Microstructural, Mechanical and Energy Demand Characterization of Alternative WAAM Techniques for Al-Alloy Parts Production

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Abstract

Additive manufacturing (AM) processes are gathering momentum as an alternative to conventional manufacturing processes. A research effort is being made worldwide to identify the most promising AM approaches. Within this category, wire arc additive manufacturing (WAAM) is among the most interesting, especially when large parts must be manufactured. In this paper, two different WAAM deposition techniques suitable for the deposition of Aluminum alloys, Cold Metal Transfer (CMT) and CMT mix drive, are analyzed and compared. With the aim of obtaining a clear picture concerning the two different techniques, microstructural analyses, mechanical property evaluation and electrical energy demand characterizations were conducted. The results revealed that both techniques allowed sound components to be manufactured and no significant differences were observed in terms of their microstructural and mechanical properties, while CMT was also found to provide a relevant energy saving. This allows the selection of the best technology taking into account not only the geometrical characteristic of the part but also the environmental impact associated to each technique.

Keywords: Additive Manufacturing; WAAM; mechanical properties; energy efficiency.

1. Introduction

Additive manufacturing (AM) processes have proven their suitability for end-use metal component manufacturing. This group of technologies has moved quickly from rapid prototyping to rapid manufacturing over the last 20 years and a large number of research groups have analyzed this process category in terms of their mechanical, economic and environmental performances. These technologies have been adopted by many industrial companies in order to reduce the product development time and enable a cost-effective production of small batches. The use of AM technologies also enables a drastic reduction of the material required for the production of a component, which can be as high as 90% compared with machining (Martina et al. 2012). This is an important advantage when the material to be used is expensive or difficult to machine. The technologies adopted by industrial companies for the deposition of metals are mainly powder-bed solutions that use a laser to melt the material (Olakanmi, 2013), with many commercial solutions already available on the market. However, powder-bed solutions suffer from some constraints: the dimension of the part that can be produced must be small, care must be taken in the management of micrometric powder to avoid health problems for the operators and the deposition rate is low compared to other technologies (Ding et al. 2015). An emerging AM approach is wire arc additive manufacturing (WAAM), which uses a welding machine to melt the material and create a 3D object using a layer-by-layer approach. The main advantages of WAAM are the high deposition rate, which can be as high as 10 kg/hour of deposited material and the virtually unconstrained dimensions of the part to be produced, an example of which is the 6 m long aerospace part produced at the University of Cranfield (Colegrove et al. 2016). Comparing WAAM with the more widespread powder-based AM technologies, WAAM achieves far higher deposition rate but with a far lower geometrical accuracy of the produced surface. Also, WAAM allows only the production of large geometrical features, while powder bed solutions can crate very complex geometries with high surface finish and small details. The main drawback of powder based technologies lies in the small dimension achievable with the available technology level (in general the base dimension is limited to 400 x 400 mm although some larger machine is arriving on the market). Given these characteristics, WAAM is a good option for large part with low surface finish requirements. Higher surface quality could be achieved only by subsequent finishing operations on a machine tool. An example of application could be a large aerospace part with stiffening ribs, designed in order to reduce the buy-to-fly ratio. For this reason, often the test sample for WAAM are simple thin walls.

In this introduction, after presenting WAAM processes, the environmental impact performance of AM (including both powder- and wire-based) processes will be discussed and the potential of WAAM to provide an energy saving will be described. Although WAAM is a promising technology for the production of metal AM parts, it still has some critical issues that must be considered when adopting such an approach. Since WAAM is based on the melting of a metal wire using an electric arc, the thermal cycles due to the layer-by-layer deposition strategy could lead to porosity, undercutting or humping (Busachi et al. 2015) and the microstructure is strongly dependent on the thermal history. An example of the thermal cycle of the part is provided in Figure 1, in which the temperature of a thermocouple on the substrate is reported; the spikes were produced by the deposition of each layer and in this test, an idle time between layers of 30 s was adopted

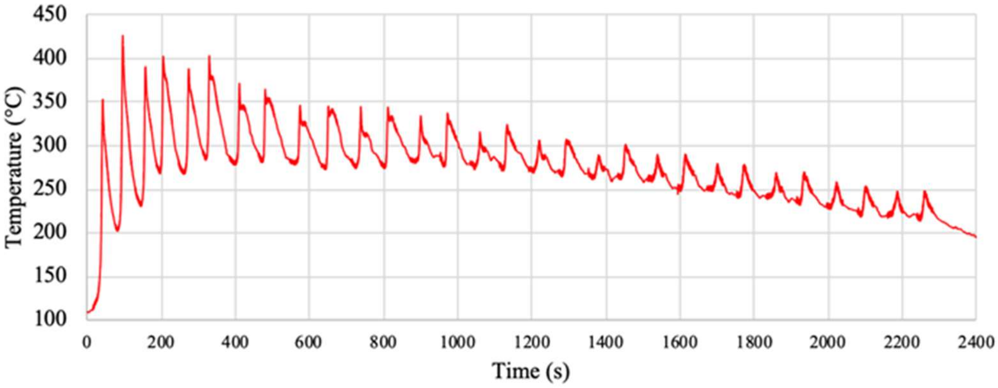

Fig. 1. Example of the temperature of the substrate measured with a thermocouple.

