Research article

Energy modeling and eco impact evaluation in direct metal laser sintering hybrid milling

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ABSTRACT

This paper presents an analytical model of energy consumption for Direct metal laser sintering hybrid milling (DMLS-HM) additive manufacturing (AM) of stainless steel 316L. The model is used to quantify energy consumption during production of a defined geometry with DMLS-HM process and compared with energy consumption in electron beam melting (EBM) and conventional machining (CM). The solid-envelope ratio ($\alpha$) was used to quantify energy consumption and eco impact of the three manufacturing processes on three different geometry models. The Gabi database and other published literature were used to establish energy consumption during primary metal production and material shaping processes. It was found that solid-envelope ratio ($\alpha$) has more impact on the energy model of the additive processes than on the subtractive maching. On average, the percentage change in $\alpha$ is equal to the percentage change in energy consumed by DMLS-HM and EBM. The CM process had very little average change of 1.5% compared to the major changes in $\alpha$. The DMLS-HM process showed dominant energy consumption during the part production stage with an average 84% more than EBM and CM processes. However, the CM was dominant in energy consumption during the primary production stage with an average 70% more energy than DMLS-HM and EBM processes. The novel outcomes of this research will contribute to the understanding of basic physics of energy consumption in AM and can be used in setting sustainable manufacturing goals. Moreover, energy consumption in metal AM also influences mechanical properties and microstructure of produced parts, so this work will further enhance prediction of their quality and service life. DMLS-HM is recently being introduced for industrial applications such as mold and tool manufacturing due to its capabilities in building free form and complex shapes that are otherwise challenging to manufacture by conventional methods.

1. Introduction

1.1. Background

Manufacturing sector is a significant source of energy consumption per U.S. Energy Information Administration (EIA). EIA report shows that about 1.35 E+19 J consumed in fabrication sector is to drive accessories such as motors, fans, pumps, heating system, material processing, material handling and other operations related to fabrication. This consumption is responsible for 521 MT CO2 eq. amount of carbon emission [1]. In 2014, highest carbon emitters in the USA were top five manufacturing countries. With the growing concern over climate change, there has been increased effort towards making energy utilization more efficient, reducing carbon footprints [2]. Additive manufacturing (AM) is one such technology with a potential of improving energy utilization in manufacturing industry and could provide sustainable advantages in form of reduced material consumption which in turn will reduce energy consumption. Moreover, inventory reduction due to AM’s ability to form parts on demand supports sustainable manufacturing goals. Due to these benefits, metal AM has become promising area of research with industrial applications ranging from automotive to mold and die manufacturing and aerospace. However, given the growing focus on cleaner production, sustainability perspective of AM has not been explored much and still remains a challenging task [3]. Moreover, low surface quality and poor dimensional accuracy produced by AM is still a big concern. Also, more often AM requires post processing operations to produce finished parts and results with increased lead time and cost. A combination of additive-subtractive system is a new type of hybrid AM technology, herein called direct metal laser sintering hybrid milling (DMLS-HM) has been introduced to exploit the strengths of direct metal laser sintering

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and traditional machining. DMLS-HM has capabilities of complex geometry generation and near-net shaped geometry and capitalizes on use of traditional machining to achieve precision and accuracy of manufactured parts. This technology eliminates the need of post processing thus reducing lead time of parts produced. Given these benefits, researchers [2, 4] claim that hybrid manufacturing (HM) may offer greater opportunity for sustainable manufacturing and use of HM could reduce the environmental burden. However, it would be premature to call HM sustainable without a comprehensive life cycle assessment. From literature survey, it was found that scope of the majority of studies [5, 6, 7] focused their work on AM and were limited to measuring operational energy consumption during process. Very few studies [8, 9] characterized environmental impacts of AM. Since DMLS-HM is new technology, study on quantitative analysis of its energy consumption has been largely unexplored. This research will close some of the gap in knowledge by comparing energy consumption and eco impact of DMLS-HM with two other competitively used manufacturing processes: conventional machining (CM) and electron beam manufacturing (EBM).

1.2. Direct metal laser sintering hybrid milling process

Direct metal laser sintering hybrid milling (DMLS-HM) in its nature is a combination of additive and subtractive manufacturing technologies. DMLS-HM process consists of three main steps: squeezing metal powder, laser sintering of metal powder and milling of sintered part as illustrated in Figure 1. In the first stage, squeezing unit supplies metal powder with a layer thickness of 0.05mm on processing table to prepare the layer for melting/sintering. In the next step, 400-watt Ytterbium (Yb) doped fiber laser beam starts sintering the metal powder layer into desired product shape. These two steps are repeated 10 times until layer thickness of 0.5 mm is achieved, then milling phase starts. An end mill cutter with spindle speed of 45000 rpm and a 1/10 taper special BT20 tool shank performs milling of the contour of the part precisely to a machine surface finish. Typical build rate of DMLS HM ranges from 10,000–35000 mm³/h.

