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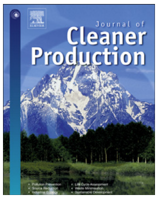

Environmental modelling of aluminium based components manufacturing routes: Additive manufacturing versus machining versus forming

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ABSTRACT

Additive Manufacturing represents, by now, a viable alternative for metal-based components production. Therefore the designer, often, has to select among three options at process design stage: subtractive, mass conserving, and additive approaches. The selection of a given process, besides affecting the manufacturing step impact, influences significantly the impact related to the material production step. If the process enables a part weight reduction (as the Additive Manufacturing approaches do) even the use phase is affected by the manufacturing approach selection. The present research provides a comprehensive environmental manufacturing approaches comparison for components made of aluminum alloys. Additive manufacturing (Selective Laser Sintering), machining, and forming processes are analyzed and compared by means of Life Cycle Assessment techniques. The effect of weight reduction enabled by additive approach is considered. The paper aims at highlighting the strong link between manufacturing approach selection and material use. In this respect, a thorough environmental analysis of the pre-manufacturing step is developed. Moreover, the influence of eco-attributes aluminium variability on the comparative analysis results is studied. The paper, therefore, contributes to the development of a methodology for manufacturing approaches comparison, providing guidelines for green manufacturing approach selection. Results reveal that, for the analyzed case studies, the Additive Manufacturing is a sustainable solution for aluminium components only under a specific scenario: high complexity shapes, significant weight reduction, and application in transportation systems.

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1. Introduction

The metal components manufacturing sector plays a significant role within the global environmental impact ascribable to the industry sector. Raw material production activities cause about 25% of global CO_2 emissions (Worrell et al., 2016). To be more specific, the top five materials alone (steel, cement, paper, aluminium, and aggregated plastics) dominate the entire world material production sector whether measured by energy used or carbon dioxide emitted. Two of the top five materials are metals: steel and aluminum are responsible for about 25% and 3% respectively of CO_2 emissions for material production (Gutowski et al., 2013).

Besides the impact of material production, the environmental impact of manufacturing has to be considered; identifying the environmental impact ascribable to metal working processes is a challenging issue as these values are often included in the material production step. Despite that, some data reporting the environmental impact of industrial sub-sectors are available for U.S. (U.S. Department of Energy, 2010) and China (National Bureau of Statistics (NBS), 2015). The analysis of these data can give a reliable idea of the responsibility of metal shaping processes within the global environmental impact. The sub-sectoral breakdown analysis of annual primary energy demand of manufacturing sector reveals that metal working processes account for about 4%. This value is much lower with respect to the impact of primary material production (Ingarao, 2017). Despite the latter statistics, scientists working in the manufacturing field play a key role also concerning

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Nomenclature

E_B (MJ/kg)	primary energy demand for aluminum bar production ($E_B = E_V + E_{HE}$)
E_{HE} (MJ/kg)	primary energy demand for hot extrusion
E_{GA} (MJ/kg)	primary energy demand for gas atomization
E^{AM}_{mat} (MJ/part)	primary energy demand for raw material production, AM approach
E^{F}_{mat} (MJ/part)	primary energy demand for raw material production, forming approach
E^{M}_{mat} (MJ/part)	primary energy demand for raw material production, machining approach
E_P (MJ/kg)	primary energy demand for aluminum powder production ($E_P = E_V + E_{GA}$)
E_R (MJ/kg)	primary energy demand for aluminum ingot secondary production (recycling)
E_V (MJ/kg)	primary energy demand for aluminum ingot primary production
m_{iA} (kg)	mass of the aluminum ingot for the AM approach
m_{iF} (kg)	mass of the aluminum ingot for the forming approach
m_{iM} (kg)	mass of the aluminum ingot for the machining approach
m_p (kg)	mass of the component
m_{sAM} (kg)	mass of the support structures
m^{f}_{sE} (kg)	mass of the scraps of hot extrusion process, forming approach
m^{m}_{sE} (kg)	mass of the scraps of hot extrusion process, machining approach
m_{sF} (kg)	mass of the machined-off material of forged components
m_{sFM} (kg)	mass of the machined-off material of AM components
m_{sGA} (kg)	mass of the scraps of gas atomization
m_{sM} (kg)	mass of the machined chips
$r_{(95\%)}$	recyclability equal to 95% (typical for bulk scraps)
$r_{(85\%)}$	recyclability equal to 85% (typical for light-gauge scraps)

