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# WIRE ARC ADDITIVE MANUFACTURING OF LOW CARBON STEEL FOR CASTING APPLICATIONS

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## Abstract

While metal AM research often focuses on high-cost materials, lower-cost alloys such as low carbon steel are used at higher volumes in the casting industry. Welding is a standard process step in casting production, but robotic automation has been limited due to this industry's low-volume and high-mix. However, advances in flexible automation show their potential. This research presents the application of WAAM using a 6-axis robot with low carbon steel castings. Process parameters, including travel speed, cooling time, and step over distance are evaluated for their effect on the resulting geometry. Demonstration parts assess the ability to produce objects with varying geometries without defects. A method is discussed for depositing material on non-planar surfaces, such as the filling of a concave feature. These findings broaden the scope of applications in which wire arc additive manufacturing can be applied in industrial applications and develops parameters for depositing within non-planar cavities.

## Introduction

Metal casting is one of the oldest manufacturing processes and has broad applications for the production of products ranging from consumer and industrial to military. Designers choose steel casting due to its ability to produce complex geometries in a cost-effective fashion with little scrap material produced. However, the process of producing metal castings can be labor intensive, such as the production welding process used to remove indications of a potential defect and replace the material using arc welding [1]. Many foundries struggle to attract labor while remaining competitive within a global market, which may be due to harsh working conditions. A potential solution to this labor shortage is for manufacturers to improve working conditions by automating dirty, uncomfortable, and repetitive tasks. Yet, many steel casting manufacturing facilities operate as job shops with low production volumes and high product mix making traditional robotic automation difficult to implement [2]. Therefore, to implement automation in this environment we need a more flexible approach to automation.

**Figure 1.** ArcMate 50iC industrial robot used for wire arc additive manufacturing of castings.

Wire Arc Additive Manufacturing (WAAM) has demonstrated potential as a flexible method of producing steel geometries without the need for expensive tooling [3]. WAAM pairs traditional arc welding processes with motion control systems such as a gantries or industrial robots to enable the freeform fabrication of metal objects (Figure 1). Similar to other Additive Manufacturing (AM) processes, the desired geometry is sliced into 2.5D layers and a tool path plan for each layer is generated. WAAM paired with a 6-axis robot provides several advantages: 1) high material deposition rates, 2) relatively low material costs, and 3) flexibility to produce complex geometries without the need for tooling [4]. This method works with a wide range of materials including steels, Inconel, and titanium, and it is often paired with high cost materials to produce near-net-shape objects that reduce material waste by reducing the buy-to-fly ratio [4]. Consequently, WAAM has potential to be applied for the automation of the steel casting production welding process, but further research is needed to develop path planning methods for the filling of highly variable sub-surface cavities, and development of process parameters to better optimize this process for the casting industry.

This study investigates the use of WAAM for automating the production welding process step for low-carbon steel castings. A method is presented for excavating a cavity to remove an indication and then refilling the cavity with a robotic gas metal arc-welding (GMAW) system using WAAM process planning principals. To achieve this, AM process parameters were developed for Lincoln Electric L-56 welding wire on 1020 steel. This investigation aims to uncover how travel speed, step over distance, and sub-surface deposition affect the resulting geometry. The findings expand the useful applications for WAAM by demonstrating its pairing with a traditional manufacturing process to improve its flexibility. Furthermore, they refine the assessment of low carbon steel parameters for use with WAAM.

## Solution Overview

To apply AM as a solution to remove indications for the production welding process, the path planning needs to account for the cavity geometry. Currently, the cavity is often manually formed in the casting using carbon arc-air gouging, which is a high material removal rate process. However, this process forms an irregular cavity geometry that would not result in an integer multiple number weld beads per layer. More importantly, it could lead to a non-planar base in the substrate that would make traditional layer based AM process planning more challenging.

