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Wire Arc Additive Manufacturing of Ti-6Al-4V components: the effects of the deposition rate on the cradle-to-gate economic and environmental performance

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Abstract

Wire Arc Additive Manufacturing (WAAM) is a direct energy deposition process based on a wire-shaped metal feedstock which is melted by means of an electric arc to produce and/or repair components in a layer-wise manner. WAAM has shown to be suitable for producing large components, in particular those with a near-to-net shape, at relatively high productivity levels. The aim of this work has been to assess the effects of the WAAM deposition rate on economic and environmental sustainability metrics. A life cycle assessment has been performed under cradle-to-gate system boundaries. Three components, with different geometrical characteristics (i.e., dimensions, masses, and solid-to-cavity ratios) and made of Ti-6Al-4V, have been considered as case studies. The effects of different deposition rates have been evaluated on the Cumulative Energy Demand, CO_2 emissions, manufacturing times and costs. The conventional manufacturing route for the production of the same components, that is, machining from massive workpieces, has been considered as a benchmark for a process performance comparison. The results show that an increase in the deposition rate determines a significant reduction (up to 25%, on average) in the production time and, consequently, in the manufacturing costs.

Keywords: Additive manufacturing; WAAM; Deposition rate; Cumulative energy demand; Cost assessment.

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1. Introduction

High rates of material deposition per hour and large build envelopes are necessary to economically produce large components with Additive Manufacturing (AM) [1]. Deposition Rates (DRs) as high as possible are desirable, while considering the productivity limits dictated by physics, to obtain low production times and low related costs [2]. To this aim, as metal AM has grown, the interest of industry has been focusing on those technologies that are suitable for producing large components at high DRs [3]. Metal Wire Deposition (MWD) processes, and Wire Arc Additive Manufacturing (WAAM) in particular, have captured attention as valid alternatives to conventional manufacturing processes. WAAM allows parts characterized by low-to-medium complexity and large sizes, which, if manufactured with traditional manufacturing routes, would lead to high buy-to-fly (BTF) ratios (i.e., the ratios between the starting workpiece to the final part mass [4]), to be produced. Together with their high material and power demand efficiency, low investment costs, simple setups, and low environmental impact [3], one of the most important advantages of MWD processes over others is

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their high DR [5]. The literature has reported several examples of experimental tests that show higher DRs for MWD processes than for powder-bed based processes. Some of them have been summarized in Fig. 1, which collects data from different research studies [6–16]. The data in this plot are clustered not only as a function of the form of the feedstock material, but also according to the heat source employed to deposit different materials (e.g., titanium, aluminium, steel, and Inconel): an electron beam, a laser, and an electric arc. Selective Laser Melting (SLM) allows up to 0.1 kg of steel to be deposited per hour, while WAAM technologies can reach values as high as 5-6 kg/h [16]. Sub-groups of experiments have also been identified for arc-based MWD processes: Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), and Gas Metal Arc Welding (GMAW), as well as the latter's Cold Metal Transfer (CMT) sub-variant. GMAW processes result in a higher productivity than GTAW or PAW [17] (even 2-3 times higher [18]). Since the metal wire (which acts as a consumable electrode) and the welding torch are coaxial in GMAW, the deposition paths are simpler than those of GTAW or laser-based MWD, and thus lead to higher DRs [6]. However, PAW and GTAW are more suitable for titanium, because of their more stable arc, since the cathode spot of the electric arc is in a fixed position, thus a stable welding is generated that is not affected by arc wandering or spattering [17, 18]. Fig.1 refers to the deposition of different materials. An effective comparison between DRs can be carried out whenever the material deposited is the same. Instead, using a volumetric or a normalized-by-mass deposition rate can lead to different results. In fact, differences in density can lead to similar mass deposition rates, even though the deposited volume per time unit is higher for lighter materials [19]. Overall, the DR of an AM process depends on several factors:

- the material that has to be deposited: some processes are preferable to others for certain materials (e.g., GMAW is particularly suitable for steel and aluminum but, as mentioned above, arc wandering issues and rough surfaces can occur when titanium is deposited, therefore GTAW and PAW are preferable for the latter material);
- the main process parameters: the combination of the energy provided from the heat source to the metal, the speed at which the wire is supplied, and the speed of the deposition head, usually affect the melting of the material [20];
- the geometrical complexity of the part that has to be deposited: if such complexity is low, especially if coupled with large component size, a WAAM process is preferable to a powder-bed based process [7];
- the equipment configuration: e.g., a double-wire deposition can be operated using a tandem torch [7, 21].

