Title:
Analysis of the Requirements of a Framework for the Hybrid Manufacturing of Large Parts

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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 manufacturing option in many industrial applications [20]. 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 [7].

According to ASTM F2792-12a [4], WAAM is classified as direct energy deposition and is basically an automatized welding process. It consists of an automatic wire feeder, a power source, a robot or a numerically controlled worktable, a welding torch and other accessories [9]. The CAD model of the part to be realized is sliced into 2.5D layers. For each layer a tool path is generated. The part is then obtained thanks to the welding gun which is moved by the anthropomorphic robot according to the generated paths [12]. WAAM is further divided into three main categories: Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) based [16]. Among these, GMAW is the most common option and 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 [18].

Nonetheless, WAAM exhibits some drawbacks and often receives less attention than other AM processes [16]. Firstly, 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 reduce such stresses. For example, in [15] the authors have pre-heated the substrate to ensure a more homogeneous temperature distribution. Another strategy 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 [14]. Another common WAAM issue is related to the poor accuracy, about ±0.2mm, and low surface finish which is usually unacceptable for many applications unless successive milling operation are performed. However, one of the critical challenges is the determination of the optimal sequence of the two processes, which must be alternated and optimized to avoid tool collisions and to reduce the final total cost [5]. Another important problem regards solid layers that cannot be filled to form a smooth surface, resulting in inner gaps or voids. Different path strategies have been studied to reduce voids and gaps [6]. Also, cold rolling has been used to increase the smoothness, also reducing the residual stresses [11].

So far, WAAM lacks an integrated, reliable and standardized process monitoring and control systems during the deposition. Sensors can be used to monitor the temperature during the deposition and to control the bead geometry [22]. In a closed-loop environment all these measures could be useful to avoid defects and to increase the quality of the final product [3]. Also, CAD tools dedicated to the WAAM process are limited and not widespread. 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 [21], a spin-off of Cranfield University, has developed four software in order to optimize and control the WAAM process: WAAMPlanner that is used to automatically generate the path tool; WAAMKeys could calculate the optimal process parameters according to the material, the geometry, the build strategy and the machine architecture; WAAMCtrl enables to control the entire deposition process from the operator's desk via user-centric interface; WAAMDisplay helps 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 that can create the tool path starting from CAD file, also generating the robot commands. 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 [8]. The authors have developed custom slicing algorithms to optimize the build direction of product features, thus guaranteeing the material deposition along multi directions. Even simulation software, such as Simufact Welding [19], Simulia [1] and Esi Sysweld [10], 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.

Such overview highlights how WAAM technology is still at an initial stage, even if a promising development 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 are just at an initial stage [14]. 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.

However, most of research is focused on single issues addressed on prototypal laboratory setups, and an overall framework aimed at the implementation of the WAAM is missing. The definition of guidelines and design rules, the selection of the most suitable candidates in an early phase, the selection of set of suitable hardware systems, software elements and data exchange capabilities would lead to a deeper understanding of WAAM, thus increasing its accessibility in the industrial practice.

Main idea:

This work presents a holistic framework, which is developed aiming at guiding the implementation of hybrid manufacturing cells based on both WAAM and subtractive machining processes. As a matter of fact, the parts produced through WAAM have poor surface quality and present surface waviness. So, the machining process is combined and integrated in the WAAM cell, guaranteeing the development of finished product. To achieve such goal, several hardware and software elements must be combined and integrated together. The main parts of this framework are summarized in Fig. 1. The elements of the proposed framework are here explained in detail.

The first step is the selection of suitable candidates for this technology. This topic has been marginally explored in the literature [17], despite its importance for a wider implementation in the industry. In [14] an effective tool to analyze the suitability of a product for WAAM production based on its geometry has been proposed. Minimum and maximum bounding box measures 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.