Acronyms

AM	Additive Manufacturing
SLM	Selective Laser Melting
LCA	Life Cycle Assessment
EoL	End of Life
BP	Breakeven Point
PSD	Process Sustainability Diagram
SEC	Specific Energy Consumption

the material production step. In fact, material usage and manufacturing processes are two strictly connected stages as the manufacturing process selection significantly affects the amount and the kind of used material. Moreover, the growing interest raised around additive manufacturing approaches makes the former statement more meaningful. As a matter of fact, additive-based approaches use powder instead of semi-finished bulk workpieces (such as bars, plates, etc.) and are claimed to use less material and produce process scraps.

Additive Manufacturing (AM) processes are being analyzed also under the environmental impact perspective (Ford and Despeisse, 2016). A study presenting a comprehensive and global sustainability assessment of 3D printing was developed by Gebler et al. (2014), who discussed the effect of additive manufacturing on all the three (economic, social, and environmental) pillars of sustainability. Specifically, this paper outlines cost and environmental impact potential reductions associated with different 3D printing spreading scenarios over the next ten years. A comprehensive overview has been recently published by Kellens et al. (2017a); the authors offered a review of the published researches on the environmental analysis of AM, outlining production scenarios where AM can be beneficial form an environmental point of view. As concerns AM processes for metal based components, environmental impact analyses have already been published on: Selective Laser Melting (SLM) (Faludi et al., 2017), Direct Additive Laser Manufacturing (DALM) (Le Bourhis et al., 2013) and Electron Beam Melting (Baumers et al., 2017; Le et al., 2017). Concerning polymers, an environmental characterization of stereolithography has been recently presented by Yang and Li (2018). Material and energy efficiency of Fused Deposition Modelling (FDM) was analyzed by Song and Telenko (2017) and Griffiths et al. (2016). A Life Cycle Assessment (LCA) based analysis on Selective Laser Sintering (SLS) of polymer was developed by Kellens et al. (2014).

Despite a few studies on environmental impact quantification of AM processes have been already developed, comparative analyses are needed to understand the actual environmental performance of AM approaches with respect to traditional manufacturing routes.

Actually, as metal shaping processes are concerned, three manufacturing approaches can be followed: mass conserving (forming processes), subtractive (machining processes) and additive based approaches. The selection of one manufacturing approach over another one could result in significant material and energy savings. In consequence, when the environmental impact of a manufacturing approach is to be analyzed, the material-related flow must not be left out and has to be followed throughout the product life (Ingarao et al., 2016b). Over the last few years, researchers have started to deal with such challenges and some comparative analyses have been published. Morrow et al. (2007) developed the first comparative analysis quantifying the energy consumption and CO_2 emissions associated with the production of molds and dies via laser-based Direct Metal Deposition (DMD) and CNC milling. Two case studies were presented in order to assess the influence of part complexity on the comparative analysis. The results revealed that conventional CNC milling is preferable over DMD processes for high solid-to-cavity ratios. Molds with low solid-to-cavity ratios are less environmentally burdensome when produced via DMD instead. Serres et al. (2011) compared the direct additive laser manufacturing (CLAD) approach with conventional machining. A LCA analysis on Ti-6Al-4V parts was developed, and proved that additive manufacturing leads to an environmental impact reduction as high as 70% (Ecoscore from Eco-Indicator 99 methodology), mainly because of the absence of scraps production. Paris et al. (2016) compared cumulative energy demand of conventional machining and EBM process to manufacture an airplane turbine made of titanium alloy. The material-related contributions were included and the influence of the machined-off material on the environmental impact was highlighted, showing that AM processes are preferable when the shape complexity increases. Tang et al. (2016) proposed a comparison between a binder jetting process and conventional CNC machining. The environmental impact saving achievable by the weight reduction obtainable by topology optimization was included, a CO_{2eq} emissions reduction of 64% was obtained by selecting the AM over machining. In this context, Faludi et al. (2015) applied a full LCA methodology to

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