To overcome these obstacles, milling is proposed as an alternative method to form the cavity geometry. A bullnose end mill is used to improve tool life and productivity, with the radius of the end mill roughly equal to a layer thickness. For each layer, space is left for one additional welding bead, such that the valleys left on a layer *n* are fully filled when layer *n+1* is deposited. This results in the terraced v-groove shape seen in Figure 2 and provides clearance for the welding torch at any depth as long as the first layer is sufficiently large. To begin, the cavity is cut into the casting using a robot with a milling spindle. Then the first layer of welding will be deposited using a welding torch. This can be a separate robot, or done using an automatic tool changer. On subsequent layers, room for an additional weld bead allows the

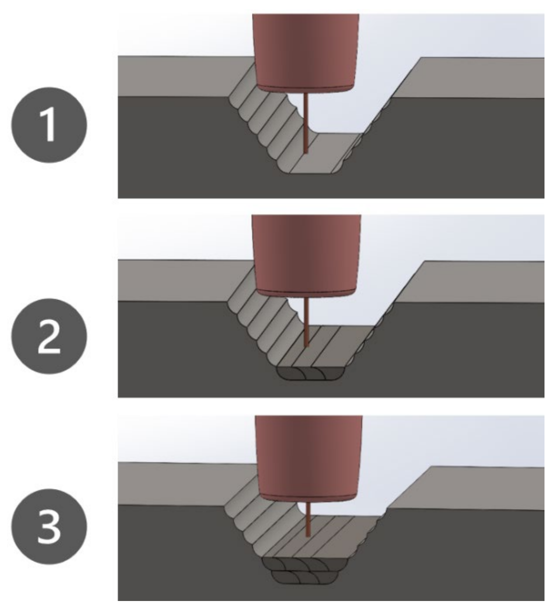


**Figure 2.** Cavity geometry and the weld filling strategy.

center of each toolpath to align with the valley below. The object may require cooling between layers to manage heat input. This process is repeated until the cavity is filled beyond the surface of the substrate. Finally, either a manual or automated grinding process will be needed to blend the proud weld with the geometry of the surrounding casting.

This approach allows for parametric control of the cavity geometry as long as the dimensions are changed at an integer multiple of layer heights or bead widths (Figure 3). A library of cavity geometries can be generated and tested to improve confidence that the weld repair process will be performed without defect. Using a standard library allows for computationally expensive simulations or verification testing to be completed offline. These standard cavity and filling geometries can be digitally fit to the location and shape of the indication on the casting using a vision system to ensure that the potential defect is repaired. Figure 3 depicts a section view of the parametric geometry and a demonstration cavity machined into low carbon steel using a bullnose end mill.

