A Framework for Hybrid Manufacturing in Robotic Cells

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Abstract. Compared to other additive technologies, Wire and Arc Additive Manufacturing (WAAM) offers high deposition rates, flexibility and a larger build volume as well as reduction of material waste. WAAM can be combined with a subtractive technology in hybrid robotic cells to further increase the application scope, thus producing products with improved surface finish where needed. However, there are some open issues that limit this process. So, the main goal of this paper is to review current research developments and provide a framework aimed at manufacturing parts by hybrid cells. A procedure is defined which moves from the evaluation of the designed shapes, their analysis to identify a proper manufacturing sequence until the elaboration of the instructions for the cell automaton controllers. Main WAAM issues are outlined to identify main research directions, and a test case is presented to highlight the process phases.

Keywords: Wire and Arc Additive Manufacturing; Process Planning; Robotic cell; Hybrid Manufacturing.
DOI: https://doi.org/10.14733/cadaps.2022.1029-1041

1 INTRODUCTION

In the last three decades, Additive Manufacturing (AM) technologies have evolved from systems able to obtain non-functional prototypes to evaluate new designs, to an effective functional manufacturing in many industrial applications [37]. AM comprises a family of different techniques to build 3D physical parts sequentially stacking a series of layers over each other. Among these technologies, Wire and Arc Additive Manufacturing (WAAM) emerges thanks to few unique characteristics. Indeed, it can produce large metal parts (steel, aluminum, titanium etc.) with a lower capital investment and higher deposition rates compared to other AM technologies [9].

According to ASTM F2792-12a [4], WAAM is classified as direct energy deposition and it is basically an automatized welding process. In Fig. 1, the main components of a WAAM cells are outlined [13, 18].

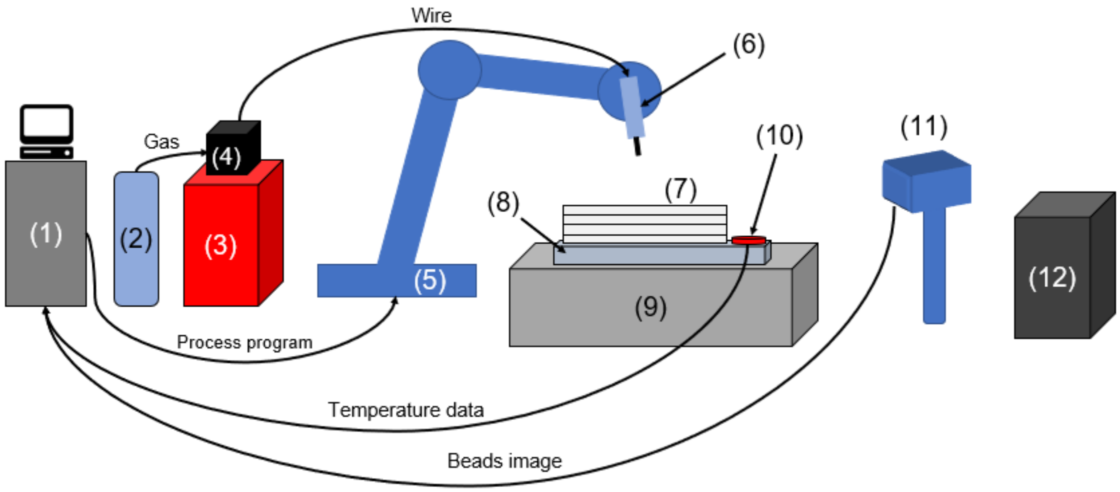

Figure 1: WAAM cell component: 1) Robot controller; 2) Shielding gas; 3) Power source; 4) Wire feeder; 5) Robot; 6) Welding torch; 7) Part; 8) Substrate; 9) Worktable; 10) Temperature sensor; 11) Camera; 12) Other accessories.

Starting from the CAD model of the part to be realized, 3D tool paths are generated. The part is then obtained thanks to the welding gun which is moved by the anthropomorphic robot according to the generated paths [24].

WAAM is divided into three main categories: Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) based [29]. Among these, GMAW is the most common option. It is a fusion-based arc welding process where the arc is formed between a tip of a consumable wire and the workpiece, using an inert or active shielding gas that also protects the weld pool and adjacent material [34].

