Journal of Machine Engineering, Vol. 17, No. 3, 2017

Received: *24 January 2017* / Accepted*: 05 June 2017* / Published online: *28 September 2017*

additive manufacturing,
5 axis manufacturing, WAAM

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INTERESTS OF 5 AXIS TOOLPATHS GENERATION FOR WIRE ARC ADDITIVE MANUFACTURING OF ALUMINUM ALLOYS

Additive Manufacturing (AM) for metal part can be divided into two different types: The powder technology and the wire technology. Usually, powder is adapted for fine components and small parts whereas wire is used for structural components and large scale part. One of the main benefits of AM is to simplify assemblies by reducing the number of components and to provide a large freedom of design. A standard AM system consists of a combination of three blocks: a motion system, a heat source and a feedstock. For Wire Arc Additive Manufacturing (WAAM), the heat source is a welding generator and the feedstock is a wire. The motion system generally used is a 6 axis robot or a CNC machine. This paper aims to propose a methodology to generate 5 axis toolpaths for WAAM and highlight the main parameters which selection is a key issue to resolve. The goal is to compare 3 axis and 5 axis toolpaths on part accuracy, depending the clearance angle of the part.

1. INTRODUCTION

Additive processes are new opportunities to manufacture directly metallic parts with high technicality. Technologies like Laser Engineering Net Shaping (LENS), Direct Metal Deposition (DMD), Electron Beam Melting (EBM) or Wire Arc Additive Manufacturing (WAAM) can manufacture parts with good mechanical skills. However, Additive processes are currently under improvement. The real benefit of additive manufacturing (AM) is the reduction of material wastage and time to market. The freedom of design is also interesting to simplify assemblies (by reducing the number of components). Hybrid manufacturing [1,2] and functionally graded materials [3,4] are also innovative processes to build part.

For WAAM, the heat source is a welding generator and the feedstock is a wire. This technology is suitable for manufacturing large scale component. WAAM aluminum alloy is currently limited by solidified defects such as porosity and solidification cracks. Porosity is the major problem of aluminum alloys [5].

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The most benefit of WAAM is for manufacturing large scale components quickly. Several improvements can be highlighted. The first section shows several simple solutions to improve manufacturing and to show WAAM possibilities. In the second part, a methodology is exposed to manufactured WAAM part, from CAD to real part for 5 axis path. The third part aims to compare the effect of 3 axis and 5 axis toolpaths on part accuracy.

2. STATE OF ART

2.1. TYPICAL WAAM SYSTEM

Several researchers have investigated wire arc additive manufacturing [6]. The motion system is often a robotic arm (5-6 axis) which flexibility is adapted to the process requirements and offers great possibilities as flexible tool orientation and large workspace. Indeed, the orientation of the torch regarding the substrate must be the same during manufacturing to guarantee constant conditions overall of the part. Three different welding systems are used for WAAM:

- GMAW: Gas Metal Arc Welding,
- GTAW: Gas Tungsten Arc Welding,
- PAW: Plasma Arc Welding.

A multi-process manufacturing platform including WAAM (Wire Arc Additive Manufacturing), HSM (High Speed Machining), and LMD (Laser Metal Deposition) processes implemented in the laboratory is shown on Fig. 1. This equipment is adapted for hybrid manufacturing (additive and subtractive).

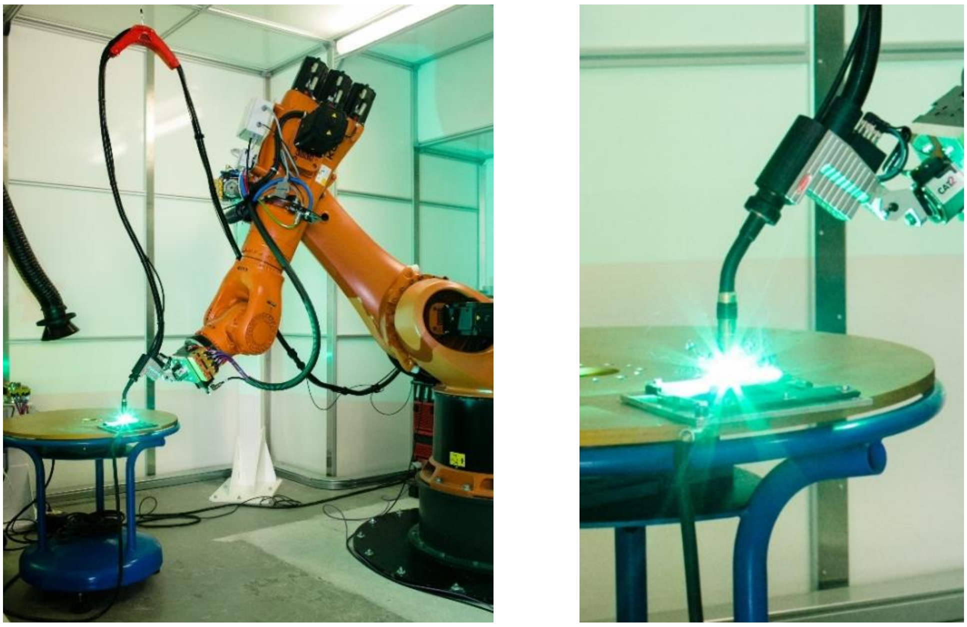


Fig. 1. WAAM system and GMAW torch

2.2. SYSTEMS IMPROVING BEAD QUALITY

Several systems or technologies can be added to WAAM process to improve bead quality, the manufacturing conditions, the microstructure of the bead… For example, technologies developed for welding as Cold Metal Transfer, which is improved GMAW welding, can improve deposit by reducing the heat impact. This process aims to reduce the heat brought to the deposit. The basic CMT consists on of moving forward and backward the wire during welding (Fig. 2).