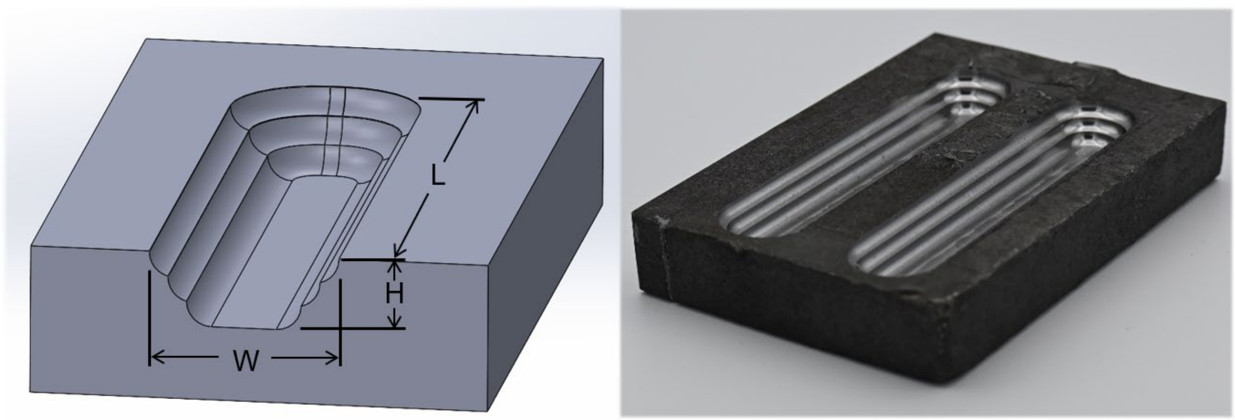


**Figure 3.** Terraced cavity geometry created using a bullnose endmill.

## Wire Arc AM Parameter Development for 1020 Steel

To evaluate the proposed method, WAAM parameters were developed for low carbon steel. This study investigates how the welding speed and step over distance affect the resulting geometry of deposited steel. Lincoln Electric SuperArc L-56 welding wire with a diameter of 0.9 mm was used with the ArcMate 50ic robotic welding center to deposit material on 1020 steel substrate. Pulsed spray transfer mode was used with a trim setting of 1.0 and a wire feedrate of 350 IPM. The robot travel speed during welding was set to 3.4, 4.2, 5.1, 5.9, 6.8, and 7.6 mm/s to produce a single weld bead on the flat surface. A cross section was taken of the weld, polished, and etched in a solution of Nitric Acid and Methanol to allow for measurements of the bead width (W), height (H) and penetration depth (D) (Figure 4).

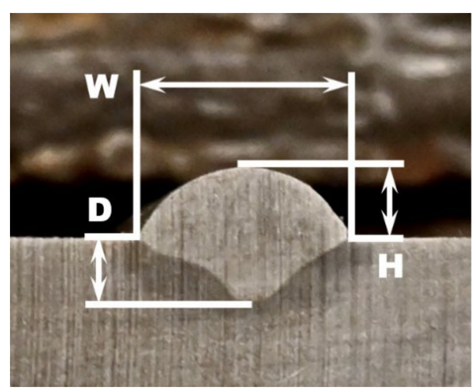


**Figure 4.** Weld bead cross section showing width (W), height (H), and penetration depth (D).

Etched cross sections of the weld beads for each travel speed visually demonstrate that the bead width is strongly affected by the travel speed (Figure 5). All of the welds were continuous, free of porosity where sectioned, and did not exhibit excessive spattering. Weld geometry had a similar level of waviness along the length of the weld for all travel speeds. The cross-section geometry is quantified in Figure 6, which shows that the bead width is more strongly affected by the travel speed. While the bead height and the penetration depth do appear to have a negative trend, it is not as pronounced.

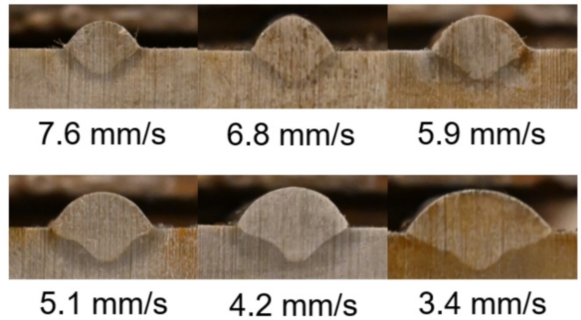


**Figure 5.** Etched cross sections of weld beads for each travel speed.

For the application of casting production welding, which requires the filling of a cavity, there may be situations where different welding parameters could be used to control the heat input into the substrate. Increasing the travel speed while maintaining other parameters results in a decrease in heat input into the part. This can be advantageous in reducing residual stress and controlling the resulting microstructure. One study found similar results suggesting that travel speed and current are the two most critical parameters for controlling the weld bead geometry, and that reducing heat input by increasing travel speed was beneficial in obtaining the desired geometry [5].