Several researchers have devoted their efforts to improving the DR of WAAM processes in different ways, e.g., by increasing the wire melting rate by changing the deposition current [5], by finding the optimal combination of wire diameter and process parameters [2], by acting on the deposition path [4], by using hot-wire [22] or extra-feeding wires [23]. However, too high DRs can lead to certain disadvantages, such as a lower geometric accuracy and higher BTF ratios: more material is deposited, and this subsequently needs to be removed to obtain the desired geometry [8]. A higher material waste occurs than for medium DR levels. Different studies have focused on the implications of higher DR on the resulting tolerance and surface finish of the deposited parts [24], on the input heat to them, on the generation of defects, and on the homogeneity of the microstructure and mechanical properties [25], as well as the overflow of the melt pool [23]. Nevertheless, there is a lack of information about the environmental and economic impacts of an increase in the deposition rate, besides the effects such an increase could have on productivity.

1.1. Aim and structure of the paper

The aim of this paper has been to evaluate the impact of a variation of the deposition rate of a WAAM process on four representative metrics of its environmental and economic performance. The three titanium components considered as case studies, the experimental setup, and the methodology employed for the environmental and economic assessment are described in Section 2. The data inventory collection is reported in Section 3. The results are presented and discussed in Section 4. The main conclusions and future research perspectives are given in Section 5.

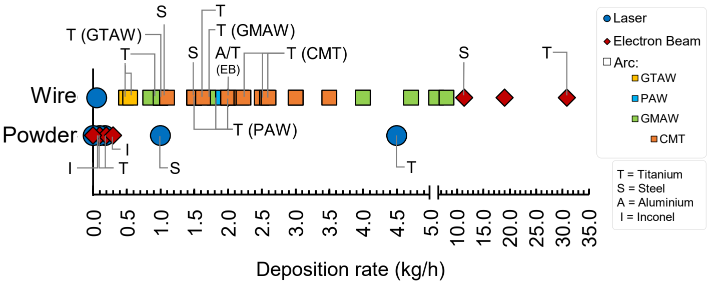

Fig. 1. Deposition rate values for the AM process taken from literature.

2. Materials and methods

In this research study, two manufacturing approaches for the production of three titanium components of different sizes have been compared: (*i*) a WAAM + finishing integrated process (hereafter referred to as WAAM-based approach, 'WB'), and (*ii*) the Conventional Machining of a massive workpiece ('CM'). Both methods were assessed though a cradle-to-gate analysis, in terms of environmental impact, productivity, and production costs. Four metrics were considered for the comparison: the Cumulative Energy Demand (CED), CO_2 emissions, the production times, and financial costs. Such metrics were normalized with reference to the mass of the produced parts, considered as the functional unit. The methodology here applied for three titanium parts was the same as the one proposed in [26], even though some details pertaining to transportation and the selection of the functional unit (i.e., a single produced part in [26]) were different. As far as the integrated WB approach is concerned, once the three components had been deposited – in reference conditions, hereafter named 'Standard' (Std) – the same components were produced by adjusting the process parameters in order to increase the deposition rate and evaluate its effect on the selected metrics (under 'High Deposition Rate' (HDR)-named conditions). Fig. 2 shows the analysis framework defined for the WB approaches, detailing the main steps the three titanium parts underwent within the chosen boundaries. The flow of material is reported for all the life-cycle phases for each part, including also the process scraps. The primary input energy for each phase, and the time required to carry out the material deposition and removal are quantified in the scheme in Fig. 2. Data regarding both the 'Std' and 'HDR' test conditions are detailed. Such a representation was inspired by the Sustainable Value Stream Mapping (Sus-VSM) concept, which is a visual tool that is useful to identify optimization opportunities from both the environmental and economic perspectives [27]. The (*i*) raw material production, (*ii*) pre-manufacturing steps, and (*iii*) machining phase were all modelled on the basis of data extracted from the CES Selector database [28], whereas the WAAM process key values were characterized experimentally. The impacts of transportation were included within the analysis boundaries, considering literature values. The Recycled Content Approach (RCA) [29] was applied for the raw material production to account for the benefits derived from the recycled content in the actual material supply. Hot forming and wire drawing were considered for the wire production, whereas forming was assumed to account for the impact of pre-manufacturing processes for the workpiece and/or substrate production [26]. As for the WB manufacturing phase, the components were deposited by means of an anthropomorphic robot arm held in a static position, a part rotator, and a tailstock to hold the fixtures in place. Plasma Torch Arc (PTA) was employed for the deposition process, and inert gas shielding was applied using the WAAM3D Closed End-Effector Mk1. Specifically, Argon was forced though the torch, thereby producing high-density energy and a stable arc, which decreases contamination, compared to other WAAM processes [14]. Moreover, gas shielding was used to protect the area under active deposition from oxygen, thus preventing both embrittlement and excessive heat accumulation [7]. The target of the process parameters was to maximize the wire feed speed and, in turn, the deposition rate (a key measure of productivity, which has repercussions on the cost), without compromising structural integrity. Preliminary experiments, as well as analytical and numerical solutions of fluid-flow models, were considered for the choice of the main process parameters. Such parameters were generally calculated a priori with minor, local variations tailored to the geometrical features (e.g., intersections and changes in the cross-sectional widths) to achieve a consistent layer height of 1.5 mm and to avoid internal discontinuities. No closed loop controls were used. A high deposition rate, up to 3.04 kg/h, was achieved by maintaining a constant voltage of 23 V and increasing the average current to 300 A, using a wire feed speed of 11 m/min, and a wire diameter of 1.15 mm.