Nonetheless, WAAM exhibits some drawbacks and it still receives less attention than other AM processes [29]. Several works have been done to improve this production method over the last decades. However, most of research is focused on single issues addressed on prototypal laboratory setups. An overall framework aimed at the implementation of WAAM is missing. The definition of guidelines and design rules, the selection of the most suitable candidates in an early phase, the selection of proper hardware systems, software elements and data exchange capabilities would lead to increase the availability of WAAM in the industrial practice.

In this context, the paper provides a literature review related to WAAM. Also, it presents a holistic framework, which is developed aiming to guide the implementation of a hybrid manufacturing processes and identify where further research is needed to cope with the required functionalities. The approach includes both additive and subtractive machining processes, to improve the surface finish where needed. The paper is structured as follow: Section 2 presents a revision of the most common WAAM open issues; Section 3 presents the definition of a process based on a hybrid robotic cell; the approach is then evaluated in Section 4 on a test case to show how to be applied; finally, conclusions and future works are outlined in Section 5.

2 WAAM REASEARCH ISSUES

WAAM has some open issues that limit its applicability in the industrial context. Firstly, from a technological point of view, the large heat input associated with welding processes can induce residual stress as well as part distortions. Many studies and attempts have been done to control such stresses. For example, in [28] the authors have pre-heated the substrate to ensure a more homogeneous temperature distribution. A strategy, available only for limited cases, is to symmetrically grow the part on both sides of the substrate by mounting it on a 5-axis robot, thus balancing the residual stresses [40].

Poor accuracy and low surface finish are another typical issue. Usually, they are unacceptable for many applications unless successive milling operation are performed. The development of hybrid robotic cell with additive and subtractive processes have been investigated to produce complex high-performance parts, combining the main advantages of the two technologies [17]. For instance, in [22] the authors have developed a hybrid cell composed of a 3D arc weld deposition process and a CNC machine. They have found that combining these two processes could save time and costs. Also, Lin et al. [26] have developed a novel six axis hybrid additive-subtractive manufacturing. In particular, the proposed system is composed of a six degrees of freedom (DOF) robot arm, equipped with multiple changeable heads and an integrated manufacturing platform. They have found that hybrid processes have potentials in reducing manufacturing time, fabricating parts with better surface quality, avoiding support structures thanks to the 6-DOF flexibility and limiting staircase surfaces.

However, one of the critical challenges in hybrid additive-subtractive manufacturing is the determination of the optimal sequence of the two processes that must be alternated and optimized to avoid tool collisions and to reduce the final total cost [5]. Such sequence includes the alternation of additive and subtractive phases, as well the definition of the trajectories of the welding gun, or of the machining tool, starting from an analysis of the CAD model as input.

Solid layers that cannot be filled to form a smooth surface is another important problem related to WAAM, resulting in inner gaps or voids [42]. Different path strategies have been studied to reduce this issue. Cold rolling has been used to increase the smoothness, also reducing the residual stresses [19]. Indeed, WAAM lacks an integrated, reliable and standardized process monitoring and control systems during the deposition. Sensors have been used to monitor the temperature during the deposition and to control the bead geometry [41]. In a closed-loop environment all these measures are useful to avoid defects and to increase the quality of the final product [3].

CAD and software tools dedicated to the WAAM process are limited and not consolidated. In [3], the authors have used Powermill® CAD/CAM software for designing parts and programming the toolpaths. Their work addresses many constraints difficult to be overcome and issues linked to the WAAM technology. Also, WAAM3D [38], a spin-off of Cranfield University, has developed four software modules to optimize and control the WAAM process:

1) WAAMPlanner to generate the path tool;
2) WAAMKeys to calculate the optimal process parameters according to the material, the geometry, the build strategy and the machine architecture;
3) WAAMCtrl to control the entire deposition process from the operator's desk via user-centric interface;
4) WAAMDisplay to help the operator interpreting all the data recorded by sensors.

Another company that has investigated the WAAM technology is ABB Robotics [2]. They have developed RobotStudio® 3D Printing PowerPac to generate robot instructions starting from GCode files of sliced parts. However, the tool path generation is not optimized considering the product geometry and WAAM parameters. This could cause printing failure or low product quality. A study in this sense, it was performed by Ding et al. in [12]. The authors have developed custom slicing algorithms to optimize the build direction of product features, thus guaranteeing the material deposition along multi directions.

