

Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions

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Summary

The additive manufacturing of metal parts represents a promising process that could be used alongside traditional manufacturing methods. The research scenario in this field is still largely unexplored, as far as the technological solutions adopted to integrate different processes are concerned and in terms of environmental and economic impact assessment. In this article, an electron beam melting (EBM) process and a machining process have been analyzed and compared using a cradle-to-grave life cycle-based approach. The production of components made of the Ti-6Al-4V alloy has been assumed as a case study. The proposed methodology is able to account for all of the main factors of influence on energy demand and carbon dioxide emissions when the component shape is varied. The results prove that, besides the direct energy intensity of the manufacturing processes, the impacts related to material usage are usually dominant. Therefore, when complex geometries have to be manufactured, the additive manufacturing approach could be the best strategy, if it enables a larger amount of material savings than conventional machining. Vice versa, when a small amount of material has to be machined off, the high energy intensity of an EBM process has a negative effect on the performance of the process.

Introduction

Manufacturing accounts for about 98% of the total direct carbon dioxide (CO₂) emissions from the industrial sector and is responsible for around 35% of the global electricity use and over one quarter of the primary resource extraction (Fischedick et al. 2014; UNEP 2011). Gutowski and colleagues (2013a) analyzed CO₂ manufacturing emissions throughout the world over the last few decades. The observed trends revealed that CO₂ emissions gradually increased from 1970 to 2002, and then a relatively sharp rise appeared (mainly attributed to the increased production activity of developing and emerging nations). In short, the total global CO₂ emissions attributed to manufacturing continued along an upward slope over the

analyzed period, with a particularly negative trend over the last 14 years. Moreover, a relevant share of CO₂ emissions can be ascribed to material production. Ashby (2013, 21) stated that “making materials” consumes around 21% of the global energy demand and causes around 20% of the global CO₂ emissions. A study by Gutowski and colleagues (2013b) offered an accurate analysis of the global energy required for material production, which is dominated by a limited number of material categories: steel, cement, paper, aluminum, and aggregated plastics. The same researchers also stated that the demand for such materials is expected to grow from 2005 to 2050. It is clear that energy- and resource-efficient manufacturing strategies have to be implemented at a global level, and research activities are therefore required in such a domain.

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State of the Art

The growing interest in quantifying the CO₂ footprint of processes has led to the development of a methodology for the systematic analysis and improvement of the manufacturing unit process life cycle inventory (UPLCI) (Kellens et al. 2012). The need for environmental impact analyses becomes more and more urgent if the increasing success of additive manufacturing (AM) approaches is taken into account. AM could be used directly to produce a final item for sale or use. Powder bed fusion processes have been developed to manufacture titanium alloys, stainless steel, and aluminum alloys (Mower and Long 2016). AM processes might enable the obtainment of a fully dense component (as mentioned by Elahinia et al. [2012], Facchini et al. [2009], and Tammis-Williams et al. [2015] for electron beam melting [EBM] processes), whose mechanical properties could be comparable with those of components achieved by conventional manufacturing. In this context, Wang and colleagues (2016) and Murr and colleagues (2009a, 2009b) have shown interesting results for the EBM of Ti-6Al-4V.

Three fundamental approaches can be followed for metal shaping: mass conserving, subtractive, and additive processes. The environmental impact of each manufacturing approach should be explored in detail in order to identify the potential of all the emerging processes. In order to tackle this challenge, manufacturing scientists have turned their attention toward environmental impact assessments over the last few years, and a clear picture of the so-far developed researches has been provided by Haapala and colleagues (2013) and Duflou and colleagues (2012). However, the route toward achieving complete knowledge of the environmental performance of metal-related manufacturing processes is still long. Currently, sustainability analyses predominantly focus on material removing processes. Several articles have either focused on the effects of process parameters (such as those of Dahmus and Gutowski [2004], Diaz et al. [2011], and Kara and Li [2011]), on machine tool architectures (Behrendt et al. 2012), or debated the demands of different processes (Gutowski et al. 2006). Much less attention has been paid to forming processes. The available studies concern LCI guidelines for hot forging processes (Buis et al. 2013) and the environmental performance of sheet metal forming processes (Santos et al. 2011; Ingarao et al. 2014).

As far as AM is concerned, a state of the art on the sustainability analyses of AM processes can be found in the article by Huang and colleagues (2016). The specific electric consumption of a large number of AM processes has also been reported in Yoon and colleagues (2015) and in Le Bourhis and colleagues (2013). So far, most of the studies have focused on polymeric materials (Kellens et al. 2014; Mognol et al. 2006). Only a few researches have been conducted on the environmental performance of AM processes for metal parts. Duflou and colleagues (2011) proposed a unit process LCI for a selective laser melting (SLM) process. The researchers also pointed out impact

reduction opportunities in that article. Baumers and colleagues (2011) analyzed the effect of capacity utilization (i.e., the utilization of the build volume) on the energy efficiency of different metal-based AM processes. The same research group proposed a cost and energy accounting model for the AM of stainless steel. The effects of the product demand were also analyzed (Baumers et al. 2013). Moreover, the influence of shape complexity on the specific energy consumption of EBM processes has recently been studied (Baumers et al. 2017). Le Bourhis and colleagues (2013) applied a life cycle assessment (LCA)-based methodology to direct additive laser manufacturing (DALM), in which electric energy, fluids, and raw material consumption were all accounted for.

However, in order to evaluate the actual environmental impact of a given manufacturing approach, the whole life cycle of the product should be analyzed. In particular, given that the three fundamental manufacturing approaches, besides adopting different setups and machine tools, also use different kinds and amounts of material, the material flow is expected to have an important effect on the performance of the environmental process. Additionally, comparative assessments are of utmost importance in order to properly label and sort the manufacturing processes from a sustainability point of view. A first comparative analysis was provided by Morrow and colleagues (2007). They produced a quantitative estimate of the energy consumption and emissions associated with the production of molds and dies by laser-based direct metal deposition and computer numerical control milling. Another comparison of different approaches was developed by Serres and colleagues (2011): The researchers compared the direct additive laser manufacturing process (Construction Laser Additive Directe; CLAD[®]) with conventional machining for the production of components made of Ti-6Al-4V. The researchers developed a full LCA analysis and proved that AM leads to an environmental impact (the Ecoscore from Eco-Indicator 99) reduction of as much as 70%. Huang and colleagues (2016) applied the comparative analysis to five case studies pertaining to aircraft components made of metallic materials by EBM, SLS, and direct metal laser sintering (DMLS). It was found that the energy savings were primarily attributed to the reductions in resource production and energy use, which, in turn, were attributable to the lower buy-to-fly ratios (given that the AM approaches used less material than the conventional processes). Ingarao and colleagues (2015) conducted an environmental comparison of a hot extrusion process (bulk forming process) and a machining process for a simple-shaped aluminum component. The results revealed that workpiece material usage was the dominant factor of influence in terms of environmental impact, even when recycling credits were considered, for different geometries (Ingarao et al. 2016). In this context, another decision-support model has recently been proposed by Watson and Taminger (2016), who established a computational model to determine when AM is preferable (in terms of energy efficiency) over subtractive machining.

