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Design and Pathway Programming of Organic Freeform Thin-walled Geometries Produced by Laser Metal Deposition

Marco Anilli[a], Magdalena Assaad[a*], Andrea Crosato[c], Ali Gökhan Demir[a], Stefano Mutti[b], Barbara Previltali[a], Daniele Tamborini[a], Lorenzo Molinari Tosatti[b]

[a] *Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy*
[b] *STIIMA-CNR, Consiglio Nazionale di Ricerca, Via A. Corti 12, 20133 Milan, Italy*
[c] *BLM Group, Via Selvaregina 30, 22063 Cantù, Italy*

Abstract

Laser metal deposition (LMD) shows great promise for producing large components as well as thin-walled structures by additive manufacturing. Compared to the powder bed fusion (PBF) techniques, LMD can exploit further flexibility in terms of tool path programming. Layer-by-layer rastering commonly used in SLM is applicable also to the LMD process, where overhang structures remain a complex issue in the absence of support structures. Concerning thin-walled parts with a symmetry axis or those that evolve around an axis, more efficient strategies may be developed. Hence, this work discusses the use of different part programming strategies for thin-walled structures employing an LMD system based on a 6-axis anthropomorphic robot and a 2-axis rotary table. The work compares, layer-by-layer, continuous pathway, and oriented reference plane strategies, study of process parameters, build failure mechanisms, as well as geometric errors are discussed. Successful deposition of thin-walled organic and freeform tubular components in AISI 316L is demonstrated.

Keywords: Directed energy deposition; Laser Metal Deposition; Design for additive manufacturing; CAD/CAM; Anthropomorphic robot

1. Introduction

Additive Manufacturing have become popular in the world of production, initially serving as a tool for rapid prototyping, some of its technologies soon evolved to become reliable manufacturing techniques in industrial sectors such that the biomedical and aerospace ones, as the process allows the direct realization of solid objects with complex custom geometries [1]. Additive manufacturing relies on the production of

[*] Corresponding author. Tel.: +39-348-161-1043 .
E-mail address: magdalena.assaad@mail.polimi.it .

parts by adding material layer by layer, saving material when compared to subtractive methods. Additive manufacturing is considered an interesting alternative in production as it promises time and cost reduction while offering more flexibility in geometries to be built.

Building methods have evolved progressively as the shapes to be printed became more complex. . Laser Metal Deposition (LMD) is one of the Additive Manufacturing techniques where powder is injected into a melt pool through a nozzle, and the final geometry is determined by the trajectory of the laser moving together with the powder flow relatively to the substrate. Layer-by-layer printing is one of the most common printing modes as it is shared with other technologies, but as LMD grew as a preferred thinwall geometry method, the printing mode had to evolve into a newer and more efficient one, namely continuous pathway where only the periphery is built continuously. Nevertheless, both methods are successful when the part is oriented in one direction.

More complex parts, typically common in industry, have more complicated geometries, and one of additive manufacturing’s advantages is reducing the amount of parts, sub-assemblies and human intervention.

Furthermore, the continuous pathway mode can be applied in not just one, but different reference planes, allowing more freedom in design. In the study below, three printing modes - layer-by-layer, continuous pathway and oriented reference plane- will be presented before the printing cell and the software used for simulations are layed out alongside the different shapes chosen to compare the different printing methods and their geometrical advantages.

2. Design pathways and part programming in LMD

In this section, the different printing modes will be presented and explained, showing their disadvantages and characteristics theoretically. An earlier work studied the feasibility of some geometries using LMD. In this work, different geometries and their optimal deposition techniques are presented.

2.1. Layer-by-layer build up

As all the layers are stacked uniformly on top of each other, slicing would be kept simple, dividing the part in small layers of constant thickness. The slicing progression is in a fixed direction, usually the vertical direction is used in to ensure perfect adherence of the substrate. Some cases show that the toolhead can be positioned with other orientations where the deposition is also successful, since in general it is parallel to the wall to be built [2]. The slicing however remains horizontal in parallel layers of constant thickness.

