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# Geometric Challenges in Designing Parts for Machining using Wire-fed DED

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## Abstract

Wire-fed DED using MIG welding systems allows for high deposition rates above 30lbs/hr, enabling much larger parts to be printed than would be possible on other DED systems. However, a drawback to this high deposition rate is a relatively low bead resolution on the printed part. Post-processing using machining is usually required on any mating surfaces printed using wire-fed DED. Problems such as residual stress in the build plate and printed part, underbuilding, and path interpolations can all lead to insufficient material deposition and deviation from the desired shape. These areas where the printed part varies from the model can leave defects on post-processed surfaces. This paper will cover common geometry issues that can arise from wire-fed DED and design changes that can be made to ensure that the printed design contains the required material to achieve the finished part.

## Introduction

Additive manufacturing enables complex parts to be produced layer by layer with minimal amount of waste material. Metal additive manufacturing usually relies on the liquification of feedstock in the form of wire or powder to deposit each layer in the form of beads. The energy input for this process usually involves lasers, electron beams, or plasma arcs to melt the metal. Among the various types of metal additive manufacturing techniques available, wire-arc additive is among the highest deposition rates available. Wire-arc additive manufacturing (WAAM) can usually be divided into two different forms: Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW). GTAW additive uses a tungsten rod as the electrode for forming an arc and then the feedstock wire is fed into the arc from the side. The tungsten electrode allows for fine control of the plasma arc. The GMAW process involves using spooled feedstock wire as the electrode to form an arc as it is continuously fed into the melt pool. This method of DED has benefits over other methods as it allows for a non-directional tool which simplifies tool path planning. The feedstock itself is also readily available due to its use in traditional welding processes. This paper will focus on GMAW processes to produce large scale metal parts. WAAM processes can have instantaneous deposition rates between 6-10 lb/hr (1, 2). Other DED processes such as blown powder additive have lower deposition rates closer to 1-7 lb/hr (1, 3). This makes WAAM processes very useful for producing large scale parts on the order of 1m or larger that would otherwise be extremely time consuming to print using other methods.

The tradeoff with the high deposition rate provided by wire-arc WAAM is the relatively poor resolution bead deposition and high heat input. Powder bed systems are often the highest resolution systems with spot sizes in the micrometer range (4). Meanwhile, WAAM systems are usually much higher with bead sizes on the scale of several millimeters (5). Due to the large bead size produced using wire-arc systems, post processing in the form of machining is usually required for any mating surfaces on a printed part. Figure 1 shows the cross section of two short walls printed using wire-arc process. The large bead size creates similarly large deviations in the final surface of a printed part on the scale of millimeters (5). The resolution can be improved by decreasing the heat input into the weld but requires a corresponding decrease in deposition rate (6). Parts printed using WAAM should be designed to take the large resolution into consideration to allow for effective post processing. Additionally, the heat input from WAAM processes is significantly higher than other metal additive techniques. Residual stress and changing layer heights based on geometry also require consideration when designing parts.

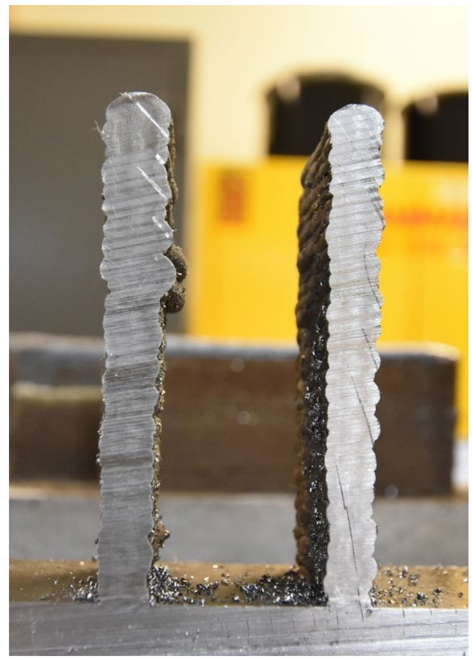
*Figure 1: Cross section of wire-arc printed walls.*

