CIRP Annals - Manufacturing Technology 65 (2016) 29–32

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Comparative environmental impacts of additive and subtractive manufacturing technologies

Henri Paris (2)[a,*], Hossein Mokhtarian[b,a], Eric Coatanéa[b], Matthieu Museau[a], Inigo Flores Ituarte[c]

[a] G-SCOP laboratory, Univ. Grenoble-Alpes, France
[b] Department of Mechanical Engineering and Industrial Systems, Tampere University of Technology, Finland
[c] Department of Mechanical Engineering, Aalto University, Finland

ARTICLE INFO

Keywords:
Electron beam machining
Energy efficiency
Environment

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

---

* Corresponding author.
E-mail address: henri.paris@ujf-grenoble.fr (H. Paris).

http://dx.doi.org/10.1016/j.cirp.2016.04.036
0007-8506/© 2016 CIRP.

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.

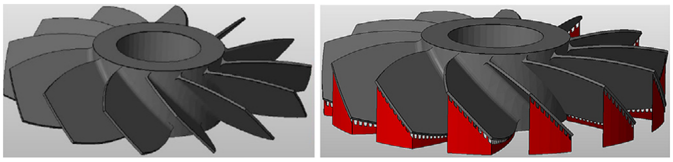

Fig. 1. The final turbine (left) and the turbine with optimized support after AM process (right).

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	