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Life cycle sustainability assessment of repair through Wire and Arc Additive Manufacturing

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Abstract Extending the useful life of a product through repair can significantly reduce the environmental impact associated with its production and it can be less resource intensive than other environmentally-virtuous practices like recycling. Wire Arc Additive Manufacturing (WAAM) appears to be a promising approach in this context, being characterized by high-resource efficiency, flexibility to perform repairs and having recently gained industrial maturity. In this work, a methodology to assess the life cycle environmental sustainability of repaired products through WAAM will be presented with a real-world, industrial case study.

Key words: Sustainability, Additive Manufacturing, Modeling and Simulation

1 Introduction

Wire and Arc Additive Manufacturing (WAAM) is a fusion and wire-based Additive Manufacturing (AM) technology that uses a robotic arm to build, layer upon layer, a desired shape [1]. It is characterised by relatively high material deposition rates that makes it well-suited to produce medium-to-large, custom-made components. WAAM is a relatively novel process that has gained considerable industrial attention thanks to its potential to reduce cost and environmental impact in comparison

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to traditional subtractive approaches. In particular, many of the mentioned advantages stem from lower material utilisation, making the process significantly more efficient [2, 3]. Furthermore, other important business drivers for the adoption of WAAM are freedom of design, customisation and faster time to market. In particular, freedom of design creates the opportunity to simplify the manufacture of complex assemblies substituting many subcomponents (that would otherwise be traditionally required) as well as produce objects not constrained by a pre-defined bounding volume [4]. The implementation of WAAM is being considered for several important sectors including aerospace, marine and construction industries [5].

Considering the novel nature of WAAM, its environmental impact has been studied only to a limited extent in the scientific literature. For example, it has been estimated that energy consumption for thin-walled parts is 34% lower in comparison to conventional milling when taking into account also of processes upstream of manufacturing but not including recycling [6]. Other studies have tried to define frameworks to assess energy consumption for additive processes in general, starting from first principles but, although useful, they are not specific enough for industrial applications [7].

WAAM products Life Cycle Assessment (LCA) has been sporadically investigated in the scientific literature. For example, a comparative "cradle-to-gate" (i.e. excluding life cycle phases beyond to shipment to the customer) analysis has been performed estimating cumulative energy consumption and carbon dioxide equivalent emissions of steel parts [8]. Earlier works included the LCA through the Eco-Indicator 99 methodology of direct additive laser manufacturing for Titanium alloys suitable for small and complex parts that showed an environmental impact reduction as high as 70%, but excluded any quantitative considerations about repair routes [9]. Product LCA of less-productive, power-based, additive processes have been studied too: Electron Beam Melting (EBM) has been compared to conventional processes using the Cumulative Exergy Demand and "CML 2 Baseline 2000" methods to assess the environmental impact in combination with dimensionless criteria to support decision making [10]. Another work focussed on novel materials aimed at improving the environmental performance, in a life cycle perspective, considering generically additive manufacturing technologies [11].

As shown, although the LCA of WAAM products has been carried out in the scientific literature, no quantitative works can be found that have comparatively assessed WAAM routes to repair as an alternative to purchasing new units conventionally manufactured. Such analysis is particularly interesting because it combines two rather peculiar characteristics of WAAM: a) enable repair of products that otherwise need to be scrapped and b) perform such repair in a resource-efficient manner. On the other hand, the scientific question arises about the fact that such repair might be offset by the cumulative environmental impact required for the transportation of the damaged products. The current work aims at addressing this question with an industrial case study that paves the way to a future, more comprehensive assessment framework.

2 Methods

Among the various defects that may occur during the operation of parts of industrial interest, this study considers, in particular, the repair by WAAM of morphological ones. Relevant examples of such defects include holes, cracks, segregation, inclusions, surface marks and notches. Such defects are normally superficial and their repair comprises three main steps: removal of defects by machining, deposit material to fill the groove by WAAM and finishing by machining.

The initial part of the study performs a comparative LCA to manufacture the product from the extraction of resource until it reaches the customer (i.e. including the environmental burden of shipment but excluding use). Such analysis allows to better contextualise the results of a second phase that compares the cumulative environmental impact of repair by WAAM with the conventional manufacture of a new item (including transportation). The LCA is carried out in four stages as specified by ISO standard 14044 [12]:

1. goal and scope definition: aim, scope and level of detail of the study are defined;
2. life cycle inventory analysis: defines the inventory of input and output metrics to assess the study previously defined;
3. life cycle impact assessment: opportunely combining the mentioned inventory, the impact can be finally quantitatively assessed;
4. life cycle interpretation: an analysis of the results obtained to enable decision making.