## Challenges in Wire-Arc Design for Post Processing

The following section will cover characteristics of wire-arc additive manufacturing that can require design modifications when attempting to post-process parts. All of the examples shown below were printed at the Manufacturing Demonstration Facility (MDF) within Oak Ridge National Laboratory. All MDF wire-arc systems use Lincoln Electric R450 welders and Autodrive 4R220 wire feeders along with a ABB IRB2600 or IRB4600 and Abicor Binzel ROBO water cooled torches. In the majority of cases 0.045 wire is used on 1" or ¼" mild steel baseplates.

### As-Printed Surface Finish

The first and most visible potential issue when designing parts for post process is the surface roughness of the finished parts. When generating G-code for a given part, the bead size is usually measured as its maximum width. However, when depositing multiple layers, the bead takes on a rounded shape, resulting in a waviness in the surface where the surface does not extend as far as the maximum width. Figure 2 shows a heatmap for the deviation from a best fit plane for a wall printed in 410SS. There is approximately 2mm of variation in surface geometry. If G-code is generated for a part using the average width as the bead width, the part will be printed smaller than the desired geometry in some places. This error can lead to the as-printed surface remaining exposed after machining. On the right of Figure 2 is a 3D scan of a part printed in 410SS highlighting an area where low spots in the as-printed surface finish led to an unmachined surface on the side of the part. Mating surfaces which are not able to fully machined may cause the part to be nonfunctional. Additional machining can be attempted to improve the surface, but only if tolerances allow for it.

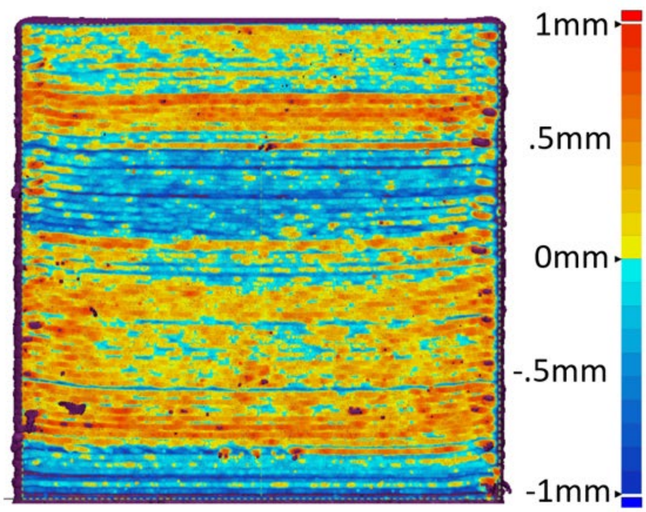

*Figure 2: Left: Heatmap deviation from average plan on a 410SS printed wall. Right: Insufficient surface material for machining process.*

### Build Plate Residual Stress

Another common issue when using WAAM processes is deformation in the build plate due to the relatively high heat input used. There are two main components to deformation of the build plate. The first is the heat input on the build plate itself. Deposition on the top surface of the build plate creates asymmetric stresses within the build plate as the top surface is melted and then cools. The melted baseplate material contracts and causes the edges of the build plate to warp upward. The second component is the impact of the material being deposited on the build plate to create the part. At MDF, mild steel is typical used for build plates. When printing on these build plate in materials other than a mild steel there will also be a difference in coefficient of thermal expansion. This difference in expansion as both materials are heated adds to the forces placed on the build plate and can increase the amount of warpage seen on the build plate after printing. Figure 3 shows a test case demonstrating the effect and scale of build plate warpage. In the figure, a 609.6mm x 101.6mm x 25.4mm build plate has had 3 layers of material deposited on it. The printed geometry was approximately 36mm x 550mm x 11mm. The deformation seen can cause issues when trying to produce accurate parts with features near the build plate. Build plate warpage is also an issue when attempting to machine the part afterwards. The build plate is often left attached to allow for fixturing during the machining process and to provide well defined corners to set a coordinate system in a CNC mill. If the build plate is warped, the plate may not function for these purposes and the bottom of the build plate may need to be machined to create a flat surface prior to machining of the part itself.