This slicing method (parallel planes of the same thickness) is referred to as 2D. This method is thoroughly discussed in many studies as it is common and already in use for other processes like Stereolithography and Powder Bed Fusion [3]. The slicing doesn’t require much computation and can be applied to an STL file with reduced 3D information[4].

2.2. Continuous pathway

The continuous pathway is a toolpath describing an ellipse, or any similar shape that does not close on itself until the end. the movement of the toolpath does not describe closed surfaces stacked on top of each other as described in the case before, but a continuous line that grows in one direction describing a shape.

This printing strategy might be more economical and efficient when thinwalls are created as the toolpath only describes peripheries (no infills are made).

Similarly to the method above, the slicing direction is kept in one direction preferably following the Z-axis.

2.3. Oriented reference plane

This method is the most challenging, as it combines the continuous pathway method with a change in direction of the slicing. It is introduced as some complex shapes are impossible to build following one slicing orientation (2D slicing) unless supports are added to hold the new layers.
The a 2-axis tilt and rotary positioning system is added to the 6-axis robot arm. It enables the reorientation of the built part by the combination of the reorientation of the toolhead and the rotation of the positioning system without an offset of the toolhead with respect to the built part in the X, Y, and Z directions. It simplifies the process planning and saves a lot of production time[5].

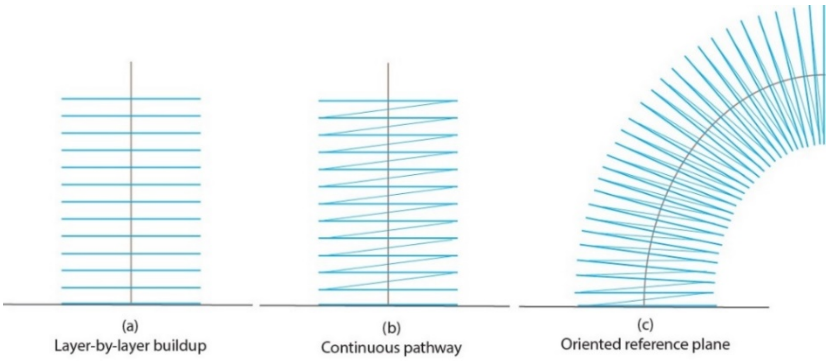


Fig.1. Simplifications of the building strategies for (a) layer-by-layer; (b) continuous pathway; (c) oriented reference plane

3. Experiments

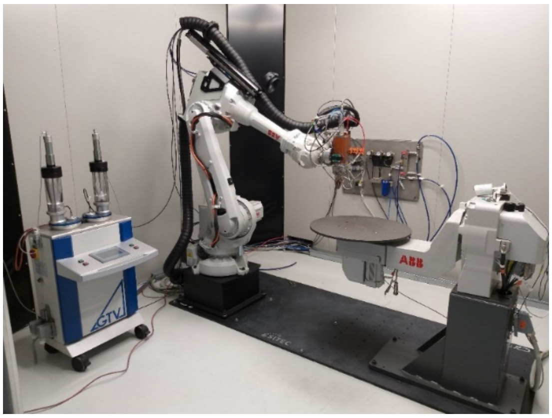


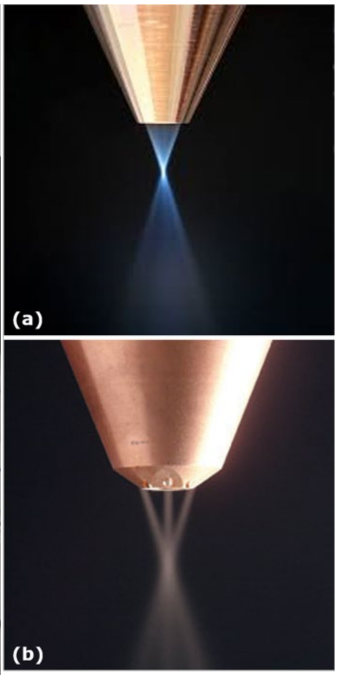
Fig. 2. BLM Additube LMD - Laser Metal Deposition cell:
a 6 axes robotic arm and a 2 axes positioner constitute the handling system of the cell.

