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The role of re-design for Additive Manufacturing on the process environmental performance

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Abstract

At present, economic and technological design criteria for products and processes should be matched with the minimization of environmental impact objectives. Manufacturing, material production, and product design are strictly connected stages. The choice of a production system over another could result in significant material and energy/resource savings, particularly if the component has been properly designed for manufacturing. In this scenario, Additive Manufacturing, which has been identified as a potential disruptive technology, gained an increasing interest for the creation of complex metal parts. The paper focuses on the tools, based on the holistic modelling of additive and subtractive approaches, which could be used to identify the production route allowing the lowest energy demand or CO_2 emissions. The models account for the main process variables as well as the impacts due to the re-design for AM for the creation of components made of Ti-6Al-4V.

Keywords: Sustainability; Additive Manufacturing; Life Cycle Assessment; Energy demand

1. Introduction

The potential of Additive Manufacturing (AM) for the production of end-use objects is nowadays well recognized. In order to fully exploit the available technologies, the design phase has to be reimagined as a function of the layer-by-layer component creation. In general, the literature highlights some pre-conditions directing the choice towards AM instead of traditional manufacturing processes, as machining. The part should be complex, requiring a labour-intensive and expensive production by means of conventional techniques. The surface quality should not be a critical issue, in order to minimize the post-AM processing steps. Low production volumes or small batch sizes have to be generally preferred [1, 2]. Klahn et al. [3] presented selection criteria to identify the components worth to be produced via AM, with respect to (*i*) the reduction of the number of parts to be assembled, (*ii*) the satisfaction of the customer needs by enhancing the product individualization, (*iii*) the possibility of the economic manufacturing of individual parts, since no tools and fixtures are required, and (*iv*) the weight reduction potential coupled with a more efficient design. Being the identified component capable to take advantages of the AM process, a re-design phase is needed. In this context, since the increase in shape complexity does not represent a constrain for the additive-based approach, the topology optimization has been widely applied. In such a way, high-strength and low-mass structural parts could be obtained [4, 5]. However, the choice of a manufacturing approach over another affects the environmental impact per produced part. Following the idea of creating decision-support tools for the selection of additive instead of subtractive manufacturing approaches [6], in this paper a methodology recently proposed by the authors [7] is extended and adapted to a typical case study. The main aim is to verify to what extent the re-design for AM could play a role in energy demand and carbon dioxide emission reduction.

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2. Methodology

Two different production approaches (in Figure 1), based either on machining or additive manufacturing, have been assessed. A cradle-to-grave analysis (recalled in the following) has been adopted to quantify the primary energy demand and the CO_2 emissions related to the life cycle of the components. A single part has been assumed as functional unit. The impacts of material production, part manufacturing, use, and disposal have been included [7]. The transportation-related impact has been excluded, even if logistics, volumetric and handling differences between the considered approaches are expected. However, the energy and CO_2 penalties for conventional transportation types (e.g., $0.94 \cdot 10^{-3}$ MJ/kg·km and $0.067 \cdot 10^{-3}$ kg/kg·km, respectively, for a 32-t diesel-engine truck [8]) provide a negligible contribution on a per-part based evaluation when small-to-medium moved weights and travelled distances are considered [9]. The methodological assumptions are discussed hereafter by accounting for the variability in Life Cycle Inventory data.

