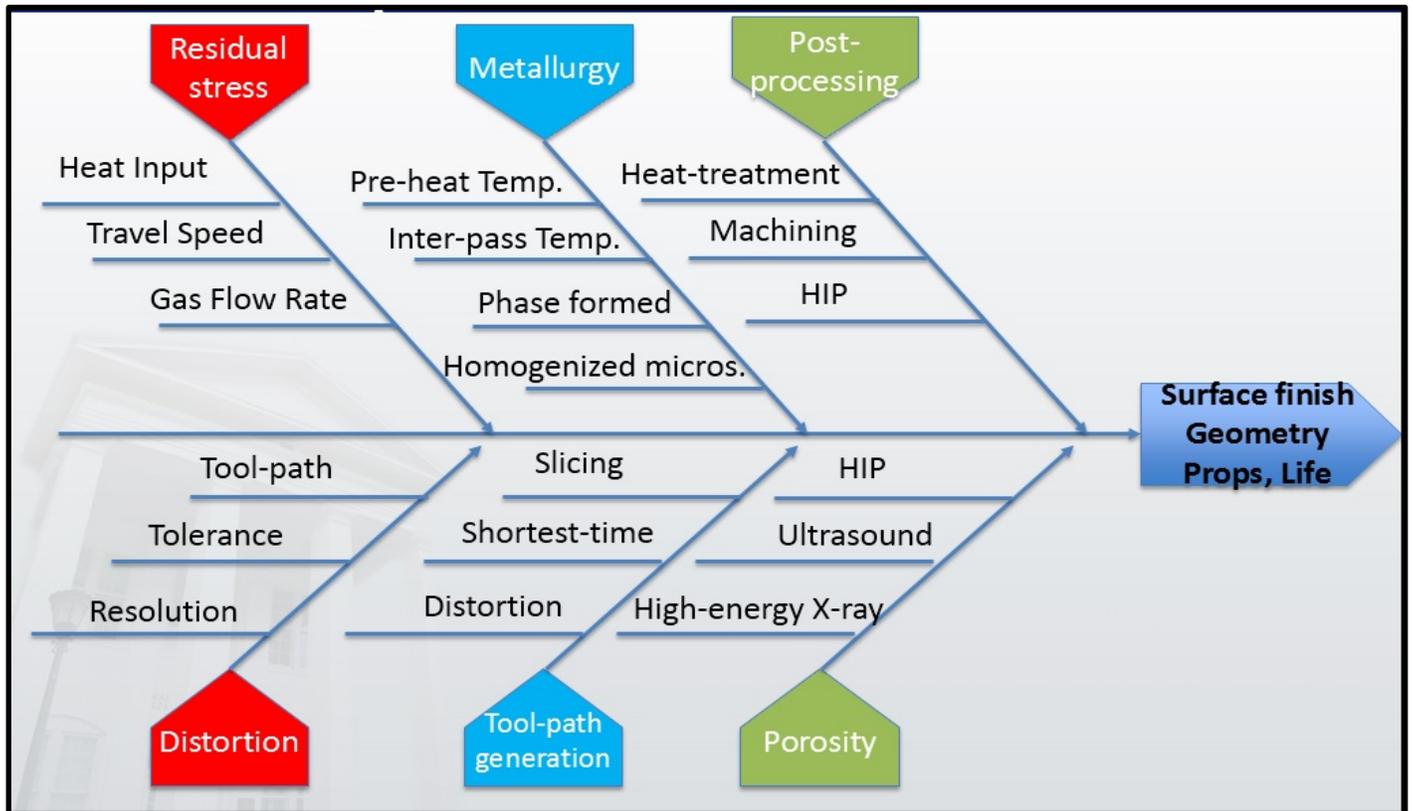


Figure 2 - Fish bone diagram of arc based additive manufacturing (ABAM)

In traditional GTAW, the wire feed is delivered by the welder, manually, however, in industrial applications, automated wire feed systems are used to increase deposition rates and repeatability of the weld. A commercially available wire feeder is coupled with the GTAW power source to fully automate the metal deposition. The wire feeder has the ability to resistively heat the incoming wire feed, which will help to reduce the thermal shock to the molten weld pool as new wire enters. Because the GTAW heat source is using less of its energy to melt the incoming wire, the deposition rate and linear feed rates of the welding torch are increased (Henon 2015). Irving et al. showed that the deposition rates of hot wire GTAW can be 300% or more than that of cold wire GTAW, as demonstrated in Figure 3 (Irving 1966).