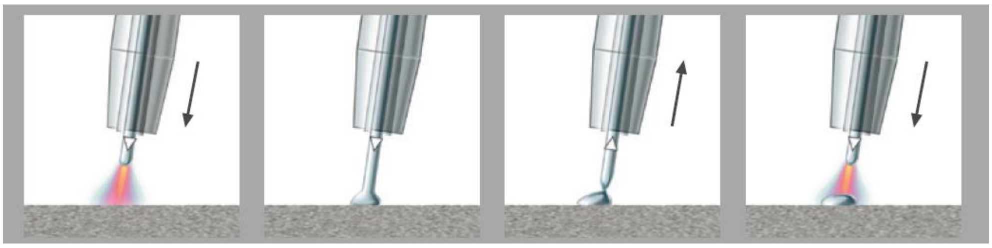


Fig. 2. CMT process stages [7]

Several improvements were developed based on CMT process:

- CMT Pulse: This process combines a pulsed cycle with a CMT cycle and so inputs more heat. The pulses are controlled and adjustable way results in a huge breadth of performance and flexibility.
- CMT Advanced: This process is cooler than CMT. In fact, the polarity of the welding current is made an integral part of the process-control. The polarity reversal takes place in the short-circuit phase, thereby ensuring the proven stability of the CMT process. The thermal input is tightly controlled, extremely high gap bridge-ability and an up to 60% bigger deposition rate.
- CMT Advanced Pulse: By combining negatively poled CMT cycles and positively poled pulsing cycles, this process achieves absolute precision and the very greatest mastery of the arc.

To improve microstructure, a rolling system can be implemented to generate stress on the deposit after welding. Different rolling loads can be applied up to 80kN for example. The load can also be controlled. A solution is to combine rolling and manufacturing on the same machine. Microstructure is really improved by this operation. In fact, the microstructure is refined and reduce residual stress[8]. However, this solution is limited to simple parts because the roller is generally profiled and not adapted for large sections, others solution could be used in this case.

Protection can also be improved with local shielding gas. This solution consists on injecting a laminar flow of shielding gas after the welding. The deposit is protected during cooling period and the oxidation effect is reduced. The gas flow rate is generally set to 10 l/min. The laminar shielding device significantly improved the protection compared to conventional protection by reducing the oxygen contamination levels[6]. Once again, this system is interesting to improve microstructure but it is limited to simple paths.

The shielding, to be efficient, must follow the path. For filling or high curvature paths, this equipment will not protect the bead as single wall bead.

2.3. PATH STRATEGY

To manufacture a single wall, path is quite easy to generate but for massive component, path strategies must be adapted for filling without lack of material which will reduce the part strength. As shown on Fig. 3, several strategies can improve the part filling [9].

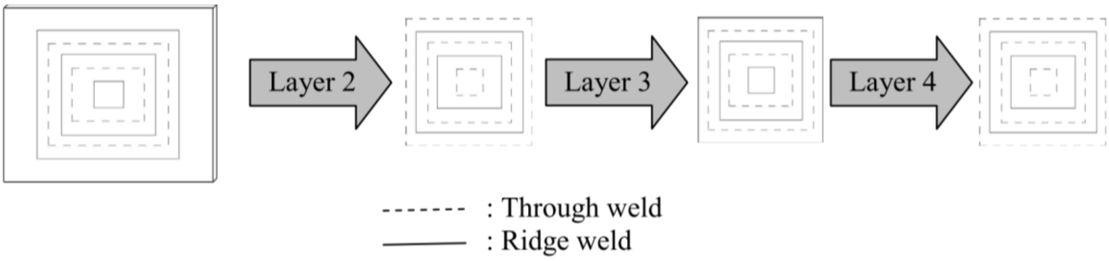


Fig. 3. Ridge and through welds inversion

Moreover, for filling paths, a new parameter is necessary for generation, called Center distance which refers to the distance between two beads. To set this parameter, several models have been developed in the literature, the optimal distance calculated between two beads is about 0.738w [10] (w is the bead width).

Depending on the shape of the part, it is sometimes necessary to add material to do a homogeneous filling. The second goal of path strategy optimization is also to smooth the path and reduce the number of start/stop of welding. Several approaches have been developed to generate path adapted to WAAM [11].

2.4. SYNTHESIS

Recent development on WAAM can be divided in two different ways of group of improvement currently investigated. The first one aims to improve microstructure and bead quality to ensure good mechanical skills by highlighting the influence of parameters and systems added on WAAM process. However, by adding these systems, the freedom of fabrication is reduced and samples are often single bead walls. The second one deals with path strategy. The goal is to include process requirement in the path generation or select the best path strategy to ensure filling.

Test parts exposed are often limited to 2.5D paths. That is why, it may be valuable to explore more complex part and including 5 axis toolpaths. Hence, it is necessary to show that 5 axis is possible and to quantify the benefit of 5 axis on part shape. A methodology is also proposed to control manufacturing with 5 axis path.

3. PROPOSED METHODOLOGY TO MANUFACTURE WAAM PARTS

The proposed approach is based on experimental tests to set process parameters. The pack of parameters is necessary to generate paths.