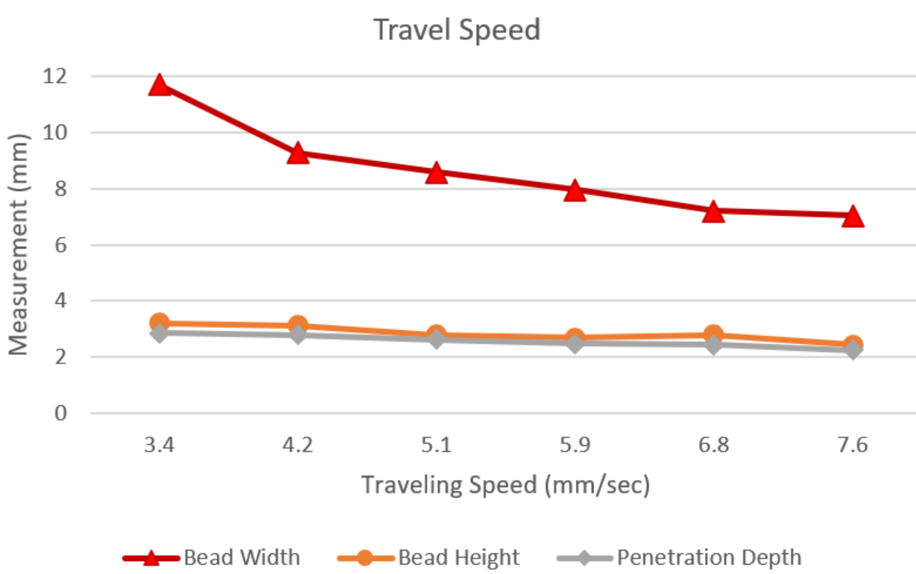


**Figure 6.** Relationship between weld geometry and the welding travel speed.

Next, the effect of step over distance on the peak height and valley depth of the weld beads was evaluated by placing six adjacent welds with centerline step over distances of 3.6, 4.6, 5.6, 6.6, and 7.6mm (Figure 7c). Based on results of the single bead geometry experiment, a travel speed of 6.8 mm/s was selected due to the lower heat input while still producing an acceptable weld. Figure 7a shows how step over distance is measured. The objective of this experiment is to find the step over distance that results in a single flat layer of material. To achieve this, the height of the weld peaks and the depth of the valleys between the weld are measured. It is ideal to minimize the depth of the valleys without causing bulging in the surface due to excess material deposition. This critical center distance for producing this flat layer surface is thought to lie between 66 – 74% of the bead width or approximately 4.6 – 5.3mm for the parameters used in this study [6]. Figure 7b shows the etched cross sections of the resulting geometry for each sample set. It is observed that the 4.6 mm step over results in a nearly flat surface while the 5.6 mm step over distance results in the presence of small valleys.