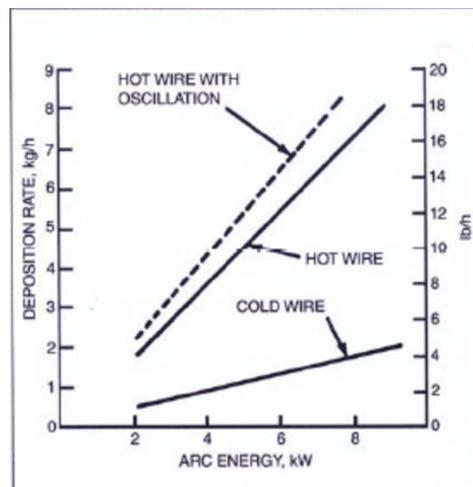


Figure 3 - Comparison of deposition rates between hot wire and cold wire GTAW systems (Henon 2015)

the solidified weld (Sakthivel 2014). The introduction of vibration in the arc weld has been shown to be a promising method to increase the quality of the resulting weld. Watanabe et. al (Watanabe 2010) showed improvement in mechanical properties of ferritic stainless steel weld metal by introducing ultrasonic vibration in GTAW. Wu et. al (Wu 2002) used low frequency oscillating filler electrode in gas metal arc welding (GMAW) and observed high surface quality weld beads. In general, the low and high frequency with low and high amplitude vibration can be achieved in a work-piece or a tool through the coupling of a motor, hydraulics and ultrasonic transducer from an auxiliary power source. In principle, the weld pool is driven by forces such as, surface tension, buoyancy, electromagnetic and arc drag. In vibration assisted welding, the vibratory effect will impose a velocity in the melt flow and thus higher cooling rates will be achieved, which may enhance the grain-refinement and homogenized microstructure during welding. It is thus considered as an external excitation method in arc welding similar to magnetic stirring and conformal cooling. In addition to the vibration on the electrode, a hot-wire GTAW will increase the deposition rate, compared to a cold-wire GTAW.

Figure 4 describes the basic operating work flow of the GTAW ABAM process used. In this process, a CAD file is converted into G & M machine codes with the use of computer-aided machining software. The numerical control program is then converted to joint and linear movements which can be read by the 6-axis robotic arm. The G & M code also programs all of the start and stop commands for the welder and wire feeder. As the robotic arm begins to interpolate the linear movements and moves to the start point of the layer, the welder uses a high frequency start to create the electrical arc between the tungsten electrode and the metal substrate. Subsequently the wire is fed through the arc and liquifies, forming a molten weld pool. As the robotic arm moves the welding torch away from its' starting point, the molten metal solidifies and a circular welding bead is left on top of the metal substrate. The computer aided machining software can account for the typical bead width and shape, and be programmed to overlap the edges creating a seamless layer. Once the first layer is complete, the robot will re-orient the welding torch in a different starting position and raise the torch by about 1.5mm and begin building the second layer of the part. Figure 5 shows a 4 layer rectangle, made with the GTAW ABAM process.