3.1. PROCESS PARAMETERS

This section shows the different stages and parameters used to realize aluminum alloy parts with WAAM. Several experiments were performed to set the value of the parameters. In fact, as shown on Fig. 4, AM parameters belong to three categories: Deposition rate, heat source power, and path parameters. A successful manufacturing strategy results from a proper combination of these three categories.

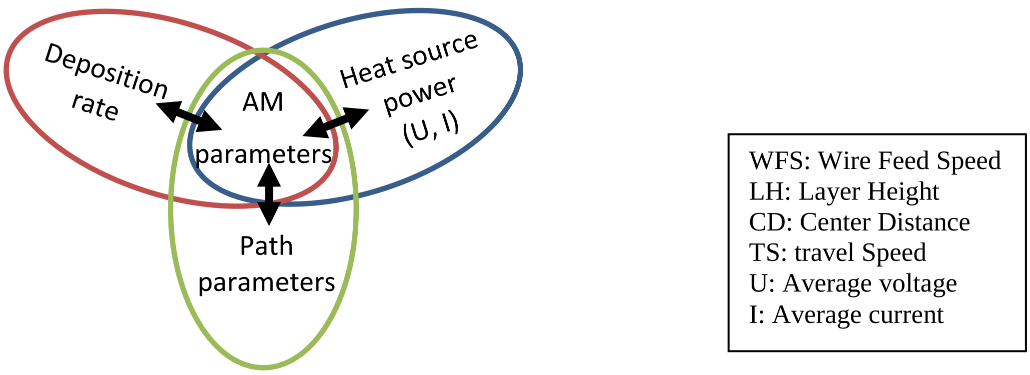


Fig. 4. WAAM parameters

With recent welding generators, parameters have been optimized: Deposition rate and heat source power are already linked. Path parameters are set with experiments on single layer bead and single bead wall. When a pack of parameters is available path generation is possible. The Center distance has not been really explored for the moment, because path parameter is linked with LH. In fact, for filling, LH will increase because the CD is lower than the bead width.

3.2. PATH GENERATION

The part, modeled with a CAD software suite, is sliced by planar sections to obtain 2D or 3D curves. The distance between sections is set by the layer height (LH) to keep the stick out distance (distance between the contact tube and the deposit area) constant. This parameter is essential. If the layer height programmed is too high, the stick out distance increases and gas protection is inefficient and the arc becomes instable. If the layer height programed is too small, the welding torch gets closer to the wall, and the gas pressure is higher on the bead (gas inclusion generates porosity). In these two cases, the manufacturing quality is bad because the deposit conditions (stick out distance) are not the same the whole of the part. It is often necessary to stop the deposition (Too high: gas protection inefficient, too small: Risk out of crash). That is why it is important to use accurately set parameters for generating the paths. The path is post processed with a specific algorithm developed in the laboratory for three or five axis manufacturing. To validate the paths, the robot movements are simulated to generate a tool path trajectory, including tool axis angle. Fig. 5 summarizes these stages. This initial toolpaths generation (which refers to the third stage of Fig. 5) can be modeled as a combination of different blocks (Fig. 6).

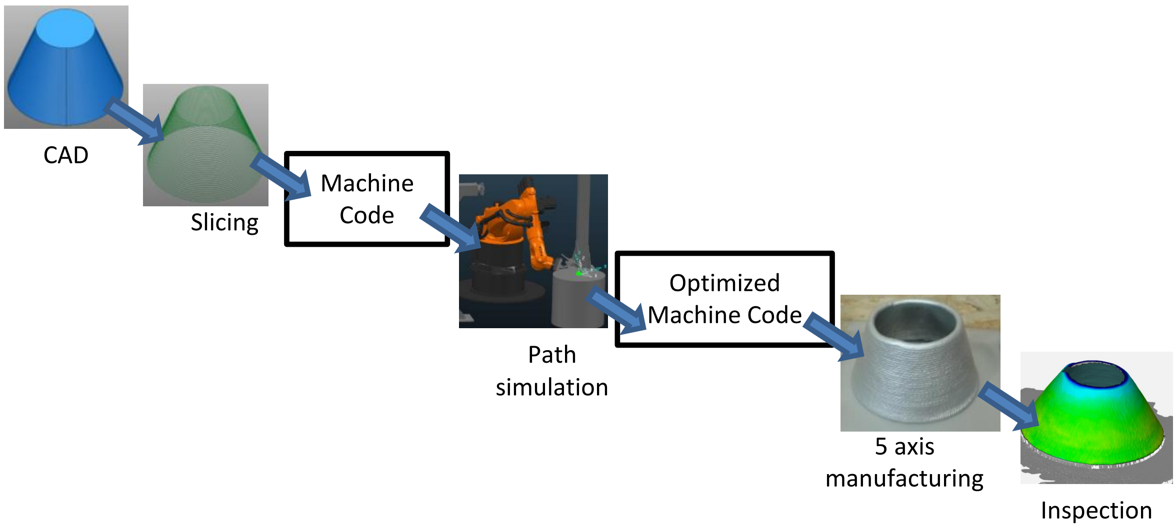


Fig. 5. From CAD file to real part

For each part, the input is always the CAD model which contains the nominal geometry. The output is the machine code generated which includes the motion system settings and the process parameters.