Fig. 3. IPG YLS 300 fiber laser source

3.1. LMD cell

The following experiments are made using the LMD cell Additube (shown in fig. 2) built by BLM Group at the Manufacturing and Production Systems sections of the Department of Mechanical Engineering at Politecnico di Milano. Unlike most of the LMD machines available on the market that are based on a cartesian architecture, Additube is equipped with a 6 axes robotic arm ABB IRB 4600-45/2.05 and a 2 axes positioner ABB IRBP A-250. The robotic arm has a featured reach of 2.05 m and a payload of 45 kg. The position repeatability is 0.05 mm and the trajectory repeatability is 0.13 mm, with a maximum error of 0.48 mm. The positioner has a maximum handling capacity of 250 kg and is equipped with a tilting arm that can tilt from -180° to +180°, on which a rotary table is placed, capable of rotating 360° in a continuous manner.

At the time of the experiments, the Additube cell is equipped with a fibre laser source YLS 3000, by IPG Photonics (fig. 3). The maximum power of the laser is 3 kW, the wavelength is 1070 nm and the source operates in continuous wave. The system is equipped with a 50 µm fiber and a coupler, by Optoskand, that allows coupling with 100 µm, 200 µm, 300 µm and 400 µm fibres.



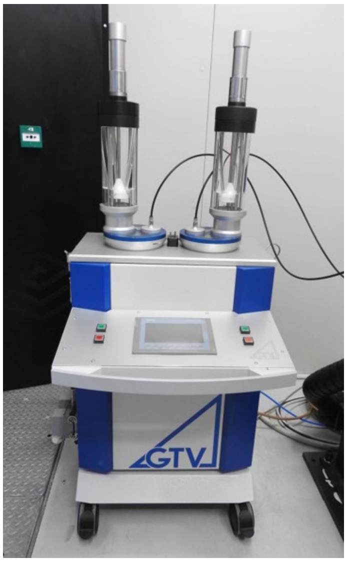


Fig. 4. Kuka Reis MWO-I Powder deposition head (left).
Fig. 5. (a) COAX-40-F nozzle; (b) 3-JET-SO16-S nozzle.
Fig. 6. GTV TWIN PF 2/2-MF powder feeder.

The deposition head, reported in fig. 4, is a Kuka Reis MWO-I Powder equipped with a collimator with a focal length of 129 mm and a 200 mm focal lens. The collimator can be manually adjusted along a 30 mm rail. The magnification ratio obtained with the 200-129 optics is equal to 1.55 and allows to focus the beam in a small spot, suitable to build thin walled features. The Kuka powder head allows to operate with two kind of nozzles: a coaxial COAX-40-F nozzle and a three jet 3-JET-SO16-S nozzle, both from Fraunhofer ILT (*a* and *b* respectively in fig. 5. The metal powder is handled by a GTV TWIN PF 2/2-MF powder feeder (fig. 6) equipped with two powder silos and capable of generating a wide range of flow rates.

3.2. CAM software

The hardware has been described above has to be integrated with a software that allows the creation of the toolpath, the application of some robotic rules and the simulation of the printing activity. The software used for this application is Siemens NX 12.0. It offers a CAD, CAE and CAM environment in which the user can design his part, study its mechanical properties and eventually plan and predict its manufacturability.

For our activity, the software's CAM environment is of supreme importance, as it is the one where the creation of toolpath is achievable, alongside the simulation of the robot activity before the printing takes place. This virtual simulation is very important as it shows the movement of the robot, the positioner, and the progressive building of the part in question. Some problems may also be identified such as collisions, axis exceeding their angle limits, …. Some of these will be described in more details in the coming sections.

The CAM environment is relatively easy to use as the main steps to be followed are shown on the home bar in the chronology in which they are to be used (fig. 7.)