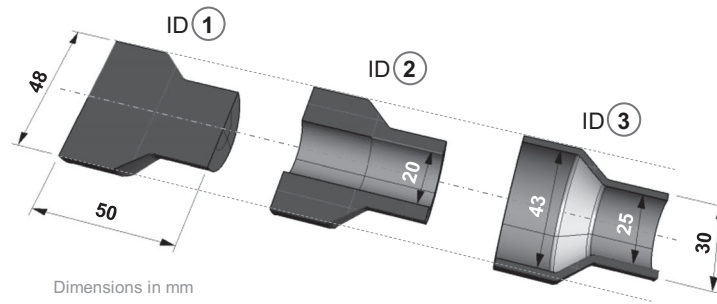


Figure 1 The three product shapes to be manufactured by additive and subtractive processes.

Aim of the Article

Some guidelines for future research have emerged from the literature review. Overall, the environmental footprint of discrete part manufacturing processes still needs to be fully understood. Moreover, there is still a need to standardize international research efforts in order to make the obtained results comparable. Currently, there is a lack of studies on the quantification of energy use (throughout the whole life cycle) and on the greenhouse gas emission implications of additively manufactured components, and the conducted research has mostly been concentrated on polymeric materials. Besides the direct energy intensity of AM processes, material-related environmental impacts should be included when cradle-to-grave boundaries are considered. Finally, comparative analyses are able to point out the actual environmental impact of different manufacturing approaches. However, these kinds of studies have rarely been applied.

The present article has the aim of partially filling the aforementioned knowledge gap. An AM process (EBM) and a conventional machining process have been analyzed, integrated, and compared for the production of components made of Ti-6Al-4V. A complete methodology, which considers all the factors of influence necessary to compile an energy and CO₂ LCI, has been implemented. Impacts related to material usage have been accounted for in a cradle-to-grave approach, and material recycling has been identified as the end-of-life (EoL) scenario. The proposed methodology also includes the process scrap and postprocessing (finish machining) operations for the EBM process. The product shape has been varied in order to analyze the effect of such a parameter on the process footprint. Summing up, the article has the aim of developing a quantitative methodology to assess the primary energy demand and the CO₂ emissions of additive and subtractive manufacturing processes. Such a tool can be expected to be useful to detect the production scenarios that make additive processes preferable (from the environmental viewpoint) over conventional manufacturing approaches.

Case Study and the Main Assumptions

A life cycle-based approach has here been proposed to evaluate the integration of AM techniques in conventional production routes based on machining processes. The goal and scope of the study have been to analyze the impact of both addi-

Table 1 Geometrical features of the three case studies

Geometry	ID 1	ID 2	ID 3
Length (mm)	50		
Maximum external diameter (mm)	48		
Minimum external diameter (mm)	30		
Maximum internal diameter (mm)	n.a.	20	43
Minimum internal diameter (mm)	n.a.	20	25
Part volume, V_p ($\times 10^3$ mm ³)	62.5	46.8	15.3
Part weight, m_p (g)	275	206	67

Note: g = grams; mm = millimeters; mm³ = cubic millimeters; n.a. = not available.

tive and subtractive manufacturing strategies in terms of energy demand, CO₂ emissions, and resource depletion. The production of components made of Ti-6Al-4V has been considered. In addition, given that the environmental performance of a manufacturing approach is affected by the type and the amount of the involved materials, an analysis has been designed, in which the component shape has been varied and different solid-to-cavity ratios have been considered. The solid-to-cavity ratio has been defined, according to Morrow and colleagues (2007), as the mass of the final part divided by the mass that would be contained within the bounding volumetric envelope of the part. The study has therefore been conducted to (1) improve knowledge concerning the key factors of influence on the impact of such processes and (2) provide guidelines in which the most energy- and resource-efficient manufacturing strategy is identified as a function of the production scenario. The functional unit, the system boundaries, and the process evaluation metrics are presented hereafter.

Functional Unit

The impact arising from the life cycle of a single component made of a Ti-6Al-4V alloy has been assumed as the basic unit for a process assessment. As shown in figure 1, three different shapes (namely, ID 1, ID 2, and ID 3) were taken into account. The main geometrical features are listed in table 1. The basic idea was to analyze the environmental performance while varying the amount of