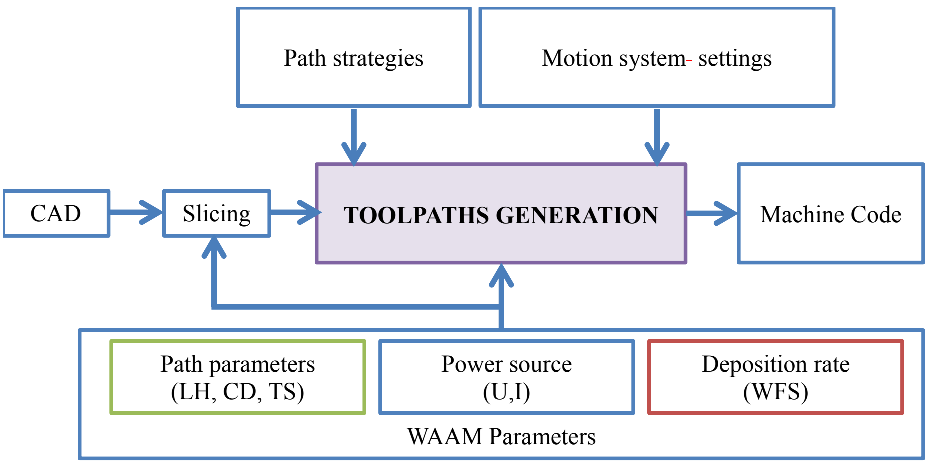


Fig. 6. Toolpaths generation

As shown on Fig. 6, it is needed to validate a pack of WAAM parameters. This adjustment can be performed with some experiments before the toolpaths generation. Other inputs as path strategies and motion system settings are also necessary to generate a complete Machine Code.

This toolpaths generation can also be divided in different stages (Fig. 8) which refer to the input needed to generate paths. Before toolpath generation, the 1st stage is always the slicing. The second one refers to the part geometry (Fig. 7). Depending on the angle and the shape of the part, 5 axis toolpaths are chosen. With 5 axis toolpath generation the main issue is how generate the tool angle to ensure a good deposit and part accuracy.

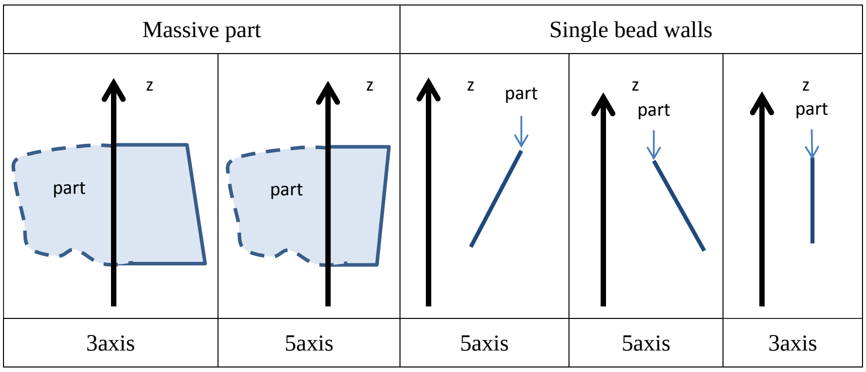


Fig. 7. 5/3 axis toolpath depending on the part geometry

This toolpaths generation can also be divided in different stages (Fig. 8) which refer to the input needed to generate paths. Before toolpath generation, the 1st stage is always the slicing. The second one refers to the part geometry (Fig. 7). Depending on the angle and the shape of the part, 5 axis toolpaths are chosen. With 5 axis toolpath generation the main issue is how generate the tool angle to ensure a good deposit and part accuracy.

The next stage consists in the filling path generation (if necessary) for massive part or local requirement of material. Many parameters (Angles between layers, start and stop position…) and path strategies (ZigZag, multibead…) can be generated to ensure a good filling and the quality of the shape.

The full generation of the Machine Code consists in compiling the toolpaths (3/5 axis and filling strategies) with the motion system settings, and the process parameters (TS, WFS, U, I).

To set WAAM parameters, some experiments were performed. The first one consists in manufacture single layer bead for different wire feed speed and travel to validate the bead geometry. The travel must not be too high to avoid humping (periodic undulation of the weld bead profile) which generate arc instability for manufacturing (stick out distance inconstancy). The bead shape, for AM, must a constant width, not with deep penetration (The goal is to manufacture). The second experiment aims to choose the layer height, by manufacturing few layers of a single bead wall and then, measuring the wall height. The real Layer Height can be calculated directly. Another measurement can also validate the LH which the wall with (W). In fact, this distance (Fig. 9) is linked with parameters TS, WFS, LH and the wire diameter ($\emptyset_{wire}$) by the expression (1):

$$LH = \frac{\pi \cdot \emptyset_{wire}{}^{2} \cdot WFS}{4 \cdot W \cdot TS} \tag{1}$$

