CAM for On-line Control for Wire Arc Additive Manufacturing

Simon Radel[1], Cyril Bordreuil[2], Fabien Soulie[3], Olivier Company[4]

[1]LMGC, Univ. Montpellier, CNRS, Montpellier, France, simon.radel@umontpellier.fr
[2]LMGC, Univ. Montpellier, CNRS, Montpellier, France, cyril.bordreuil@umontpellier.fr
[3]LMGC, Univ. Montpellier, CNRS, Montpellier, France, fabien.soulie@umontpellier.fr
[4]LIRMM, Univ. Montpellier, CNRS, Montpellier, France, company@lirmm.fr

Corresponding author: Simon Radel, simon.radel@umontpellier.fr

Abstract. Wire Arc Additive Manufacturing (WAAM) has the possibility to build metallic structures in 3D space. WAAM system is based on welding process to deposit metallic material and on a robot that moves the welding torch to add material at a given position. For large skeleton structures, it was chosen to deposit material point by point. Welding process induces fluctuations.To be fully scalable, two main features must be taken into account. First, monitoring of the process is necessary. Local control on the geometry of the deposition must be used to reach the final shape. Secondly, some deposition strategies must be implemented to manage branch intersections. To reach these two objectives, an adaptive and modular slicer and a process manager have been developed in order to implement this control. It allows us, if an error occurs during the deposition, to change the position of the effector. To obtain the desired geometry, the CAM software have to be able to, (i) do a slicing during the additive process of the part with a variable deposit height in order to take into account variation of the deposition process and (ii) manage the deposition strategy at intersection to output the position of the torch.

Keywords: Additive Manufacturing, Wire Arc Welding, Adaptive Slicer, Skeleton Freeform Shapes
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1 INTRODUCTION

Additive Manufacturing (AM) seems to be a promising process. It allows to create specific shapes with a large range of materials. The principle of additive manufacturing is based on addition of 2D layers of material piles one on top of the other [8]. These systems have numerous advantages compared to classical processes of manufacturing: a reduction of the quantity of material used [3] and no needs for dies or specific tooling. Adding material allows the manufacturing of more complex shapes than the ones obtained by direct machining. The main steps in AM process can be described as shown in figure 1.

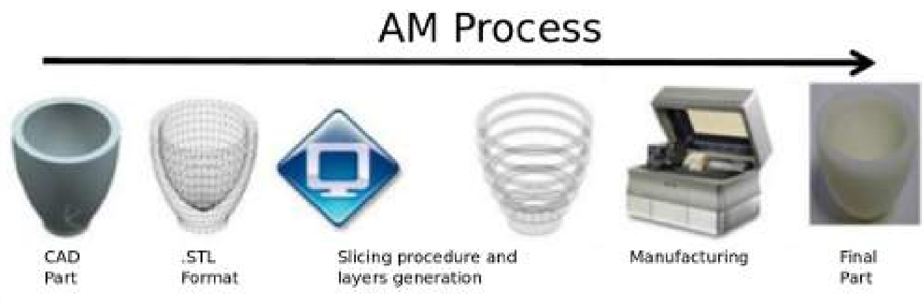

Figure 1: Computer Aided Design (CAD) ; Generation of a STL file ; Slicing of the file into layers ; Generation of the trajectories ; Manufacturing of the part [4].

For the manufacturing of metallic parts, the heat source is usually a laser or an electron beam and the raw material is in powder form. They allow the manufacturing of precise geometry but are expensive and complex to implement. That is why the use of a welding process is furthermore studied instead for its cheaper implementation costs and because there is no loss of material when using wire material. The use of this technology is known as Wire Arc Additive Manufacturing (WAAM).