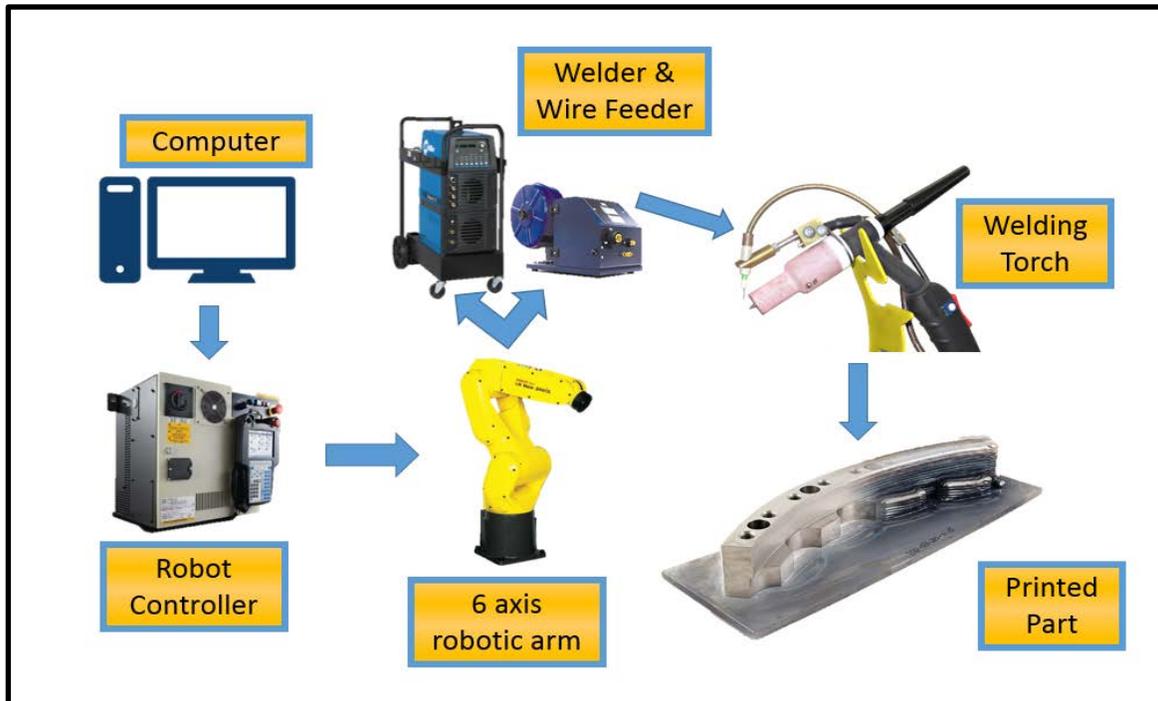


Figure 4 - ABAM process diagram and major components

Most additive manufacturing methods use a .stl file type to process a solid object into a format suited for a layer by layer build process. Once a .stl file is created from a solid body, it is then generally post processed by a 3D printing software, and the infill pattern, or space between the critical dimensions, of the .stl is created along with the support material locations. While in ABAM process, however, there is a need for a new type of tool path programming, depending upon the industrial robot. There is not a current tool path programming methodology available which can minimize residual stress and distortion. Typically the fewer starting and stopping points per layer there is, the better the accuracy and uniformity of the welded bead. Also, each start and stop of the weld introduces localized heating and cooling rates which are not uniform throughout the entire layer. However if a single start and start point can be used per layer, then the cooling rate of the metal can be controlled based on the linear feed rate of the robot, and wire feed speed. For this study, an industrial robot and their software generally designed for welding automation is used to program the tool-path.

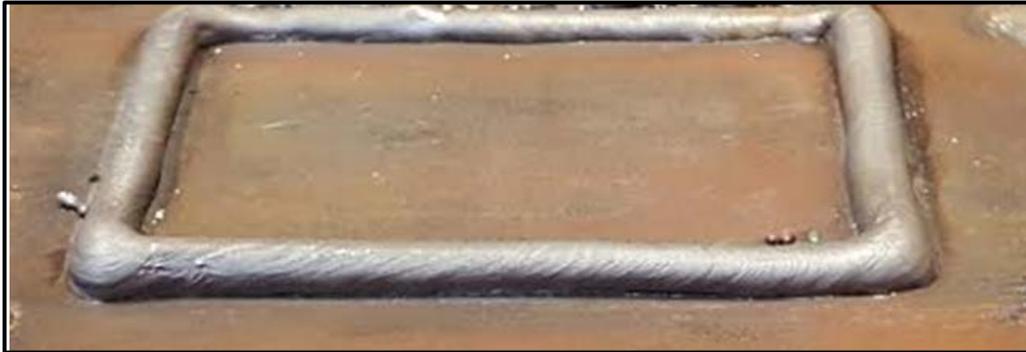


Figure 5 – Rectangular (200mm length, 100mm width) profile built with 4 layers in additive layer process with GTAW