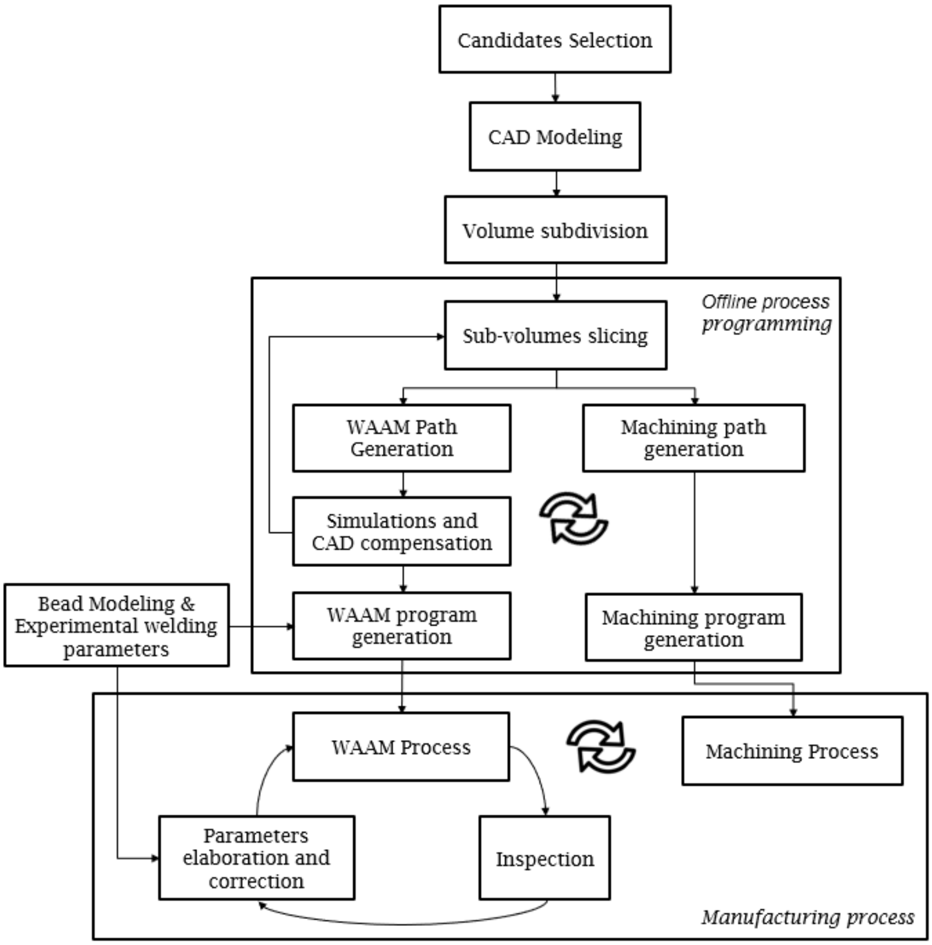

Fig. 1: General framework to approach a WAAM hybrid manufacturing process.

Once suitable candidates have been identified, their geometry is obtained according to the specific design requirements. In this step, CAD systems, 3D scanning and Topology Optimization (TO) software is mostly used. Furthermore, the designer must consider the compatibility of the generated geometry with post processing operations, including machining on functional faces. As introduced in the previous section, the development of design guidelines, i.e. a Design for WAAM (DfWAAM), would ensure better part design, thus optimizing the materials waste and production cost. Finally, CAD model should be stored through suitable standard formats (stl, 3MF, STEP, etc.), which are asked to be able to convey geometry as well as annotations with process related attributes.

Following Fig. 1, a next step is given by the volume subdivision, an important phase for a good achievement of quality parts. The subdivision of whole solid in volumes allows to define a sequence of separated growing steps, possibly interleaved by machining phases. Each subdivision must be optimized to guarantee a feasible growing path, minimize overhang portions and required supports, but also to 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 [8]. Indeed, a correct alternation between additive and subtractive phases is mandatory to achieve the required surfaces quality while containing the overall manufacturing times and cost.

Next, the process moves on to the offline programming step. This phase is composed of different sub-steps. First, the sub-volumes are sliced along their optimal direction. According to [8], the optimal build direction could be identified by using Gauss Maps and multi criteria decision making approaches. The literature reports few slicing approaches, such as uniform or adaptive, planar or non-planar slice generation [23]. After the slicing process is completed, 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 [6]. Here, it is important to leverage experimental bead creation models to understand how related dimensions, such as height and thickness, depend on the process parameters.

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 [13].

Once the offline simulation and planning activities have been completed, the manufacturing step can be accomplished. 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 [22], 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, and aims at adapting 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.

Conclusions:

This paper presents a holistic framework to foster hybrid manufacturing by means of robotic cells including WAAM and machining technologies. The approach covers all the phases of the product development in a hybrid manufacturing context. It is composed of five main phases: candidate selection, CAD modeling, volume subdivision, offline process programming and manufacturing process. Special attention has been given to flexibility and closed loop control strategies to ensure best manufacturing quality.

References:

[1] 3DS Simulia, https://www.3ds.com/, Dassault System. Accessed on 29 Jan 2021

[2] ABB Robotics, https://new.abb.com/, Accessed on 29 Jan 2021

[3] Artaza, T.; Alberdi, A.; Murua, M.; Gorrotxategi, J.; Frías, J.; Puertas, G.; Melchor M. A.; Mugica, D.; Suárez, A.: Design and integration of WAAM technology and in situ monitoring system in a gantry machine, Procedia Manufacturing, 13, 2017, 778-785. https://doi.org/10.1016/j.promfg.2017.09.184

[4] ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies, (Withdrawn 2015); ASTM International: West Conshohocken, PA, USA, 2012.