The idle time is strongly dependent on the thermal input of the deposition source, the thermal diffusivity of the material and the volume of the “heat sink” of the part, usually the substrate. This affects both the productivity of the process and the mechanical properties of the material. Concerning the environmental impact of the AM process category (including both powder- and wire-based approaches), it is characterized by some features which, in theory, would make this manufacturing approach an environmentally friendly one. In fact, there is no need to create a tooling for the part fabrication, with an environmental impact reduction especially on low volume production. Nevertheless, the environmental benefit of AM processes is still an open issue and apparently, their suitability in this respect is limited to some specific production scenarios. A comprehensive overview by Kellens et al. (2017) outlined production scenarios in which AM can be beneficial from an environmental perspective. The authors stated that the AM process category includes environmentally friendly options for: 1) lightweight components for aerospace sector production; 2) small batch sizes; and 3) component repair/remanufacturing or spare part production. Gutowsky et al. (2017) further discussed drawbacks in the energy efficiency of AM processes; in this paper, several metals and polymer-based platforms were analyzed. The authors identified the slow print rate (depending on the material and the technologies, could be around tens of grams per minute for powder-bed machines) as the main barrier to the use of AM as an actual manufacturing alternative. In a very recent review paper (Ruschi Mendees Saade et al. 2020), an analysis of life cycle assessment approaches applied to AM processes was reported. The authors again underlined that the environmental competitiveness of AM processes depends on the production scenario. In addition, they identified the need for higher energy/emission efficiency in the printing process as a strategy to increase AM's environmental competitiveness. Regarding powder-based AM processes, aluminum alloys are typically processed by selective laser melting (SLM). It is worth mentioning that, among metals, aluminum is one of the most challenging materials to process using AM. In fact, its high reflectivity as well as its high thermal conductivity (Sistiaga et al. 2016) require a high power laser source to melt the aluminum powder layer by layer. Moreover, aluminum is particularly sensitive to thermal cycling and its deposition using WAAM often leads to intergranular cracks if the heat input and idle time between layers are not properly selected (Horgar et al. 2018). The only paper analyzing the energy characterization of aluminum alloy processing via AM was developed by Faludi et al. (2017) In this paper, a life cycle assessment approach was applied to analyze the environmental impact of the SLM of aluminum alloys. Such aspects make aluminum alloys processing via AM a very high energy demanding approach. In 2018, Ingarao et al. (2018) provided a complete manufacturing approach comparison for aluminum-based components. Specifically, turning, forming and SLM performances were compared from an environmental perspective. All of the energies and material flow of the three different manufacturing approaches were taken into due account. The results revealed that in most of the analyzed scenarios, AM did not appear to be a green solution. The only suitable scenario for aluminum alloys AM application envisages weight reduction and use phase benefits are included; specifically, AM is preferable over conventional manufacturing if the designed component is part of an aircraft assembly. WAAM could be suitable candidate to overcome the environmental sustainability issues of powder-based AM systems; in fact, it is characterized by a higher deposition rate as well as lower power demand of the machine (Jackson et al. 2016). A couple of research papers (Campatelli et al. 2020, Bekker and Verlinden 2018) demonstrated that WAAM can lead to a substantial environmental impact saving compared to conventional manufacturing processes (machining and sand casting) for steel-based part manufacturing. To the authors' best knowledge, the electric energy characterization of WAAM processes for aluminum alloys has not yet been analyzed; this aspect is crucial to explore the sustainability of such a process category for aluminum alloy parts manufacturing.

In this study, the mechanical properties and electrical energy demand of two alternative deposition techniques were compared. The chosen techniques are the Cold Metal Transfer (CMT) and CMT Mix Drive. These techniques are characterized by very different deposition rates; in fact, CMT Mix Drive could be 3.5 times faster than CMT. The process selection led to these two candidates in order to compare two very different set up among the ones suitable for the manufacturing of thin wall with a welding grade aluminum alloy (AWS A5.10 ER4043). The selection is limited since a “cold” process is required in order to reduce the idle time between the deposition of two consecutive layers. CMT and CMT Mix Drive are quite peculiar processes patented by Fronius®, since they couple the pulsing of current and voltage, adopted by other deposition technique, with the oscillating movement of the feed wire that is actuated by a small electrical motor located in the torch. The main difference between the two processes is that CMT mix drive switches between pulsed and CMT, whereas the CMT process is initiated by wire movement reversal. This allows a higher deposition rate but, on the other hand, increases the heat input with respect to the “pure” CMT. The heat input is compatible with the deposition of aluminum, but the thermal history shows generally a higher temperature of the welding bead. The comparison allowed the effect of thermal input on both mechanical properties and electrical efficiency to be evaluated.