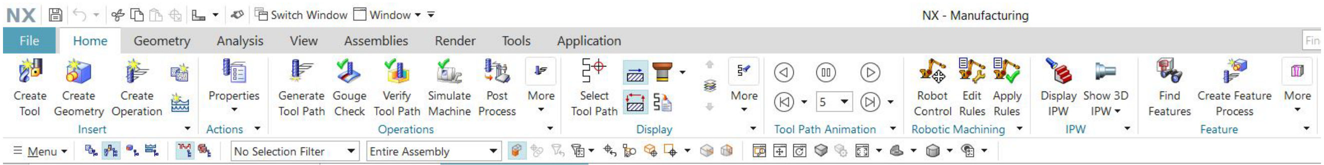


Fig. 7. Siemens NX's CAM interface

First, the process is to be selected, in our case it's a direct energy deposition process. Later the machine is to be chosen from the library. A 3D model of both the robot and the positioner mentioned above are saved as machines parts. By doing so, when the simulation takes place, each axis would rotate within its given movement range to mimic and predict the real robot movement when the real printing takes place.

Later the tool can be added from the software's tool library. These variables are added fast when using the software, however good attention should be given during their initial installation and use. The coordinates of the tool mount, as well as the distance and relative position of the robot and the table, and of the tool (with correct stand-off distance) and the table are very critical. An elaborate calibration is to be made: if any of these values/positions is not reported well, the software simulation of the deposition process would not conform to the true deposition which can result in the failure of the printing (at best) or in possible collisions and robot/equipment damage. Hence the accurate and precise numbers and positions are of extreme importance for the effective use of the software.

Once this is done, the geometry to be printed can be added with a base plate. Following the same logic stated above, as the software environment should simulate the real printing process, the omission of the base plate in the software would lead to wrong coordinates and subsequently the failure of printing.

Once the part is referred to the base, this one is selected as the geometry to be built and it is possible to create the toolpath. There are about 8 additive features for DED (in the newly released version, an extra 9^{th} is added). Each feature has its own deposition strategy.

NX Siemens offers different features for the layer-by-layer printing method, in these experiments, the zigzag feature will be the one used for the four geometries built. For the continuous pathway, the planar additive thinwall profile helical feature and for the oriented reference plane, the tube additive thinwall. Once a mode is chosen, the toolpath can be created depending on the printing strategy and the geometry. Different case studies will describe the capabilities and limitations of each of these methods.

3.3. Case studies

In order to compare the different printing methods, different geometries (of increasing complexity) are considered. The different geometries are: a tube with fixed diameter (fig. 8. (a)), a turbine blade (b), a cone (c), and a horn (d). The dimensions shown are in millimeters. All geometries are thinwall, which means that LMD is used to build their peripheries and not their infill volume. In this mode, it will be imperative to focus on the quality of the total depositions and not on the quality of singular printed layer.

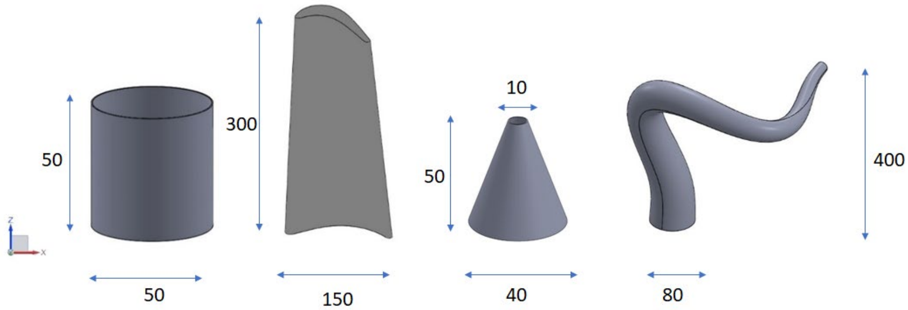


Fig. 8. Different geometries to be built following different deposition modes (a) a tube; (b) a turbine blade; (c) a cone; (d) a horn.

3.3.1. Layer-by-layer build up

For this building feature, the variables chosen are the geometry to be built. It is also imperative to set a printing speed, the layer thickness and the overhang percentage.