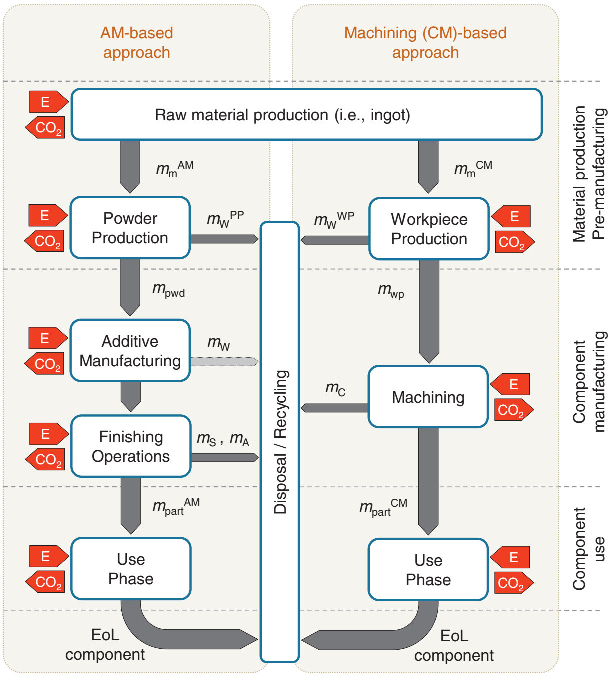

Figure 1. Energy, CO_2 emissions, and material qualitative flows for the AM- (*left*) and machining- (*right*) based approaches.

2.1. Material flows

The amount of raw material needed for both the AM-based (m_m^{AM}) and the machining-based (m_m^{CM}) approach has to be produced by means of primary and/or secondary routes (i.e., recycling), as depicted in Figure 1. Afterwards, each manufacturing approach requires a specific material input, and additional powder and workpiece production processes have to be considered, together with their resulting material wastes (m_W^{PP} and m_W^{WP}). In powder-bed AM processes, the unused powder could be reused in subsequent prints [10, 11]. Therefore, the mass of powder required for AM (m_{pwd}) has to compensate for the mass of component (m_{part}^{AM}) plus the mass of material wastes. During Electron Beam Melting (EBM), the in-process material losses (m_W) could be associated with sieve filtering of reused powder, residues accumulated in the system filters, emissions of aerosols, and platform separation operations [12]. The in-process material losses, amortized per each produced part, have been assumed to be negligible in the present study. Then, post-AM operations are needed to remove the support structures (weighing m_S) and, when necessary, to achieve a smoother surface finish. In this research, a material removal (i.e., milling) process has been supposed to guarantee the surface quality of coupling surfaces, and a machining allowance (m_A) has been considered. No other finishing processes were assumed. For the conventional machining approach, the exceeding material is removed from the workpiece (weighing m_{wp}) in the form of chips (m_C) to obtain the finished part. One of the key differences between the two approaches could be traced back to the masses of produced parts. The re-design for AM could lead to a reduction of the mass of the additively manufactured component while ensuring the same in-work performance of conventionally machined products. Therefore, a k factor (defined as the ratio of m_{part}^{AM} and m_{part}^{CM}) accounting for the light-weighting has been introduced in the analysis.

2.2. Environmental impact assessment

With respect to Figure 1, the total primary energy demand for the AM-based approach (E^{AM}, in MJ/part) could be computed according to Equation 1.

$$E^{AM} = \overbrace{m_m^{AM} \cdot E_E}^{Material\,production} + \overbrace{m_m^{AM} \cdot E_A}^{Powder\,production} + \overbrace{m_{pwd} \cdot E_{AM}}^{AM\ \ process} + \underbrace{+ m_S \cdot E_{SR} + m_A \cdot E_{FM}}_{Finishing\,operations} + E_{use}^{AM} \quad (1)$$

where:

- m_m^{AM} : mass of raw material for the AM-based approach (kg);
- E_E : embodied energy of the raw material (MJ/kg);
- E_A : energy demand for atomization (MJ/kg);
- m_{pwd} : mass of powder needed for the AM-based approach (kg);
- E_{AM} : energy demand per unit weight of deposited material (MJ/kg);
- m_S : mass of the support structures (kg);
- E_{SR} : energy demand to remove the support structures (MJ/kg);
- m_A: mass of the machining allowance (kg);
- E_{FM}: energy demand for finish machining operations (MJ/kg);
- E_{use}^{AM}: energy demand for the use phase of the AM part (MJ/part).

The total primary energy demand for the machining-based approach (E^{CM}, in MJ/part) could be similarly quantified, as shown in Equation 2.

$$E^{CM} = \overbrace{m_m^{CM} \cdot E_E}^{Material\,production} + \overbrace{m_m^{CM} \cdot E_F}^{Workpiece\,production} + \underbrace{m_C \cdot E_M}_{Machining\,process} + E_{use}^{CM} \quad (2)$$