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Comparative environmental impacts of additive and subtractive manufacturing technologies

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ABSTRACT

Additive manufacturing technologies are opening new opportunities in term of production paradigm and manufacturing possibilities. Nevertheless, in term of environmental impact analysis supplementary research works require to be made in order to compare and evaluate them with traditional manufacturing processes. In this article, we propose to use Life Cycle Assessment (LCA) method and to associate decision criteria to support the selection of manufacturing strategies for an aeronautic turbine. The dimensionless criteria allow to define environmental trade-offs between additive and subtractive methods. This study provides an approach generalizable to other parts and processes.

1. Introduction

The use of additive manufacturing (AM) technologies for industrial applications has increased substantially during the past years [1,2]. Technological advances contributed to the deeper understanding of AM processes, such as selective laser sintering (SLS) and electron beam melting (EBM) [3]. Currently, these AM processes allow cost effective manufacturing of metal components for end-use applications, especially when production volumes are low and geometrical complexity is high [4]. In this scenario, AM technologies could compete with traditional manufacturing methods based on formative and subtractive processes [5]. Nevertheless, criteria to support the selection of different manufacturing methods have still to be developed to compare technologies and select easily the most appropriate manufacturing methods. The purpose of this article is to propose and present combined criteria taking into account not only the manufacturability but also the environmental impacts.

The principles of metal component manufacturing using AM technologies are based on building the geometry layer by layer in a sequential manufacturing process [6]. Typically, the EBM process selected in this study requires sintering and melting the base material which is in powder form. After the additive process, the final geometry of the part is close to nominal values. However, finishing operations are needed when technical requirements imply high geometrical and dimensional tolerances as well as good surface quality [7].

Some of the advantages of the additive process versus conventional subtractive manufacturing methods include that the raw material consumption is reduced. The volume of raw material used during the AM process is in practice close to the volume of the part before the finishing phase, and therefore the metal powder that has not been affected by the laser or electron beam during the AM process can potentially be recycled. The waste of the process, such as material or fluid, is decreased substantially as opposed to traditional subtractive manufacturing processes, in which the generated waste is usually higher [8].

Based on this initial presentation, it seems that AM is capable of reducing the impact of the industrial and manufacturing activity on the environment [9]. However, this assumption must be demonstrated. For instance, to obtain the powder material for the AM process, a considerable amount of energy is required, and this process intrinsically generates waste, which is released to the environment. Consequently, the trade-offs in emerging AM processes need to be studied further to be able to replace established conventional subtractive methods. This study proposed an approach to define this trade-off between additive and subtractive methods.

In the context of a sustainable manufacturing process, it is necessary to estimate and compare the environmental impact and energy efficiency of established and emerging manufacturing processes. To achieve this goal, cooperation initiatives, such as “CO2PE!” [10], have the aim to research in deep the environmental footprint of manufacturing industry. Also, more standardized methodologies for systematic analysis and improvement of manufacturing process life cycle inventory [11] need to be implemented, as presented by [12].

Although, Life Cycle Assessment (LCA) method is the most commonly used methodology by which environmentally conscious design is carried out, substantial improvements have to be made in order to develop simple criteria allowing engineers to select quickly between different manufacturing options for given objectives. The present article is proposing a combination of

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criteria for comparing additive and subtractive methods from the environmental impact.

The document is organized in the following manner. In Section 2, different eco-indicators developed in the literature are briefly summarized and key literature references are provided. In Section 3, the case study key characteristics are described. In Section 4, the different manufacturing strategies considered in the article are summarized, as well as the initial conditions and hypotheses of the study. This section is also introducing a new dimensionless indicator specifically proposed to compare additive and subtractive methods. Its usage and its interest to support selection decision between both processes are presented. Section 5 summarizes the key results of the study. Finally, Section 6 concludes the article and presents the future work.

2. Background related to environmental metrics

Environmental evaluation analysis methods such as LCA require detailed information about the studied product or process. The concept of Exergy, introduced by Rant [13] offers a solution for an environmental evaluation during the early stages of the design process [14]. Another works compared the exergetic approach with LCA eco indicator 99 (H) [15] and demonstrated the equivalence between the two approaches. Exergy is a thermodynamic metric that can be used to evaluate the environmental impact but also the material and resource consumption. Eco-indicators can be organized in two key categories, thermodynamic metrics and other LCA metrics.

LCA is the most commonly used approach during the design process to determine the final environmental impact [16]. To assess the environmental impacts, an array of impact category indicators such as Eco-Indicator 99 (EI 99), Cumulative Energy Demand (CED). CML 2 Baseline 2000 or Cumulative Exergy Demand (CExD) can be used [17]. The LCA software SimaPro describes the four stages as (1) characterization, (2) damage assessment, (3) normalization and (4) weighting. Only the first step is required by ISO standards, not all assessments include the last three steps. The results must be thought out and communicated in a careful and well-balanced way as not to cause confusion as to their meaning.