3.3.1.a Tube and turbine blade

The toolpath created for the tube (fig. 9) and the turbine blade (fig. 10) seem successful as it shows layers of the same thickness and dimension deposited on top of each other. The yellow lines show the transition of the toolhead to a new level, in a laser off mode, while the blue lines show these transitions on the same level. The starting point of each layer is chosen to be different than the one at the layer below for a better surface finish.

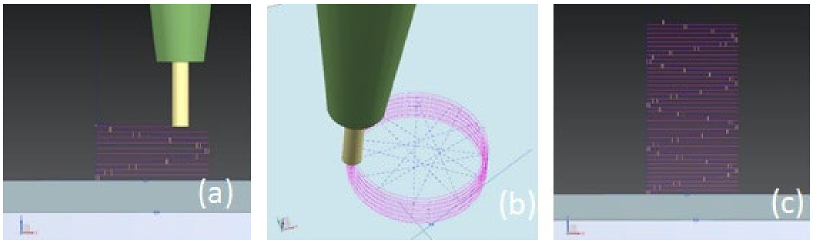


Fig. 9. (a) the tube's toolpath in progress front; (b) and top; (c) the overall toolpath showing a certain amount of layers stacked on top of each other.

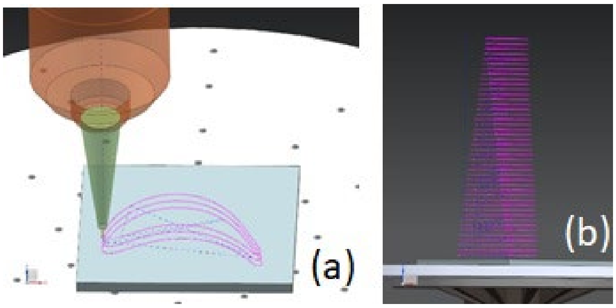


Fig. 10. (a) the blade's toolpath in progress from the top; (b) the overall toolpath showing layers stacked on top of each other.

3.3.1.b. Cone

The cone's toolpath is built similarly to that of the tube and the turbine blade. Looking at fig. 11. (a) and (c), it seems feasible enough as it describes different layers deposited on top of each other. However, focusing in fig. 11.(b), it can be seen that the gradual layers are not built on previous pre-existing layers, which means the powder won't solidify on a substrate leading to the failure of the printing operation.

The printing of the cone would not be successful with this deposition method (limitations exist in relation to the angle of the cone – surfaces inclined more than 10° with respect to the vertical direction cannot be reliably built).

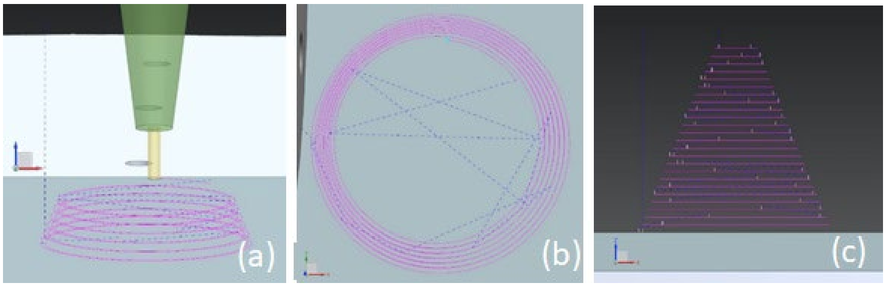


Fig.11. (a) printing of the cone in progress from the front; (b) and the topp; (c) the overall toolpath for the printing of the cone.

3.3.1.c. Horn

Finally, the toolpath of the horn is built by the layer-by-layer deposition strategy. Similarly to the cone described above, the toolpath shows a trajectory where the printing would fail as new layers are built on "thin air" where no previous layers or supports exist. The green line shown in fig. 12. (a) shows the travel of the tool in a non-printing mode, once the printing restarts, the powder would fall without solidifying impeding the progressive printing of the part. Fig. 12.(b) shows the overall toolpath where this phenomenon occurs on more than one layer.