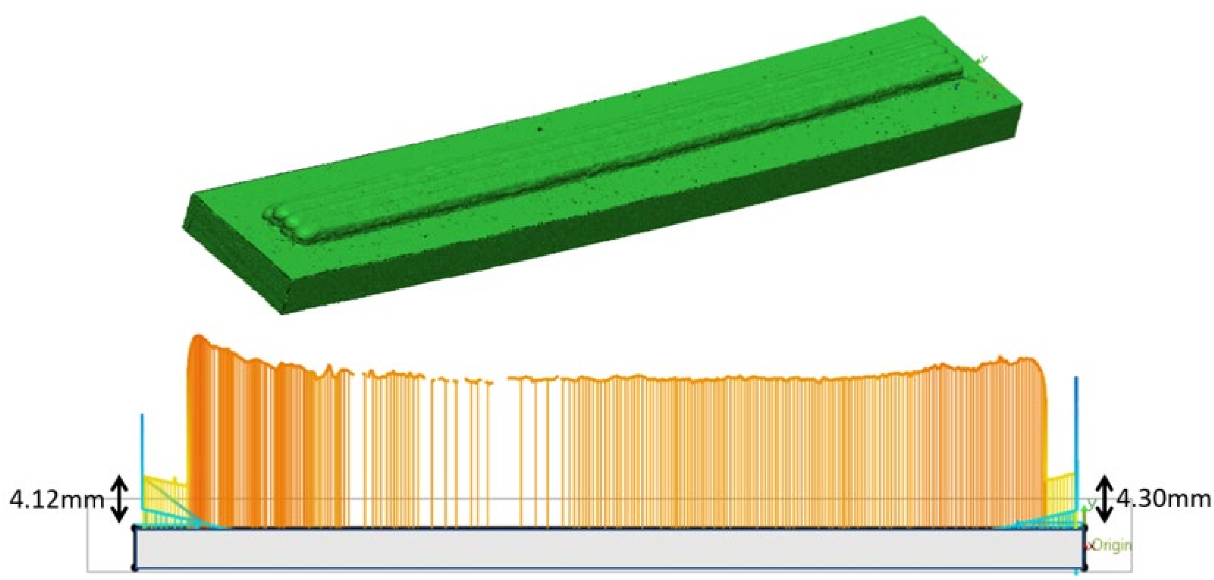


*Figure 3: 3D scan of build plate showing exaggerated view of deflection in build plate and deposited material.*

## Part Residual Stress

In addition to the potential for residual stresses causing deformation in the build plate, the same problem can occur in the printed part itself in some cases. When the printed part is asymmetric, there is the potential for imbalances in the stresses within the part as it cools. Deformation in the part itself is typically only seen in tall, thin features made of materials with high coefficients of thermal expansion. Figure 4 shows one example of this deformation in a curved wall section printed in 316L stainless steel. The curved shape of the wall allowed for asymmetry in residual stress, resulting in visible movement between each layer deposition and on the overall part.