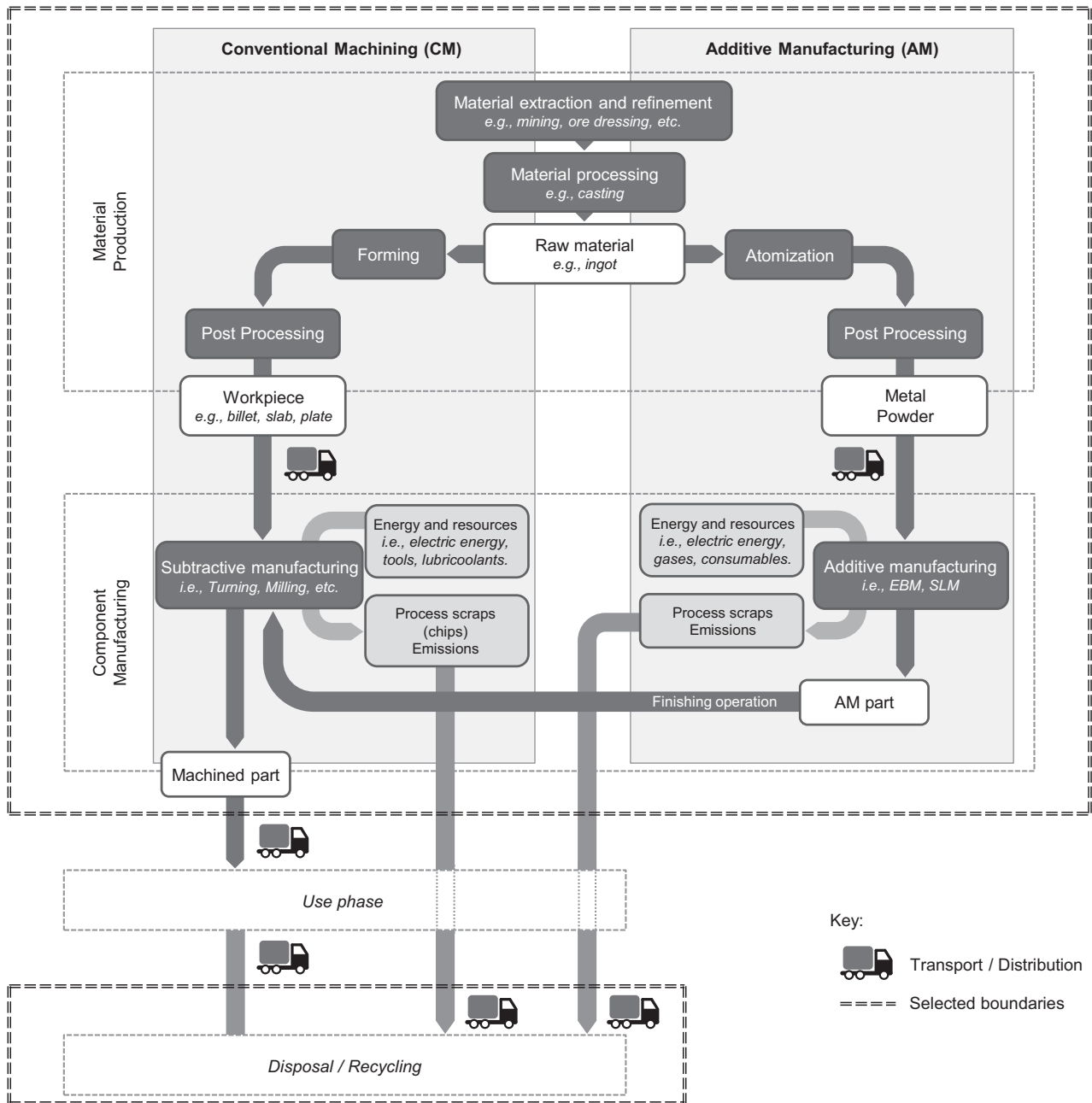


Figure 2 System boundaries for the comparative analysis. EBM = electron beam melting; SLM = selective laser melting.

process scraps for subtractive approaches (i.e., the machined-off material) and verify whether additive manufacturing could be a more efficient strategy than traditional subtractive processes.

System Boundaries

A cradle-to-grave system boundary has been adopted, and recycling has been selected as the EoL scenario. The impacts of material production, product manufacturing, transportation, and recycling were evaluated. It was assumed that all the components (made either by a subtractive approach or additive

manufacturing plus finish machining) complied with the same product specifications. As a result, it was possible to neglect the differences in environmental impact during the use phase (given that the in-use performance was expected to be the same). Figure 2 shows a sketch of the system boundaries, together with the main considered factors, as well as the energy and resource flows. Differences in feedstock material production and component manufacturing were considered, as pointed out in *Life Cycle Inventory*. Moreover, transportation impacts due to material shipment from the production site to the manufacturing plant and from the manufacturing plant to the recycling site were also estimated.

Impact Indicators

The energy demand and the CO₂ emissions have been assumed as metrics for the process assessment. The electric energy consumption was converted into (primary) energy source consumption by considering an average efficiency of 34% (Jeswiet and Kara 2008) to account for the energy generation and the transmission losses. The CO₂ emissions attributed to electric energy consumption were computed using the carbon emission signature (CES) method proposed by Jeswiet and Kara (2008) and applying data for the Italian energy mix (IEA 2015).

Life Cycle Inventory

In this section, the main considered factors of influence are explained for each life cycle stage. Because material recycling is considered as the EoL strategy, the material production and the EoL phases are discussed together in *Material Usage and Recycling-Related Benefits*, for the sake of clarity. It is appropriate to remark that, when combining different energy demand contributions, all the values should be traced back to the same level. Therefore, unless otherwise specified in the text (i.e., for the electric energy consumption), all the presented values (also from literature) are assumed to refer to their primary energy source consumption.

Material Usage and Recycling-Related Benefits

When comparing different technological approaches, such as additive manufacturing (AM) and conventional machining (CM), the different routes for the production of the materials being processed have to be considered (figure 2). First, raw materials have to be extracted and refined in order to obtain the usable, in-stock materials. The energy per unit mass needed to make a material from its ores and feedstock is defined as its embodied energy (Ashby 2013). Then, materials have to be further processed in order to produce the metal powder for AM, or the workpiece for CM. For instance, gas atomization can be applied to produce Ti-6Al-4V powder (Dawes et al. 2015), whereas forming processes are used to create billets, plates, slabs, etc. Postprocessing operations, such as the thermal treatments of the formed parts, should also be included. Overall, the energy necessary for material production (E_{mat} , in MJ/part) can be computed, for each produced part, according to equation (1):

$$E_{\text{mat}} = m \cdot (E_E + E_{\text{Pr}}) \quad \left(\frac{\text{MJ}}{\text{part}} \right) \quad (1)$$

where:

- m (in kilograms [kg]) is the weight of the material that has to be processed by AM or CM;
- E_E (in megajoules [MJ]/kg) is the embodied energy necessary to obtain the usable material from ores and feedstock;
- E_{Pr} (in MJ/kg) is the energy necessary to further process the material into powder (AM) or a workpiece (CM).

The energy necessary for material production, for both the subtractive and additive manufacturing approaches, should account for the benefits that can be derived from recycling. However, there is no single criterion that is able to account for recycling credits. The substitution method, which considers the impacts on the present climate on the production and supply of the material (cradle-to-gate), and gives a recycling credit for future recyclability (EoL), has been applied in the present article (Hammond and Jones 2010). For materials that do not suffer from losses in their inherent properties, such as metals, the embodied energy (E_E , in MJ/kg) is obtained by means of equation (2), in which the fraction of material recycled at the EoL (r) and the embodied impact arising from the recycled material input (E_R , in MJ/kg) are included. E_V is the embodied energy for the primary production of the material, whereas E_D represents the energy involved when scraps are handled. If E_D is neglected, equation (2) can be rewritten as equation (3), where the embodied energy savings ($E_V - E_R$, in MJ/kg) are directly proportional to the material recyclability. CO₂ emissions can be assessed in a similar manner.

$$E_E = r \cdot E_R + (1 - r) \cdot (E_V + E_D) \quad \left(\frac{\text{MJ}}{\text{kg}} \right) \quad (2)$$

$$E_E = E_V - r \cdot (E_V - E_R) \quad \left(\frac{\text{MJ}}{\text{kg}} \right) \quad (3)$$

Machining

The weight of the material that has to be processed for CM, or rather of the workpiece, corresponds to the sum of the weight of the part that has to be obtained (m_p) and the weight of the machined chips (m_c), as shown in equation (4).

$$m^{\text{CM}} = m_p + m_c \quad \left(\frac{\text{kg}}{\text{part}} \right) \quad (4)$$

The process scraps (i.e., the chips obtained from the turning process as by-products), as well as the component (which is disposed of at the end of its first life) are assumed to be recycled. As far as the recyclability of chips and bulk material are concerned, specific data can be obtained for some materials, such as aluminum alloys (Ingarao et al. 2016), but there is a lack of literature information on Ti-6Al-4V. In the present article, the recyclability of the bulk material and chips has been hypothesized to be equal to 0.80 (Mayyas et al. 2012). A forming process to create the workpiece (a 50-millimeter [mm] diameter and 50-mm-long billet) was included in the workpiece material production process. The eco-properties of Ti-based alloys were extracted from Ashby (2013) and are listed in table 2.