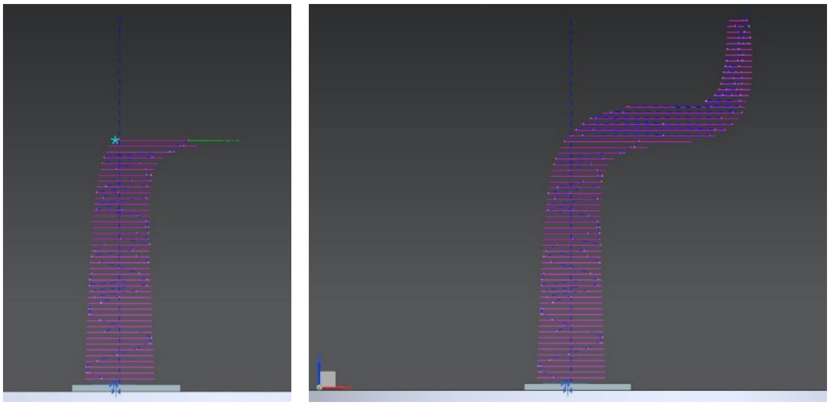


Fig.12. (a) printing of the horn in progress; (b) the overall toolpath for the printing of the horn.

3.3.2. Continuous pathway

Similarly to the layer-by-layer build up strategy, the variables chosen are the geometry to be built and the base surface. It is also imperative to set a printing speed, the layer thickness and the overhang percentage.

Using the continuous pathway method, the printing of the tube (fig. 13.(a)) and the turbine blade (fig. 13.(b)) is possible. The horn, that was unachievable with the layer-by-layer method is still impossible to build: the toolpath created shows layers printed without having any layers below for support (fig. 13.(c)).

The cone is achievable in this method. Using the layer-by-layer method, each layer built has a definite size, which means the changing diameter wouldn't be achievable unless the layers are very thin and the printing speed is very low[6]. With the continuous method, the progressive continuous toolpath mimics the evolving surface of the cone (it is a spiral helicoid), which means that the diameter changes progressively and not at once, leading to the success of the printing process. Again limitations exist, but the range of inclinations that may be printed is considerably wider (fig. 14).

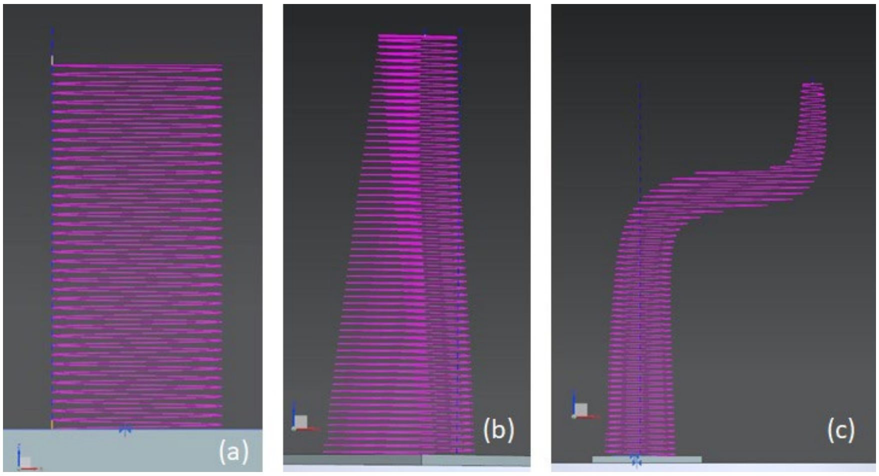


Fig. 13. (a) printing of the horn in progress. (b) the overall toolpath for the printing of the horn.