Specialized simulation software, such as Simufact Welding [35], Simulia [1] and Esi Sysweld [15], only consider a single building direction, thus limiting their applicability for more complex toolpaths. Finally, process control software is limited. A continuous exchange of data among the system in the robotic cell is necessary to ensure flexibility to the process, thus compensating any problems that may occur during the building process.

The previous overview highlights how WAAM technology is still at an initial stage, even if promising developments can be envisaged. Companies and designers need knowledge about this technology, given the absence of clear and defined guidelines aimed at supporting the design of both the products and the relative manufacturing cells. Some studies in this sense can be found in [27], where the authors have highlighted the principal design capabilities of WAAM, developing initial assessment criteria aimed at selecting candidates. Then, they have developed recommendations to select the most suitable build orientation. In the following, a wider framework is proposed.

3 PROPOSED WAAM PROCESS FRAMEWORK

Several aspects must be evaluated during the WAAM manufacturing process definition, even more when this production process is combined with subtractive technologies. So, the main goal of this paper is to propose a framework aimed at improving the implementation of a hybrid cell including its software components. Contributions from the literature are considered and combined in a comprehensive approach.

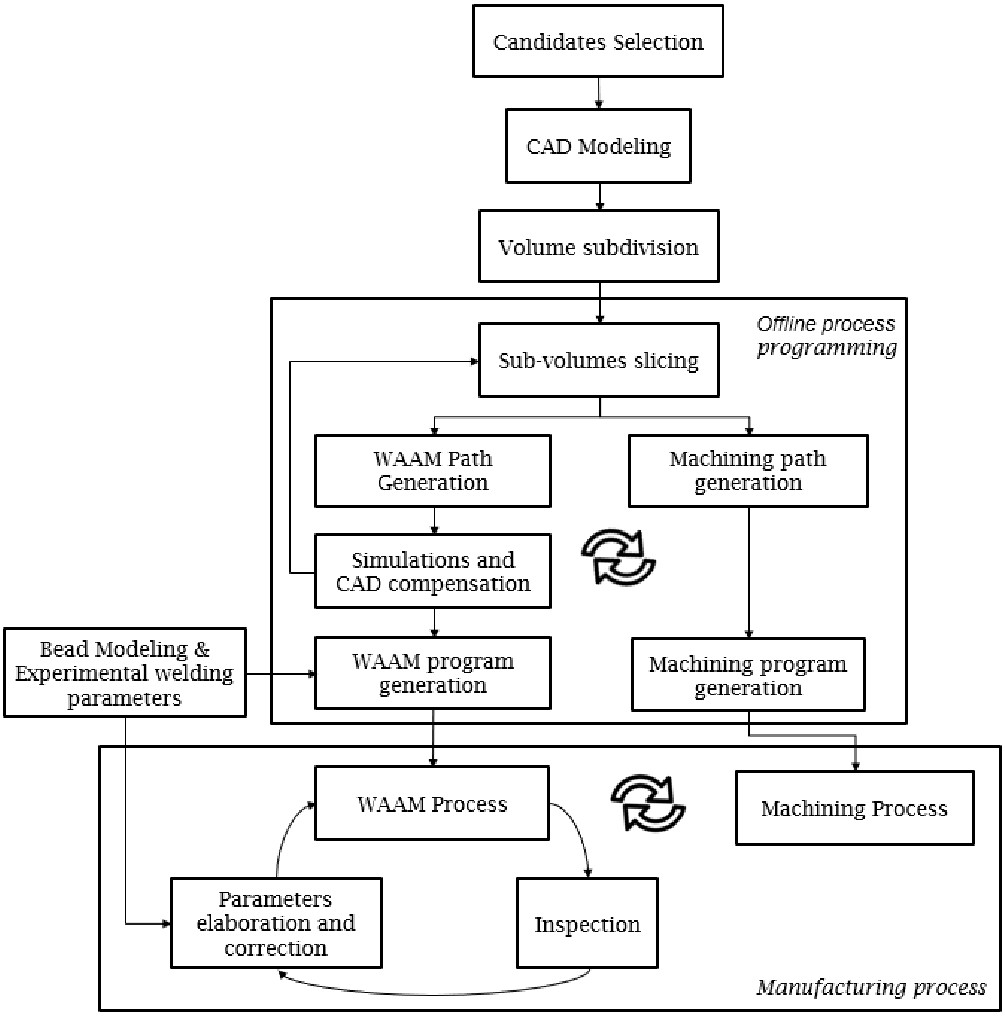

Figure 2: General framework to approach a WAAM hybrid process.