Our system is based on a welding GMAW torch to deposit metallic material as a 3D printer would do. This welding process can be integrated to different manipulators such as 3 axes tables or modified machines [1]. The use of an six axis robotic arm for our system allows to operate in a wider area of deposition. In addition, it is possible to deposit material in other directions than only the vertical one without the use of a support material. The possibility to extrude material in 3D space and not only layer by layer can be used to build skeleton freeform shapes [9]. It allows a faster method for prototyping an overall part shape at real length scale and to verify the 3D design. It can also be used to manufacture lighter parts, with the adequate quantity of material to support the load lines. The use of arc welding for additive manufacturing present several advantages. The main one is the capacity of welding processes to deposit high ratio of material in kilograms by hour. Comparatively to other AM technologies such as Selective Laser Melting, the WAAM is more efficient. The deposition rates can vary between 1kg/hour to 10kg/hour [10]. Moreover, the mechanical properties of the parts manufactured with this technology appears satisfactory [7]. Another advantage is the ease to implement WAAM processes. In contrast with the vast majority of powder based systems, the use of a protective chamber is not necessary when using welding technologies. The use of a wire filler material need less safety protection than powder and is therefore cheaper. WAAM systems by exploiting a welding system, are also cheaper in term of integration costs.

However, welding is a complex process involving a lot of influencing parameters, that can induce a lot of uncertainties [2]. The energy supplied (voltage and current) directly impacts the final geometry of deposited material. The mass of deposited metal depends on the wire feed speed, but there are also other parameters that may change the desired shape. For example, the thermal transfert change during the building and the temperature increases with the successive layers deposited if the cooling is not long enough. Because of the process itself, it is very difficult to attain the precision possible in other AM technologies such as laser powder ones [11]. For Selective Laser Sintering (SLS) the layer thickness is around a tenth of a mm to a hundredth of mm, whereas for WAAM the accuracy is in the range of few millimetres. This lead to the problematic of staircase effect. For a WAAM process, the difficulty to deposit small layers tends to accent this problematic.

A difference in the height deposition from the planned one for a layer will conduct to a risk of getting the deposited metal to be in collision with the welding torch in cumulated layers. Any defect will spread over the part if it is not detected. To build freeform solid, the CAM software must manage the propagation of point along the different branches and intersection of the skeleton. The increment of propagation is determined thanks to the monitoring. The development of a slicer which can manage the change in position or the process parameters is the goal of this work. In skeleton freeform manufacturing, it is specially important when dealing with intersection area of multiple beams which can diverge or converge together that the shapes are in an accurate position. A bad positioning may lead to a deviation from the desired geometry.

This work will focus on skeleton freeform shapes. The most significant difference with surface building is that the welding torch will not move during the deposition, but will stay still to deposit only a point of material. One of the most important parameter for this way of building is the welding time. There is common problems such as overlapping of material [6, 5] that must be adapted for skeleton freeform shapes.

We will first present the preliminary preparation needed for a geometrical definition of the desired part and then we will explain the main challenges to overcome when dealing with skeleton freeform shapes. In a second section, we will discuss about the functioning of the slicer mainly on intersections management. Finally, we will present the test case used to test the proper functioning of the slicer, the experimental set up used to manufacture the test sample and the results obtained.

2 CAM FOR WAAM

Figure 2 presents the flow of information involved in WAAM process. CAD can be any type of geometry that can be converted to lines. It can even be a .STL that can be skeletonized. Our CAM software is therefore doing the link between a desired geometry and process parameters. The development of a tool which can deal with defects created during manufacturing requires possibility to set different parameters of the process in regard of the deposited geometry. More important, the ability to change the positioning of the torch requires the capacity of the slicer to modify parameters such as layer height on a branch to correct fluctuations.