This short presentation of environmental metrics is highlighting the lack of more specific manufacturability criterion. In a manufacturing process, the environmental impact is one criterion but there is also a need to deepen the analysis and to consider also criteria such as shape, size of parts and size of raw part as well as important trade-off between material removed during a milling process and energy consumed by both processes. The following sections are deepening this analysis.

3. Case study presentation

The case study in Fig. 1 shows the CAD representation of the geometry used in this article, it is an aeronautical turbine composed of 13 blades, operating at very high rotation speed (over 50,000 rpm). Its nominal dimensions are ∅ 130 mm by 30 mm. The diameter of the central hub is ∅50 mm and the volume of the finished part is 53.56 cm^3. The base material of the turbine is a Titanium alloy (Ti6AlV). Its surface quality must be very high, typically lower or equal to *Ra* 1 μm.

The conventional manufacturing process implies having parts machined from a raw cylinder with an initial volume of 406 cm^3 (∅130.4 mm by 30.4 mm). The machining strategy requires several steps including, roughing, half-finishing, and finishing operations. The entire milling operation is performed with the same milling tool, which is a ball end mill with ∅;6 mm, and cutting speed of 50 m/min. The conventional manufacturing process requires subtracting 87% of the initial volume during the milling process. This is generating an important amount of wasted material, having a negative influence on economic and environmental parameters. Additive manufacturing is usually hypothesized to reduce drastically the waste material and energy consumption. However, a post-processing milling phase is required to meet the roughness and dimensional requirements.

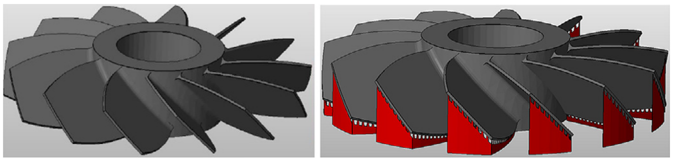

Fig. 1. The final turbine (left) and the turbine with optimized support after AM process (right).

The AM machine selected in this study to provide the alternative manufacturing process of the part is an EBM machine from ARCAM. The part is manufactured layer-by-layer using an electron beam melting the powder. During the process, supports are necessary to control the deformation of the part and create overhanging structures. After the AM process, the supports are separated from the part will become waste and will be recycled. The supports and the final part are presented in Fig. 1.

4. Life cycle analysis of manufacturing processes of the turbine

4.1. Goal and scope definition

The goal of this study is to compare the environmental impacts associated with the manufacturing of one turbine, from a raw cylinder of titanium using conventional manufacturing processes or from titanium powder using additive manufacturing processes. It should be noted that the geometry has not been optimized topologically for AM manufacturing. In our case study, the geometry of the part is identical for both processes. This is improving the comparability of the processes. Nevertheless, in theory, AM technologies could have been used to produce a topologically optimal geometry for the function and working conditions of the turbine [18]. Hence, it would have been possible to minimize the weight, general dimensions and material volume for this specific application. This aspect has to be considered in future studies.

4.2. Functional unit

The assessment and comparison of the environmental impacts of the two processes are based on the manufacturing of one turbine.

4.3. System boundaries (life cycle and elements considered)

The study is conducted over three main life cycle phases: production, use and end-of-life (EOL) phases. The system includes all elements necessary to machine the turbine: the milling machine, the EBM machine and the treatment of the chips until recycling. Table 1 shows the inventory of the elements used, the amount of input materials and energies. The lifespans of the milling machine and the EBM machine are not taken into account. The number of pieces

Table 1
Inventories used and the amount of input materials/energy.

Atomization: for 1 kg of titanium powder		Recycling titanium for 1 kg of waste
Argon	5.5 m^3	– (in a vacuum)
Electricity	6.6 kWh	4.08 kWh
Water	155 l	155 l
Titanium	1.03 kg	1 kg
EBM	**Duration**	**Energy consumption**
Vacuum	1 h	1.5 kWh
Heating	1.5 h	3.75 kWh
Melting	9 h	19.2 kWh
Cooling	2 h	1.6 kWh
Milling	**Specific energy consumption**	
Roughing and 1/2 finishing	0.061 kWh/cm^3	
Finishing	0.219 kWh/cm^3	

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produced per machine through its life cycle is not the same. A future study is needed to identify the influence of the lifespans and the recycling of the milling machine and EBM machine.