Experiment

There are several important variables to control when building parts using the ABAM process. Some of the variables are as follows;

1. Welding current level
2. Wire current level
3. Torch linear movement rate
4. Wire feed rate
5. Torch height
6. Shielding gas & flow rate
7. Tool path orientation
8. Oscillation frequency

While tool path orientation and optimization is completely controlled within the tool path planning, series of experiments have been performed to identify the benefits of the hot wire feed and the vibrational feed mechanism, using a constant wire feed speed and travel speed. These preliminary tests have shown that higher deposition rates are achievable with the hot wire current and active vibrating wire feed, and while ABAM can be used without both of these parameters, the uniformity of the weld bead and the overall structure are more desirable with them. A high-speed digital photography and an optical 3D measurement system were used to analyze the weld bead shape and metal transfer process.

Four methods were analyzed in this experiment; Traditional GTAW with hot wire & vibration, traditional GTAW (cold wire), traditional GTAW with hot wire and traditional GTAW with vibration. For each inspection method several samples were prepared with and without hot wire feed and vibrational feed. All samples were welded with an arc current of 150A on the main welder, an automatic wire feed rate of 1.27 meter/minute, and a constant travel speed of 150 mm/minute. The total length of the weld bead was approximately 60 mm in length. Figure 6 shows a typical experimental GTAW welding setup with the welding torch perpendicular to the metal substrate, and filler metal entering above the tungsten tip into the weld pool. For the hot wire and vibration feed, a current level of 90A and an electrode vibration frequency of 230 Hz was used. The samples were made using ER70-S filler metal and a low carbon surface ground plate acted as the substrate for welding. After the deposition, the most uniform samples from each test was cut from the rest and inspected using a Keyence optical microscope (Figure 7). To further investigate the droplet formation and melting of the wire feed material, high speed digital photography was used to capture the welding arc and wire feed. The extreme brightness of the welding arc

typically drown out all other sources of light and will be the primary source of illumination when it is photographed or videoed. To filter out a portion of the arc light so that the weld pool would be visible, commercial lighting equipment was used to illuminate the subject matter, and an IR 3.0 lens was fixed in front of the camera to provide additional filtering. A Photron Fastcam Mini AX200 was used to record video of straight line welding at 6000 fps. The camera was positioned to see the horizontal movement of the welding torch, as it moved in a downward linear motion. The same four methods of welding used before were repeated using the same process parameters and weld materials

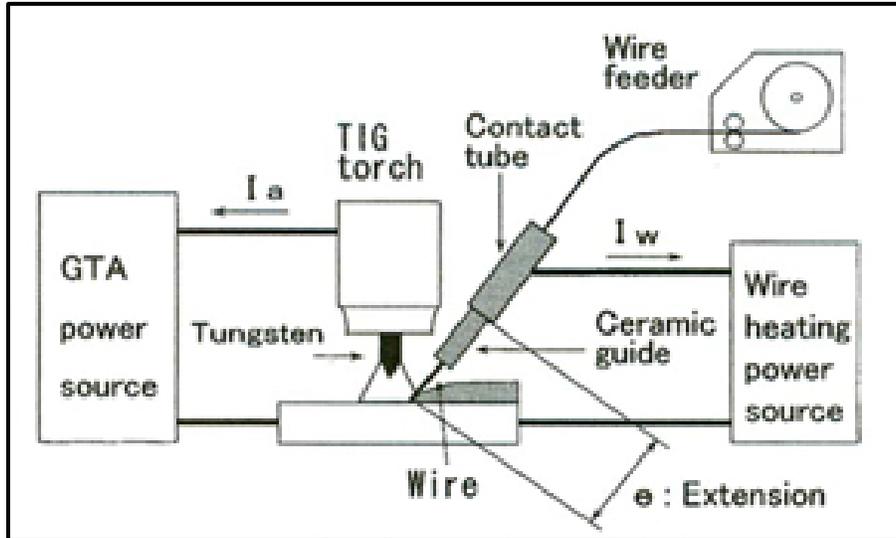


Figure 6 - Experimental GTAW welding setup (Hori, et al. 2004)