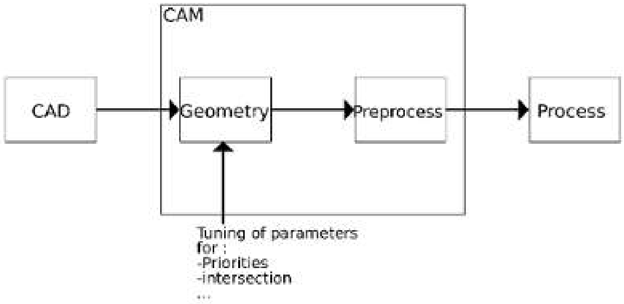

Figure 2: Numerical chain for WAAM

To manage on-line slicing, the geometry is first described then the main issues arising during freeform building are presented.

2.1 CAM Geometry Description

To split a CAD geometry in elementary shapes, it is converted in a list of points. A continuing set of points linked one by one is called a polyline. The geometry is then defined as a list of polylines. An exemple is

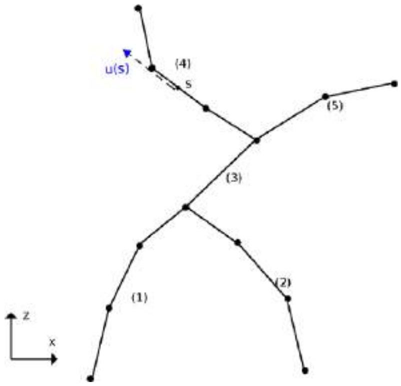

Figure 3: Example of a multi polylines shape in a XZ plan. For a point at a given curvi-linear abscissa s, the related normal vector is $u(s)$ (in dashed line arrow).

given in figure 3. Each polyline is located between intersection with other polylines. They are identified by a polyline Id. Other type of curve can be implemented. The only constraint is that the curve can give a spatial coordinate and an unit direction for a given curvilinear abscissa. This vector is represented by $\vec{u}(s)$ on figure 3. It will be usefull to control the position and orientation of the welding torch.

Points are basic entities (figure 4). The main property is to know if the point is shared by another polyline, in order to propagate the slicing between polylines. A degree describes the number of polylines adjacent to this point. When a point with a degree higher tant 2 is reached, adjacent lines are searched and points are propagated on them. Polylines are set under construction. Every polyline under construction has a built point and all built points are stored in a list. Polylines have an attibute to know its priority in the building. The priority allows to build some polylines before the others.

Finally, each polyline has a deposited radius property which represents the thickness of the skeleton freeform shapes.

To complete the CAM geometry, a starting plane and a building direction are defined.

2.2 Main Issues for Skeleton Freeform Shapes in WAAM

Three main problems can occur during the manufacturing of skeleton freeform : (i) collision or (ii) obstruction between already deposited materials and the torch and the overlapping points at branches intersections.

The first one is a potential collision between the welding torch and already deposited material as it is shown on figure 5. This can occur because of priority selection for the manufacturing of polyline and at certain intersections where the angle of the two branches is high.

The obstruction problem can appear due to building priorities on branches (figure 6). To solve this problem, the possibility to orientate the welding torch can help to overcome these difficulties with an adequate strategy of motion (figure 6 last configuration).

Last, at intersection zones metal deposition can be done several times. The already deposited material has to be taken into account to avoid an over-deposition of material by welding two points close enough to overlap one with the other. If it happens, too much material is deposited, and the whole geometry manufactured after the intersection may be offset (figure 7).

These different problems that can appear during manufacturing will be solved in the CAM.

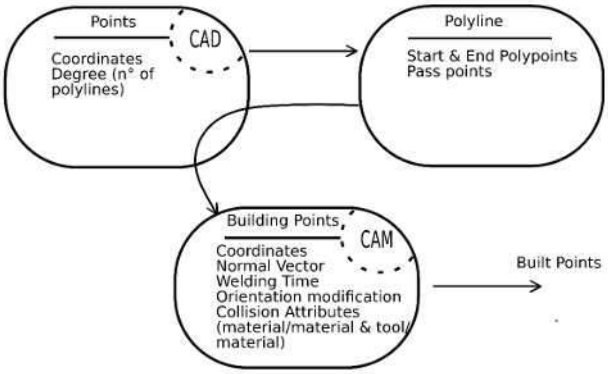

Figure 4: Connection between points and polylines for the manufacturing of skeleton freeform shapes.