Additive Manufacturing

The weight of the powder necessary to properly accomplish the AM process (equation (5)) should include the weight of the part that has to be obtained (m_p), the machining allowance

Table 2 Eco-properties assumed for Ti-6Al-4V

Eco-property	Average value (range)
Embodied energy for primary production, E_V (MJ/kg)	685.0 (± 35.0)
CO ₂ footprint for primary production, CO _{2V} (kg/kg)	46.5 (± 2.5)
Embodied energy for recycling, E_R (MJ/kg)	87.0 (± 9.0)
CO ₂ footprint for recycling, CO _{2R} (kg/kg)	5.2 (± 0.5)
Forging/Rolling energy (MJ/kg)	14.5 (± 0.5)
Forging/Rolling CO ₂ (kg/kg)	1.15 (± 0.05)

Source: Adapted from Ashby (2013).

Note: CO₂ = carbon dioxide; MJ/kg = megajoules per kilogram; kg/kg = kilograms per kilogram.

for postprocessing finishing operations (m_a), and the weight of process scraps (m_s).

$$m^{AM} = m_p + m_a + m_s \left(\frac{\text{kg}}{\text{part}} \right) \quad (5)$$

The weights of the parts (m_p) are listed in table 1, for each case study. EBM is suitable for obtaining free-form parts, and it is successfully used for various applications, such as for the production of components for biomedical implants (Bartolo et al. 2012). However, the achieved surface quality is not usually adequate to meet the strict requirements of the aerospace and automotive industry (Priarone et al. 2012). The arithmetic mean of the roughness of EBM-made parts is between 25 and 35 micrometers. In addition, whereas SLS, DMLS, and selective laser melting (SLM) processes produce parts with dimensional errors of less than 0.1 mm for a 100-mm length, EBM dimensional precision is only half as good (Vayre et al. 2012). Therefore, a further finishing turning operation has been considered for the three case studies. A constant and uniform machining allowance of 1 mm was assumed (Rännar et al. 2007). Figure 3 compares the material usage for CM and AM, as a function of the case study.

Further, the process scraps should be included in the analysis. m_s accounts for both powder losses and material losses attributed to support structures. As far as powder recyclability is concerned, there is still a need for systematic studies to demonstrate the stability of the powders for the use over extended periods of time. Some articles dealing with Ti-6Al-4V powder recyclability in EBM processes have recently been published (Petrovic and Niñerola 2015; Nandwana et al. 2016). These research activities have proved that EBM-processed Ti-6Al-4V powder properties are conserved in consecutive builds with recycled powder. A significant amount of raw material can be saved by means of powder recycling given that, despite numerous reuses, the chemical contents of the powder material are maintained, and the aeronautical standards are thus satisfied. As for the support structures, the material losses are generally related to the geometrical complexity of the components that have to be additively manufactured. In the present article, m_s has been hypothesized to vary for AM as a percentage of the mass of the component plus the machining allowance ($m_p + m_a$).

The energy necessary for material production was computed according to equation (1). The titanium ingots were assumed to be subjected to an atomization process in order to obtain suitable powders for the EBM process. Therefore, the environmental impact attributed to the atomization process has to be added to those of material extraction, refinement, and preprocessing. Only a few articles provide useful information on how to model the impact of titanium powder production (Serres et al. 2011; Baumers et al. 2017). The material for the gas atomization process is melted and then atomized by means of high-pressure jets of gas (argon or nitrogen). The energy necessary for melting as well as for gas production should be included in the LCI step. Energy and resource demands for titanium powder production were reported in Serres and colleagues (2011): It is possible to compute a specific electric energy consumption of 1.95 kilowatt-hours per kilogram (kg) from the researchers' data and an argon flow rate of 0.21 liters (L) per kg. According to Weir and Muneer (1998), the embodied energy for argon can be assumed to be 0.672 kilojoules per L. On the basis of such information, the energy necessary for gas atomization should be around 20 MJ/kg. On the other hand, other researchers (Baumers et al. 2017) estimated 31.7 MJ/kg for the atomization process. In the present article, the latter value was conservatively assumed to consider the gas atomization of Ti-6Al-4V.

Manufacturing

Machining

Several energy consumption assessment models have been proposed for machining (such as the ones by Kara and Li [2011]; Mori et al. [2011]; Mativenga and Rajemi [2011]; Li et al. [2013]). Black-box approaches empirically correlate the input machining parameters to the energy demand, whereas bottom-up approaches divide the total energy consumption into the contributions attributed to machine states and/or components (Guo et al. 2015). In the present research, the specific energy consumption (SEC) was related to the material removal rate (MRR) by applying the model shown in equation (6), proposed by Li and Kara (2011). The specific coefficients C_0 and C_1 of the machine were experimentally assessed for when Ti-6Al-4V is machined using a Graziano 101 SAG CNC lathe.

$$SEC = C_0 + \frac{C_1}{MRR} \left(\frac{J}{\text{mm}^3} \right) \quad (6)$$

Only a few studies (such as those of Rajemi et al. [2010]; Mativenga and Rajemi [2011]; Liu et al. [2016]) account for indirect energy consumption attributed to cutting tool usage. The tooling footprint could be modeled according to equation (7) (Mativenga and Rajemi 2011; Ingarao et al. 2016), where E_{ct} is the energy necessary for tooling (including the embodied energy of tungsten carbide and tool manufacturing), n_e is the number of cutting edges of the turning insert, t_c is the cutting time necessary to produce a part, and T_L is the tool life of each cutting edge.

$$E_{\text{tool}} = \frac{E_{ct}}{n_e} \cdot \frac{t_c}{T_L} \left(\frac{\text{MJ}}{\text{part}} \right) \quad (7)$$

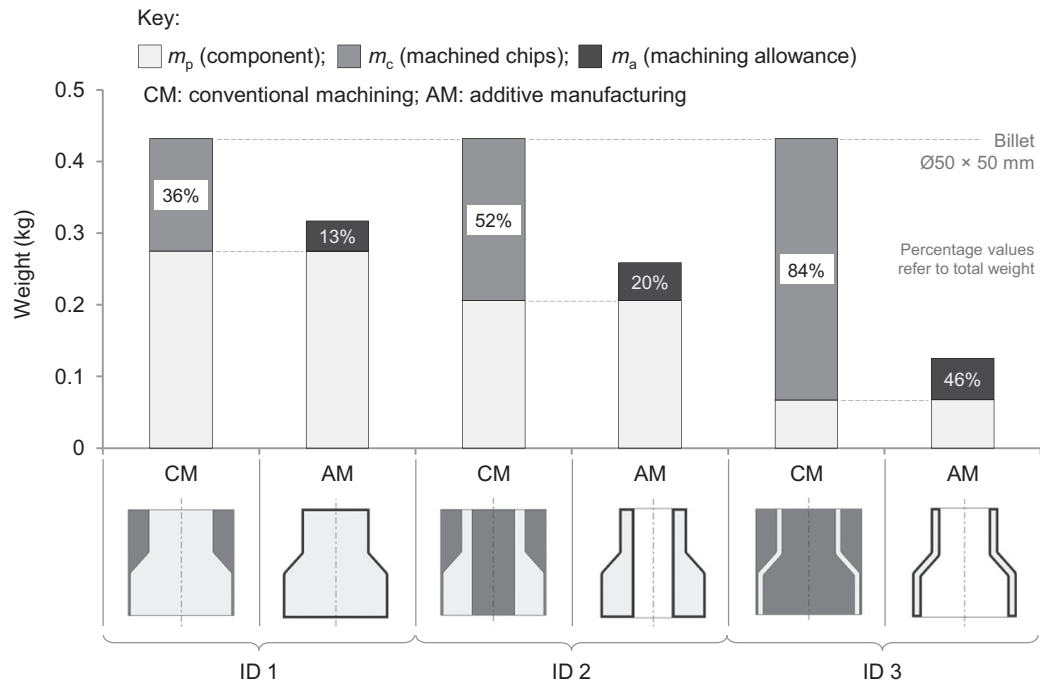


Figure 3 Material usage for conventional machining (CM) and additive manufacturing (AM) as a function of the component shape (for AM, $m_s = 0$). For definitions of ID 1, 2, and 3, see figure 1 and table 1.