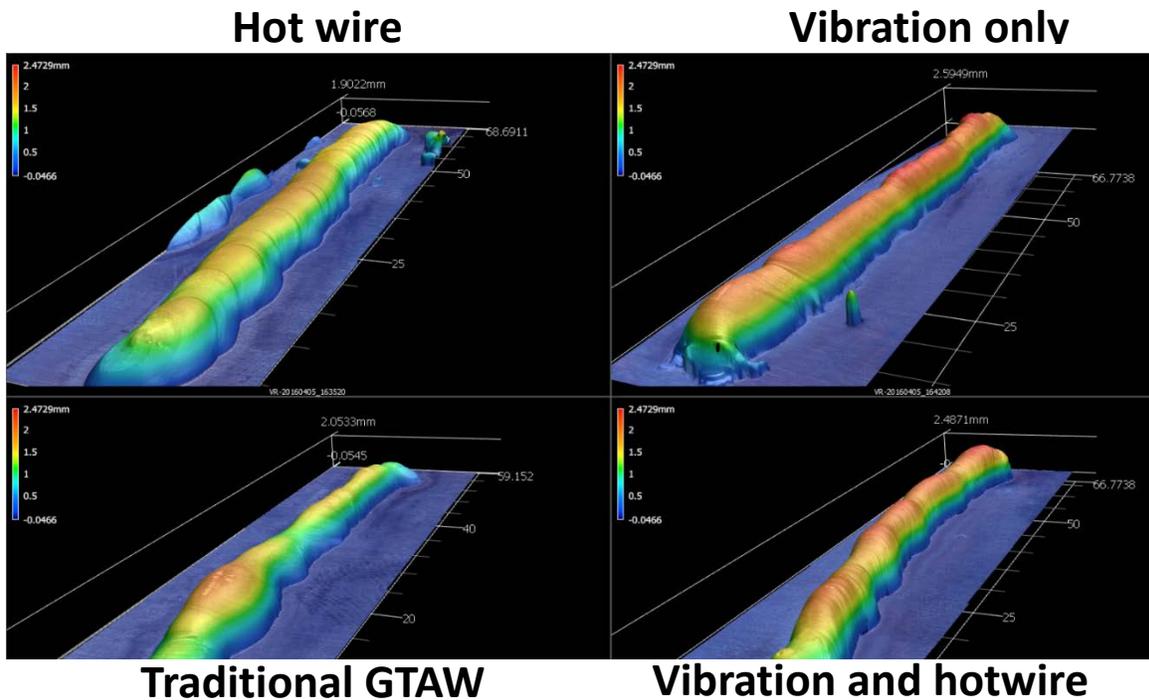


Figure 7 - Scanned image of weld bead using different methods using an optical microscope

Results an

The welding parameters without vibration or hot wire (traditional GTAW) has yielded a non-uniform weld bead at higher linear feed rate and wire feed rate (Figure 7). This is due mainly to the fact that the wire, when fed in to the molten pool region, requires a significant portion of the welding power to melt it, and the lower amount of power available, the welding torch must be moved slower to ensure uniformity in the weld pool's solidification. The remaining three methods of welding parameters show uniform weld beads. However with only hot wire, the weld bead is wider than higher. The height of the bead is 27% lower than the height of the other two methods of welding. Because the material in this method of welding is more prone to fall to the sides of the weld bead, it can be assumed that the more overlap between layers would be needed to maintain a constant layer height.