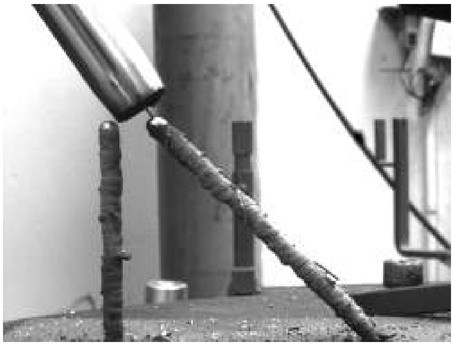

Figure 5: Risk of collision during an experiment.

3 ADAPTIVE SLICER AND INTERSECTION MANAGEMENT

In classical slicing procedure, the slicer does the whole slicing on the base of the wanted geometry during the pre-processing. Trajectories are then stored and re-used without any modification. For welding point additive manufacturing the slice must be able to adapt the step of each layer because the height of the deposit can vary due to process problem or because of thermal modification during the process. At intersections, the deposition should also be tuned to fit the different constraints that can occur due to geometrical description. Deposition strategies must be implemented. This will be done by modifying tool position or even some process parameters during the manufacturing. With this possibility we can implement different manufacturing strategies for critical areas and use an on-line control with the feedback from a camera for example.

In this section, the treatement of how implemented algorithm propagates point in a regular operating mode is presented and the management of intersections is then explained.

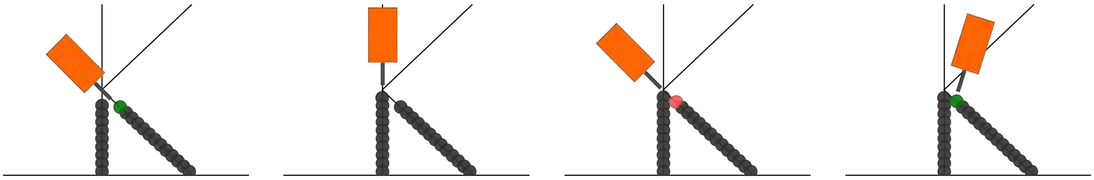

Figure 6: Different positions for the deposition of liquid metal during intersection manufacturing. The third configuration from the left corresponds to an impossible deposition configuration (for the red dot).

Figure 7: Example of a difference between the desired geometry (in full black lines) and the deposited geometry after the intersection (white dotted line is the neutral axis of deposition).

3.1 Adaptive Slicer Principle

To be adaptive, propagation must be done by a affinement of the different points during the manufacturing. To slice the skeleton, the CAM software must have a starting plane and a building direction. First points are detected and are stored in a points to build list. A lowest point is chosen and then is built. This point is popped from the list. This point is also propagated, by adding the step increment value, to new points to build that are pushed back into the list. When the new point reaches an ended point, it is pushed to adjacent polylines if they exist. With this way of slicing, the increment height between each point can be changed before the propagation. It allows a refinement of the process in critical areas, and to increase the increment in less functional sections to reduce the manufacturing time needed (figure 8).

The priority attribute forces the decision of the CAM software about which poly-point will be chosen first in the list of points to build. The polypoints associated with higher priority polylines should be built and propagated until the difference between the height of the coordinates in the building direction of these points meets the distance requirement between lower priority polylines. As explained previously, the values of distance between n levels of priority are choosen before the manufacturing.

At a given moment of the manufacturing, it is possible to know which points are built (they are stored and saved in a list after they are built) and which must be built (i.e. next points to build for each polyline under construction). With this information it is possible during the propagation of a new point to compute the possible collision between already deposited material and the needed position and orientation of the welding torch. If a collision with the welding torch may occur, a correction can be set to change the position of this last one.

