Life Cycle Assessment of Wire Arc Additive Manufacturing Products

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Abstract. The industrial progress over these years has led to fast, good-quality production. Despite this progress, the impacts related to such type of production, whether these are social, economic, or environmental, have not been, at times, studied extensively. The industry realized the importance of a greener approach and as a result, new sustainable technologies, such as additive manufacturing (AM), have emerged. To generalize the environmental benefits of AM over traditional manufacturing, methodologies like Life Cycle Assessment (LCA) are used. The proposed work has the intent of understanding and quantifying the environmental impacts associated with a particular AM technique for the fabrication of metal parts, Wire Arc Additive Manufacturing (WAAM). An LCA is conducted and, considering the same circumstances, the environmental impacts related to the production of 3 different metal parts are analysed. In order to understand the results obtained, Computer Numerical Control (CNC) milling, which is also used for the fabrication of metal parts, is equally considered. In this particular application, when compared to CNC Milling, WAAM proves to have a 12%-47% in the environmental impact, depending upon the geometry considered. The environmental hotspot identified for both processes is the production of the raw material.

1 Page layout

The intensive exploitation of natural resources that has occurred in recent years as a result of industrial development has reached alarming proportions and begun to have a significant negative impact on the environment, the economy, and society [1]. Consequently, the focus on environmental awareness has become a priority in society's thinking, and the desire to achieve a sustainable way of living has become a conscious trend. Consumer pressure exerted on companies to produce greener products also led to stricter environmental legislation [2], which obligated companies to comply with more sustainable production practices [3]. The

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need to develop new sustainable technologies and improve existing ones in order to increase efficiency led to the development of an innovative technology called AM. This technology integrates sustainability into manufacturing systems and provides an alternative path to traditional manufacturing methods [1, 4].

Through the layering of materials, AM produces physical objects from 3D CAD files [4, 5]. Increasingly popular, this process optimizes product or part production through weight reduction, customization, and complex shape printing without consuming additional resources [3, 6]. It is worth noting, despite its advantages, that this technology has some drawbacks, mainly in terms of environmental impacts (high energy consumption) and manufacturing constraints (unsuitable for mass production. In order to optimize production without compromising quality, as well as reduce costs and environmental impacts, the limitations of this model should be exploited further. Consequently, tools such as LCA have been developed to facilitate the analysis and later evaluation of the environmental impacts [7].

When comparing WAAM to conventional manufacturing techniques, taking an LCA perspective is essential to demonstrating the process' future potential [8]. As a contribution to this field, the present paper employs Life Cycle Assessment (LCA) methodology for assessing the environmental impacts of both traditional (CNC milling) and alternative (WAAM) manufacturing processes for the production of metallic parts. Three different complexity metal parts are produced in the practical case: a gear, a cylinder, and an S-shape. SimaPro 9.2 was used to analyze their environmental impacts and, with the results obtained, both processes were compared in order to draw conclusions relative to their sustainability potential for this particular application.

In this article, a literature review is conducted in Section II in order to understand the two processes involved in the practical case study along with the methodology used. Subsequently, the case study is presented in section III, and the results obtained are represented graphically to be discussed in section IV. Lastly, conclusions are drawn, and recommendations are suggested in section V.

2 Literature Review

2.1 Computer Numerical Control Milling

Essentially, CNC milling is the process of gradually removing material from a workpiece to produce a custom-designed part or product [9]. Figure 1 depicts the entire production process as a schematic. Firstly, the inputs are established: the raw material, the CNC machine, the cutting tools, and the machining technology. Afterwards, the process parameters must be defined, as well as the process plan defining milling operations sequence that will lead to the final product. Finally, the machining operations begin, and the final product is obtained. In order to distinguish the conforming from non-conforming products, it is essential to also perform a quality control after the process is finished [10].

Relatively to new emergent technologies, it is mentioned in the literature that this process has a huge disadvantage in terms of energy consumption and efficiency. The complexity of CNC machines has led to the development of multiple mathematical models aimed at solving these problems. However, exploitation of these models remains unexplored due to the complexity of the characteristics of CNC machines [11].