The production phase deals with the process to obtain the raw cylinder of titanium used in conventional manufacturing, the powder used during EBM, and the energy consumed to process them. As the powder not affected by the beam during additive manufacturing is recycled, the volume of the powder included in our study is only the volume of the turbine and its supports, not the volume of the global built. The Titanium in powder form is obtained by atomizing liquid phase. The principle is to warm titanium, causing its melting. The melted metal then flows through a nozzle under the effect of gravity and pressure. It is then pulverized by argon jets, and solidifies in the form of spherical drops [19]. The efficiency of the atomization is high: 97% of the titanium used at the beginning of the process is present into powder form. The material and energy consumptions to obtain 1 kg of powder are 5.5 m^3 of argon and 6.6 kWh of electricity. The EOL phase addresses the transports of waste (chips and supports) from the production site to their recycling site and their recycling treatments. The use phase includes the energy consumption of the milling machine and EBM machine when machining the turbine.

4.3.1. Milling process

For the traditional manufacturing process, a subtractive milling operation is performed. As mentioned above in paragraph 3.1, three steps are required to machine the stock cylinder and obtain the desired geometry: roughing operation, 1/2 finishing and finishing, with a manufacturing time of 5 h 53 min and an energy consumption of 27.5 kWh.

4.3.2. EBM and milling process

The EBM machine is able to manufacture five parts simultaneously but the process is evaluated for one part only for comparison purpose. The following stages in the additive manufacturing EBM process have been considered to compute the energetic efficiency of the process (Table 1):

- creation of vacuum,
- heating of the start plate,
- melting of the parts, and
- cooling of the machining and cancelling the vacuum.

The finishing step implies to machine the part using a five axes milling machine similar to the one used for the competing fully milling process. The process time was 2 h and 5 min, with an energy consumption of 8.3 kWh. For the milling operations considered in the two processes, it should be mentioned that the evaporation of the cooling fluid has been neglected: the cooling fluid flows at a constant volume in the machine and does not appear in the process description.

4.4. Proposal of combined metrics to compare different manufacturing processes from a life cycle perspective

This research aims at defining a general approach able to facilitate the selection process between alternative manufacturing processes. This study is comparing milling with AM (EBM) from an environmental point of view. Since the last stage, the finishing is similar between both alternatives; the selection approach is considering only the stages before the finishing process.

SIMAPRO with the Cumulative Exergy Demand (CExD) and “CML 2 Baseline 2000” methods is used in this article to assess the environmental impact. The method CExD has been developed in order to quantify the life cycle exergy demand of a product. The CExD is defined as the sum of exergy of all resources required to provide a process or product [20]. The ratio R of the indicators between EBM and milling is providing a dimensionless indicator allowing the comparison of AM and milling processes from an environmental point of view.

$$R = \frac{\text{Environmental impact of EBM process}}{\text{Environmental impact of milling process}}$$

Below a value of 1, it is more interesting to select EBM; above a value of 1 it is more valuable to select milling. If the ratio is equal to 1 then both options are similar in term of impact.

Nevertheless, a factor such as raw part shape is playing an important role in the evaluation of the process to be selected. It is valuable to combine together the ratio with another criterion considering raw part shape. By analogy with the Ashby shape ratio developed for material selection [21], it is possible to create a dimensionless shape factor comparing a reference process. This shape factor K is a ratio constructed to evaluate the amount of material removed by subtractive techniques in order to obtain the final part. The ratio is providing an aggregative evaluation of the shape and complexity of parts.

$$K = \frac{\text{Volume of material required in milling process}}{\text{Volume of the part}}$$

The shape factor K is used to compare in our case EBM and milling. The volume removed during the finishing process common to both processes is subtracted from the volume of material required in both cases.

For the milling process with a raw cylinder of the following dimensions $\varnothing$130.4 mm by 30.4 mm, $K = 7.08$.

5. Results

The results are a comparison of the relative weight of the environmental impacts of these two processes, on a scale of 100%, according to 10 environmental impacts that have been selected because they represent the main environmental impacts after normalization of the LCA in Simapro. Six coming from the method “CML 2 Baseline 2000”: abiotic depletion (1), acidification (2), global warming (3), fresh water aquatic ecotox (4), marine aquatic ecotoxicity (5), terrestrial ecotoxicity (6) and 4 coming from the method CExD: non-renewable fossil (7), non-renewable nuclear (8), renewable potential (9), and renewable water (10). It can be seen in Fig. 2, for $K = 7.08$, that EBM process generates always less environmental impacts than the milling process.