Finally a deposited radius is set for every branch to allow to compute a ratio of volume to deposit if a propagating point is sharing its volume with already deposited material. Each deposited point will be modelised

Figure 8: Left: Virtual model with small increment; Middle: Virtual model with high increment; Right: Virtual model with variable increment.

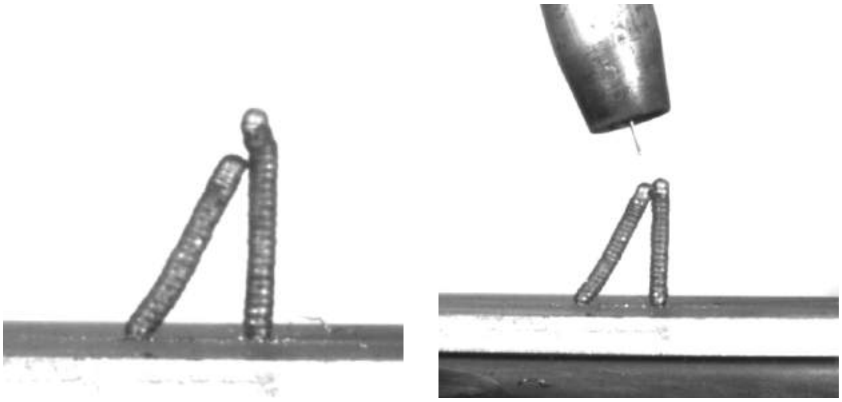

Figure 9: Left: Example of an aggregation of deposition on the right skeleton freeform shape; Right: Example of reorientation of the welding torch to avoid the obstruction problem.

as a spherical cap with a given radius.

In the next subsection, we will discuss about the strategies implemented for intersections, especially the ones dealing with this overlapping problem.

3.2 Intersections Management

For the intersection areas, the three main problems mentioned previously (collision, orientation and overlapping) must be solved. The collision (figure 5) is out of the scope of this paper.

Figure 10 presents the case of a divergent intersection. It is an intersection between three polylines identified by $L1$, $L2$ and $L3$ at a point marked P1. The strategy is to build first $L1$ and $L2$ wich have high priority and then to build $L3$ in this intersection area. Because some material is already deposited in this area, the quantity of material to deposit have to be decreased for the building of $L3$.

A module was developed to calculate this volume of intersection, and the slicer computes a new welding time in order to deposit less of material, taking then into account the metal already in place. The quantity of material

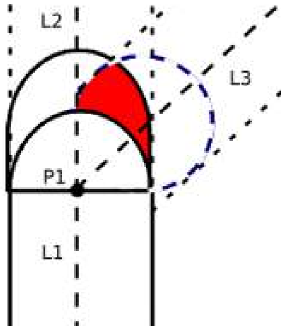

Figure 10: Scheme for a divergent intersection area.

supplied to the system can be approximated by $V_w \frac{\pi d_w^2}{4} W_{FR} T_w$ where V_w is the volume deposited (supposed to be a spherical cap metal deposition), d_w is the diameter of the wire, W_{FR} is the wire feed rate and T_w is the welding time. This approximation is true under the hypothesis that there is no loss of material by projection and the wire feed rate value is accurate. It is therefore possible to tune the welding time T_w with a ratio of correction. The calculation of the ratio is done with the formula : $NewT_w = AverageT_w * (1 - overlapping_{\%})$ with : $AverageT_w$ the average value for welding time used in non-critical areas and $overlapping_{\%}$ the percentage of overlapping volume for the next deposition. The management of the ratio given a geometrical overlapping is then linear between 0 (no material deposited) and 1 (full sphere of material deposited).

During the manufacturing with priorities management, if the next point to build is occulted, the normal vector of the torch is reoriented and if an overlapping is detected a ratio is also used. On the base of this information, the torch is moved and the next point is manufactured (figure 9). From this new deposition, the whole procedure is repeated with the possibility of changing the layer height for the next point.