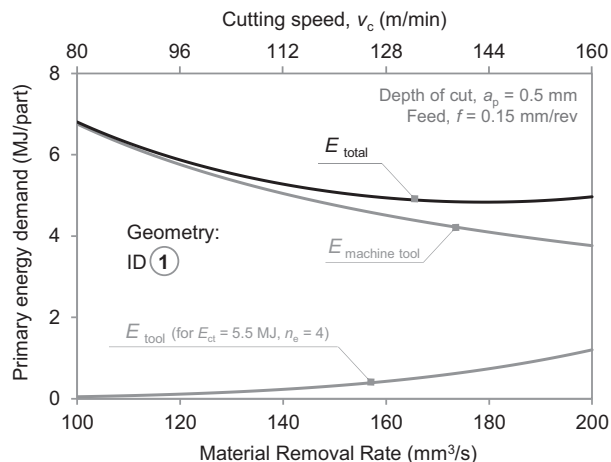


Figure 4 Effects of MRR on the energy demand when turning an ID 1 geometry component. MJ = megajoules; m/min = meters per minute; mm = millimeters; mm/rev = millimeters per revolution; mm^3/s = cubic millimeters per second; MRR = material removal rate.

Figure 4 plots the direct and indirect contributions to the energy demand when a component with an ID 1 geometry is produced. According to the SEC model, the energy necessary for the turning process (which was computed directly by referring to the primary energy source consumption) decreases when the material removal rate is increased. Vice versa, the increase in the material removal rate (obtained by increasing the cutting speed in the present case) results in an increase in the tooling footprint, attributed to an increase in tool wear. The

cutting parameters that can minimize the direct and indirect energy demand should be identified for each specific case study. However, in the present research, because low MRRs were chosen experimentally, only the direct electric energy demand for machining has been considered. ID 1 was assumed to be produced by longitudinal external turning, whereas minimum internal diameters of 20 and 25 mm were obtained for ID 2 and ID 3 by considering drilling with twist drills. The cutting speed for turning was 90 meters per minute (m/min), the feed was 0.15 millimeters per revolution (mm/rev), and the depth of cut was 0.5 mm. The cutting speed for drilling was 35 m/min and the feed was 0.05 mm/rev. All the cutting operations were performed under conventional flood cooling, which is a widely applied industrial standard.

Additive Manufacturing

As far as the inventory analysis of the EBM process is concerned, the electric energy consumed by the used platform has to be monitored and, subsequently, ascribed to the functional unit. An SEC value for EBM-sintering Ti-6Al-4V was proposed by Baemers and colleagues (2011, 2017). They quantified the SEC for each deposited kilogram of material as 59.96 MJ/kg, which includes the energy consumption due to both productive and non-productive modes. The authors proved there is no direct link between energy consumption and shape complexity for EBM (Baemers et al. 2017). As a consequence, such an SEC value might be used to quantify the production energy of any component made of Ti-6Al-4V and manufactured via EBM. However, it is worth mentioning that the utilization of the build volume affects the process energy, and therefore the SEC

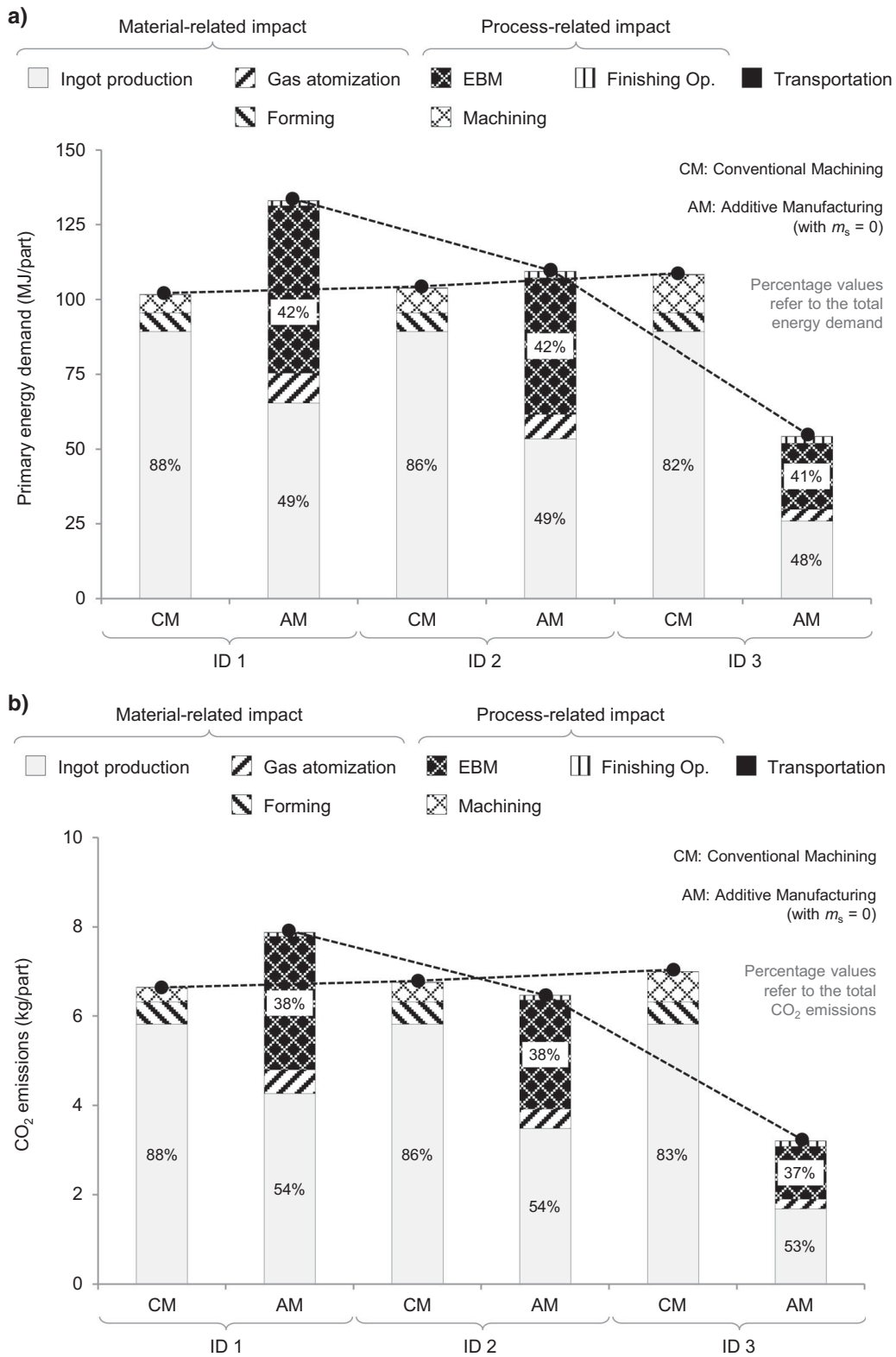


Figure 5 Shares of the energy demand (a) and CO₂ emissions (b). Note: The impact of transportation is negligible. CO₂ = carbon dioxide; EBM = electron beam melting; kg = kilograms; MJ = megajoules.