The environmental impact parameters considered are provided by Ansys Granta EduPack [13] specifying a range of typical minimum and maximum values. The analysis is performed considering first mean values of such ranges and then combining the “best” and “worst” case scenario for each manufacturing route that are used to construct error bars. One exception to the above is the environmental impact metrics of the material deposition step of the WAAM process that have been estimated from industrial laboratory measurements. Furthermore, for the assessment of the transportation phase, the intermediate value of environmental impact is not exactly the arithmetic mean of the “best” and “worst” case scenarios but simply the value of a plausible shipment route that falls within the two more extreme cases.

Environmental indicators provided by the database are normalised by mass of material, thus the calculation process performs first material flow calculations to estimate the characteristic mass at each step and then computes appropriately the impact at each stage. To this end, a modern Fortran application stores the LCA routes in the form of a mathematical direct acyclic graph that is first topological sorted and then solves the material flows applying simple mass conservation in conjunction with a scalar root finder (if necessary by the arrangement of steps).

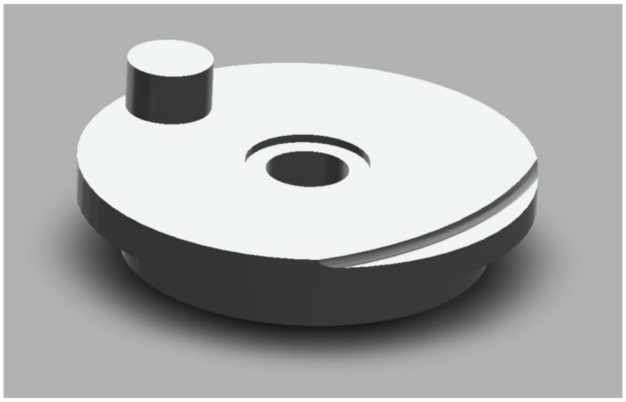

Fig. 1 Simplified CAD model of the driver disk considered as a case study.

Table 1 Materials of the driver disk used for the case study. The WAAM wire is used to deposit the pin on a cylindrical substrate.

Part	Material
Conventional disk	34CrNiMo6
WAAM Wire	ER70
WAAM Substrate	YS600

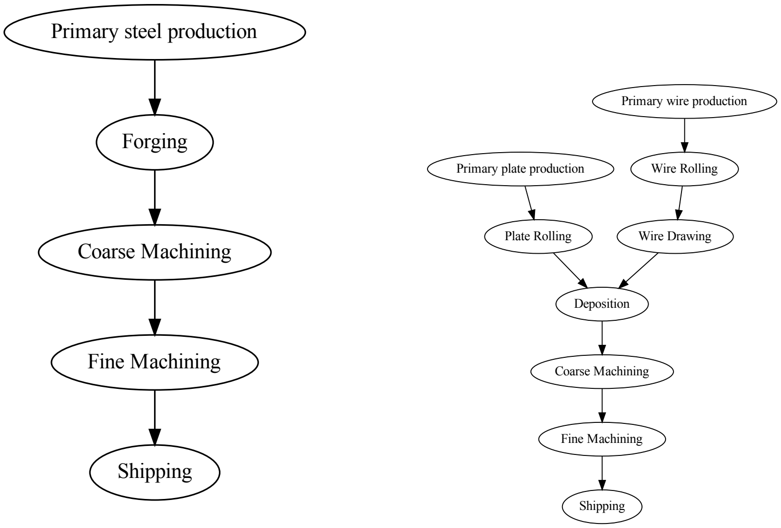

Fig. 2 Conventional (left) and WAAM (right) manufacturing routes to assess the environmental impact of the driver disk used for the case study.

3 Case study

The case study is a steel disk that drives a crank using a protruding pin. A simplified 3D drawing of the part is shown in Fig. 1, whereas similar types of steel are used to manufacture the part (Table 1) according to the conventional and WAAM routes (Fig. 2). The pin is deposited by the WAAM process starting from a wire and all other geometrical features are obtained by machining. For the shipping phase, the final customer is located in Norway and the manufacturing plants are considered in Spain for the conventional case and in Belgium for the WAAM one. An estimate of the distances considered for each mode of transportation is summarised in Table 2 detailing different scenarios (see Methods in Sect. 2). The chosen environmental indicators are the cumulative energy consumption and the amount of equivalent carbon dioxide emissions.

Table 2 Assumptions about the shipping modes and relevant distances for the shipment from the manufacturer to the customer of the driver disk considered as a case study.