3. Data inventory

The mass flows for the WB approach are quantitively reported in Fig. 2. The mass-related data for the machining-based approach are instead listed in Table 1. As for the material yield factors (i.e., the input/output material ratio that characterizes the different unit processes), 1.05 and 1.14 were considered for hot forming and wire drawing, respectively [28]. A 98%-material utilization fraction was considered for the WAAM process [26]. The eco-properties detailed in Table 2 [28] were used to estimate the energetic burden of the different life-cycle steps. The average embodied energy of the raw material was 556.2 MJ/kg, and the average carbon footprint was 33.0 kg/kg, according to the RCA. A ± 5% range of variation in input data was assumed to account for variability. Details on the WB process are reported in Table 3, together with information on the process parameters, and on the time and shielding gas consumption. The primary energy required for the WB process accounted for the electric energy consumed by the welding machine, and the energy associated with Argon consumption. The electric energy consumption was converted back to oil-equivalent MJ through a 0.38 primary-to-secondary energy conversion factor. As for the GHG intensity of the electric grid, an average value of 0.447 $kgCO_2/kWh$ was used to represent EU electricity production, as in [26] (of which the present research study represents an extension). Nevertheless, this value can be cautiously considered the input of a worst-case scenario, due to the increasing decarbonization of the electric grids through the use of greener energy mixes expected by the 2030 [30]. The Argon production data were extracted from [32]. The arc-on time was varied according to the increased deposition rates (Table 3), while the arc-off time for motion and purging was specifically designed to control the bead geometry and thermal characteristics. The loading and unloading of the part as well as the setup operations, were assumed to last around 2 h. Material Removal Rates (MMRs) of 1.58–2.23 kg/h were considered for roughing and 0.16–0.23 kg/h for finishing for all the machining operations, in both the WB and CM scenarios [26]. The specific energy consumptions for both operations were extracted from the database and are detailed in Table 2. They are expected to include the energy demand for material processing, for operating both the milling machine and the auxiliary equipment, and for the production of the tools and lubricants [28, 31]. A total of 80% of the material was assumed to be removed by rough machining and 20% by finish machining in all the operations. The machining time was estimated as a function of the MRR and the amount of material to be removed. A 32-metric-ton diesel-powered truck, characterized by 0.94 MJ/(ton·km) of primary energy demand and 0.067 kg/(ton·km) of carbon footprint, was assumed to be employed to establish the impact of transportation [33]. Even taking into account the worst-case scenario, i.e., the shipment of the heaviest component, this contribution would result negligible with respect to the total environmental impact [34].

3.1. Cost assessment

As regards the cost evaluation [35], the purchasing of the material was determined as 44.8 €/kg and 112.0 €/kg for the bulk material for the substrate and the titanium wire, respectively. The WB costs were estimated by WAAM3D Limited; the cost of the materials, the capital cost of the equipment, which was amortized over a 5-year period, an 80% utilization factor, labor, and utility costs were all included. The machining-related costs were estimated by considering an indirect cost rate of 17.5 €/h, and standard industrial values for tools, labor, and utility costs.