value itself (Baumers et al. 2011). In the present research, the electric energy consumption for EBM has been assumed to be 59.96 MJ/kg, and operation at full machine capacity has been considered. The energy for the post-processing finish machining operations was computed, for the three considered case studies, by applying the cutting conditions for turning detailed in *Machining*.

Transportation

Given that the two manufacturing approaches involve different amounts of material, different amounts of material have to be shipped, which, in turn, leads to different transportation-related environmental impacts. The impact attributed to material shipment from the titanium production site to the manufacturing plant and attributed to the scrap shipment to the recycling plant was modeled according to the guidelines provided in Ecolnvent, that is, 300 kilometers (km) for the shipment to the manufacturing plant and 300 km for shipping the process scraps to the recycling plant. Moreover, impacts attributed to the transportations identical for the two manufacturing paths were not included. Energy and the emission factors (equal to 0.71 MJ/tonne·km and 0.05 kg/tonne·km, respectively) concerning a 55-tonne truck were used (Ashby 2013).

Results and Discussion

The life cycle results for the primary energy demand and CO₂ emissions are presented in figures 5 and 6. The contribution of each considered factor as well as the shares of those of most influence are highlighted. Overall, it is possible to note that the material-related impact always plays a significant role. In fact, it accounts for more than 80% in all the considered scenarios for CM, whereas it is lower for the AM approach. For the ID 1 part geometry, CM results in substantial energy and CO₂ emission savings, even though the process scraps for AM (m_s) are nullified, as shown in figure 5. Vice versa, for the ID 3 part geometry (which exemplifies a thin-walled component), AM appears to be the best solution for both the considered metrics, even when a certain amount of process scraps is included. Figure 6 plots the results as a function of m_s (computed as a percentage value of $m_p + m_a$) with reference to this claim. Specifically, the m_s value has been varied from 0% to 40%. The material-related impact as well as the process-related impact have been estimated, together with the impact of transportation. When m_s increases, the energy demand and the CO₂ emissions consequently increase. However, under the chosen hypothesis, the impacts of AM are always lower than those of CM. Higher m_s values than 105% and 124% would be necessary for the energy demand and CO₂ emissions, respectively, to make the CM process preferable over the AM one.

The impact of transportation appears to be negligible (figures 5 and 6) under the assumptions outlined in *Transportation*.

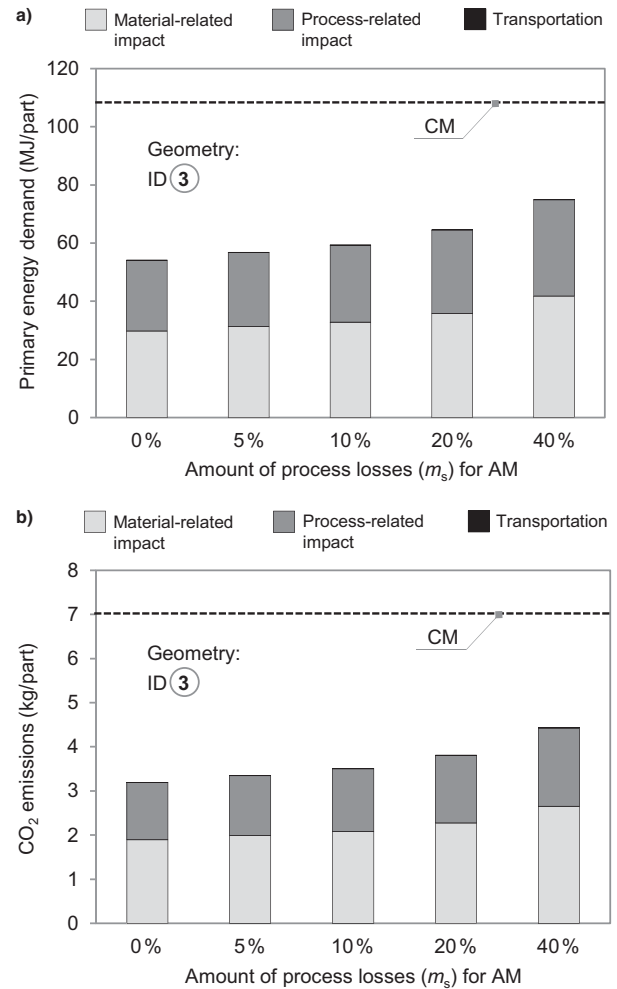


Figure 6 Variations in the energy demand (a) and CO₂ emissions (b) as functions of m_s for AM

Note: The impact of transportation is negligible. AM = additive manufacturing; CM = conventional machining; CO₂ = carbon dioxide; EBM = electron beam melting; kg = kilograms; MJ = megajoules.

Therefore, volumetric and handling differences related to workpiece and powder shipment were not analyzed in detail. Overall, it can be observed that the outcomes are mainly affected by the different amounts of used material and by the different SEC values of the two manufacturing approaches. When moving from ID 1 to ID 3, the machined-off material increases for the CM approach. As a result, the gap in material usage between the two approaches increases. On the other hand, the manufacturing step is energy intensive for AM, especially when a large amount of material has to be deposited layer by layer (ID 1). In fact, the energy demand and the CO₂ emissions for ID 1 attributed to AM largely surpass the savings attributed to the reduction in material usage. On the contrary, when the solid-to-cavity ratio decreases, the performance of the CM approach is affected negatively by the larger amount of used material, and, as a result, the AM approach appears to be the best strategy.

Conclusion and Outlooks

A methodology for quantifying the factors of influence for both additive and subtractive manufacturing has been proposed. A CM approach has been compared with an EBM process (followed by finish turning operations) for the production of parts made of Ti-6Al-4V. The proposed methodology does not focus only on the direct energy intensity of the processes, but also includes all the impacts related to the energy and material requirements throughout an LCI analysis. Three component shapes, characterized by different solid-to-cavity ratios, have been considered to analyze the effects of material-related aspects on process performance. The energy demands and CO₂ emissions for AM and CM have been shown to be affected by material usage. When enabling significant material savings, the AM approach appears to be the best strategy from the environmental viewpoint. On the other hand, when a small amount of material has to be machined off, the high energy intensity of the EBM process has a bad effect on the AM performance. Therefore, it is not correct to a priori label the AM or CM approach as energy efficient, given that the component features should also be taken into account.