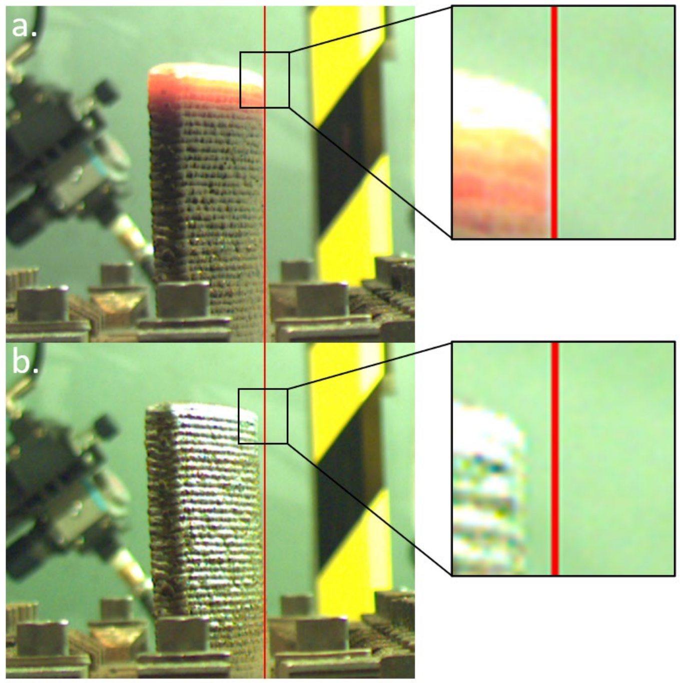


*Figure 4: Curved 316L wall showing (a) directly after deposition, and (b) 20 seconds after deposition.*

After each layer deposition the wall expands and contracts varying amounts based on the heating and cooling rates for that layer. The result is a printed wall that is warped from the desired final geometry. Figure 5 shows the results of a 3D scan of the wall as a heat map of geometric deviation in reference to the desired final geometry. This build was paused halfway through to allow the build to fully cool before continuing, resulting in a visible shift in layers due to residual stress.

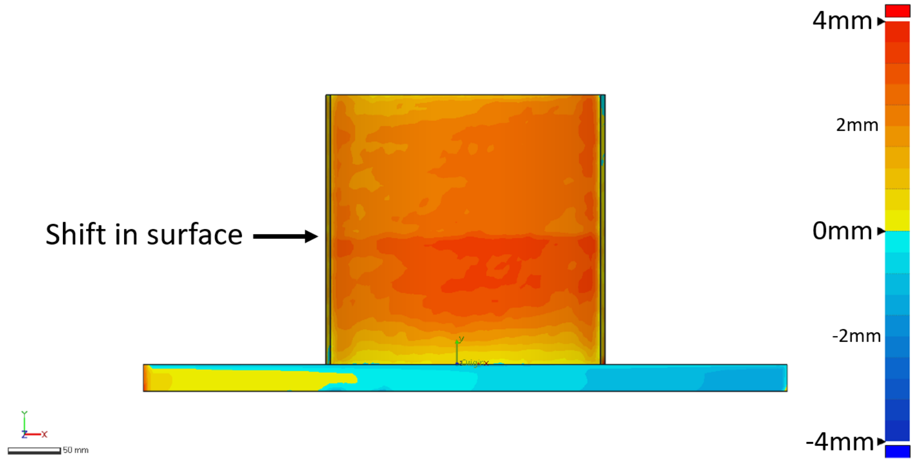


*Figure 5: Curved 316L wall showing visible shift due to part warpage halfway through the build.*

## Overhang Features

When producing more complex parts using wire-arc systems, the ability to accurately print parts with overhang features becomes more important. The level of overhang that can be produced varies between systems but is often around 20°. Since the material being deposited is in the liquid form, overhangs rely on the material solidifying before it can flow off the previous layer since at least some of the material will have no surface directly below it. However, as the overhang angle increases, the material being deposited will increasing flow over the edge of the overhang. Figure 6 shows an example of this where overhangs of increasing angle were printed with the same designed overall height, but can be seen to be produced with consistently shorter heights as angle increases. This change in bead height is due to more of the material rolling over the edge of the overhang causes overhung features to build shorter relative to other features in a part. When a part then needs to be machined after printing, this may result in the overhung feature being located lower than anticipated and there will be insufficient material to properly machine the surfaces.