2. Experimental procedure

2.1. WAAM processes set-up

The sample geometry selected to evaluate the mechanical and energy demand of WAAM was a vertical straight wall with a thickness of a single bead, since a thin structure represents the best application of WAAM, such as stiffened aeronautical panels (Venturini et al. 2016). The wall length was 140 mm in order to enable the production of samples for mechanical testing. The wire used for the tests was standard welding grade AWS A5.10 ER4043 aluminum with a diameter of 1.2 mm. The chemical composition of the wire is reported in Table 1.

Composition	Si	Fe	Cu	Ti	Al
ER 4043 Wire	5.0	≤ 0.80	≤ 0.30	≤ 0.20	Bal.

Table 1. Chemical composition of ER4043 aluminum wire (wt.%)

The shielding gas was pure argon with a flow rate of 14 dm^3/min. A picture of the produced samples is reported in Figure 2.

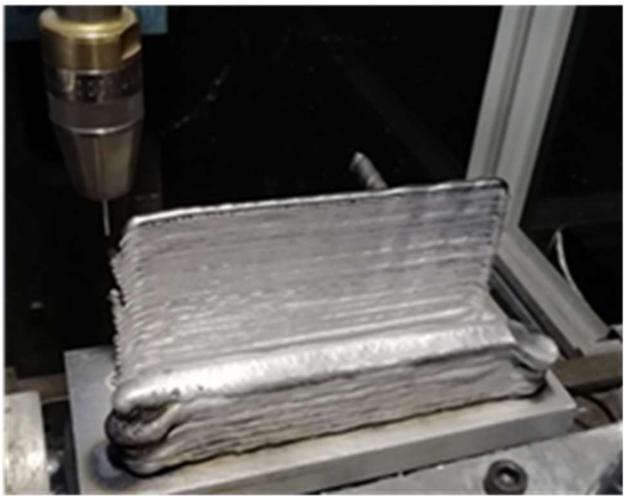

Fig. 2. Examples of the manufactured samples

CMT and CMT mix drive have been initially tested in order to find the optimal process parameters setup able to provide a porosity and cracking free configuration. The welding machine used is a TPSi 320 CMT manufactured by Fronius® that, like many other top-class solutions produced by different manufacturers, uses “synergic modes” that allows the process parameters to be automatically controlled in order to keep the electric arc stable. Small variations of the deposition parameters are automatically and continuously selected by the machine in spite of arc length and arc electrical resistance. These synergic mode cycles are defined by the welding unit manufacturer for different material, including the one used for the tests. Each synergic cycle proposes a set of parameters (voltage, current, wire speed) correlated together, able to adapt their values during the welding process in order to keep the characteristic of the welding bead as constant as possible. It is possible to select one of these three parameters and the others are automatically defined. However, the synergic cycle could be adjusted using the Arc Length Correction factor. In the preliminary tests, after the definition of a welding speed, the wire feed has been changed till achieving a stable geometry of the bead. A small change in the Arc Length Correction has been required only for the first two layers in order to increase the penetration of these beads up to a satisfying value. As briefly explained in the introduction, CMT is a patented technique developed by Fronius® that allows the thermal input of the deposition to be reduced thanks to the synchronous use of micromovements of the welding wire and a voltage pulse with a specific waveform and timing. As soon as the arc is ignited and the tip of the wire is melted, the arc is switched off and the wire is quickly pushed into the melting pool; then it is retracted until it reaches a position where the arc could be ignited again in order to melt another section of the wire. This technique is able to reduce the mean current used to melt the material and thus reduce the heat input of the process, which also leads to an easier deposition of difficult-to-weld materials such as aluminum. There are many variants of CMT that are responsible for different deposition rates and thermal inputs, the one selected for the comparison is CMT mix drive. CMT mix drive has a higher heat input with respect to “pure” CMT since it switches continuously between a pure pulsed mode and a CMT one. This results in a higher thermal input that leads to higher penetration and deposition rate, still maintaining the conditions required for welding Aluminum alloys.