Briefly speaking, at first the shape design is evaluated, then an offline task programming phase follows. The last part is the online control and optimization of the process. The main parts of this framework are summarized in Fig. 2.

The selection of suitable candidates is the initial step. This topic has been marginally explored in the literature [30], despite its importance for a wider implementation in the industry. In [27] an effective tool to analyze the suitability of a product for WAAM production based on its geometry has been proposed. Dimensions of the bounding box of the analyzed part have been considered, as well as buy to fly ratio and mass. However, a more generic tool should be developed which is not strictly related to the geometry of the final part, also considering redesigning possibility.

Once suitable candidates have been identified, their geometry is defined and optimized according to the specific design requirements. In this step, CAD systems, 3D scanning and Topology Optimization (TO) software is to be used. Furthermore, the designer must consider the compatibility of the generated geometry with post processing operations, including machining of functional and interface surfaces. The development of design guidelines, i.e. a Design for WAAM (DfWAAM), would ensure optimal part design, thus reducing material waste and production cost. Finally, the CAD model are stored and exchanged by suitable standard formats, for example stl, 3MF or STEP. These formats are asked to be able to convey geometry as well as annotations with process related attributes.

Following Fig. 2, the next step is given by a part volume subdivision. The subdivision of the whole solid in separate portions allows to define a sequence of distinct growing steps, possibly interleaved by machining phases. Each subdivision must guarantee a feasible growing path, minimizing overhang portions and required supports. Also, it must provide tool accessibility during the machining phases. A progressive volume subdivision based on concave loops extraction has been explored as an approach to accomplish this step [12]. The extraction of the Medial Axis (MA) of a geometry, also known as skeletonization, is an alternative method that can be used for the volume subdivision. The MA, or skeleton of the set D of 3D space, is defined as the locus of points which lie at the centers of all closed balls. These balls are maximal with respect to D, together with the limit points of this locus. A closed ball is maximal if it is contained in D but is not a proper subset of any other ball contained in D [32]. In 2D space, disks are used instead of balls. The MA is a powerful tool as it gives useful topological information of a given part such as the thickness at each shape point [36]. Focusing on WAAM, MA can be effectively used to divide the solid into sub volumes, also identifying the directions of growth. Scarce applications have been found in the literature that use this method to divide volumes. For example, the authors in [39] have used a skeleton-based approach for partitioning a shell model into parts which are support free structure when fabricated. While using skeletons for 2D shapes is a covered area, the skeleton extraction for 3D geometries is a more complex topic. Also, the MA of generic 3D parts are two-dimensional structure, and they are complex to use in generating WAAM growing paths. One-dimensional skeletons can be directly extracted with special algorithms [36].

The robot offline programming is the next step of the process. First, the sub-volumes are sliced along their optimal direction. According to [12], the optimal build direction could be identified by using Gauss Maps and multi criteria decision making approaches. Otherwise, the MA could be used as slicing direction. The literature reports few slicing approaches, such as uniform or adaptive, planar or non-planar slice generation [45]. Depending on the considered feature, the most suitable slicing strategy must be selected to obtain the best performances, thus exploiting the flexibility that this production process guarantees.

Then, the torch path can be computed for each slice. The optimal path strategy should be selected, avoiding voids and gaps, also minimizing the residual stresses [11]. Different path strategies have been studied over the last decades, both for CAM and standard AM applications. Best reported patterns are: raster, zigzag, spiral and contour [42]. The raster path planning method uses parallel lines in the same moving direction to fill the layer [14]. This algorithm is easy to implement and guarantees optimal filling but is not suitable for WAAM production. As a matter of fact, the beads are deposited in the same direction, thus increasing the residual stresses and reducing the layer flatness [42].

Zigzag paths are the most widely used. Arc starting and stopping are minimized in this path strategy, also reducing the residual stresses [41]. Numerous studies have been done over the years to optimize zigzag path planning. For example, the authors in [31] have studied the best scan direction to increase the layer filling. Another work focused on dividing layers of complex geometry into simpler subsections. Then, the zigzag path planning is generated for each sub-section and finally the different paths are connected [11].