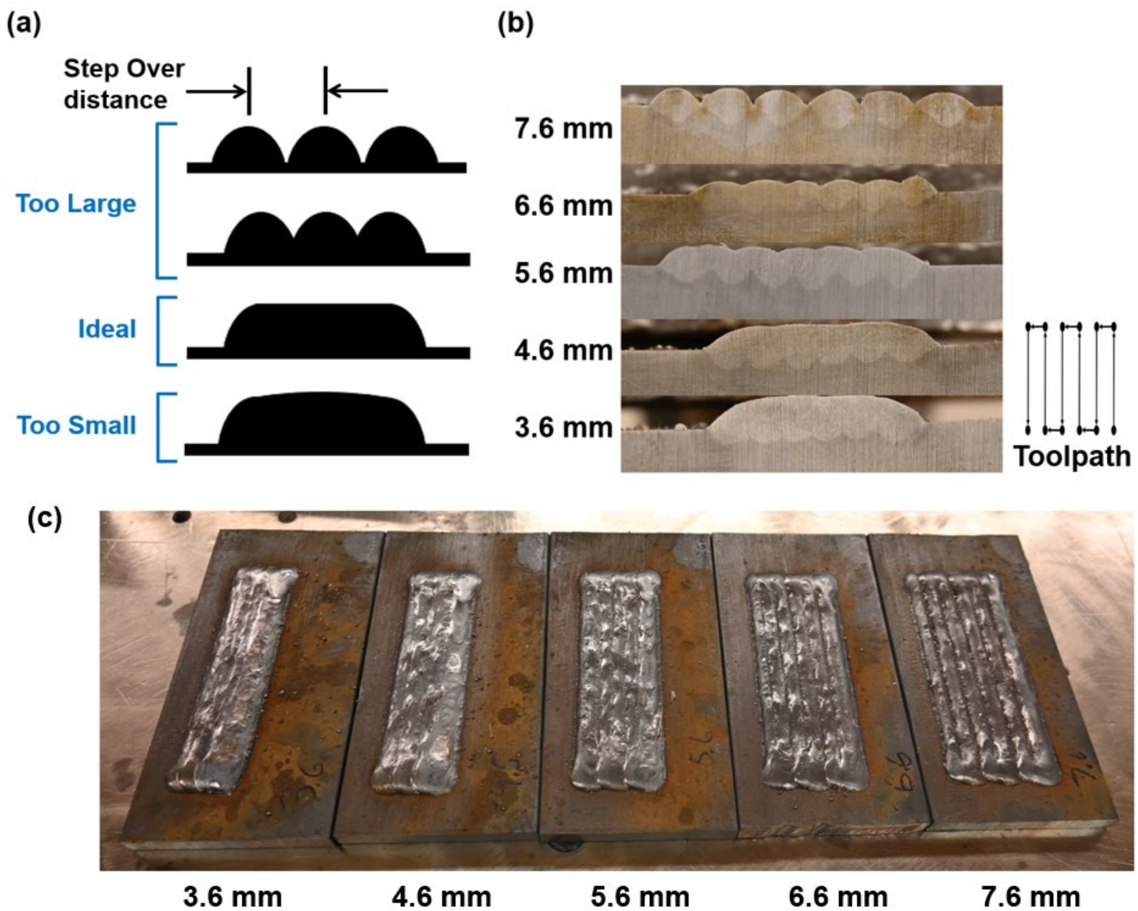


**Figure 7.** Geometry obtained by adjusting the step over distance with a travel speed of 6.8mm/s.

Measurements of the average peak height and valley depth for the sample produced at each step over distance is seen in Figure 9. There is a general trend that as step over distance decreases, the average peak height increases and the average valley depth decreases until the valley becomes near zero. As the step over distance increases, moving the weld beads further apart, the peak height eventually reaches the value of a single weld bead, and the valley depth becomes equal to the peak. From these parameters, a step over distance of 4.6 mm is selected, and a demonstration part is produced by stacking 14 repeating layers of the toolpath used for the step over distance experiment (Figure 8). Deformation of the

**Figure 8.** Demonstration 3D geometry from stacked layers with a 4.6mm step over.

substrate likely caused by residual stress in the part resulted in an irregular shape. The residual stress may have been substantial due to quenching between layers.