The objective of this paper is to evaluate the effect of the two different metal transfer techniques on the mechanical and metallurgical characteristics of the metal. Since the two techniques have quite different heat inputs, the idle times were selected in order to maintain a similar behavior for the cooling of the material. The strategy adopted was based on an adaptive ideal time based on the temperature of the substrate. The process was set up in order to start the next layer only when the temperature of the substrate (measured with a thermocouple installed at 2 mm from the base of the wall) became lower than 200°C. This temperature has been suggested by the technical assistants of both wire and welding unit manufacturers. This avoids an excessive re-melting of the lower layers. The test cases were designed to have approximately the same weight (150 g) at the end of the deposition; due to the different geometry of the wall, a lower number of beads was required for CMT mix drive. The mean idle time for CMT was approximately 25 s, while for the other case the idle time required to meet the same objective was about 140 s. With this set-up, the overall deposition rate of the two strategies, taking the idle time into account, were quite similar. The process parameters used for CMT and CMT mixed drive are reported in Table 2.

	Current (A)	Voltage (V)	Wire Speed (m/min)	Torch speed (mm/min)	Deposition rate for a single bead (mm^3/s)	Overall deposition rate (mm^3/s)
CMT	32	11.1	1.8	300	35.3	18.7
CMT Mix Drive	133	18.5	6.0	300	113.5	20.6

Table 2. Process parameters used for CMT and CMT mixed drive

The data in the table show how CMT is characterized by a lower deposition rate during the building up of the bead due to the lower wire speed, but also a lower heat input due to less demanding electrical parameters. This is true if the production of a single bead is considered, like in a traditional welding process. When taking into account the idle required for the production of thin wall structures, no relevant difference between CMT and CMT mix drive is observed. The higher deposition rate of the CMT mix drive has a reduced effect on productivity of thin wall than traditional welding. The mean building time for CMT was 2’818 s for 143 g while for CMT mix drive 2’732 s for 151 g. Furthermore, the geometry of the bead is quite different, CMT is responsible for a thin bead, while CMT mix drive creates very large beads that have a low vertical layer-by-layer progression, as reported in Figure 2.

2.2 Electric energy demand measurement

In order to enable a comparison of the processes, the energy consumption of the welding machine was recorded during the deposition using a high frequency data logger embedded on the power source. The data were acquired for each layer (deposition length: 140 mm) and a very good repeatability was found between layers; small variations were due to the synergic approach that slightly adapted the wire speed and process parameters in order to maintain the stability of the arc.

From the acquired data, reported in table 3, it was possible to calculate the Specific Energy Consumption (SEC) for a kg of deposited aluminum for the two deposition strategies, as presented by Campatelli et al. (2020). SEC, expressed in MJ/kg of deposited material, could be obtained dividing the energy consumed to create each bead by the weight of the bead itself, obtained by the bead volume. It represents the energy required to deposit a reference quantity of a material, usually one kg. SEC could be used to compare the energy efficiency of different processes. In section 3.3 of SEC of alternative AM processes to create an Aluminum part is provided.

	Current (A)		Voltage (V)		Wire speed (m/min)		Bead volume (mm^3)		Electric energy required for a single bead (kJ)		SEC (MJ/kg)	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
CMT	32.1	0.32	11.2	0.25	1.80	0.06	958	33.1	9.28	0.32	3.58	0.14
CMT Mix Drive	132	0.33	18.8	0.20	6.02	0.04	3307	41.1	78.4	0.76	8.78	0.12

Table 3. Main electrical data for energy measurements (mean - μ- and standard deviation - σ- are provided)

2.3. Testing procedure for mechanical and morphological analyses

In order to analyze the mechanical properties of the obtained samples for the two different CMT welding techniques, tensile tests and microhardness measurements were performed. In relation to the tensile test, three different samples were cut from the WAAM-processed parts along two different directions. The ASTM E8 standard was followed to cut off proper tensile test shapes. Specifically, the tensile test samples were designed to test the mechanical properties along two orthogonal directions: along (longitudinal samples) and transverse (transversal samples) to the disposition direction. The samples' positioning is highlighted in Figure 3.