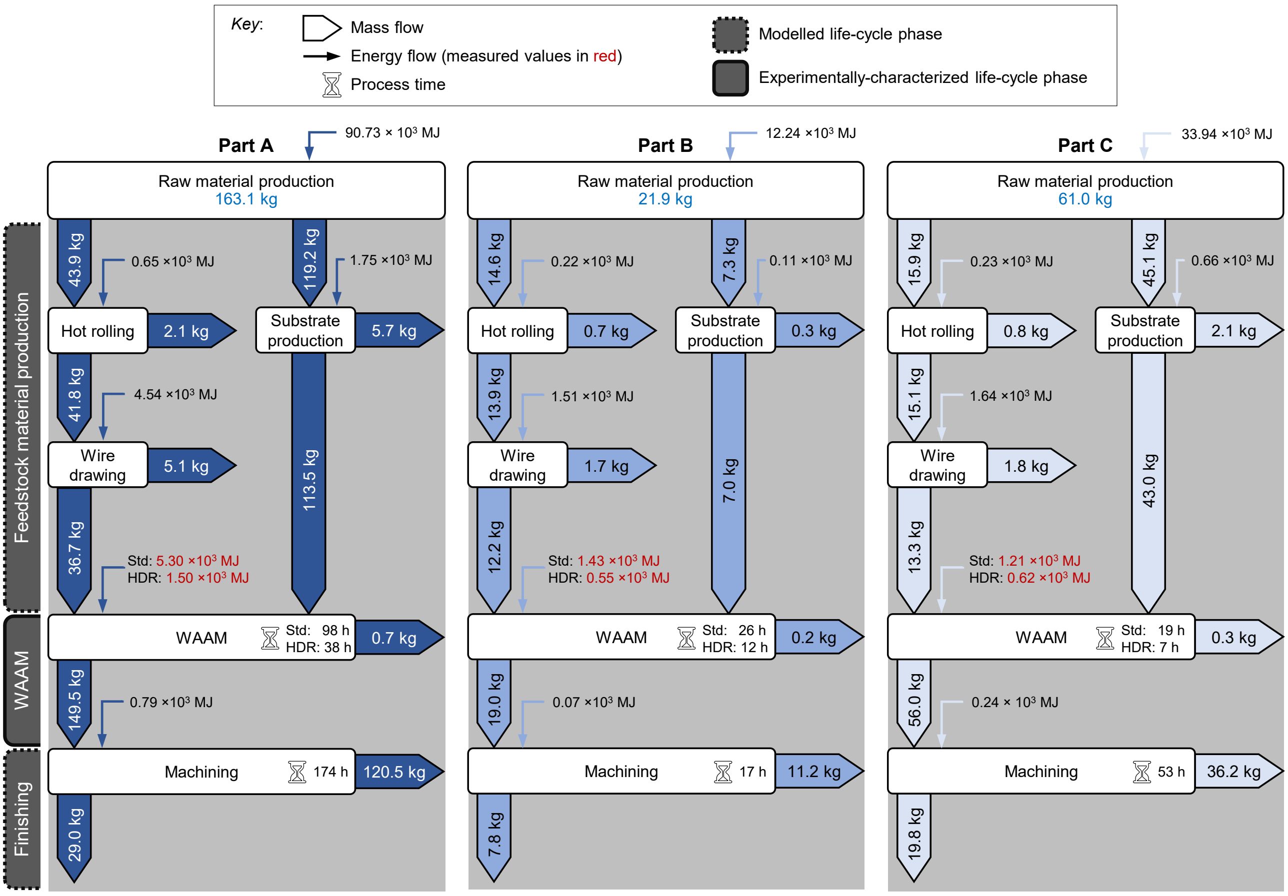

Fig. 1. Framework of the cradle-to-gate assessment, including the mass and the primary energy flows, and the production time for the three titanium parts.

4. Results and discussion

Table 4 shows the results of all the selected metrics considered in the cradle-to-gate analysis. As it can be noted, the HDR-W values are lower than the Std-W ones for each metric. The carbon footprint and the costs of each manufacturing scenario for the titanium components are plotted in Fig.3, with reference to the unit of mass of the final part. The main contribution to carbon emissions is material production, in spite of the benefits derived from the recycled material content in the current supply being included. This is followed by the impact of the pre-manufacturing phase. Metal deposition and removal (considering material removal either as a finishing operation or as the main manufacturing process) contribute to a small portion of the total specific carbon emissions. Despite all this, an increase in the DR for WB production, leads to a lower energy consumption, and thus to lower specific CO_2 emissions, which can be considered as a proxy of the primary energy demand [33]. This reduction can mainly be traced back to the less time needed in HDR tests to deposit the given amount of material; even though higher levels of power are used for the deposition, they are required for a shorter time. The time decrease also affects the quantity of Argon consumed during the (lower) arc-on times. The specific CO_2 emissions are on average lower for additive-based production than for machining for Parts B and C (conventionally characterized by high BTF ratios of 8.0 and 7.0, respectively).