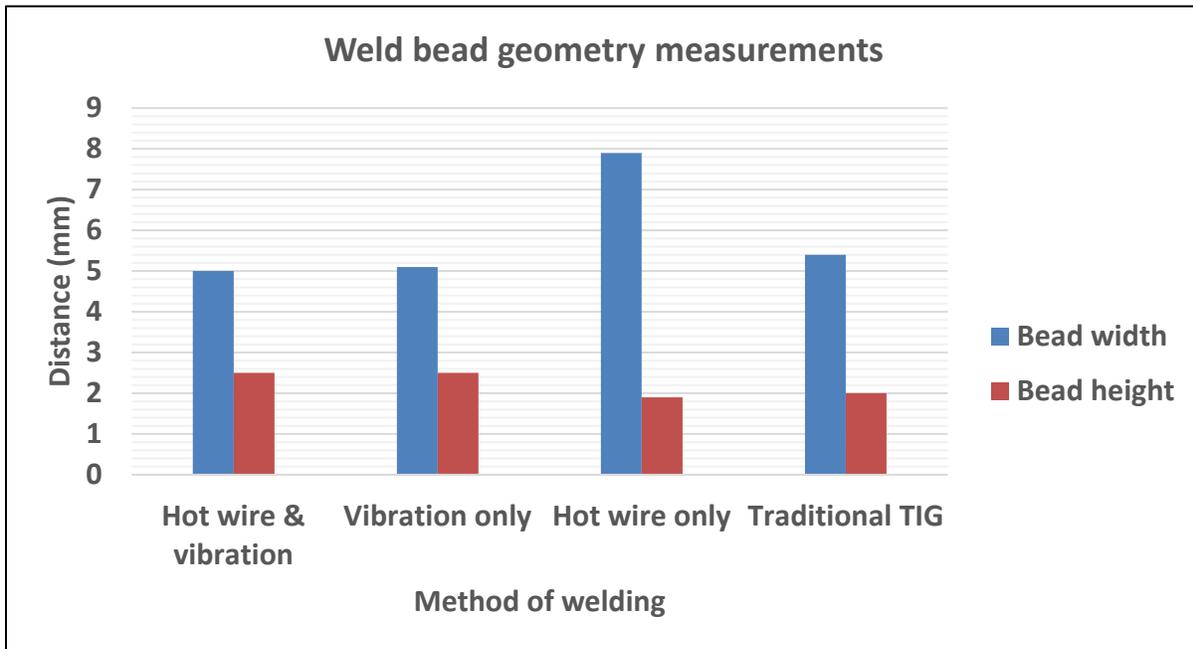


Figure 8- Measurements of weld bead height and width with different methods

When using only vibration or both vibration and hotwire the bead shape is uniform in terms of height and width, is narrow, and has a high peak. This would be ideal for creating parts with low manufacturing times and costs associated with them, where mechanical properties are not critical, in the layer by layer additive method because overlap between the beads would not have to be large, and would also reduce power and filler material consumption.

The topology of each bead was examined in the viewer software, the beads were measured normal to the welding substrate. Figure 8 shows the data of the average bead width and height for each method of welding. The dimensions obtained from the viewer software confirms the conclusion made from the topology imaging. Hot wire only, or no vibration or hot wire have significantly lower bead heights, where the molten metal spreads outward creating a wider welding bead. From Figure 8 it can be also seen that using only vibration, when compared to hot wire and vibration, that the bead shape is not consistent. This could be due to the lower amperage of wire feed into the molten pool, whereas when the wire is vibrated as it is fed through the welding arc it enters the molten pool, it appears to enter and melt at the same position throughout the entire weld. The hot wire and vibration used together may be the most desirable bead shape for additive manufacturing, when considering the droplet detachment rate, within this welding heat source, however multiple series of experiments need to be performed in order to reach any conclusion.

Figure 9 shows several frames that capture the formation and detachment of the molten droplet using hotwire and vibrational wire feed. The weld pool is not disturbed by the entrance of the metal filler wire, even as it creates an electrical arc with the weld pool. When the filler wire arcs with the molten weld pool, the welding arc shape will be disturbed, this is seen in this fourth and fifth image from the left below. This is due to wire being electrically charged with the resistively heated process. Without a hot wire feed the arc is not disturbed, however

the wire takes significantly more time to form a droplet and detach, and passes further through the welding arc before detaching, which is not an ideal location.