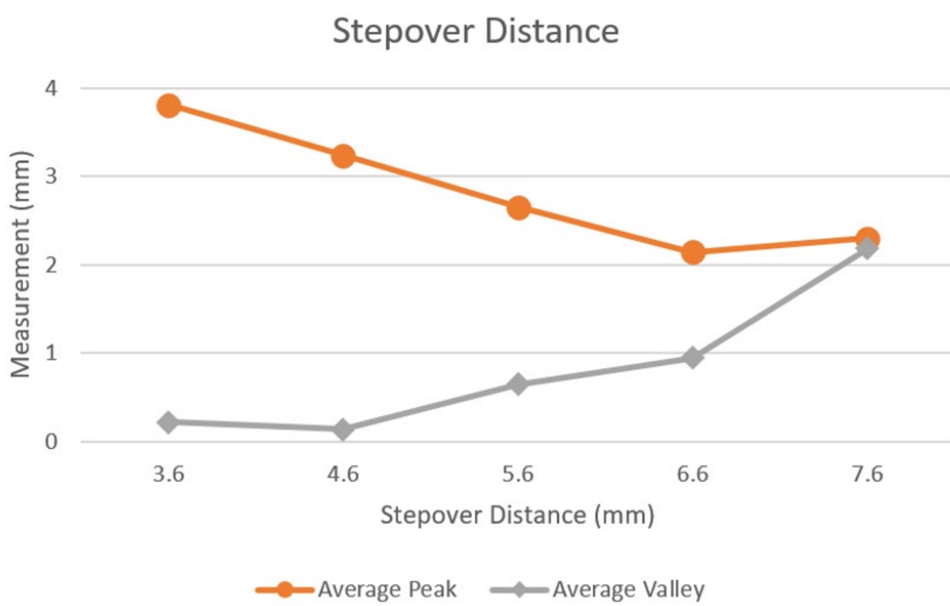


**Figure 9.** Average peak height and valley depth resulting from different step over distances.

## Standard Cavity Geometry for Production Welding of Castings

To achieve the objective of this study, we must bring together the findings of the parametric studies in the previous section with the proposed standard geometry for production welding of castings. A 25.4 mm diameter bullnose endmill with a 3.2 mm corner radius was used to machine a single layer and three-layer deep cavity using a HAAS UMC750 machining center. In order to eliminate a valley forming between the substrate wall and the first weld bead, the zero had to be offset so that the first weld centerline was only 1 mm from the cavity wall. The cavity width was reduced accordingly. There is a future opportunity for a more in-depth study of the step over distance from the substrate to the first and last weld beads.

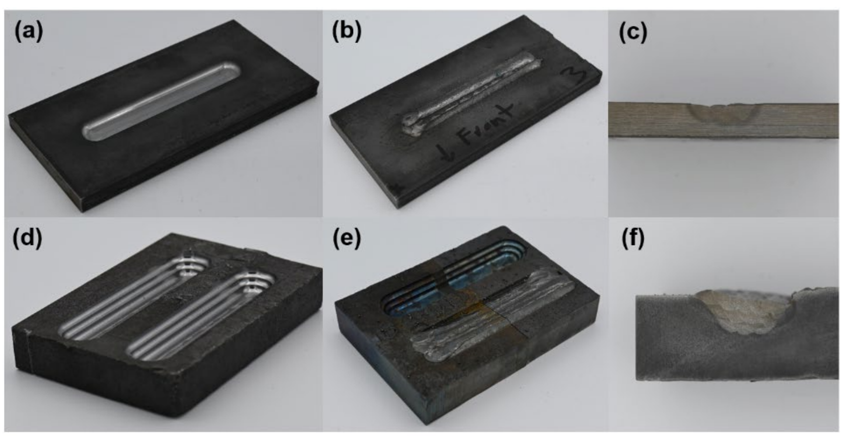


**Figure 10.** Production welding demonstration showing, a) single layer cavity, b) single layer weld, c) etched cross section of single layer weld, d) three layer cavity, e) three layer weld, f) etched cross section of three layer weld.

Production welding of castings requires the material deposited during welding to protrude beyond the substrate surface to ensure the casting geometry can be fully reconstructed. Figure 10 demonstrates that this was not completely achieved in this study. More work is needed to tune the layer thickness when welding inside of a cavity to ensure the welded material extends past the casting surface.

## Conclusions

This study presented a novel method for the automation of casting production welding. A standard terraced v-groove geometry was developed to allow for the parametric variation of the geometry based on an integer multiple of bead widths of layer thicknesses. This approach allows for the simulation, testing, and validation of a standard shape to ensure a weld of sufficient quality to meet customer requirements is produced. This standard geometry will be fit to the region on a casting containing an indication identified as requiring material removal and refilling. A parametric study was conducted for WAAM using low carbon steel with pulsed GMAW with industrial robot motion control. These findings were used to select travel speed and step over distance parameters for use in the welding of cavities in castings. These cavities were produced in low carbon steel substrate and filled with weld material using the WAAM parameters identified to demonstrate the proposed method.

Further research is needed into the interaction between the deposited weld bead and the side wall of the cavity to better understand the resulting weld geometry, eliminate voids, and ensure structural performance. In addition, a better understanding of how welding in a cavity affects the layer thickness is needed to ensure weld material extends beyond the original surface of the casting. While this research is presented using GMAW and low carbon steel substrate, the method can be applied using a variety of arc welding technologies with different alloys. There are opportunities for this approach to be applied to non-ferrous casting or for the repair of non-cast objects. Lastly, while the motivation was to use WAAM for filling production weld repair cavities on castings, applications could exist where this approach to pocketing and weld filling could be the 'root' structure foundation for the WAAM-addition of custom, complex features to an existing part. For example, custom features could be added to high volume production castings such as special flanges, interfaces, or additional complex features that could be appended to parts via WAAM.

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## Disclaimer

The publication of this material does not constitute approval by the government of the findings or conclusion herein. Wide distribution or announcement of this material shall not be made without specific approval by the sponsoring government activity.

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