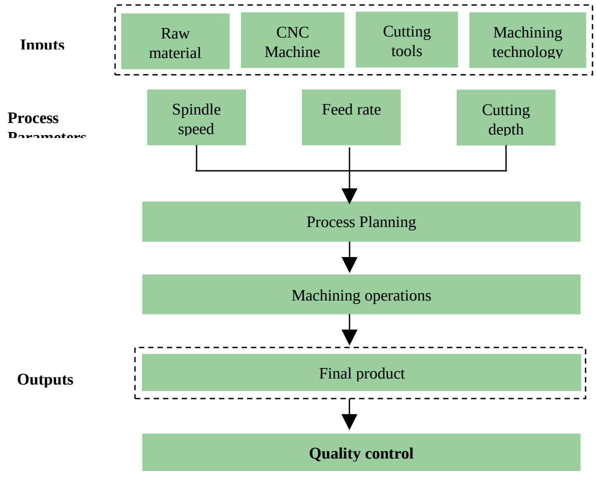

Fig. 1. CNC process. Adapted from [11].

2.2 Wire Arc Additive Manufacturing

WAAM is a layer-by-layer welding method that uses wire feedstock and standard arc welding equipment, in order to create three-dimensional shapes [5]. The major steps needed to create a part using this method are shown in Fig. 2. In the first step, a computer-aided design (CAD) is used to create a three-dimensional representation of the part to be manufactured. In order to use the 3D representation as an input for the slicing software, the representation must be saved in a standard format. With the software, a 3D model is transformed into layers, thick enough to be deposited precisely, appropriate parameters are defined (according to the material of the part being produced), and an optimum path for depositing material is calculated. Then, is generated a computer numerical control (CNC) code that will send as control information to the machine tool (robotic arm) the specific motion, speed, and operations to be followed. When the parameters are chosen and the machine is set, the product starts to be built layer by layer until the whole component is complete.

One of the most mentioned disadvantages in literature relatively to this process is that, most often, the part produced still needs post-treatment to improve some quality requirements, such as surface finish [12].

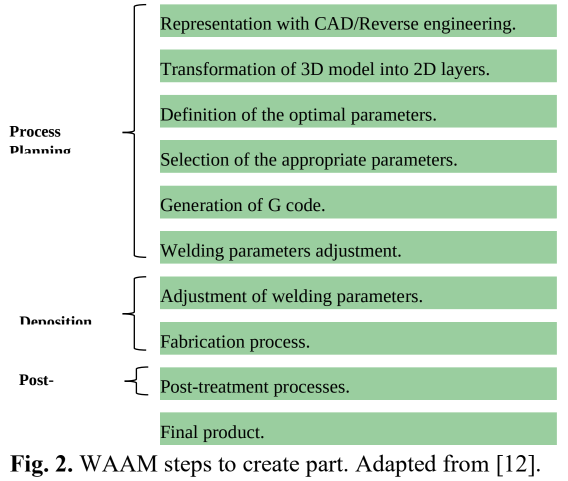

Fig. 2. WAAM steps to create part. Adapted from [12].

2.3 Life Cycle Assessment

Through LCA, the environmental impacts of a product system can be quantified and characterized at various stages of its life cycle, including those associated with raw materials extraction, production, use, transportation, and end-of-life discard [13]. In accordance with ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [14], LCA comprises four phases [14]. In the first phase, the study goal and scope are defined, and it is possible to understand why the evaluation is being performed. A detailed explanation of the functional unit, system boundaries, methods, categories of environmental impacts, and assumptions used is provided during this main phase. During the second phase of this methodology, an environmental inventory analysis is conducted to identify and analyse all inputs and outputs relevant to the process (raw materials, electricity, consumables, waste, and emissions). A variety of data sources are used in this phase, such as literature, experiments, and databases. In the third phase, the environmental impact assessment, where a characterization of the impacts involved in the functional unit's life cycle is made. Consecutively, an interpretation of the results is done and conclusions relative to the environmental performance of the production are withdrawn. Finally, it should be highlighted that LCA is a systematic process therefore, all the information initially established can be rearranged throughout the course of the study.

3 Case Studies

In figure 3 it is possible to observe the different geometries that were obtained with the WAAM process. A 0.178 kg gear, a 0.186 kg cylinder, and a 0.109 kg S shape of ER90 steel (low alloyed steel) were produced, under the same circumstances and considering the same process parameters. Table 1 depicts the parameters that were set for WAAM. While CNC milling was considered an after-process operation in WAAM production, it could not be executed due to the lack of appropriate tools (carbide cutting tools). In this sense, to calculate compressed air, lubricating oil, water, and electricity, the Ecoinvent 3 database had to be used. Using SolidWorks, data about the final part's volume and mass also had to be estimated. Following the methodology described previously, WAAM's environmental impacts were identified and characterized, and further compared with those of pure CNC milling. This section will approach and explain the LCA model used for both processes.