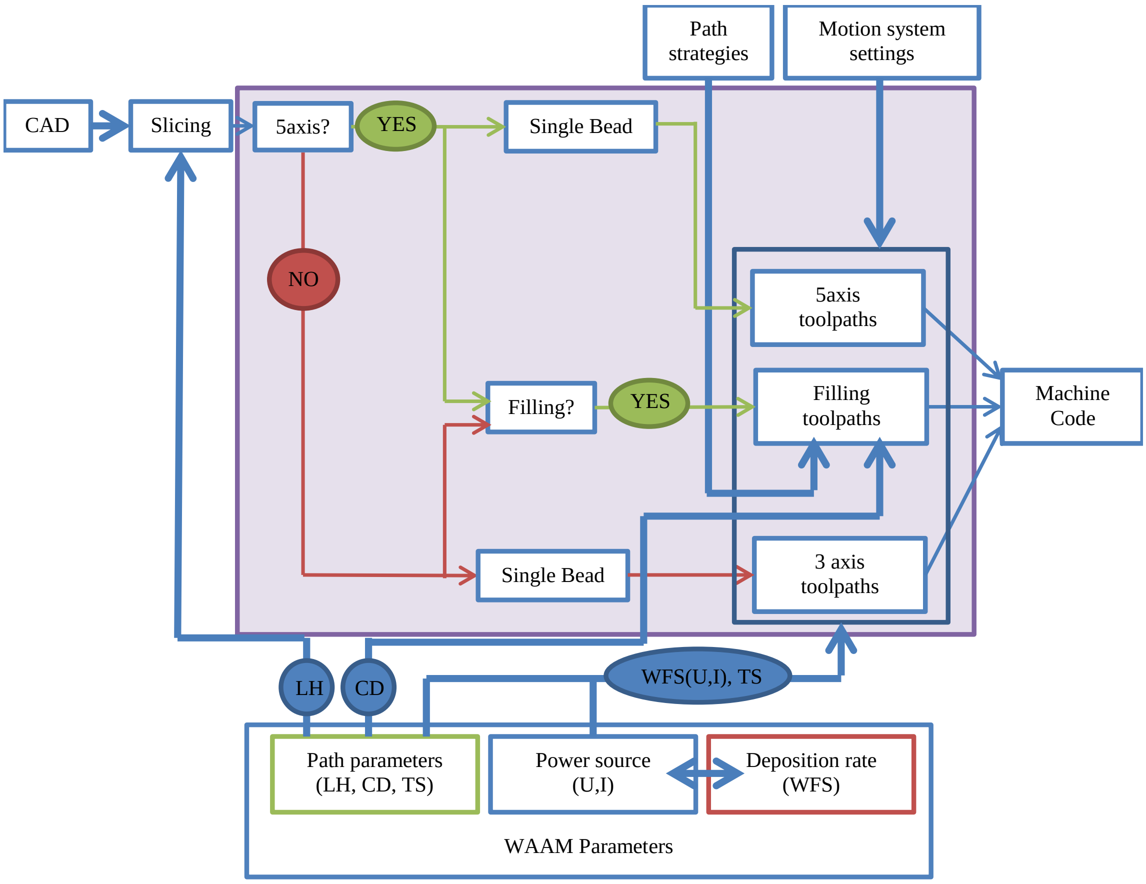


Fig. 8. Toolpaths generation details

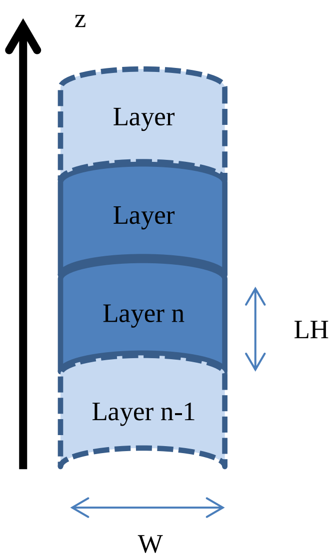


Fig. 9. Single bead wall parameters

This expression is validated for the programmed Layer Height for a cone manufactured with WAAM (single bead wall). This method can be envisaged for several packs of parameters to enlarge WAAM capability to manufactured variable walls thickness or only by adjusting settings (TS and WFS).

3.3. WELDING GENERATOR AND MOTION SYSTEM

The welding generator is a FRONIUS. The stick out distance was always kept constant throughout the study. The shielding gas is pure Argon (99.998%) for all welding tests. The welding wire was 5356A (1.2 mm diameter).For most of the parts shown in this paper, the Wire Feed Speed (WFS) was set to 7 m/min for CMT Advanced mode because the bead geometry combined with the travel speed was adapted for manufacturing. For CMT pulsed mode, the WFS was set to 6 m/min, to improve penetration but with high heat impact.

The motion system was a KUKA Kr 500 robot. The torch was always perpendicular to the substrate for 3 axis manufacturing but for 5 axis, the tool orientation was set by the part curvature (depend on the path generation).

4. SYNTHESIS

AM can be divided in three different shapes of manufacturing; Walls, wide walls and massive parts. For single walls, after adjusting the Wire Feed Speed and the travel speed to ensure good bead geometry for manufacturing, it is necessary to set the layer height to keep a constant stick out distance. The conditions are nearly the same all along the part, except the first layers. WAAM gives good results if settings are adapted.

For a wide wall, whose thickness is between 6 and 25 mm (4 single beads), the manufacturing become quite complex. In fact, multiplying bead alongside on each layer in the same direction amounts to build separate wall along side. This phenomenon depends on the part size. For small parts (around 100-150mm long), the link between the walls is good and the part homogenous but for long and wide wall, the inter-pass temperature is too high, between two passes, and the melted area is not enough wide to link wall together. Several solutions can be envisaged to solve this problem as path strategy or welding parameters. Preliminary trials show that a of zig zag strategy with ensures a good filling, but, the heat impact can be significant.

For massive parts, filling strategies as zig zag path or sweeping provide good results. Crossing the path between layers is an efficient strategy to ensure a homogeneous filling, without lack of material.

The last case is for parts which combines two or three different shapes, several problems appear. In fact, for single, wide walls and massive part, the layer height is different (up to 25% if the travel speed and the wire feed speed are kept constant. that is why, constant slicing seems to be not adapted. Thermal effect will also be very different depending on the area of the part. In fact, the filling operation brings a lot of heat to the material whereas with single beads heat impact is reduced.