Table 1. Mass flow for the CM-based production of the three titanium parts.

Mass flow contribution (kg)	Part A	Part B	Part C
Raw material	161.7	65.5	145.5
Workpiece	154.0	62.4	138.6
Scraps, workpiece production	7.7	3.1	6.9
Chips, rough machining	100.9	52.4	111.6
Rough-finished component	53.1	10.0	27.0
Chips, finish machining	24.1	2.2	7.2
Component	29.0	7.8	19.8
Buy-to-fly ratio	5.3	8.0	7.0

Table 2. Eco-properties of Ti-6Al-4V [28].

Eco-property	Value
Embodied energy, primary production (MJ/kg)	688.5 ± 5%
CO_2 footprint, primary production (kg/kg)	40.4 ± 5%
Energy for hot forming (MJ/kg)	14.7 ± 5%
CO_2 emissions for hot forming (kg/kg)	1.1 ± 5%
Energy for wire drawing (MJ/kg)	108.5 ± 5%
CO_2 emissions for wire drawing (kg/kg)	8.1 ± 5%
Energy for rough machining (MJ/kg)	2.7 ± 5%
CO_2 emissions for rough machining (kg/kg)	0.2 ± 5%
Energy for finish machining (MJ/kg)	22.1 ± 5%
CO_2 emissions for finish machining (kg/kg)	1.7 ± 5%
Embodied energy, recycling (MJ/kg)	87.2 ± 5%
CO_2 footprint, recycling (kg/kg)	6.8 ± 5%
Recycled fraction in the current material supply (%)	22.0 ± 5%

Only for Part A the total specific CO_2 emissions for the WAAM-based approach are higher than for the machining-based one. This is due to the large amount of feedstock material required for the substrate and the environmental impact associated with its production. The effect of an increase in the deposition rate on the economic burden of a kilogram of processed titanium becomes more evident for the specific cost attributable to the deposition phase. This is mainly due to the reduction of the time the WAAM machine is used. Overall, in this study, the geometry of the components has not been specified for confidentiality reasons. However, the obtained results could, to some extent, be related to the factors of influence already highlighted in other research studies [26].

Table 3. Experimental values pertaining to the WAAM process.

	Part A		Part B		Part C	
Test condition	Std	HDR	Std	HDR	Std	HDR
Arc-on active power (kW)	5.5	9.0	6.1	9.0	6.0	9.0
Wire feed speed (m/min)	1.8	11.0	2.4	11.0	2.8	11.0
Deposition rate (kg/h)	0.50	3.04	0.66	3.04	0.77	3.04
Arc-on time (h)	72.4	11.9	18.2	4.0	16.8	4.3
Arc-off time, Motion (h)	5.5		0.2		0.2	
Arc-off time, Purging (h)	18.3		5.3		n.a.	
Gas consumption, Arc-on time (m^3)	684.0	111.9	165.5	72.1	1.1	0.3
Gas consumption, Purging (m^3)	164.7		48.0		145.0	

Table 4. Cradle-to-gate assessment results for (*i*) Raw material production (RMP), (*ii*) Pre-Manufacturing (Pre-Man), (*iii*) WAAM, (*iv*) Machining.