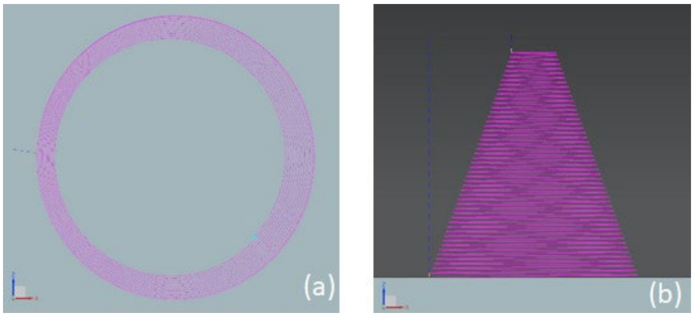


Fig. 14. (a) printing of the cone in progress from the top. (b) the overall toolpath for the printing of the cone.

3.3.3. Oriented reference plane

In addition to the variables required in the previously mentioned deposition mode, this one requires the selection of a centerline. This centerline is used as a guide for the slicing orientation as the slicing is not occuring in one direction as before.

The horn, that was not possible to build with the previous method due to its complicated shape is better sliced in this mode, where all new levels come supported by the previous ones. This flexibility is reached thanks to the software's ability to slice in 2.5 D but also thanks to the positioner's ability to tilt and rotate the part, keeping the new layer relatively horizontal (because we select a deposition on a flat horizontal section of the part under realization).

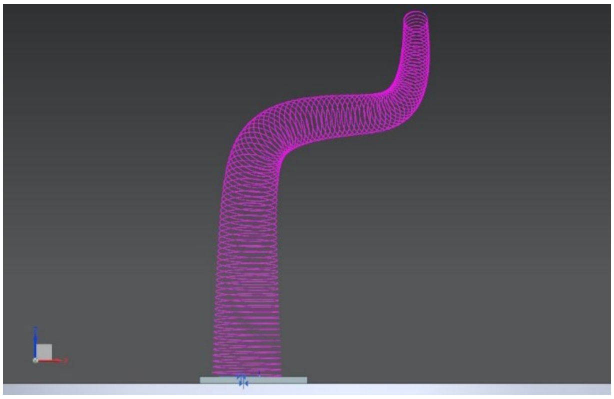


Fig.15. Sucessful toolpath of the horn.

4. Evaluation of geometrical capabilities and defects in different deposition strategies

It is important to note that many variables would affect the printing quality of a part such that the printing speed [7], laser power (around 400W), mass flow rate, [8] …. In these experiments, the stand-off distance is kept at 12mm for the 3-jet nozzle and 7mm for the coaxial nozzle [9]. The laser spot diameter is 1,2 mm. All of these are kept constant in order to focus on the effect of the deposition method.

4.1. Layer-by-layer build up

Using the layer-by-layer build up mode, simple geometries can be created yet the surface finish of the part is not optimal, as the stacking of the different layers is visible. This is referred to as the “staircase effect”,and can be corrected with subsequent machining.

This method would not allow the building of an object unless its slicing orientation is unique. The orientation of the toolhead affects the printing quality of the tube, whereas, the printing quality is optimal when that is vertical or close to the vertical direction.

As long as the powder deposition takes place on a horizontal surface, the results are expected to be satisfactory.

Occasional problems might occur. Given that the part is built layer by layer, the laser has to be turned off and on whenever a layer is finished and a new one is to be started. This consecutive action might affect the final printing quality, as the starting points of each layer would be more visible on each layer. If each layer starts at the same point as the previous one, a line (made up of all starting points) would be visible (fig. 16.(a)).

Using NX, it is possible to avoid this line by manually selecting a different starting point for each layer, but this activity may be tedious in case the geometry shows a high number of layers.

The layer-by-layer technique may be more appropriate when full surfaces are to be created and not peripheries.

This method wouldn’t lead to successful results if the geometries exhibit bends or changes in diameter. The limitation in wall inclination is important.

Fig. 16. (a) shows the tube built in this manner with a huge visible line caused by the inconsistency of the laser being turned off and on repeatedly.

4.2. Continuous pathway

This method is faster than the layer-by-layer method since the laser is not turned off until the printing is over, the robot continues its movement and doesn't go back to a specific point and the staircase effect is less visible.