A better approximation of the desired geometry can therefore be reached. For intersection area, the adaptive slicer follows the algorithm presented on figure 11. The CAM software retrieves the next point to

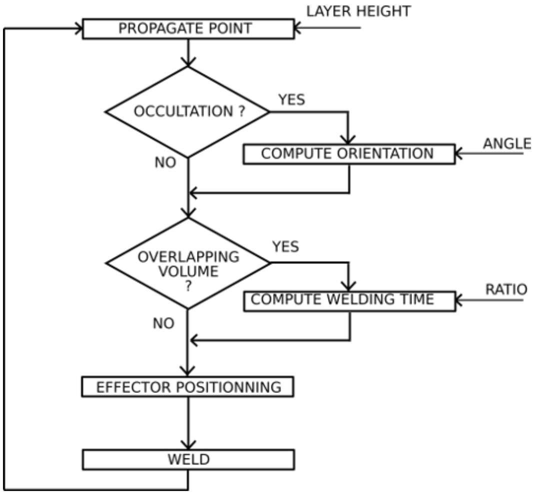

Figure 11: Functioning of our CAM software for intersection areas.

build by computing the layer height on the geometry of the part with the knowledge of the previous deposited point.

4 TEST CASES FOR THE ADAPTIVE SLICER

4.1 Experimental Set-up

The WAAM system is based on the use of a robotic 6-axis HP6 Motoman arm to ensure the motion of a welding torch. The controller for the robotic arm is a NX100. The tool-setting dimensions of the robotic arm need to be initialized manually.

The metal deposition is provided by a controlled short-circuit Gas Metal Arc Welding (Fronius CMT). The feeding material is a G3Si 1mm diameter wire. This material is frequently encountered in welding applications. The shielding gas is a binary mixture : 92%Argon and 8%CO_2. For the welding power supply, we used a synergic curve already implemented in the welding power source. We chose the G3Si1 linked curve, which imposes, for a feeding rate, the current and voltage delivered by the system. We had to determine the range for those parameters in order to build our parts. The average value for welding parameters such as wire feeding rate or energy input were chosen to insure a good deposition in non-critical areas.

The data of movement for the effector are sent in the form of 3 space coordinates in the cartesian frame for the positioning and 3 angular coordinates for the orientation of the welding torch. The communication between the supervisor computer and the NX100 controller is performed trough a serial communication port.

In a same way, a communication was established with the welding generator, with the use of an Arduino cardboard, in order to directly control the welding generator.

The whole process is monitored by a supervisor computer.

4.2 Experimental tests

When applying the slicer procedure to manufactured example cases, the developed code can give first a virtual simulation of the WAAM process in order to verify and ensure the correction of all intersection zones and trajectories. It includes the orientation of the welding torch for the intersection zones, allowing the change of angle on close points as shown in figure 9. In order to test the quality of the slicer procedure, different parts were built with an increasing complexity. Geometries were chosen to avoid any collision. The first tests concern divergent intersections. The divergent tests were conducted with the priority attribute affected to the center vertical polyline (figure 12). It results in a good positionning of the two other skeleton freeform branches in this divergent intersection. Another series of tests concern K shape in order to test convergent intersection but also the manufacturing of a convergence and a divergence intersection in a same area (figure 13).

Figure 12: A divergent intersection test with use of priority.

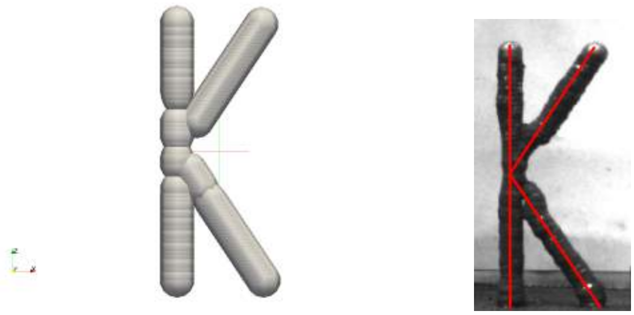

Figure 13: Left: Targeted virtual K shape with ratio management ; Right: K shape freeform manufactured sample. In red full line is represented the virtual CAD definition.