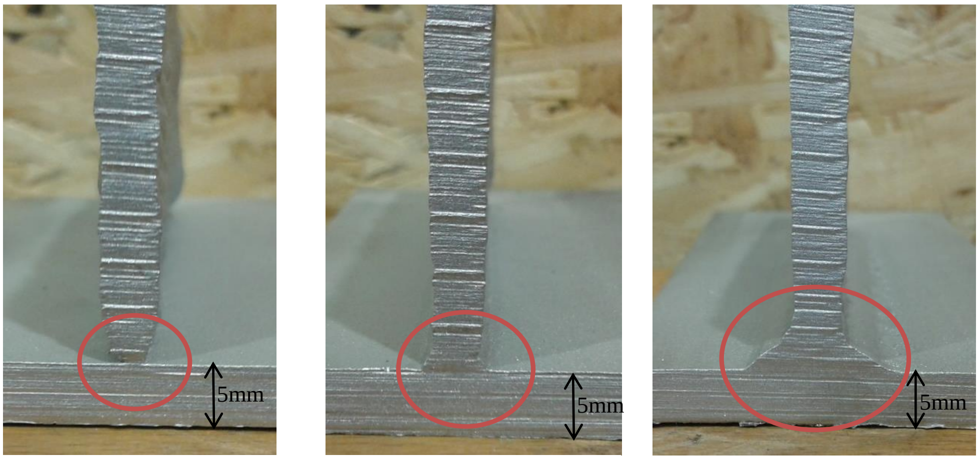
As a result, even if WAAM is adapted to several types of part, simple geometry with different types of shapes can be very difficult to manufacture with constant process parameters.

5. EXPERIMENTS

5.1. MECHANICAL LINK WITH THE SUBSTRATE

The first observations on manufactured parts show that the wall is thinner at the bottom than the rest of the wall. This difference can be explained by two reasons. For the first layer, the part temperature is ambient, the gap of 650°C (aluminum alloy melting temperature) is too high to ensure a deep and wide heat affected zone (HAZ). Moreover, the heat impact, generated by the welding power source, is spread in the whole of the substrate. Fig. 10a shows this phenomenon: The bead width on the 1st layer is very strait; the penetration (depth of the first bead) is not deep. The extraction strength was measured with a traction test machine. The ultimate tensile strength was about 40 MPa. Current and average voltage are very low with CMT Advanced, (interesting to reduce the heat and to build wall but, it is not efficient for penetration in the substrate).

To enlarge HAZ and the first bead width, it was chosen to select a powerful mode, CMT Pulsed on the first layer (Fig. 10b): The first bead is wider than the rest of the wall; the penetration is deeper than CMT Advanced Mode. The ultimate tensile strength was about 125 MPa). This still can be improved by adding sweeping. On the two firsts layers, the pulsed mode was selected and sweeping was performed to improve link. The ultimate tensile strength was 130 MPa. The wire ultimate tensile strength was also measured. The average value was about 185 MPa. The pulsed mode improves significantly the link between the wall and the substrate, but, for thin sheet, the heat impact can be important and generate deformations.



a) CMT Advanced Mode only
b) CMT pulsed Mode on the 1 st bead
c) CMT pulsed Mode on the two first layers+sweeping

Fig. 10. Comparison of wall link with the substrate

5.2. EXAMPLES OF PARTS MANUFACTURED USING WAAM WITH ALUMINUM ALLOY

Several parts manufactured are shown on Fig. 11, with the proposed approach:

Fig. 11a. This part is 162 mm high and composed of 90 layers. For each layer start/stop of welding are moved on the path to smooth the surface. Path strategy is efficient to improve shape quality.

Fig. 11b. This cone is manufactured by using five axis tool paths. The welding is continuous from the first point until the last one. The path strategy is very interesting to remove the start/stop effect which can create holes or hump. Moreover, with this strategy, deposit conditions are constant all along the manufacturing which can generate defect near the support.

Fig. 11c. Incurved wall manufactured with 5 axis path tool generation. This path combines 3 axis and 5 axis cinematic. This wall is built by goings and comings deposits (Zig zag tool paths). The benefit is the filling of holes caused by welding stop and the manufacturing time optimization. However, inter-pass temperature is not optimal, mostly on small part.

These different parts need complex tool paths and a well set of welding parameters.