It also provides a better surface finish, as the laser is not turned on and off repeatedly, affecting the solidification status of the powder grains. Fig. 16.(b) shows the same tube in Fig. 16. (a) yet built using the continuous pathway method. It clearly shows a better surface finish. The cone in (c) and the turbine blade in (d) are also printed in this mode. (e) shows an attempt to build the horn yet the printing failed as the geometry exhibited a bend superior to 20° (15° can be considered always safe).

4.3. Oriented reference plane

This method is fast as the toolpath is continuous and progressively moves along the periphery of the object, with the added flexibility of multiple slicing orientation, allowing the part to rotate, keeping the last layer horizontal for good adherence of the new layer. The geometries built with this method cannot be built in any other way unless supports are added. It is important to mention that the first few layers must be absolutely horizontal for them to adhere well to the base plate. Some difficulties might emerge while using this method due to the movement of the positioner: Collisions are very probable, yet they can be avoided using the software's "anti-collision" feature. Fig. 16.(f) shows the horn built successfully with this deposition strategy. It is important to note that its size was increased in order to facilitate its printing without risking collisions.

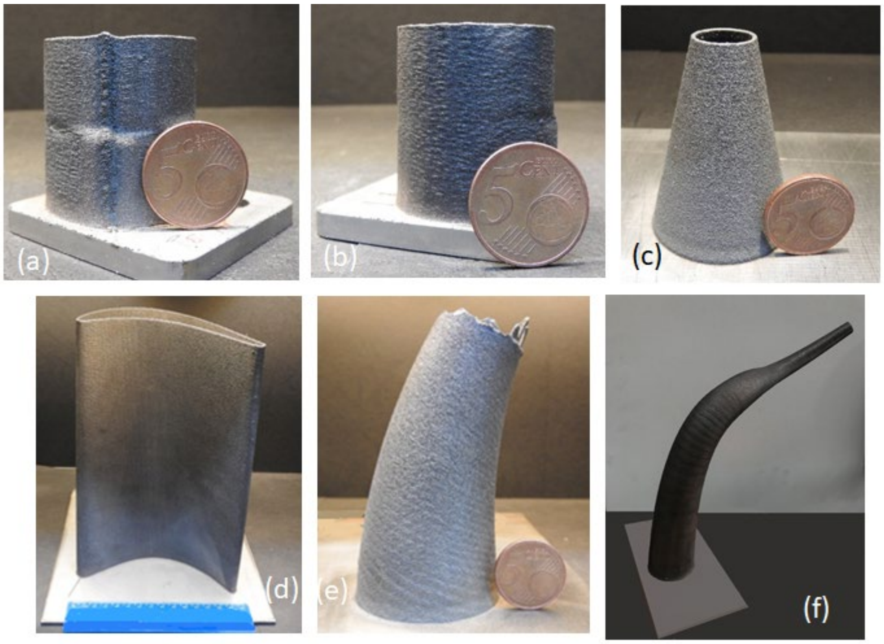


Fig. 16. (a) tube printed layer-by-layer; (b) tube printed with continuous pathway; (c) cone printed with continuous pathway; (d) turbine blade printed with continuous pathway; (e) horn printed with continuous pathway; (f) horn printed with oriented reference plane.

Table. 1. Summary table showing the fattibility of each geometry depending on the deposition method

Deposition Method	Tube	Turbine Blade	Cone	Horn
Layer-by-Layer Build up	Si	Si	No	No
Continuous Pathway	Si	Si	Si	No
Oriented Reference Plane	-	-	-	Si

6. Conclusions

As it had been shown in the previous sections, all three modes of deposition are useful, yet not all of them are successful, as that would depend on the geometry of the piece. Some simple shapes wouldn't require sophisticated slicing methods, while other would require more elaborate slicing. The use of supports is not considered in this study for the building of complex shapes as the creation and removal of supports would add time and cost to the manufacturing process and hence their addition contradicts the argument of using Additive Manufacturing in the first place. The shapes considered in this study are just taken as experimental parts, yet the use of LMD and its intricate 2.5D slicing method would allow the building of very complex industrial parts, with the advantage of reducing some assembling steps like welding, but also changing the design perspective, from designing for the ease of machinability, to designing for better functionality.

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