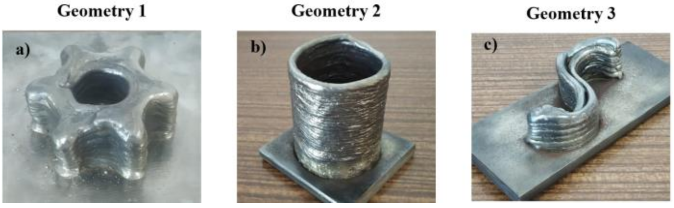

Fig. 3. Final parts produced a) geometry 1 – gear shaped, b) geometry 2 cylinder shaped, and c) geometry 3 – S shaped.

This study analyses and quantifies the environmental impacts of WAAM when producing three metallic geometries: gear, cylinder, and S shape. Geometry 1 refers to the gear shape part, geometry 2 to the cylinder shape part, and geometry 3 to the S shape part. As a complement to the analysis of the environmental impacts related to WAAM, in order to give the study some context and further elaborate comparisons, the impacts associated with a traditional manufacturing process, CNC milling, were also analysed.

Table 1. WAAM Process Parameters.

Process parameters	Geometry 1	Geometry 2	Geometry 3
Shielding gas flow rate (l/min)	16	16	16
Voltage (V)	18	18	18
Wire feed speed (m/min)	3	3	3
Travel speed (mm/min)	360	360	360
Interlayer cooling time (s)	180	180	180
Layer height (mm)	1.5	1.5	1.5
No. of layers	12	32	32

3.1 Goal and Scope definition

This study analyses and quantifies the environmental impacts of WAAM when producing three metallic geometries: gear, cylinder, and S shape. Geometry 1 refers to the gear shape part, geometry 2 to the cylinder shape part, and geometry 3 to the S shape part. As a complement to the analysis of the environmental impacts related to WAAM, in order to give the study some context and further elaborate comparisons, the impacts associated with a traditional manufacturing process, CNC milling, were also analysed.

3.2 Functional unit and system boundaries

The functional unit of the present study is a one-unit metal part. The phases that are part of the assessment are illustrated in Figure 4 along with the system boundaries. This cradle-to-gate study includes every production phase of the product, from the extraction of natural resources to the production of the final part. The use and disposal phases, as well as transportation, were not considered. SimaPro 9.2 software's ReCipe 2016 (Hierarchical) method was used to conduct the evaluation. The production of three alternative geometries served as the basis for a comparison of the two procedures. As this study is relative to specific values of kilograms of steel, and the values available in the Ecoinvent database are only relative to 1 kg of steel, those had to be converted. There was no sensitivity or uncertainty analysis conducted.

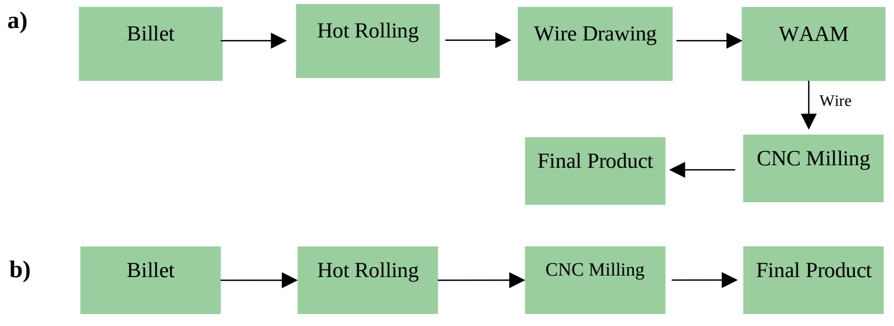

Fig. 4. System boundaries for a) WAAM b) Pure CNC milling.

3.3 Environmental Inventory Analysis

The inventory of the WAAM process with all the assumptions made relative to the data used, for all the geometries produced, was depicted in Table 2. The inventory of the CNC Milling process with all the assumptions made relative to the data used, for all the geometries produced, was depicted in Table 3.