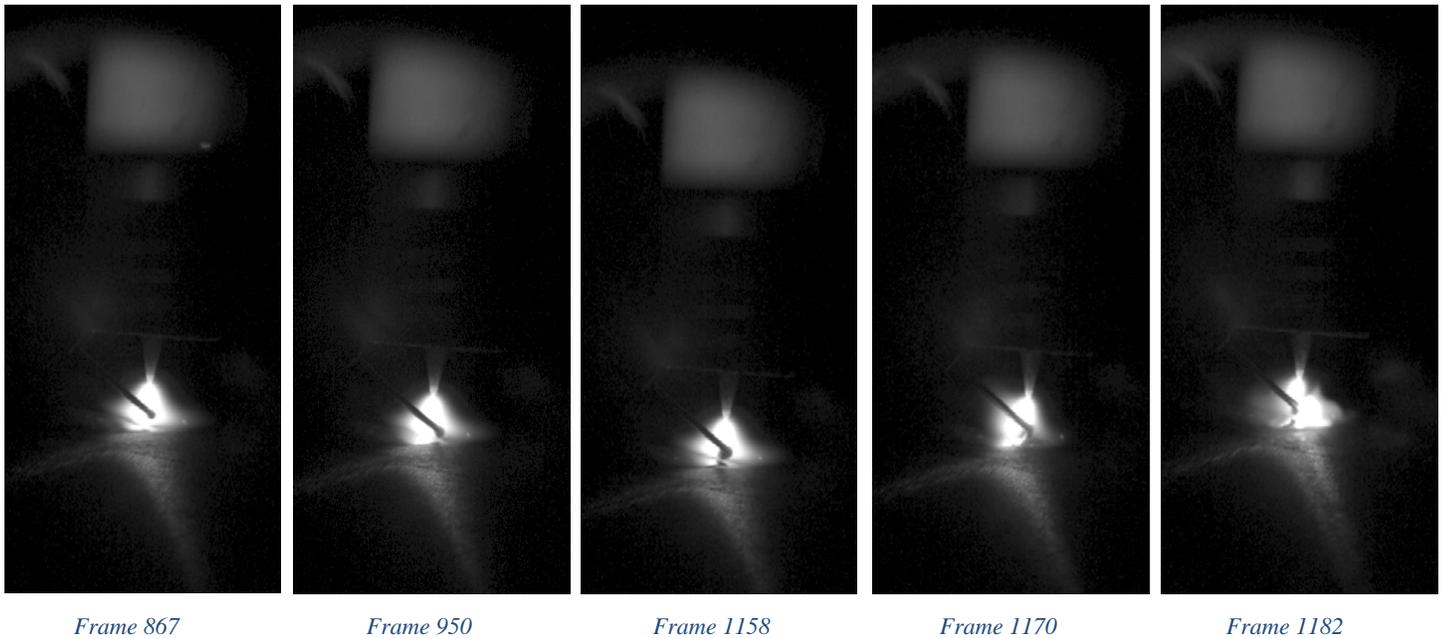


Figure 9 Droplet detachment in hot wire and vibration assisted GTAW (images captured at 6000 fps, images show a 52 millisecond span)

Conclusion

Arc based additive manufacturing utilizing hot-wire GTAW and lower frequency electrode vibration has been investigated as a viable power source. Different methods were used separately while keeping the heat input, wire feed and travel speed constant. Reinforcing traditional GTAW with hot-wire and vibration has increased the droplet detachment rate, deposition rate, however not a significant difference in bead geometry was observed. There is no difference in arc shape while using hot-wire and vibration, while small constriction on the arc during detachment process was observed.

Overall, the parts made by the ABAM process have a lower accuracy and resolution than other types of metal additive manufacturing, but the capital equipment cost is lowered with ABAM process. There are many challenges need to overcome as depicted in the fish bone diagram, such as tool path development minimizing residual stress and distortion based upon a CAD file in ABAM process.

Future work will be performed to better understand the mechanical properties and bead shape for the differing process parameters of the welder. A higher frequency vibration, which provides a wider bead by using the momentum during droplet detachment while lowering the main welding current, will be used to understand the effect on the cooling rate and fluid flow which is important to make arc welding viable for ABAM process. Similarly, software and tool path programming will be develop to better optimize the heating and cooling cycles that the part experiences as it is built.

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