In the present study, simple part geometries have been assumed as case studies, given that the basic idea has been to analyze the impact related to material usage and, in particular (for CM), to the amount of the machined-off material with respect to the volume of the part. It is worth pointing out that the technological potential of AM has already been shown for the creation of complex geometries or parts redesigned for additive manufacturing (i.e., by means of topological optimization practices). The AM processes might also enable new product design scenarios that could result in a substantial weight reduction. This, in turn, could lead to a further reduction in material usage for AM approaches over CM ones, which could result in further energy and CO₂ emission savings. In addition, the manufacturing process can be considered to have a significant effect on the impacts of the use phase, because it establishes the quality and functionality of the finished part. From this perspective, the decision on which process to select comes down to which process can provide the right balance of quality per unit resources consumed. In this context, the identification of the main factors of influence when all the possible production scenarios (such as material ecological properties, shape complexity, and batch size) are varied becomes a milestone to stimulate the scientific debate on the environmental performance of processes. Such knowledge will enable new green manufacturing guidelines to be defined.

References

- Ashby, M. F. 2013. *Materials and the environment*. Boston, MA, USA: Butterworth-Heinemann/Elsevier.
- Bartolo, P., J.-P. Kruth, J. Silva, G. Levy, A. Malshe, K. Rajurkar, M. Mitsuishi, J. Ciurana, and M. Leu. 2012. Biomedical production of implants by additive electro-chemical and physical processes. *CIRP Annals—Manufacturing Technology* 61(2): 635–655.
- Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, and R. Hague. 2011. Energy inputs to additive manufacturing: Does capacity utilization matter? In *Solid freeform fabrication proceedings*, 30–40. Solid freeform fabrication; An additive manufacturing conference. Austin, TX, USA: University of Texas.
- Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague. 2013. Transparency built-in energy consumption and cost estimation for additive manufacturing. *Journal of Industrial Ecology* 17(3): 418–431.
- Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague. 2017. Shape complexity and process energy consumption in electron beam melting: A case of something for nothing in additive manufacturing? *Journal of industrial Ecology* 21(S1): S157–S167.
- Behrendt, T., A. Zein, and S. Min. 2012. Development of an energy consumption monitoring procedure for machine tools. *CIRP Annals—Manufacturing Technology* 61(1): 43–46.
- Buis, J. J., J. W. Sutherland, and F. Zhao. 2013. Unit process life cycle inventory models of hot forming processes. In ASME 2013 International Manufacturing Science and Engineering Conference collocated with the 41st North American Manufacturing Research Conference, 10–14 June, Madison, WI, USA.
- Dahmus, J. B. and T. G. Gutowski. 2004. An environmental analysis of machining. In Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition (IMECE2004-62600), 13–19 November, Anaheim, CA, USA.
- Dawes, J., R. Bowerman, and R. Trepleton. 2015. Introduction to the additive manufacturing powder metallurgy supply chain exploring the production and supply of metal powders for AM processes. *Johnson Matthey Technology Review* 59(3): 243–256.
- Diaz, N., E. Redelsheimer, and D. Dornfeld. 2011. Energy consumption characterization and reduction strategies for milling machine tool use. In *Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, edited by J. Hesselbach, and C. Herrmann, 263–267. Braunschweig, Germany: Technische Universität Braunschweig.
- Dufloy, J. R., K. Kellens, and W. Dewulf. 2011. Unit process impact assessment for discrete part manufacturing: A state of the art. *CIRP Journal of Manufacturing Science and Technology* 4(2): 129–135.
- Dufloy, J. R., J. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, and K. Kellens. 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals—Manufacturing Technology* 61(2): 587–609.
- Elahinia, M. H., M. Hashemi, M. Tabesh, and S. B. Bhaduri. 2012. Manufacturing and processing of NiTi implants: A review. *Progress in Materials Science* 57(5): 911–946.
- Facchini, L., E. Magalini, P. Robotti, and A. Molinari. 2009. Microstructure and mechanical properties of Ti-6Al-4V produced by electron beam melting of pre-alloyed powders. *Rapid Prototyping Journal* 15(3): 171–178.
- Fishedick, M., J. Roy, A. Abdel-Aziz, A. Acquaye, J. M. Allwood, J.-P. Ceron, Y. Geng, et al. 2014. Industry. In *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, UK; New York: Cambridge University Press.
- Guo, Y., J. R. Dufloy, J. Qian, H. Tang, and B. Lauwers. 2015. An operation-mode based simulation approach to enhance the energy conservation of machine tools. *Journal of Cleaner Production* 101: 348–359.