The deposition of more than a hundred points of liquid metal is necessary to manufacture the K shape sample. The whole structure height is 120mm. There is quite good adequation between the desired CAD geometry and the manufactured sample. The discrepancies in elevation positions is limited to 1mm in excess and the angular difference in the orientation of K branches is lower than 3 degrees. These differences can be explained by gravity effects and the inherent variations of welding process.

A last test was realised on a larger 3D part including different convergent and divergent intersections as shown in figure 14.

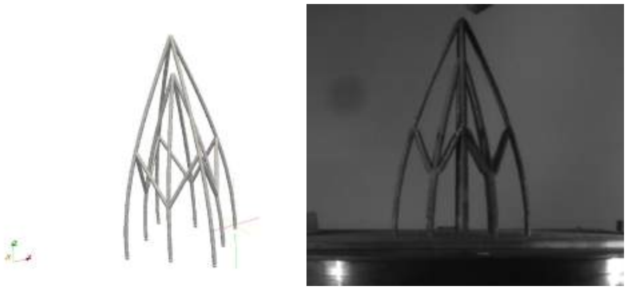

Figure 14: Left: Targeted virtual structure including convergent and divergent intersections ; Right: 3D manufactured structure sample.

The height of this structure is about 300mm for a base diameter on the substrate of 180mm. This type of structure allows to test the performance of the slicer procedure, including the orientation of the welding torch. The influence of this strategy can be seen in figure 15. The first picture is without any orientation correction, and we can notice a lack of material between the two polylines. The second picture corresponds to a situation for which the strategy of orientation was realised. We can observe that the gap previously observed is filled with metal and the connection between the two polylines is correct.

5 CONCLUSIONS

The CAM software presented in this paper is therefore adaptive and modular. The CAM software is able to correct usual errors that can occur when manufacturing skeleton freeform shapes. It was developed for some

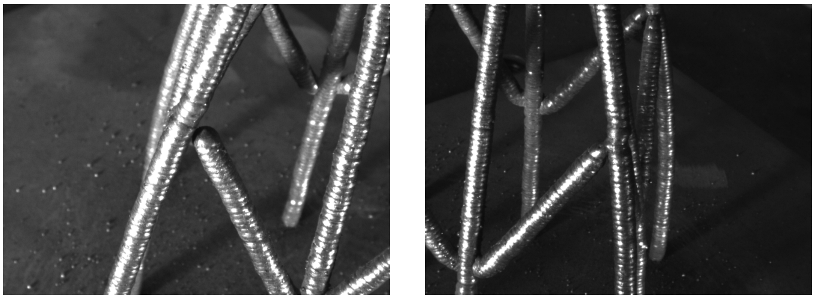

Figure 15: Left: Intersection with a bad deposition (lack of material); Right: Intersection with a better filling.

critical areas such as intersections but also for other problems such as the cooling time for a deposition, a better starting of the manufacturing on a metal plate, the positioning of the welding torch to avoid collisions or a change in the influential parameters of welding. With these different strategies and possibilities of modifying the manufacturing parameters, better overall shapes were obtained, with error degrees that seem acceptable for a welding process. The detection of problems emerging during manufacturing is an interesting field of investigation for future work. It could be used to implement an on-line control of the whole process with a closed loop. The slicer was developed in order to take into account corrections for the position or orientation of the effector, and to manage the process parameters during the manufacturing for critical areas. The closed loop will permit to detect the creation of defects and to correct them with the strategies implemented in this CAM software.

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