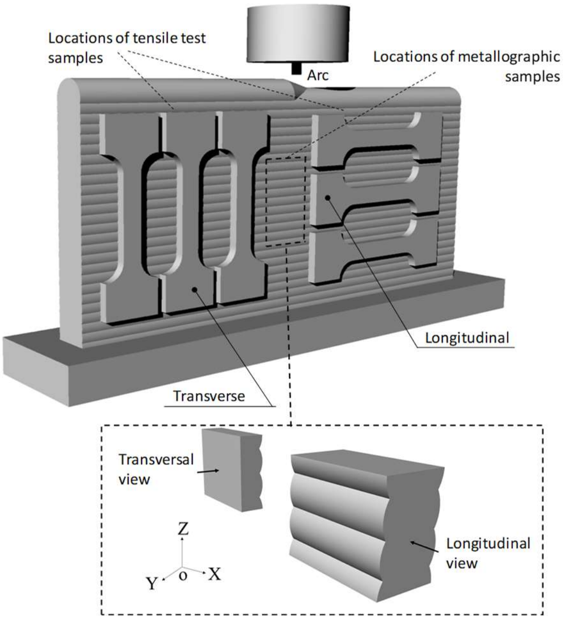

Fig. 3. Positioning of the samples for mechanical properties characterization

In this figure, the position of the sample cut from the part for hardness and morphological analyses are also reported. For each welding technology, microhardness tests were conducted on two different cross sections as reported in Figure 3. To be more specific, Vickers method was applied with a load equal to 500 gr, the hardness values were acquired in order to uniformly cover all the analyzed sections.

For the morphological analyses, the samples were embedded, ground, polished and etched using Keller's etchant (190 mL water, 2 mL HF, 3 mL HCl and 5 mL H_3NO_2) to reveal the microstructure. Optical microscopy was used to show the morphological characteristics of the obtained WAAM-processed parts.

3. Results

3.1. Microstructure analysis

Optical microstructure analyses showed fully sound samples as neither porosity nor intergranular cracks were observed.

In figure 4 the analyzed cross section for the CMT mix drive is reported. As it can be observed all the deposited layers are visible. In figure 4 enlargements of four different zones (zone a,b,c,d) are reported. In general, the microstructure of the deposited materials for CMT mix drive had the typical solidification structure of Al-Si alloys. It was composed of an aluminum solid solution with a dendritic aspect separated by an Al-Si eutectic. In addition, no visible difference was observed with varying the section orientation, Therefore, for the sake of clarity, only comments on the longitudinal view will be reported here.

Overall, a quite fine distribution of the dendrite cells could be observed and, in the analyzed samples, equiaxed dendrites were observed as no obvious morphological orientation was visible. Also, no relevant difference was observed in size and orientation of the microstructure moving from zone a up to zone d.

In the CMT mix drive samples, it was observed that the size of the dendritic structure changed in the interlayer zones (b and c) of the analyzed section. Actually, a refinement occurs in the interlayer because of a faster cooling rate.

As a matter of fact, two zones characterized by two different sizes could be identified. For the sake of clarity, in figure 5 an evident refinement phenomenon, detected in one of the analyzed samples, is shown. The refinement occurred in the interlayer region highlighted in with the boundary layer dotted line. Similar results using this alloy were obtained by Miao et al. (2020). The authors identified two zones: the heat affected zone (HAZ, coarser structure) and Arc Zone (AZ, finer structure) and they explained that the formation of HAZ with larger grains was due to the reheating process in multi-layer deposition processes where the reheating of a region belonging to the previous deposited layers occurs, causing grain growth.