Alternatively, the spiral method guarantees a continues path, but it is suited only for specific geometry [33]. The contour method consists in offsetting the layer boundary by a certain distance until the target shape is filled [16]. Compared to the zigzag path planning, contour method guarantees the target shape filling more accurately. However, it may cause gaps and voids with small features angle [42]. A hybrid zigzag and contour path planning was used in [20] in order to exploit the advantages of both methods. The authors in [8] have developed an algorithm that offsets the medial axis of a given shape. This path planning avoids the formation of voids and gaps but requires post processing to remove the excess deposited material. Subsequently, the authors have improved the algorithm thus reducing the need of post machining [10]. Finally, the authors in [21] have developed an algorithm to generate a closed contour path, thus improving the efficiency of the process. In this step, it is also important to leverage experimental bead creation models to understand how related dimensions, such as height and thickness, depend on the process parameters.

Following Fig. 2, a successive WAAM process simulation is carried out to foresee the distortions induced by the programmed process. Few systems are available on the market to accomplish such evaluation aiming at calculating a displacement field to be used to compensate the original CAD model and reduce the deviations in the final part. In the meanwhile, machining programs are generated using standard CAM software to compute optimal chip removal paths, minimize execution times and avoid collisions among tools, worked part and robotic cells components. However, anthropomorphic robots exhibit low stiffness and significant joints' backslashes compared to traditional CNC machines. Suitable assessments of the achievable precision as well as compensation strategies are necessary to ensure the required quality [25].

Once the offline simulation and planning activities have been completed, the manufacturing step can be entered. The additive and subtractive steps occur in sequence, as defined in the offline phase. As previously mentioned, the bead formation strictly depends on the process parameters. According to [41], the development and implementation of monitoring and control strategies are mandatory to improve the robustness and the repeatability of WAAM process. The closed-loop control system includes high speed cameras, thermal, acoustic, spectral and proximity sensors. They could be used to adapt the process parameters, such as torch distance, welding power, travel speed of the torch, speed of the wire, etc…, according to pre-elaborated bead formation models and correction strategies. Such strategy could be conveniently based on Machine Learning (ML) algorithms which have been trained based on an extensive experimental campaign [7].

4 ILLUSTRATIVE TEST CASE

This section presents a test case to highlight the steps of the proposed process and how they should be addressed to fully exploit the developing process. The considered test case is a support for large and heavy shelf (Fig. 3). This bracket is composed of a base and four links. The base is hold to the wall by three screws or studs. Also, the longer links have two holes for fixing. The bounding box measures are 755 x 425 x 365 mm and structural steel has been selected as material.

According to Lockett in [27], this part is suitable for WAAM as it has a buy-to-fly ratio of 10 and its features are thicker than 2mm. Indeed, limited production batch does not justify standard forming technologies such as casting.

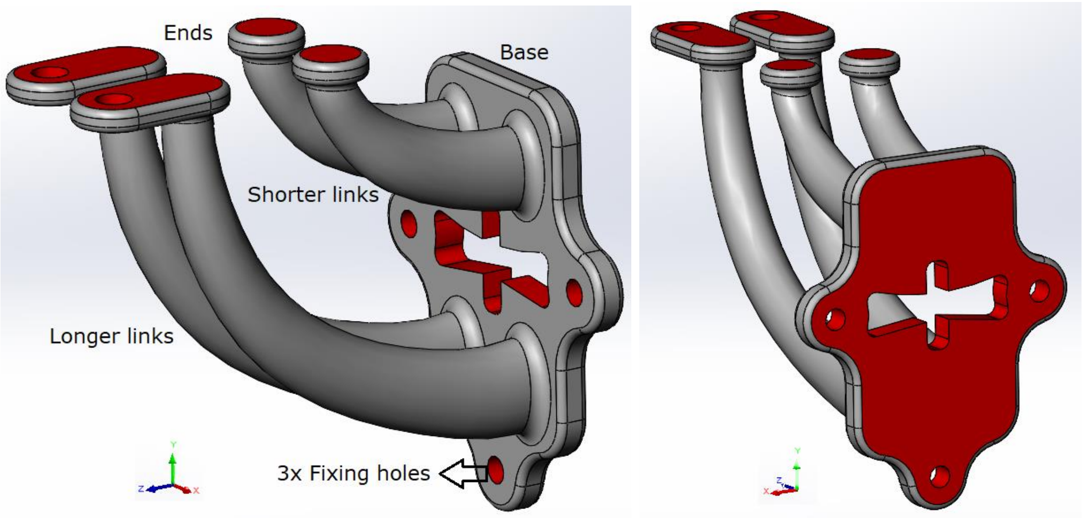

Figure 3: Shelf support with machined features in red.