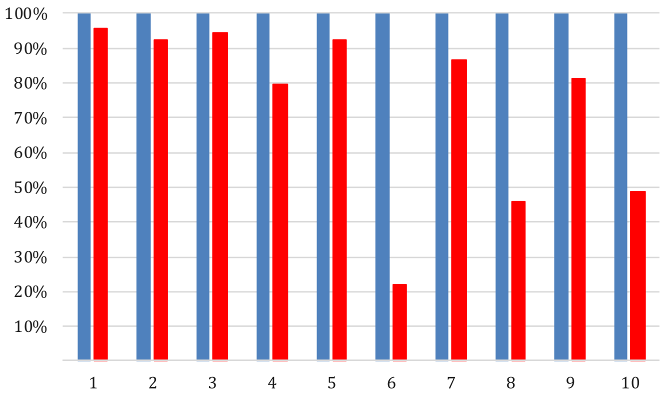

Fig. 2. Environmental impacts of EBM (red) and milling (blue) for $K = 7.08$.

Fig. 3 shows the evolution of the ratio indicators R “CML2 Baseline 2000” according to K. Below a value ratio of 1, the EBM is more environmentally friendly. EBM is more environmentally friendly for a K value between 4.5 and 5.5 based on the indicators 1–4, 6.4 for the indicator 5 and all value of K for the indicator 6, respectively. Fig. 4 shows the evolution of the ratio indicators “CExD” according to K. EBM is more efficient for K superior to 5, 7 based on the indicator 7 and for K superior to 2.6 and 3 based on the indicators 8–10. According to this approach parts implying a low amount of material removal (in the worth case below $K = 2.6$),

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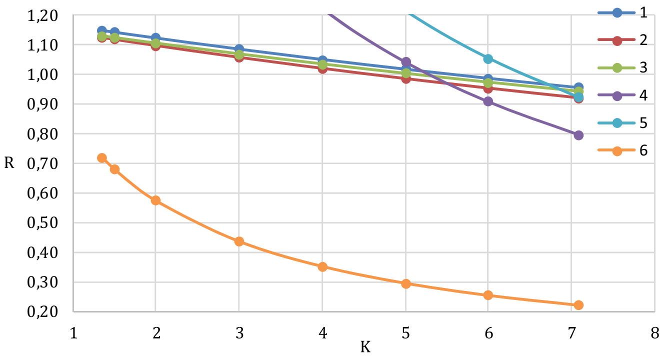

Fig. 3. Correlation between R and K for environmental impacts "CML 2 Baseline 2000".

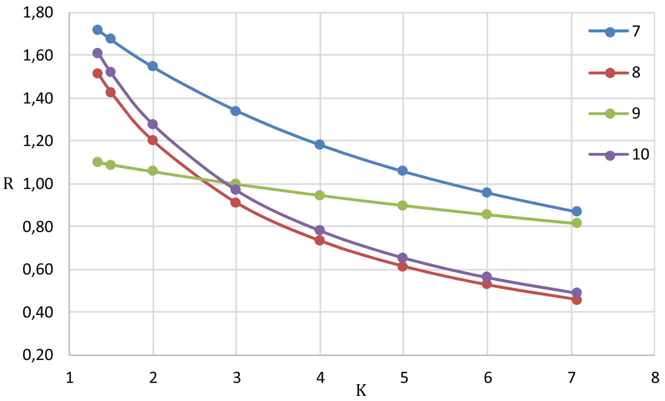

Fig. 4. Correlation between R and K for environmental impacts "CExD".

the milling process is environmentally competitive. For parts above $K = 7$ EBM is always the best option. Taking into account the variability of the results depending of the eco-indicator selected, it can be said as a general summary of the results that from an environmental point of view, milling is remaining interesting for parts with an acceptable level of shape complexity for the milling process. On the contrary EBM seems more adapted for parts of high shape complexity.

6. Conclusion

The study has proposed a combined indicator for environmental impact ratio and volume of material removal ratio. It appears that EBM is more environmentally friendly and also a good manufacturing option for parts with shape complexity requiring strong material removal with subtractive methods. On the contrary, part with acceptable level of complexity for five axes milling process will generate a lower environmental impact with a milling process.

During the manufacturing of the part itself, the energy consumed by EBM and milling is almost identical. What makes the difference in term of environmental impacts is mainly the manufacturing of the powder for EBM process, and the production and recycling of the chips for the milling process. Thus, by using a raw part with geometry close to the final part, milling process is still competitive in term of environmental impacts.

In this case study, the geometry of the manufactured part is the same for both processes. In a general case, taking into account the knowledge on manufacturing process during the design stage, the geometry of the part can be optimized for the selected process. This is of special interest at the early stage of the development process. The approach presented in this paper can provide a significant support at early stage to integrate manufacturing concern as early as possible in the development process. This can have later a significant positive impact on the manufacturability aspects. The fundamental added-value of this research can be obtained if the indicators are used at the early design stages.

Thus it should be possible to reduce the amount of powder used by EBM to produce a part fulfilling the same function than a part produced by milling. This supplementary aspect potentially changes the trade-off between milling and AM processes in term of environmental impacts and has to be considered in future studies.

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