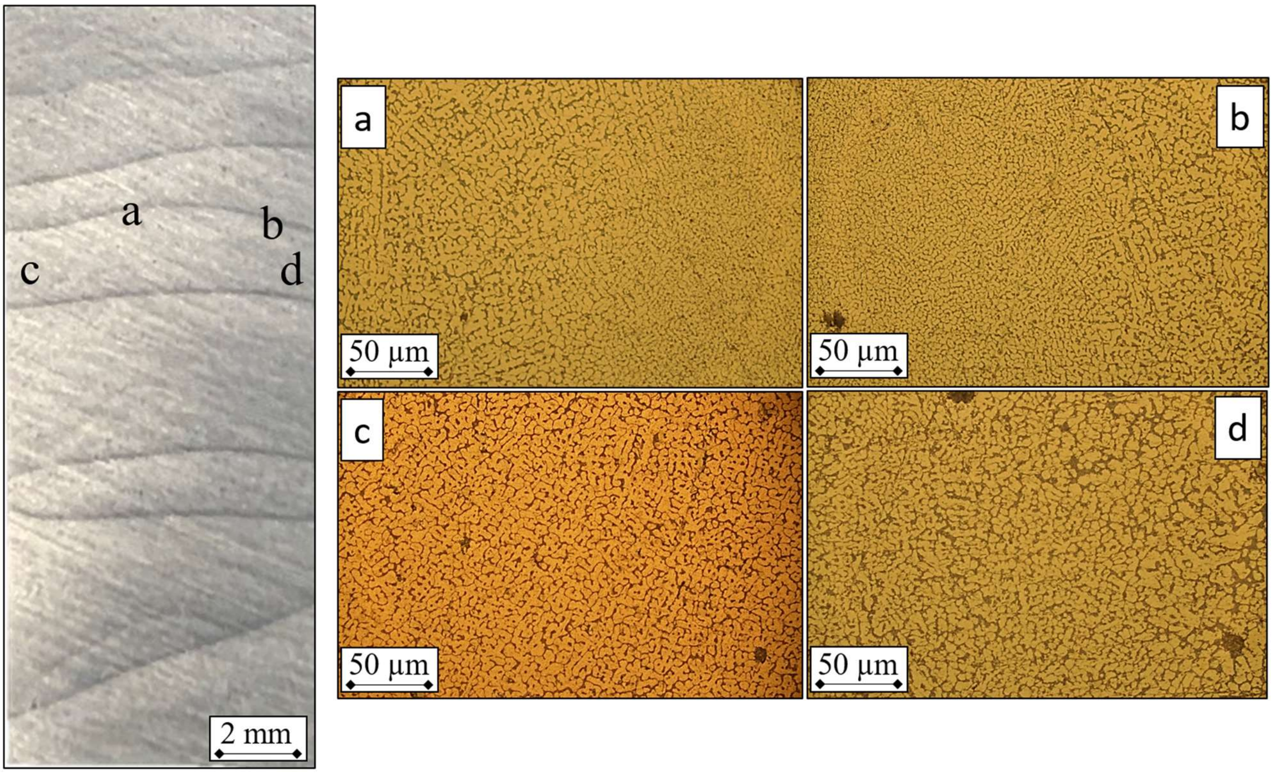

Figure 4: Cross section (longitudinal view) of WAAM CMT mix drive, esthetical appearance and optical micrographs (a,b,c,d).

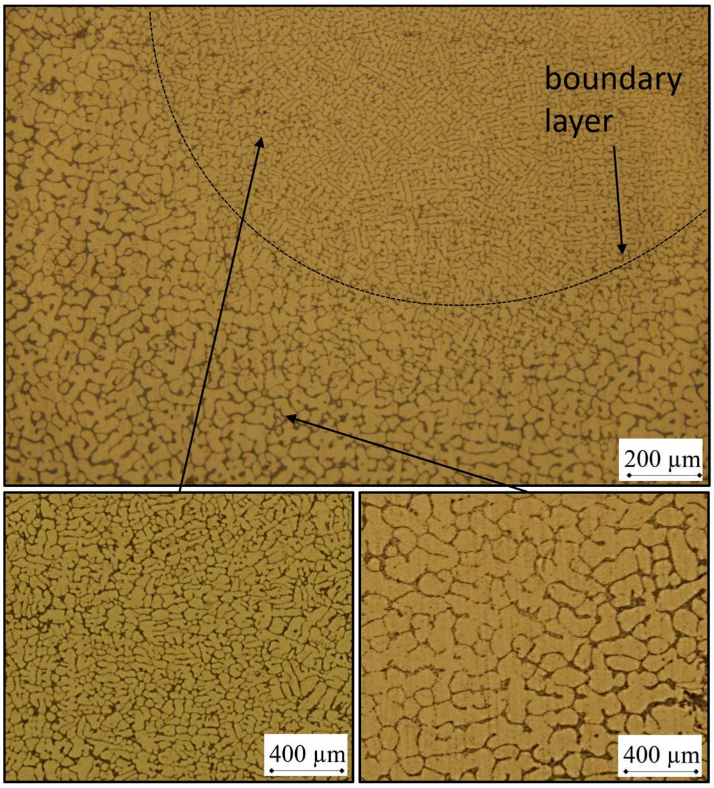

Fig. 5. Example of boundary layer for WAAM CMT mix drive.

In the CTM sample (see Figure 6), a less uniform structure was observed with a comparable (slightly larger) microstructure size with respect CMT mix drive if the zone above the boundary layer of figure 5 (Arc zone) is considered. The microstructure size of CMT is finer in the other zones of the samples. This is due to both the lower heat input as well as a thinner wall size of the CMT technology. The refinement in the interlayer zone is less evident but still visible (see figure 6 zone c)

Moreover, a difference in morphology was apparent. In fact, along with some equiaxed dendrites, some columnar dendrites could be observed (see figure 6 zone a)