However, some interfaces require a grade of precision stricter than WAAM can guarantee. Thus, in Fig. 3 the features that requires further machining are highlighted in red: the holes, the center cross cutout and the functional surfaces that are in contact with other bodies. So, the intermediate geometry manufacturable through WAAM is presented in Fig. 4.

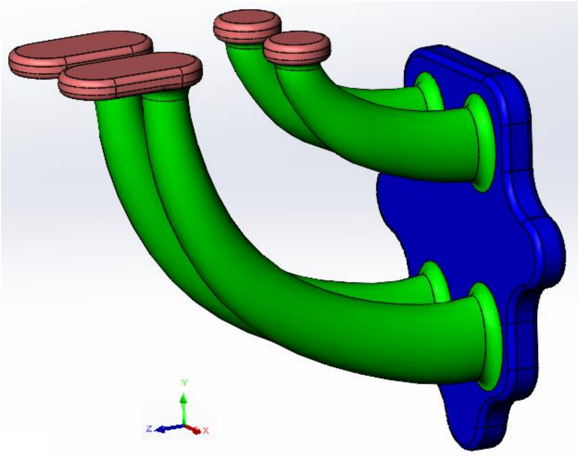

Figure 4: Intermediate shelf support with different sub-volumes: the base (blue), the 4 links (green) and the ends of links (red).

Focusing on the volume subdivision stage, it is possible to identify 9 sub-volumes by using concave loop extraction: the base, the 4 links and the supporting ends of the links.

Next, the slicing trajectory needs to be identified for each sub-volume. The base slicing direction should be selected carefully. In Fig. 5, the solution is presented. D1 is selected for the centered part of the base. D2 and D3 are the slicing direction of the two overhangs. Here, the welding torch is rotated 90 degrees to guarantee the correct manufacturing [23, 43]. Before continuing with WAAM, subtractive process is performed to manufacture the fixing holes and the centered cross, also increasing the surface finish.

As an alternative, the base could be produced from a sheet metal by laser cutting. Then, the links are added by WAAM.

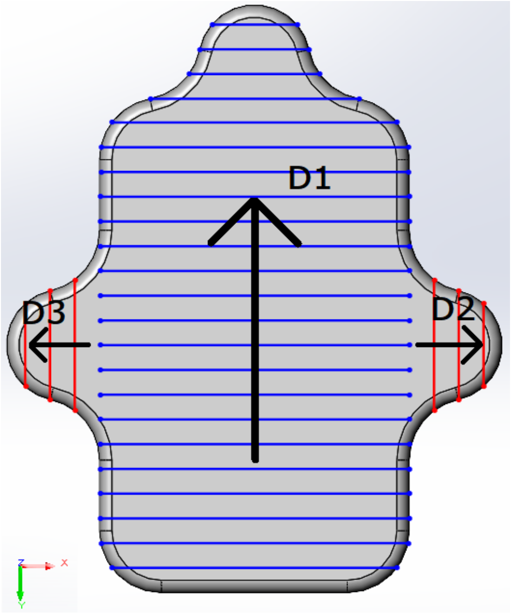

Figure 5: Slicing directions of the base.

Focusing on the 4 links, the slicing direction is drawn from the MA. Generally speaking, considering cylindrical shapes, it is possible to identify two opposite cases for MA extraction. The first case is shown in Fig. 6a where the cylinder has the diameter much granter than its length. The MA is composed of two cone frustums. Here, the building direction must be tangent to the central planar disk surface highlighted in green in Fig. 6a. On the contrary, a cylinder much higher than its diameter, the MA is identified as two cones connected by a line. This line corresponds to the cylinder axis as reported in Fig. 6b. In this case, the MA is approximated to the cylinder axis. In both cases, some extremal portions of the MA must be excluded and simplified to identify curves and/or surfaces whose tangents can drive the growing path.