Table 2. LCI Of WAAM for all Geometries Produced.

Material/ Process	Geometry 1	Geometry 2	Geometry 3	Units	Type of data	Reference
Steel billet	0.329	0.238	0.177	kg	Calculated	Ecoinvent 3 database
Shielding gas	230.4	238.9	200	l or dm3	Measured	Measured data
Hot Rolling	0.329	0.238	0.177	kg	Calculated	Ecoinvent 3 database
Wire Drawing	0.314	0.227	0.168	kg	Calculated	Ecoinvent 3 database
WAAM Deposition	0.302	0.218	0.162	kg	Measured	Measured data
Electricity (WAAM)	0.418	0.436	0.365	kWh	Calculated	Calculated data
Electricity (Milling)	0.517	0.133	0.222	kWh	Calculated	Ecoinvent 3 database
CNC Milling	0.124	0.032	0.053	kg	Calculated	Calculated data
Final Product	0.178	0.186	0.109	kg	Estimated	SolidWorks

Table 3. LCI Of WAAM for all Geometries Produced.

Material/ Process	Geometry 1	Geometry 2	Geometry 3	Units	Type of data	Reference
Steel billet	0.534	0.635	0.555	kg	Calculated	Ecoinvent 3 database
Hot Rolling	0.534	0.6345	0.555	kg	Calculated	
Compressed Air	0.399	0.536	0.571	m3	Calculated	
Lubricating Oil	0.001	0.002	0.002	kg	Calculated	
Water	0.005	0.007	0.007	m3	Calculated	
Electricity	1.3	1.746	1.858	kWh	Calculated	
CNC Milling	0.312	0.419	0.446	kg	Calculated	Calculated data
Final Product	0.178	0.176	0.109	kg	Estimated	SolidWorks

4 Results and Discussion

In order to conduct an environmental impact assessment, an impact assessment method must be chosen. ReCiPe 2016 (Hierarchist) was used for the assessment of these case studies. With ReCiPe, impacts can be calculated either for a single environmental problem (midpoint indicators) or aggregated into levels (endpoint indicators). The analysis made considered the total impact caused by each process, i.e., the aggregation of impacts of the three main endpoint indicators: Human Health, Ecosystems, and Resources. Uncertainty was not assumed in the aggregation process. Impact factors are provided in millipoints (mPt), and 1 mPt is one thousandth of a single score point.

4.1 Overall analysis

Figure 5 demonstrates the results obtained for the production of the different geometries, considering both processes. Conclusions were withdrawn in the following items.

• Depending on the geometry being produced, the suitability of each process might differ. WAAM presents better results, i.e. lower total impact values, in the production of the geometries that are less filled because there exists a lower need to deposit material. On the other hand, for CNC Milling, better results are obtained if the geometry is more filled because the need to remove material is lower.

• WAAM was the best ecological option. For geometry 1 production WAAM presented a 12% improvement. Since removing material to obtain this geometry is relatively similar to depositing it, the differences between the two processes are almost non-existent. WAAM, on the other hand, had a notable advantage for geometry 2 and geometry 3 production, where it improved by respectively 45% and 47%. This is mainly due to the need to remove material being significantly higher than the amount of material deposited.

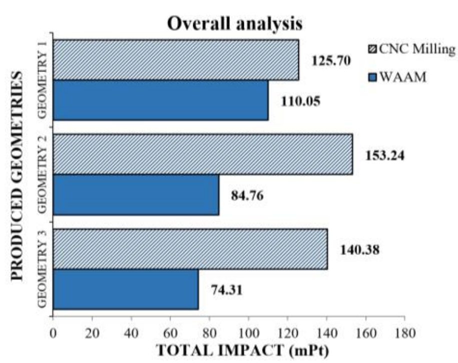

Fig. 5. Overall environmental impacts CNC Milling and WAAM for each geometry.

4.2 CNC Milling and WAAM analysis

The different contributions of the inventory inputs for both processes were displayed in figure 6 and figure 7, to be easily analysed. Conclusions were withdrawn in the following items:

• For both processes, production of the steel billet contributed the most (hotspot) to total environmental impact. The inventory inputs used for WAAM are responsible for 42%, 50%, and 53% of the total environmental impact of the three geometric configurations (geometry 3, geometry 2, and geometry 1), respectively. In geometry 1, CNC milling accounted for 75% of the total environmental impact, in geometry 2, it accounted for 74%, and in geometry 3, it accounted for 70%. The results obtained were foreseeably since the production of steel billet is made by a process that has several environmental issues adjacent, the continuous casting.