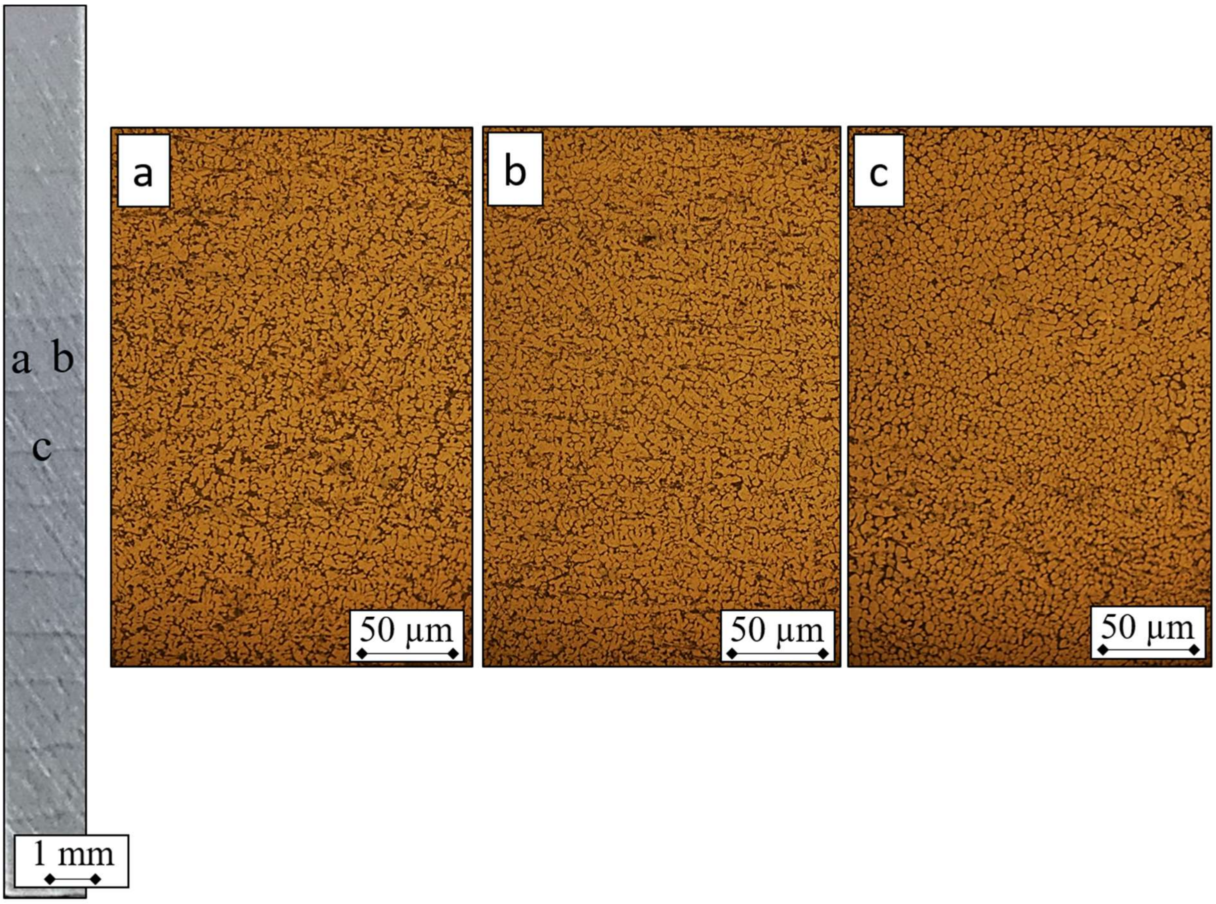

Figure 6: Cross section (longitudinal view) of WAAM CMT, esthetical appearance and optical micrographs (a,b,c).

Nevertheless, such a slight worsening in structure morphology and structure did not affect the mechanical properties of the CMT WAAM-processed component compared to the CMT version; these aspects are discussed in section 3.2.

3.2. Mechanical properties

Ultimate tensile stress (UTS) and microhardness values (HV) are discussed in this section to characterize the mechanical properties of the WAAM-processed samples for both of the considered technologies. The average value of the HV of the analyzed sections along with the obtained UTS values are reported in Figure 7. For each UTS value, the scattering due to test repetition variability is reported. Since three tests were performed for each sample, the scattering refers to the minimum and maximum value recorded. Concerning microhardness values, no significant difference across the analyzed sections were observed.

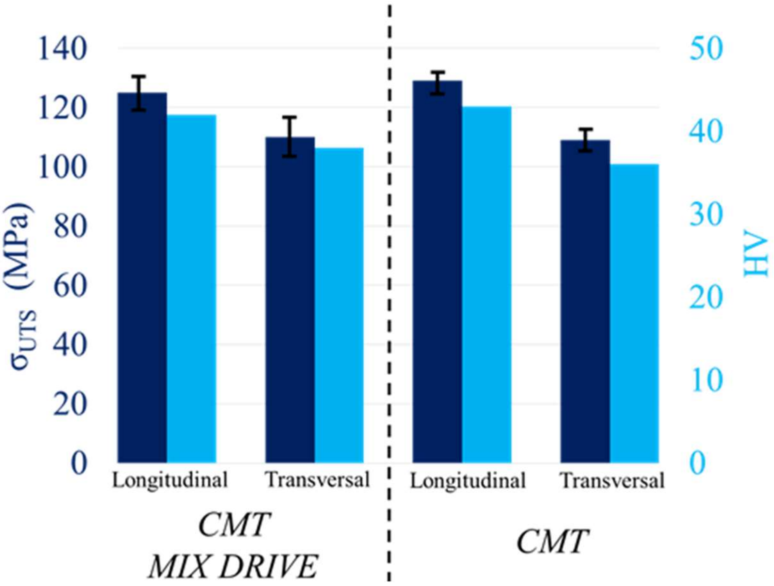

Fig. 7. Mechanical properties of the analyzed samples.