		Part A			Part B			Part C		
		Std-W	HDR-W	M	Std-W	HDR-W	M	Std-W	HDR-W	M
CED ($\times 10^3$ MJ)	RMP	90.73	90.73	89.94	12.24	12.24	36.44	33.94	33.94	80.94
	Pre-Man.	6.94	6.94	2.38	1.84	1.84	0.96	2.53	2.53	2.14
	WAAM	5.30	1.50	-	1.43	0.55	-	1.21	0.62	-
	Machining	0.79	0.79	0.80	0.07	0.07	0.19	0.24	0.24	0.46
	Tot.	**103.76**	**99.96**	**93.12**	**15.58**	**14.70**	**37.59**	**37.92**	**37.33**	**83.54**
CO_2 emissions ($\times 10^3$ kg)	RMP	5.38	5.38	5.33	0.73	0.73	2.16	2.01	2.01	4.80
	Pre-Man.	0.52	0.52	0.18	0.14	0.14	0.07	0.19	0.19	0.16
	WAAM	0.25	0.07	-	0.07	0.03	-	0.06	0.03	-
	Machining	0.06	0.06	0.06	0.01	0.01	0.01	0.02	0.02	0.03
	Tot.	**6.21**	**6.03**	**5.57**	**0.95**	**0.91**	**2.24**	**2.28**	**2.25**	**4.99**
Time (h)	WAAM	98	38	-	26	12	-	19	7	-
	Machining	174	174	177	17	17	40	53	53	96
	Tot.	**272**	**212**	**177**	**43**	**29**	**40**	**72**	**60**	**96**
Cost ($\times 10^3$ €)	RMP + Pre-Man.	9.20	9.20	6.90	1.68	1.68	2.80	3.41	3.41	6.21
	WAAM	14.41	5.91	-	3.77	1.85	-	4.35	2.65	-
	Machining	7.14	7.14	7.25	0.70	0.70	1.77	2.17	2.17	4.20
	Tot.	**30.75**	**22.25**	**14.15**	**6.15**	**4.23**	**4.57**	**9.93**	**8.23**	**10.41**

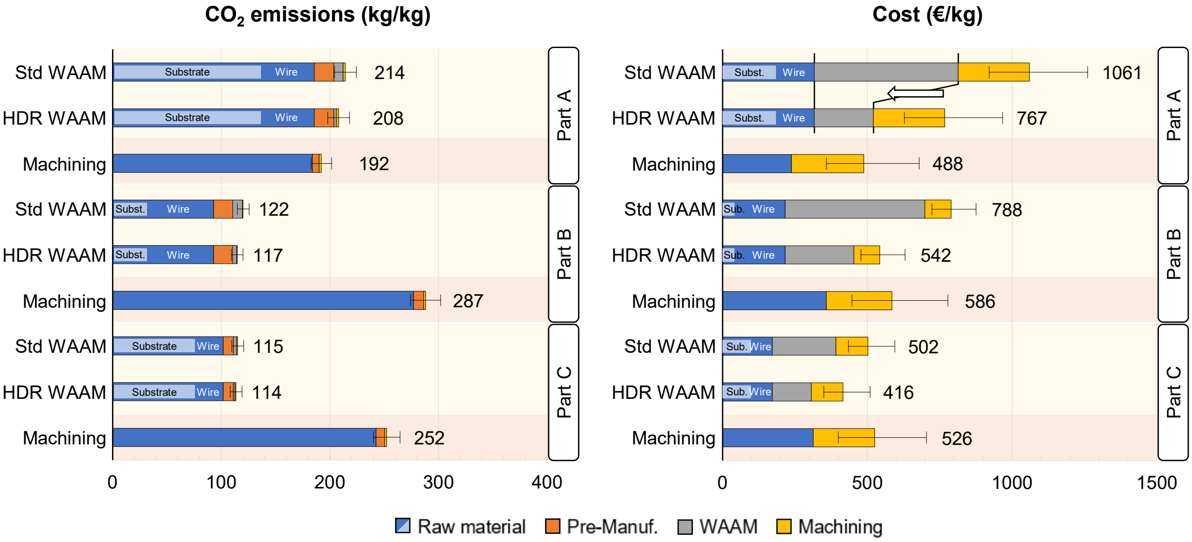

Fig. 3. CO_2 emissions and cost per unit mass of the final part, under cradle-to-gate system boundaries, for both the manufacturing approaches.

5. Conclusions and outlooks

The environmental and economic impacts of the production of three different Ti-6Al-4V components have been assessed by comparing a WAAM-based manufacturing approach and a conventional machining one. Using the same equipment, the deposition rate was increased in the WAAM-based approach by tuning the process parameters. The aim of this research has been to assess the impact of such an increase in the deposition rate on four environmental and economic performance metrics: CED, CO_2 emissions, production times, and production costs. According to the results obtained, changing the process parameters to obtain higher deposition rates can lead to significantly shorter production times and, consequently, to lower associated costs. Most of the environmental impact related to the energy demand and the carbon footprint is associated with material production and pre-manufacturing. Therefore, an optimization aimed at maximizing the energy efficiency of the WAAM unit process might not be sufficient to highly reduce the total impacts if a cradle-to-gate computation is carried out. Even though the overall impact of 'high deposition rate' WAAM-based productions is lower than the corresponding 'standard' ones, the WAAM-based approach is not always more advantageous than the CM-based one. Hence, decision-making strategies are necessary to determine the most sustainable manufacturing approach on a case-by-case basis.

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