• As far as the overall environmental impact is concerned, hot rolling has the lowest contribution compared to both processes. In WAAM, this stage had a 3% impact on the production of the analysed geometries. In terms of CNC milling, an impact of about 5% was found for all geometries analysed. There are a few environmental implications associated with the hot rolling process. In addition, it is clear that, based on the case studies developed and the technologies used, this process represents only a small part of the overall process.

• As a result of the WAAM process, the total impact on the environment was shown to be lower than CNC milling, which demonstrates its higher material efficiency compared to CNC milling.

• Concerning the production of steel billets, the solutions proposed were mainly related to recycling methods, complementary equipment, and the management of waste, that are found in the process.

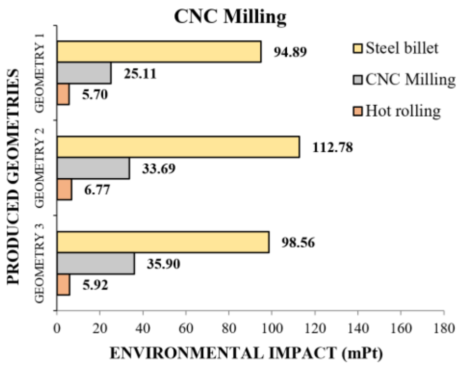

Fig. 6. CNC milling environmental analysis for each shape produced.

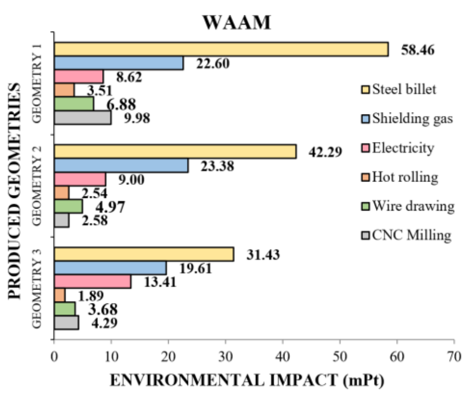

Fig. 7. WAAM environmental analysis for each shape produced.

5 Conclusions

With the application of the LCA methodology in the production of three different geometries: a gear, a cylinder, and an S shape, the present study aimed to characterize and compare the environmental impact of WAAM and CNC milling processes, as well as identify possible improvements. In accordance with the ISO 140044:2066 standard: Environmental management - Life cycle assessment - Requirements and guidelines [14], a life cycle assessment was conducted through SimaPro 9.2 software, considering the total environmental impact [14].

For this particular application, when compared to CNC Milling, WAAM proved to be less environmentally damaging mainly due to its high material efficiency and low material waste. The environmental hotspot identified for both processes was the production of the steel billet. This stage of the process allows to obtain the raw material needed for the manufacturing of the parts identified. Therefore, it is urgent to develop more studies to understand and identify possible solutions related to this environmental hotspot. This study contributed to the body of knowledge regarding the application of LCA methodologies in WAAM. However, the results of this study are focused on the comparison between WAAM and CNC milling for its environmental impact. Additional comparison evaluations should be conducted to better generalize WAAM's environmental performance, including other processes (traditional or alternative) besides CNC Milling as well as other materials, process settings, and geometries. In future projects, the life cycle assessment should include the use and disposal phases and, to complement the work developed, an economic and social assessment should be conducted.

Acknowledgments

Radu Godina acknowledges Fundação para a Ciência e a Tecnologia (FCT-MCTES) for its financial support via the project UIDP/00667/2020 and UIDB/00667/2020 (UNIDEMI). JPO acknowledges funding by national funds from FCT - Fundação para a Ciência e a Tecnologia, I.P., in the scope of the projects LA/P/0037/2020, UIDP/50025/2020 and UIDB/50025/2020 of the Associate Laboratory Institute of Nanostructures, Nanomodelling and Nanofabrication – i3N. This activity has received funding from the European Institute of Innovation and Technology (EIT) – Project Smart WAAM: Microstructural Engineering and Integrated Non-Destructive Testing. This body of the European Union receives support from the European Union's Horizon 2020 research and innovation programme.

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