- Gutowski, T. G., J. B. Dahmus, and A. Thiriez. 2006. Electrical energy requirements for manufacturing processes. In Proceedings of the 13th CIRP Conference on Life Cycle Engineering, 623–627, 31 May–2 June, Leuven, Belgium.
- Gutowski, T. G., J. M. Allwood, C. Herrmann, and S. Sahni. 2013a. A global assessment of manufacturing: Economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling. *Annual Review of Environment and Resources* 38: 81–106.
- Gutowski, T., S. Sahil, J. Allwood, M. Ashby, and E. Worrell. 2013b. The energy required to produce materials: Constraint on energy intensity-improvements, parameters of demand. *Philosophical Transactions of the Royal Society A* 371(1986): 20120003.
- Haapala, K. R., F. Zhao, J. Camelio, J. W. Sutherland, S. J. Skerlos, D. Dornfeld, I. S. Jawahir, A. F. Clarens, and J. L. Rickli. 2013. A review of engineering research in sustainable manufacturing. *Journal of Manufacturing Science and Engineering* 135(4): 041013.
- Hammond, G. and C. Jones. 2010. *Inventory of carbon and energy (ICE), annex B: How to account for recycling; A methodology for recycling*. Bath, UK: The University of Bath.
- Huang, R., M. Riddle, D. Graziano, J. Warren, S. Das, S. Nimbalkar, J. Cresko, and E. Masanet. 2016. Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components. *Journal of Cleaner Production* 135: 1559–1570.
- IEA (International European agency). 2015. Key trends in CO₂ emissions from fuel combustion. Excerpt from: CO₂ emissions from fuel combustion (2015 edition). www.iea.org. Accessed 27 February 2016.
- Ingarao, G., H. Vanhove, K. Kellens, and J. R. Dufloy. 2014. A comprehensive analysis of electric energy consumption of single point incremental forming processes. *Journal of Cleaner Production* 67: 173–186.
- Ingarao, G., P. C. Priarone, F. Gagliardi, R. Di Lorenzo, and L. Settineri. 2015. Subtractive versus mass conserving metal shaping technologies: An environmental impact comparison. *Journal of Cleaner Production* 87: 862–873.
- Ingarao, G., P. C. Priarone, R. Di Lorenzo, and L. Settineri. 2016. A methodology for evaluating the influence of batch size and part geometry on the environmental performance of machining and forming processes. *Journal of Cleaner Production*. DOI: 10.1016/j.jclepro.2015.11.041.
- Jeswiet, J. and S. Kara. 2008. Carbon emissions and CESTM in manufacturing. *CIRP Annals—Manufacturing Technology* 57(1): 17–20.
- Kara, S. and W. Li. 2011. Unit process energy consumption models for material removal processes. *CIRP Annals—Manufacturing Technology* 60(1): 37–40.
- Kellens, K., W. Dewulf, M. Overcash, M. Z. Hauschild, and J. R. Dufloy. 2012. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)-CO₂PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. *The International Journal of Life Cycle Assessment* 17(1): 69–78.
- Kellens, K., R. Renaldi, W. Dewulf, J.-P. Kruth, and J. R. Dufloy. 2014. Environmental impact modeling of selective laser sintering processes. *Rapid Prototyping Journal* 20(6): 459–470.
- Le Bourhis, F., O. Kerbrat, J. Hascoet, and P. Mognol. 2013. Sustainable manufacturing: Evaluation and modeling of environmental impacts in additive manufacturing. *International Journal of Advanced Manufacturing Technology* 69(9): 1927–1939.
- Li, W. and S. Kara. 2011. An empirical model for predicting energy consumption of manufacturing processes: A case of turning process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 225(9): 1636–1646.
- Li, L., J. Yan, and Z. Xing. 2013. Energy requirements evaluation of milling machines based on thermal equilibrium and empirical modelling. *Journal of Cleaner Production* 52: 113–121.
- Liu, Z. Y., Y. B. Guo, M. P. Sealy, and Z. Q. Liu. 2016. Energy consumption and process sustainability of hard milling with tool wear progression. *Journal of Materials Processing Technology* 229: 305–312.
- Mativenga, P. T. and M. F. Rajemi. 2011. Calculation of optimum cutting parameters based on minimum energy footprint. *CIRP Annals—Manufacturing Technology* 60(1): 149–152.
- Mayyas, T. A., A. Qattawi, A. R. Mayyas, and M. A. Omar. 2012. Life cycle assessment based selection for a sustainable lightweight body-in-white design. *Energy* 39(1): 412–425.
- Mognol, P., D. Lepicart, and N. Perry. 2006. Rapid prototyping: Energy and environment in the spotlight. *Rapid Prototyping Journal* 12(1): 26–34.
- Mori, M., M. Fujishima, Y. Inamasu, and Y. Oda. 2011. A study on energy efficiency improvement for machine tools. *CIRP Annals—Manufacturing Technology* 60(1): 145–148.
- Morrow, W. R., H. Qi, I. Kim, J. Mazumder, and S. J. Skerlos. 2007. Environmental aspects of laser-based and conventional tool and die manufacturing. *Journal of Cleaner Production* 15(10): 932–943.
- Mower, T. M. and M. J. Long. 2016. Mechanical behavior of additive manufactured, powder-bed laser-fused materials. *Materials Science and Engineering A* 651: 198–213.
- Murr, L. E., S. A. Quinones, S. M. Gaytan, M. I. Lopez, A. Rodela, E. Y. Martinez, D. H. Hernandez, E. Martinez, F. Medina, and R. B. Wicker. 2009a. Microstructure and mechanical behavior of Ti-6Al-4V produced by rapid-layer manufacturing, for biomedical applications. *Journal of Mechanical Behavior of Biomedical Materials* 2(1): 20–32.
- Murr, L. E., E. V. Esquivel, S. A. Quinones, S. M. Gaytan, M. I. Lopez, E. Y. Martinez, F. Medina, et al. 2009b. Microstructure and mechanical properties of electron beam-rapid manufactured Ti-6Al-4V biomedical prototypes compared to wrought Ti-6Al-4V. *Materials Characterization* 60(2): 96–105.
- Nandwana, P., W. H. Peter, R. R. Dehoff, L. E. Lowe, M. M. Kirka, F. Medina, and S. S. Babu. 2016. Recyclability study on inconel 718 and Ti-6Al-4V powders for use in electron beam melting. *Metallurgical and Materials Transactions B* 47(1): 754–762.
- Petrovic, V. and R. Niñerola. 2015. Powder recyclability in electron beam melting for aeronautical use. *Aircraft Engineering and Aerospace Technology: An International Journal* 87(2): 147–155.
- Priarone, P. C., S. Rizzuti, L. Settineri, and G. Vergnano. 2012. Effects of cutting angle, edge preparation, and nano-structured coating on milling performance of a gamma titanium aluminum, *Journal of Materials Processing Technology* 212(12): 2619–2628.
- Rajemi, M. F., P. T. Mativenga, and A. Aramcharoen. 2010. Sustainable machining: Selection of optimum turning conditions based on minimum energy considerations. *Journal of Cleaner Production* 18(10): 1059–1065.
- Rännar, L.-E., A. Glad, and C.-G. Gustafson. 2007. Efficient cooling with tool inserts manufactured by electron beam melting. *Rapid Prototyping Journal* 13(3): 128–135.
- Santos, J. P., M. Oliveira, F. G. Almeida, J. P. Pereira, and A. Reis. 2011. Improving the environmental performance of machine-tools: Influence of technology and throughput on the electrical energy consumption of a press-brake. *Journal of Cleaner Production* 19(4): 356–364.

- Serres, N., D. Tidu, S. Sankare, and F. Hlawka. 2011. Environmental comparison of MESO-CLAD[®] process and conventional machining implementing life cycle assessment. *Journal of Cleaner Production* 19(9–10): 1117–1124.
- Tmmas-Williams, S., H. Zhao, F. Léonard, F. Derguti, I. Todd, and P. B. Prangnell. 2015. XCT analysis of the influence of melt strategies on defect population in Ti-6Al-4V components manufactured by selective electron beam melting. *Materials Characterization* 102: 47–61.
- United Nations Environment Program (UNEP). 2011. Investing in energy and resource efficiency (part II); Manufacturing. In *Towards a green economy: Pathways to sustainable development and poverty eradication*. www.unep.org/greeneconomy. Accessed 27 February 2016.
- Vayre, B., F. Vignat, and F. Villeneuve. 2012. Metallic additive manufacturing: State-of-the-art review and prospects. *Mechanics & Industry* 13(2): 89–96.
- Wang, P, X. Tan, M. L. S. Nai, S. B. Tor, and J. Wei. 2016. Spatial and geometrical-based characterization of microstructure and microhardness for an electron beam melted Ti-6Al-4V component. *Materials & Design* 95(5): 287–295.
- Watson, J. K. and K. M. B. Taminger. 2016. A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption. *Journal of Cleaner Production*. DOI:10.1016/j.jclepro.2015.12.009.
- Weir, G. and T. Muneer. 1998. Energy and environmental impact analysis of double glazed windows. *Energy Conversion and Management* 39(3–4): 243–256.
- Yoon, H.-S., J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, and S.-H. Ahn. 2015. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *International Journal of Precision Engineering and Manufacturing—Green Technology* 1(3): 261–279.

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