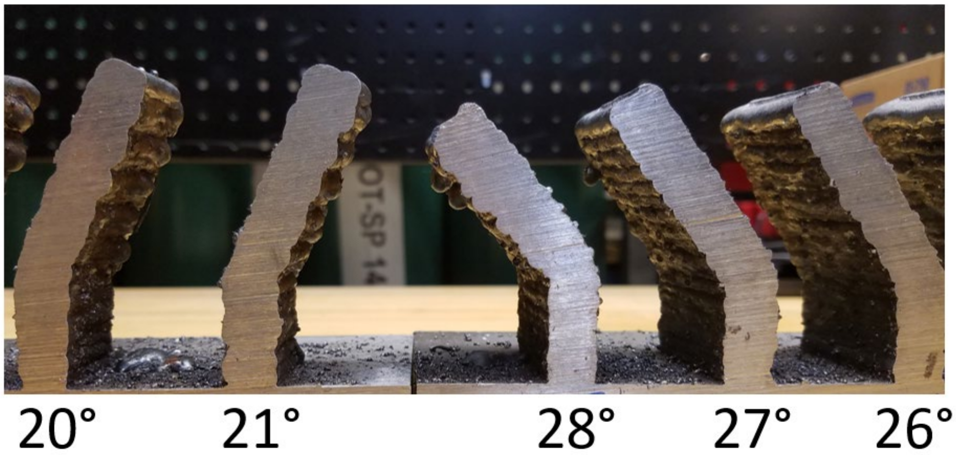


*Figure 6: Height comparison of 2 bead walls with varying overhang angles.*

## Underbuilding

The same mechanisms that cause overhanging features to build lower than expected can also impact builds without overhangs. When depositing material, each bead tends to overlap with adjacent bead due to the surface tension of the material and the bead spacing designed in the path plan. As a result of this, each bead takes on an asymmetric profile that slopes away from the bead that it is deposited adjacent to. The overall profile of the combined beads remains flat except for the outermost bead which does not have an adjacent bead on one side. This causes the outermost perimeter of the part to under build as consecutive layers continue to slope downward at the edges of a part. Figure 7 shows two examples of perimeter underbuilding.

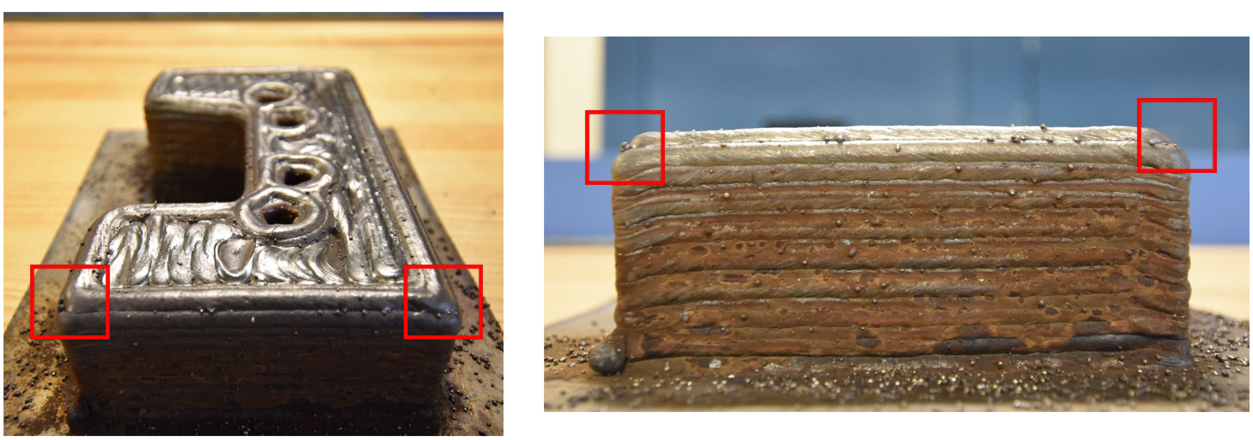

*Figure 7: Underbuilding occurring on the perimeter of parts.*

Underbuilding along the edges of parts can result in missing material on features and leave unmachined surfaces after post processing. This issue also has the potential to propagate as the outer bead underbuilds enough to not provide support for the beads further into the part.