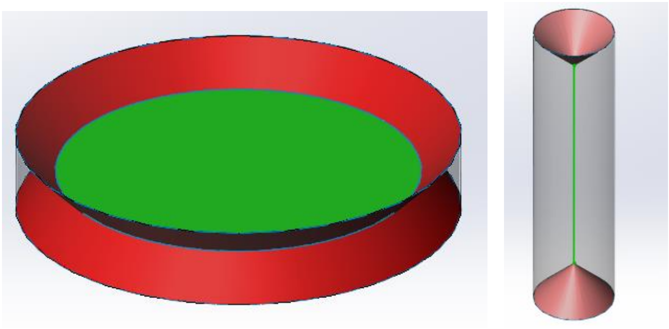

Figure 6: Medial axes of cylindrical shapes: a) flat and wide cylinder, b) thin and long cylinder.

Focusing on the test case, the MA of a shape with non-uniform section ranging from an ellipse to a circle, is quite complex: it exhibits some extremal portions to be simplified while in the mid zone is given by a surface. However, as shown in Fig. 7, it could be approximated to a medial curve that connect the two centers of the start and final section, similarly to the case in Fig. 6b. So, the approximated medial curve of the link is used to generate slicing planes normal to it.

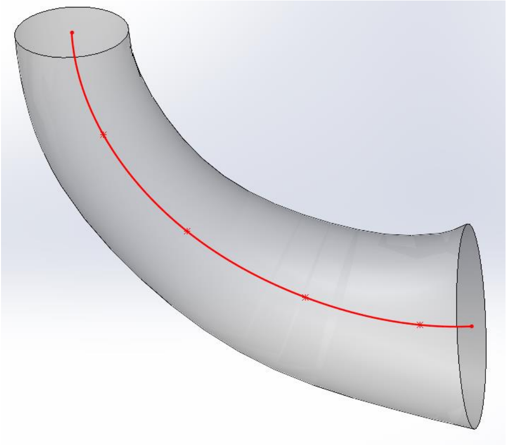

Figure 7: Medial axis of a shape with non-uniform section: approximated MA.

Considering the ends of the links, two different cases are given. On one case two flat cylinders are connected to the short links and their axes are used as slicing direction. On the other case, the ends of the longer links have a large overhang. So, the slicing direction needs to be selected to guarantee a support free growing, also avoiding torch collision with the part. A solution is presented in Fig. 8.

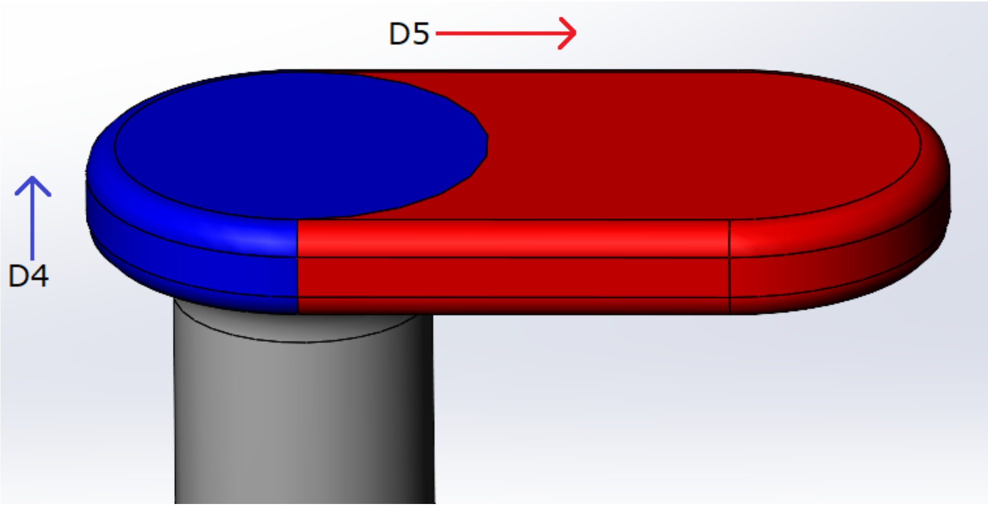

Figure 8: End of the longer links: D4 is the slicing direction for the buildable part (blue); D5 is the slicing direction for the overhanging portion (red).