As already highlighted by other researchers (Qi et al. 2018 a, Qi et al. 2018 b), hardness and UTS values were slightly lower along the transversal direction for both of the analyzed strategies. Larger differences in mechanical properties were obtained for the CMT technology, which was due to the less uniform structure with some columnar dendrites, as described in section 3.1. Overall, it can be stated that no significant differences in mechanical properties between the two different CMT technologies were observed.

3.3. Electric Energy demand characterization

The specific energy consumption (SEC) is the most commonly used metric for comparing the electrical performance of manufacturing processes (Gutowski et al. 2017). It refers to the electrical energy needed by a given manufacturing process to process a unit mass of material. It is used for characterizing both subtractive (energy needed/kg of removed material) and additive (energy needed/kg of deposited material) processes. In order to present the electric energy performance of the analyzed processes, the calculated SEC values have been listed in Table 4 and compared to those characterizing the AM powder-based (powder bed) processes. In particular, for the latter process, the SEC value characterizing the SLM of aluminum alloys quantified by Faludi et al. (2017) was used. For the SLM process, two values are reported corresponding to single part manufacturing and to full build experiments with multiple parts. In fact, it has been shown that the capacity utilization has an impact on process energy efficiency (Baumers et al 2011).

AM technology	SEC (MJ/kg)	Reference
SLM Full build	471	Faludi et al. (2017)
SLM Single part	984	Faludi et al. (2017)
WAAM CMT Mix Drive	8.8	Quantified
WAAM CMT	3.6	Quantified

Table 4. SEC values for different aluminum AM technology

The CMT process provides the best performance and allows a substantial energy saving with respect to the mix drive version. In addition, the SEC of powder-based SLM approaches are higher by more than on order of magnitude with respect to WAAM. This large difference highlights the potential of WAAM processes in reducing the environmental impact of AM aluminum-based components. It is not fair to label a priori the wire-based process as more environmentally friendly with respect to powder-based AM approaches, however. As a matter of fact, the WAAM process has a worse deposition resolution and therefore, is a less efficient solution due to the amount of the material it uses and the requirement for additional finishing operations. In conclusion, for WAAM, the amount of material to be machined off during finishing operations is higher with respect to the AM powder-based processes. Depending the production scenario (product geometry complexity and required surface finish), both electric energy consumption and material production related impacts are to be considered when identifying the greener technology.

4. Conclusions

In this paper, a comparative analysis between two different deposition techniques for WAAM was applied to the manufacture of Al-alloy components, namely CMT and CMT mix drive. These techniques were analyzed from different perspectives; In fact, microstructures, mechanical properties and electrical energy demands were quantified and compared.

Both of the selected techniques allow defect-free thin walled parts (most common application of WAAM) to be produced. The tests highlighted that the parts were fully dense, and no intergranular cracks were observed. Although CMT resulted in a less uniform microstructure with some columnar dendrites, no significant difference in mechanical properties was observed respect to CMT mix drive, characterized by a far larger heat input. In fact, similar hardness and tensile strength values were obtained for the two analyzed deposition techniques. Microstructures and mechanical properties were analyzed along two orthogonal directions: along and transverse to the disposition direction. No significant differences were observed with varying orientation for the analyzed output.

Unlike the microstructural and mechanical property performances, a substantial difference was found in electrical energy demands. In this paper, the SEC was used as a metric to characterize the energy demand of both CMT and CMT mix drive deposition techniques. The results revealed that CMT offers an energy saving as high as 61% with respect to CMT mix drive. In addition, a comparison with the SEC values reported in the literature for aluminum SLM processes demonstrated that the electric energy demand of WAAM is lower by more than one order of magnitude. Although analyses concerning the material usage are still necessary, since a post processing with a machine tool for surface finishing is often required for WAAM, these results show the potential of WAAM processes to reduce the energy consumption for the production of a metal part using AM techniques. A further step, to a full understanding WAAM environmental impact characterization, could be a comparative analysis including conventional and powder-based manufacturing approaches with varying components geometries and materials.

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