[5] Chen, L.; Lau, T. Y; Tang, K.: Manufacturability analysis and process planning for additive and subtractive hybrid manufacturing of Quasirotational parts with columnar features, Computer-Aided Design, 118, 2020; 102759. https://doi.org/10.1016/j.cad.2019.102759

[6] Ding, D.; Pan, Z. S; Cuiuri D.; Li, H.: A tool-path generation strategy for wire and arc additive manufacturing, The international journal of advanced manufacturing technology, 73(1), 2014, 173–183. https://doi.org/10.1007/s00170-014-5808-5

[7] Ding, D.; Pan, Z.; Cuiuri, D.; Li, H.: Wire-feed additive manufacturing of metal components: technologies, developments and future interests, The International Journal of Advanced Manufacturing Technology, 81(1-4), 2015, 465–481. https://doi.org/10.1007/s00170-015-7077-3

[8] Ding. D.; Pan, Z.; Cuiuri, D.; Li, H.; Larkin, N.; Van Duin, S.: Automatic multi-direction slicing algorithms for wire based additive manufacturing, Robotics and Computer-Integrated Manufacturing, 37, 2016, 139-150. https://doi.org/10.1016/j.rcim.2015.09.002

[9] Ding, J.; Martina, F.; Williams, S.: Production of large metallic components by additive manufacture – issues and achievements, 1st Metallic Materials and Processes: Industrial Challenges, Deauville, FRANCE, 2015.

[10] Esi Sysweld, https://www.esi-group.com/, Esi Group. Accessed on 29 Jan 2021

[11] Hönnige, J. R.; Colegrove, P. A.; Ganguly, S.; Eimer, E.; Kabra, S.; Williams, S.: Control of residual stress and distortion in aluminium wire + arc additive manufacture with rolling, Additive Manufacturing, 22, 2018, 775–783. https://doi.org/10.1016/j.addma.2018.06.015

[12] Knezović, N.; Topić, A.: Wire and arc additive manufacturing (WAAM)–A new advance in manufacturing, In International Conference “New Technologies, Development and Applications”, Springer, Cham, 2018, 65-71. https://doi.org/10.1007/978-3-319-90893-9_7

[13] Lehmann, C.; Pellicciari, M.; Drust, M.; Gunnink, J. W.: Machining with industrial robots: The COMET project approach, Communications in Computer and Information Science, 371, 2013, 27-36. https://doi.org/10.1007/978-3-642-39223-8_3

[14] Lockett, H.; Ding, J.; Williams, S.; Martina, F.; Lockett, H.: Design for Wire + Arc Additive Manufacture: Design rules and build orientation selection, Journal of Engineering Design, 28(7-9), 2017, 568-598. https://doi.org/10.1080/09544828.2017.1365826

[15] Mughal, M. P.; Fawad, H.; Mufti, R. A.; Siddique, M.: Deformation modelling in layered manufacturing of metallic parts using gas metal arc welding: effect of process parameters, Modelling and Simulation in Materials Science and Engineering, 13(7), 2005, 1187. https://doi.org/10.1088/0965-0393/13/7/013

[16] Pan, Z.; Ding, D.; Wu, B.; Cuiuri, D.; Li, H.; Norrish, J.: Arc welding processes for additive manufacturing: a review, In Transactions on intelligent welding manufacturing, Springer, Singapore, 2018, 3-24. https://doi.org/10.1007/978-981-10-5355-9_1

[17] Raffaeli, R.; Lettori, J.; Schmidt, J.; Peruzzini, M.; Pellicciari, M.: A Systematic Approach for Evaluating the Adoption of Additive Manufacturing in the Product Design Process, Applied Sciences, 11(3), 2021, 1210. https://doi.org/10.3390/app11031210

[18] Rodrigues, T. A.; Duarte, V.; Miranda, R. M.; Santos, T. G.; Oliveira, J. P.: Current status and perspectives on wire and arc additive manufacturing (WAAM), Materials, 12(7), 2019, 1121. https://doi.org/10.3390/ma12071121

[19] Simufact, https://www.simufact.com/, MSC Software. Accessed on 29 Jan 2021

[20] Thompson, M. K; Moroni, G.; Vaneke, T.; Fadel, G.; Campbell, R. I; Gibson, I.; Martina, F.: Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints; CIRP annals 65(2), 2016, 737-760. https://doi.org/10.1016/j.cirp.2016.05.004

[21] WAAM3D, https://waam3d.com/, Accessed on 29 Jan 2021.

[22] Xia, C.; Pan, Z., Polden, J.; Li, H.; Xu, Y.; Chen, S.; Zhang, Y.: A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system, Journal of Manufacturing Systems, 57, 2020, 31-45. https://doi.org/10.1016/j.jmsy.2020.08.008

[23] Zhao, G.; Ma, G.; Feng, J.; Xiao, W.: Nonplanar slicing and path generation methods for robotic additive manufacturing. The International Journal of Advanced Manufacturing Technology, 96(9), 2018, 3149-3159. https://doi.org/10.1007/s00170-018-1772-9