Option	Route	Mode	Distance (km)
Mostly air	Conv	Air freight	2150
		2-axle truck	50
	WAAM	Air freight	1065
		2-axle truck	50
Mostly sea	Conv	Coastal freight	4410
		2-axle truck	30
	WAAM	Coastal freight	970
		4-axle truck	210
		2-axle truck	30
Mostly road	Conv	6-axle truck	2413
		Coastal freight	165
	WAAM	6-axle truck	1250
		Coastal freight	165

The results (Fig. 3) show clearly how the material efficiency of WAAM has a significant impact on the overall environmental impact of manufacturing: in fact, steel primary production (although, more rigorously, a collection of steps combining a number of raw materials) dominates clearly the total result for both metrics. It is notable also that even in the unlikely combination of the worst case scenario for WAAM, it still outperforms conventional manufacturing in terms of cumulative energy consumption whereas equivalent carbon dioxide emissions show a slight overlap of error bars.

However, it is the repair scenario that shows the significant extent of the environmental benefit of enabling repair through WAAM (Fig. 5). The repair is enabled by WAAM with the shipment of the damaged disk back to Belgium, the repair (removing and re-depositioning the pin) and finally the return of the component to Norway (see Fig. 4) according to the same modes of transportation and distances of Table 2,

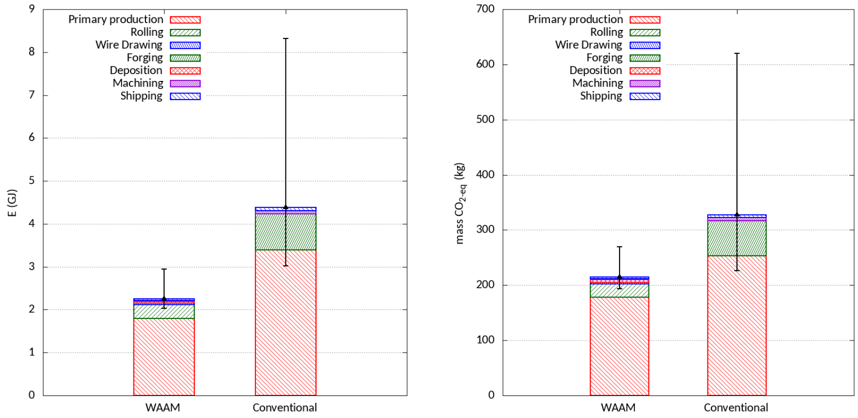

Fig. 3 Cumulative Energy Consumption (left) and cumulative carbon dioxide equivalent emissions (right) associated with the Conventional and the WAAM routes to manufacture the driver disk used for the case study.

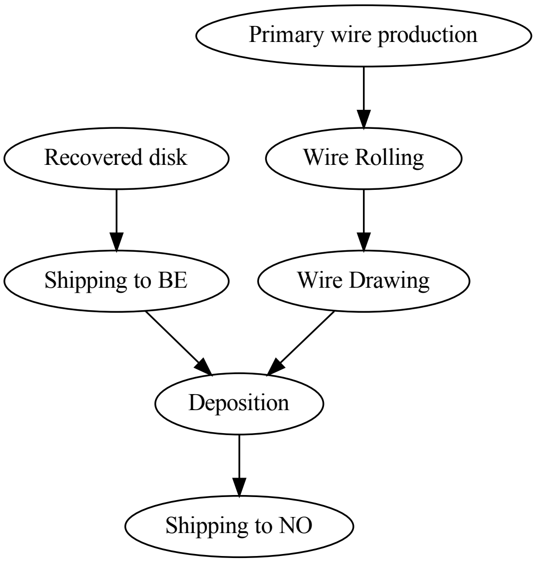

Fig. 4 Repair through WAAM route to assess the environmental impact of the driver disk used for the case study. BE: Belgium; NO: Norway.