### Incompatibility Between Bead Geometry and Part

When designing parts for wire-arc systems, the bead size can cause issues when trying to produce parts with small features on them. The bead size can also cause geometric inaccuracies on large parts if the toolpath for the part is created incorrectly. In order to produce a solid part, it is critical to ensure that each deposited bead is approximately spaced at even distances from neighboring beads. An example of these problems is shown in Figure 8. To achieve this, it is often necessary to design parts with dimensions in multiples of the correct bead spacing.

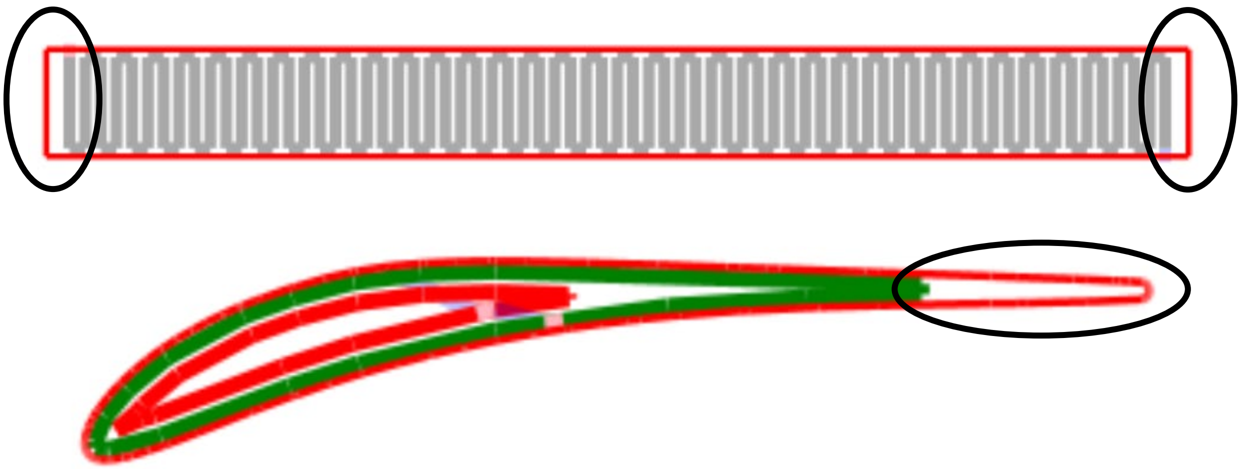

*Figure 8: Two example toolpaths that are improperly spaced for bead geometry.*

## Designing Parts for Post Processing

### Overbuilding

In order to ensure that the printed part contains the required material to fully machine or post process afterward, the most effective solution is to modify model of the desired final part to add excess material to compensate for the potential geometric issues that have been previously discussed. Figure 9 below shows a 3D scan of a printed part overlayed over the desired final model. The part was printed taller and thicker than the final part to compensate for any underbuilding effects and to ensure that the surface could be fully machined without leaving any as-printed surfaces behind.