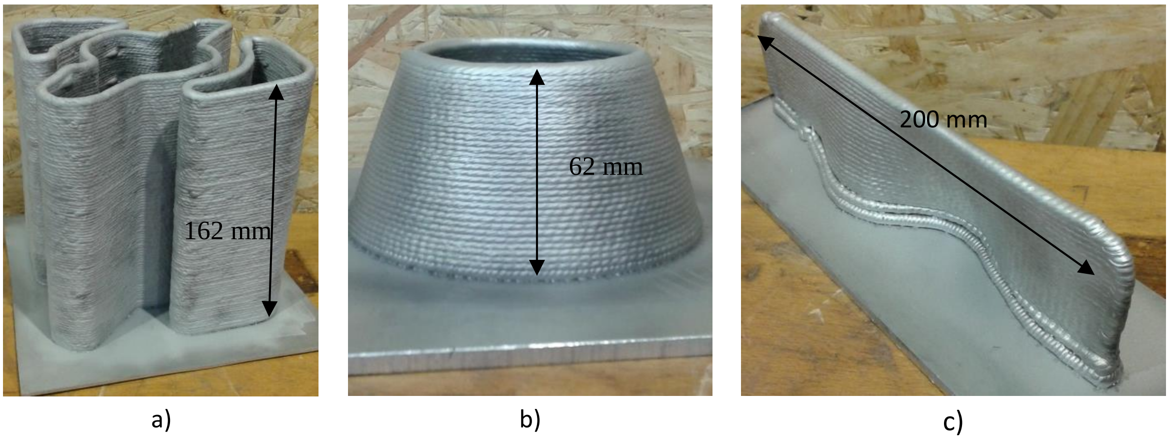


Fig. 11. Examples of Parts manufactured with WAAM process

5.3. INTERESTS OF FIVE AXIS MANUFACTURING FOR WAAM

Five axis manufacturing is an adequate solution for building with clearance parts. For example, it is efficient for a cone. The goal is to show the effect of 5 axis tool paths on part geometry. The methodology consists in manufacturing part in 3 axis and 5 axis and to compare the geometry obtained with the real shape. A comparative study between 3 axis and 5 axis manufacturing for a cone was fulfilled. The interest of 5 axis in this case is tool orientation: for 3 axis, the torch is always vertical whereas for 5 axis, the tilt follows the shape of the part. On Table 1 and Fig. 12, the tangent layer height (1.8 mm for all tests) and the normal layer height (parameter for slicing) are shown. However, it is important to note that the tangent layer height is the same for 3 axis and 5 axis, only orientation tool angle is added in 5 axis.

Table 1. Tangent and normal layer height

Cone angle (°)	Tangent layer height (mm)	Normal layer height (mm)
10	1.8	1.77
15		1.74
20		1.69
25		1.63
30		1.56

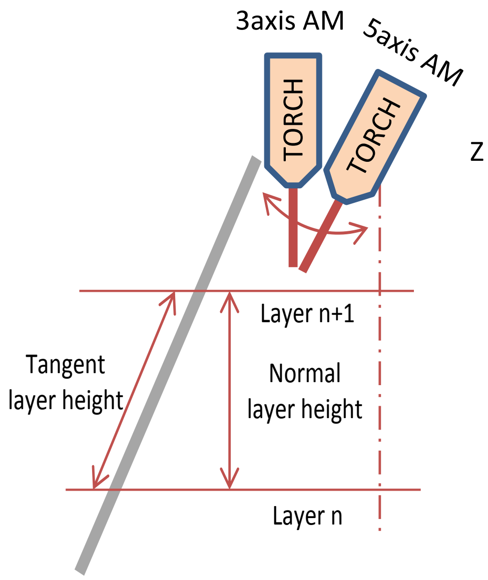


Fig. 12. Tangent and normal layer height

Manufacturing time was about 15 minutes per sample. The substrate dimension was 170x170 mm (thickness: 5 mm). This was clamped on two sides.

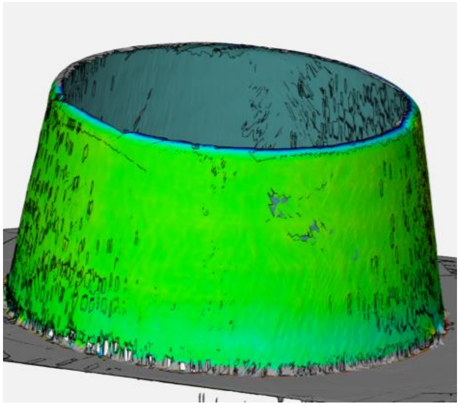
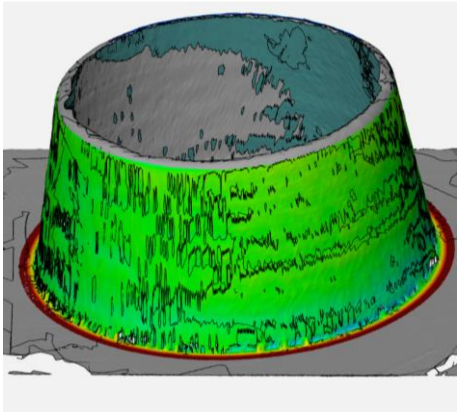
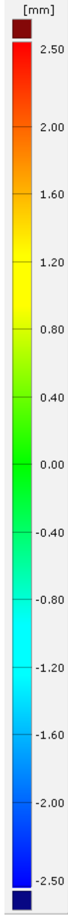
6. RESULTS AND DISCUSSIONS

The cones manufactured were scanned with a 3D optical scanner. The CAD file obtained and the nominal external surface were compared after automatic prepositioning. The gap between the nominal surface and the real surface was represented on the real element. The results are shown on table for each cone angle and 3 axis/5 axis manufacturing.

As shown on Table 2 and Fig. 13 for 3 axis path, from 25° cone angle, the defect of the top of the part is about 1.7mm compared to the real surface. For 5 axis, defects are always below 0.8 mm, and seems to be stable.

Even if WAAM is adapted for structural parts, the lack of accuracy can generate some issues. In fact, if the defect is higher than 1.5 mm (compared to the bead width), manufacturing should be difficult to perform because the position of the previous layer is not adequate compared to the position of the effector manufacturing the next layer. In fact, this position is generated from the CAD model (nominal geometry).