In conclusion, the whole set of selected build direction are summarized in Fig. 9. Dl1 and Dl2 are the slicing direction of the longer and shorter links respectively. D5 is the slicing direction for the overhang part of the ends of the longer links. D4 is the slicing direction for the ends of the shorter links and for the buildable part of the ends of the longer links. By using this growth sequence, it is possible to produce this part without the use of supports, minimizing material waste and avoiding tool collisions.

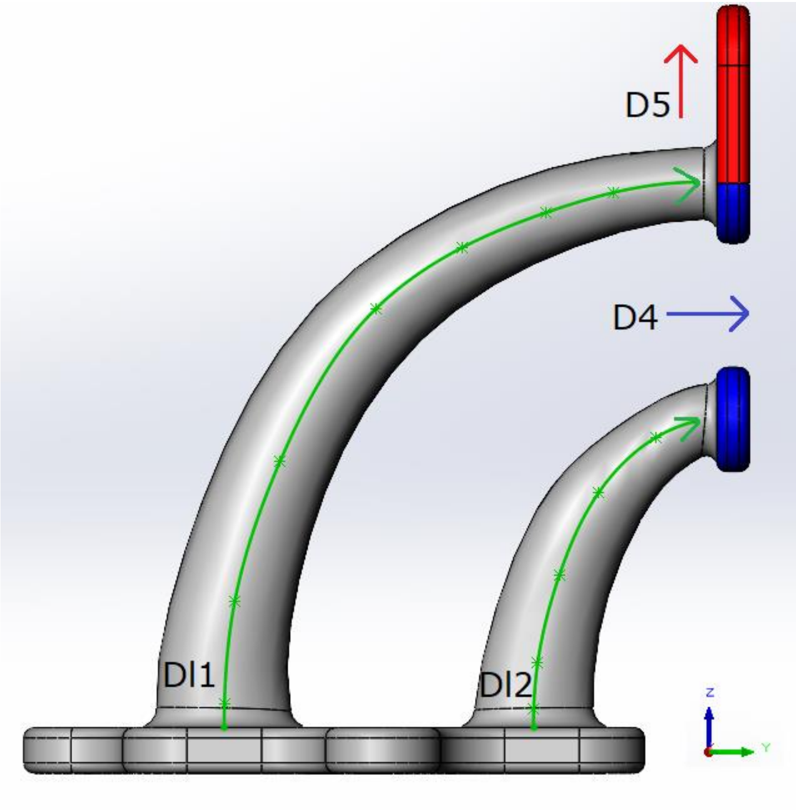

Figure 9: Sub-volumes slicing directions.

The identified growing strategy requires adaptive slicing algorithm with non-uniform thickness which are used for the four links as it drastically reduces the staircase effect [43]. Indeed, planar slicing is applied when possible, even if non planar slices may be required as along direction D5.

For each layer, torch paths are generated to cover the slice area according to standard approaches, by following the perimetral border curves and filling with zigzag trajectories since it is versatile and it reduces residual stresses [44, 45].

The final stage of the process is given by the elaboration of the offline programs for the cell control systems. It consists of the controllers of the robot, the welding gun, the spindle for machining operations. The whole process is then coordinated by a PLC which receives the signals from the sensors and feedback systems and provide instructions to the various controllers.

5 CONCLUSIONS

WAAM provides excellent potential to produce large metal parts with a lower capital investment and higher deposition rates compared to other AM technologies. However, there are many challenges to implement this technology in real production environments. This paper has presented a holistic framework to foster hybrid manufacturing by means of robotic cells including WAAM and machining technologies merging contributions from the literature. The approach covers all the phases of the product development in a hybrid manufacturing context.

A test case is proposed to underline the heterogeneous steps to be accomplished and supported with adequate algorithms.

As future work, such directions need to be explored in detail to fully-automate the geometrical processing of the models. First, candidate selection procedures can be developed as it is an almost uncovered topic in the literature. Also, the medial axis extraction can be leveraged as a powerful tool to drive manufacturing sequence definition. For instance, it could be used as volume subdivision driver and to determine the slicing direction. Then, optimal slicing strategies need to be investigated and tested to minimize part distortion. Finally, the whole framework needs to be implemented to conduct tests in order to measure performances and optimize algorithms and devices.

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