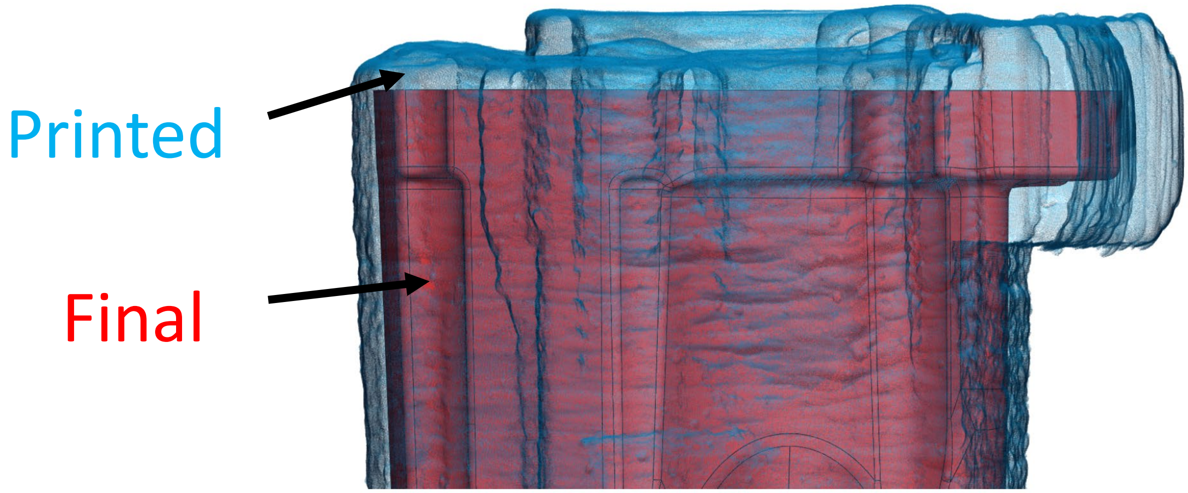


*Figure 9: 3D scan of a printed part overlayed over final machined CAD model.*

To avoid any potential build plate distortion effecting features on the printed part, additional material should be extruded down from the bottom surface of the part to raise the printed part around 0.25" to 0.5" off of the initial deposition surface. This also allows for easier sectioning of the part from the build plate.

**Match Features to Bead Width Integers**

In addition to overbuilding the part, taking into consideration the geometry of the bead will avoid leaving unexpected gaps in the part due to bead that are unable to fit into small geometries. Figure 10 below shows two examples of designing parts for wire arc additive. Figure 10a. shows an airfoil profile that has been modified to allow sufficient room for the bead geometry to fully fill in the part. The long, tapered end from Figure 8 has been expanded to allow for a perimeter and inset to be printed and the rounded front of the airfoil has been squared off to avoid any gaps inside the material. Figure 10b. shows the path for a rectangular section that has been designed before path planning to match the width of four beads to ensure that there is no mismatch between the model and path plan.

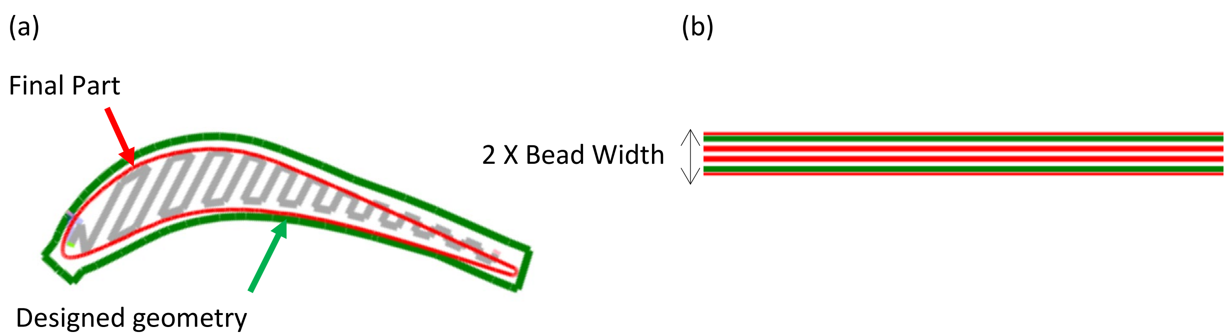


*Figure 10: Toolpath plans for geometries designed for wire arc additive.*

## Conclusion

In conclusion, the issues discussed in this paper can be summarized with three key characteristics of wire arc additive manufacturing. The first deformation of the part and build plate due to residual stress. Deformation of the build plate will occur almost always, while part deformation typical only occurs on specific materials. Second, due to the nature of wire arc additive, the deposited material is always temporarily in a liquid state and can be influenced by gravity. This can result in undesirable geometry as the material flows out. Finally, the rough surface finish that is produced due to the large bead size should be considered and sufficient overbuilding should be designed in to allow for the surface to be fully machined. Taking these characteristics into consideration will help towards designing parts that can be properly post processed and implemented into a system.

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