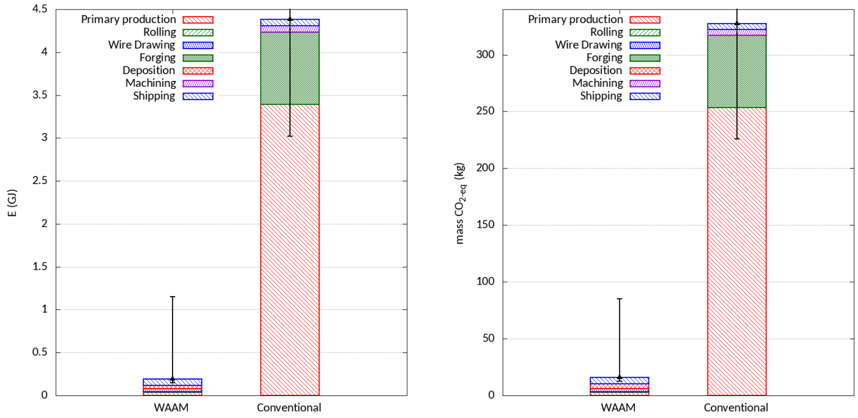

Fig. 5 Cumulative Energy Consumption (left) and cumulative carbon dioxide equivalent emissions (right) associated with the repair using WAAM of the driver disk used for the case study and production of a new one by conventional manufacturing.

4 Conclusion and further work

This work has presented an approach to quantify the environmental benefit of repair opportunities of industrial components by Wire and Arc Additive Manufacturing (WAAM) repairs in a life cycle perspective. A provisional calculation framework has been outlined and, then, illustrated considering a case study based on real data of a steel disk driver. Product life cycle phases from use and beyond were excluded by the scope of the study but the impact of transportation between the manufacturer and the customer was included. It can be observed that the material efficiency of WAAM in comparison to conventional, subtractive manufacturing routes determines a clear advantage on the associated cumulative energy consumption and cumulative equivalent carbon dioxide emissions. When the repair of the disk (re-depositioning its pin) is enabled by WAAM, the avoided manufacture of an entire new component reduces significantly (i.e. by order of magnitude) the environmental impact of the component.

To further extend this study, the following future development aspects are envisioned.

- Consider parts characterised by different geometries and materials.
- Follow a more realistic and rigorous treatment of uncertainty avoiding to conservatively combine “best” and “worst” case scenarios of the input parameters. To this goal, both an analytical or numerical (i.e. Monte Carlo) approach can be considered.
- Include reuse and recycling of products in the life cycle phases.
- Consider more comprehensive methods for the life cycle impact assessment (e.g. ReCiPe2016 [14])

- Include and combine other metrics of industrial interest to assess also financial, productivity, responsivity and quality aspects.

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References

1. Wu B, Pan Z, Ding D, Cuiuri D, Li H, Xu J, Norrish J (2018) A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. Journal of Manufacturing Processes 35:127–139
2. Priarone PC, Pagone E, Martina F, Catalano AR, Settineri L (2020) Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. CIRP Annals, 69(1):37–40
3. Bekker ACM, Verlinden JC (2018) Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel. Journal of Cleaner Production, 177:438–447
4. Frazier WE (2014) Metal Additive Manufacturing: A Review. Journal of Materials Engineering and Performance, 23:1971–1928
5. Busachi A, Erkoyuncu J, Colegrove P, Martina F, Ding J (2015) Designing a WAAM Based Manufacturing System for Defence Applications. Procedia CIRP 37:48–53
6. Campatelli G, Montevecchi F, Venturini G, Ingarao G, Priarone P (2020) Integrated WAAM-Subtractive Versus Pure Subtractive Manufacturing Approaches: An Energy Efficiency Comparison. International Journal of Precision Engineering and Manufacturing – Green Technology, 7(1):1–11
7. Peng T (2016) Analysis of Energy Utilization in 3D Printing Processes. Procedia CIRP, 40:62–67
8. Priarone PC, Campatelli G, Montevecchi F, Venturini G, Settineri L (2019) A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. CIRP Annals, 68(1):37–40
9. Serres N, Tidu D, Sankare S, Hlawka F (2011) Environmental comparison of MESO-CLAD© process and conventional machining implementing life cycle assessment. Journal of Cleaner Production, 19(9–10): 1117–1124
10. Paris H, Mokhtarian H, Coatanéa E, Museau M, Ituarte IF (2016) Comparative environmental impacts of additive and subtractive manufacturing technologies. CIRP Annals, 65(1):29–32
11. Faludi J, Van Sice CM, Shi Y, Bower J, Brooks OMK (2019) Novel materials can radically improve whole-system environmental impacts of additive manufacturing. Journal of Cleaner Production, 212:1580–1590
12. International Organization for Standardization (2018) BSI Standards Publication Environmental Management – Life cycle assessment – Requirements and Guidelines. ISO 14044:2018
13. Ansys Granta (2021) Ansys Granta EduPack. https://www.ansys.com/en-gb/products/materials/granta-edupack
14. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Hollander A, Van Zelm R (2016) ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. RIVM Report 2016-0104. Bilthoven, The Netherlands

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