Table 2. Comparison between 3 axis and 5 axis tool paths

<table>
<tr><th>Cone angle</th><th>3 axis tool paths</th><th>5 axis tool paths</th><th>Scale</th></tr>
<tr><td>10°</td><td></td><td></td><td rowspan="2">
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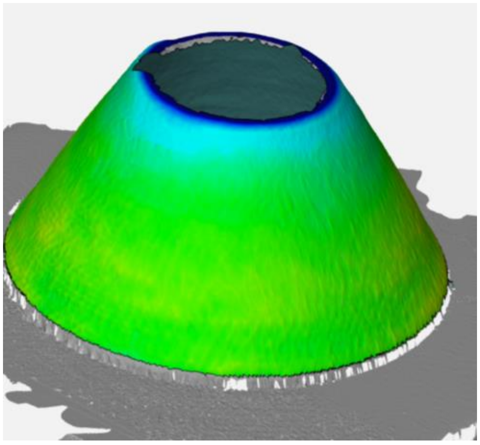
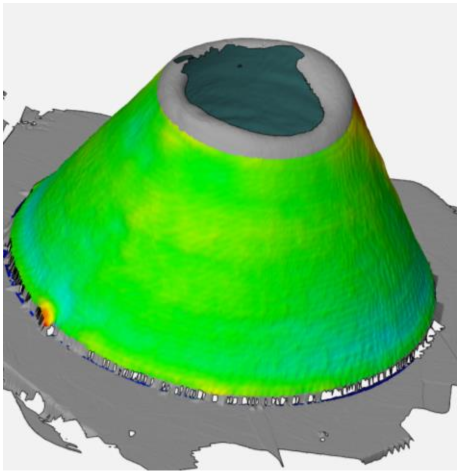
<tr><td>30°</td><td></td><td></td></tr>
</table>

Moreover, for 3 axis the deviation is increasing with the part elevation. With 5 axis tool paths, the maximal defect is concentered at the bottom of the part. This defect can be explained by the vertical strength applied by the arc on the melted area which generated a flow of melted material. For 5 axis toolpaths, the strength direction follows the cone angle and cancels the effect of flow.

The maximal angle for 3 axis toolpaths seems to be between 20 and 25° (for a cone). For 5 axis, no real limitation was found, the most important issue is the path and the robot reactivity which generate defect (Too much material). With 5 axis toolpaths, manufacturing with clearance angle is possible. Complex part including different shapes can be manufactured. Moreover, the part geometry is respected.

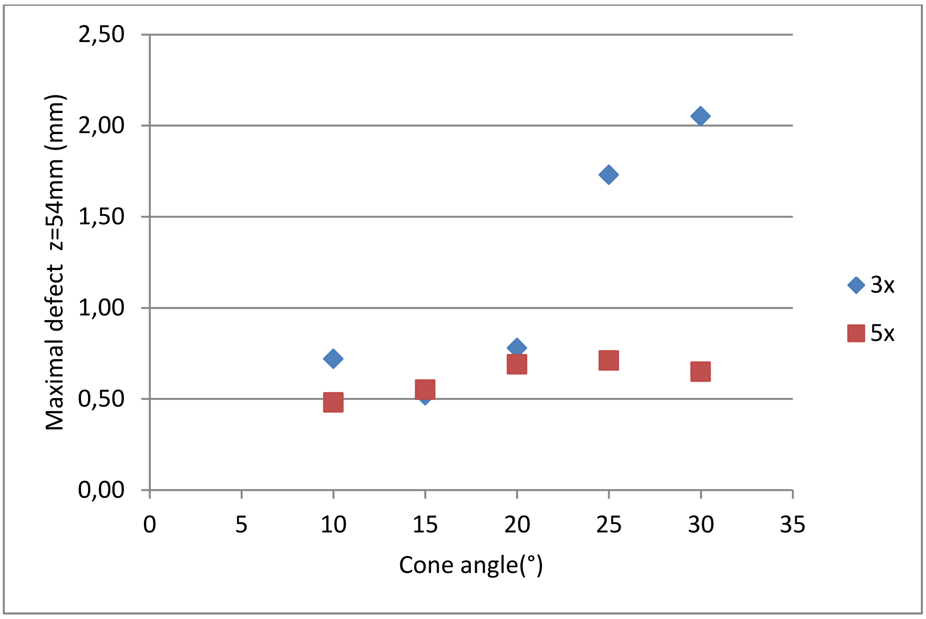


Fig. 13. Maximal defect (z=54 mm)

The benefit of using cones for this comparison is the net shape. However, this type of path in 5 axis is demanding and can generate travel speed gap which deteriorate the shape (Travel Speed decrease but WFS is kept constant). Another geometry might be envisaged to eliminate this problem like lean wall.

7. CONCLUSION

WAAM is often limited to test parts with simple toolpaths (2.5D toolpaths). To manufacture more complex parts (with clearance angle or variable thickness), it is necessary to explore more complicated tool paths and strategies. In this paper, a methodology is proposed to manufacture WAAM parts. This methods, based on experimental settings, sum up all the key stages to ensure manufacturing. It was highlighted that the toolpath generation, which is a key stage of design/manufacturing chain, require adapting some parameters and analyzing the geometry to ensure the part accuracy. Moreover, the process requirements (Interest of high welding power and path strategy on the firsts layers…) and the motion system capability (Tool orientation…) must be taken into account to manage WAAM part.

ACKNOWLEDGEMENTS

The authors would like thank the partners of this DGA/DGAC funded research project: STELIA Aerospace, CT INGENIERIE, CONSTELLIUM and Ecole Centrale de Nantes. The goal of this project is to develop AM processes for aerospace structural components.

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