1.3. Energy modelling in additive-subtractive manufacturing

Studies on energy modelling of additive hybrid subtractive manufacturing systems are very few; though, there are separate studies in the two processes. Jackson et al. [2], were first to develop energy model that accounted for energy consumption during metal production, deposition and machining phases in additive-subtractive manufacturing hybrid system. Their work compared the energy consumed by powder-based additive-subtractive manufacturing systems with wire-based additive manufacturing and concluded that processing energy in both processes are the same. In metal alloys additive manufacturing, Morrow et al. [11] quantified energy consumption and environmental impact associated with processing of mold and tooling when manufactured by direct metal deposition (DMD) and CNC milling operations. Their research concluded that samples with low solid-cavity ratio in DMD consumed less energy than CNC milling and sample with high solid-cavity ratio is more economical when manufactured through CNC milling. Baumer et al. [12] investigated the correlation of sample geometry with energy consumption with Electron Beam Melting (EBM). They found weak correlation between complexity of geometry and energy consumed by EBM. It was reported that smart tools such as topology optimization provides optimal geometries and increased cost has no bearing on cost of finished parts. Peng and Sun [13] developed an analytical model for quantification of energy consumption in fused deposition of thermoplastics. Notable contribution on energy modelling in subtractive systems was made by Gutowski et al. [14] by introducing a novel mathematical model for energy requirement in milling. This work was further improved on by Mori et al. [15], Diaz et al. [16] and Balogun and Mativenga [17].

2. Methodology

2.1. Material life cycle assessment

Figure 2 shows typical four stages of a product life cycle beginning from extraction, material production, product manufacture and product use. The stainless steel 316L (SS 316) grade is the second most common austenitic stainless steel with primary alloying constituents after iron, chromium (16–18%), nickel (10–12%) and molybdenum (2–3%). The addition of molybdenum provides it with greater corrosion resistance than stainless steel 304. Some of its major applications include in chemical and petrochemical industry, potable water and wastewater treatment, marine applications and architectural applications near the seashore or in urban areas. Steel production starts with material extraction from natural ores and during production, recycle percentage of scrap stainless steel in current supply of raw material is in the range of 35–40% [18]. Embodied energy of SS 316 is the energy consumed by all the processes associated with the production of SS 316, from the mining and processing of natural resources to manufacturing, transport and delivery. The primary material production energy is usually energy intensive.
process and energy consumption is higher than material produced from scrap steel. For example, stainless steel’s embodied energy from recycling is around 22–25 MJ/kg and embodied energy during primary production of material is 77–85 MJ/kg.

2.2. Goal and scope

The goal is to develop an analytical model of energy consumption for DMLS-HM process and use this framework of energy model, Figure 3 to
evaluate total energy consumed during manufacture of stainless steel 316L part. Further, the total energy consumed, and environmental impact of DMLS-HM are compared with conventional milling and electron beam melting (EBM) processes for manufacturing of the same part geometry.

2.3. Functional unit

The functional unit is used to provide a reference where the life cycle analysis inputs and outputs are standardized. The functional unit established for this study is one unit of Stainless Steel 316L produced.

2.4. System boundary

The system boundary is used to define which processes from the life cycle assessment analysis will be included or excluded. The life cycle analysis will track the inputs and outputs from each of the unit processes of DMLS-HM, conventional milling and EBM from resource extraction and processing to transportation and to emission control measures. In this study, the system boundary includes all the stages starting with material extraction from natural resources, to material processing and part manufacturing. The energy consumption during the product’s usage and disposal is not considered.

2.5. Energy model and life cycle inventory (LCI)

The assessments and comparisons are based on the total energy consumption and environmental impact assessment of three samples of 316L steel with three different geometries, each manufactured through three distinct processes namely: conventional milling, EBM and DMLS-HM. The total energy consumed from cradle to gate by each process was determined. The data on energy consumption during primary metal production as well as material shaping/forming processes such as extrusion and rolling was collected from Gabi database and other published literature. Few authors [19, 20] have described the discrepancies in the available data knowledge. Keeping this in mind, rigorous effort has been made to assure good representation of the data by taking average of collected energy consumption values. Moreover, the energy values reported considered the machine parameters and process environment. The energy consumption during each unique process was estimated analytically, using standard machine parameters as suggested by machine manuals for producing the final parts. The solid-envelope ratio as employed by Watson and Taminger [21] was used as a common framework to compare energy efficiencies of these processes. The solid-envelope ratio is the ratio of volume of solid material and the bounding volumetric envelope of part denoted with $\alpha$ in this paper. It is used to estimate total energy required by the three different processes to manufacture the parts to their final geometries. Each geometry considered has a unique value of $\alpha$ that will capture the energy requirement in the process used to make it as shown in Table 1. The cross sectional views of the three geometries evaluated are shown in Figure 4. Table 2 shows the life cycle inventory of stainless steel 316L and how they were obtained for this work.

The embodied energy per kg ($\text{EPS}$) to produce the parts from combination of recycled and primary sources can be estimated with Eq. (1):

$$\text{EPS} = \text{Ep}(1-r\%) + \text{Ep}r\%$$  

Here, $r\%$ represents the percentage of recycled steel scrap used in the production process. Typically, percentage of recycled steel during production ranges from 35-40%. Total life cycle energy consumption per unit for a material stock of mass (m) in the case of conventional machining (CM) can be modeled with Eq. (2):

$$E_{\text{LC1}} = m_{\text{CM}}(E_f + \text{EPS}) + E_{\text{CM}}$$  

Similarly, Eqs. (3) and (4) are used to model total life cycle energy per unit of mass $m_{\text{AM}}$ and $m_{\text{HMSS}}$ in case of EBM and DMLS-HM respectively:

$$E_{\text{LC2}} = m_{\text{AM}}(E_f + \text{EPS}) + E_{\text{AM}}$$  

$$E_{\text{LC3}} = m_{\text{HM}}(E_f + \text{EPS}) + E_{\text{HM}}$$  

The total life cycle energy per unit of mass model Eqs. (3) and (4), do not include energy associated to powder feedstock recycling because the study focuses on energy requirements during single build. In addition, little to no reliable data in literature related to energy consumption, especially, for DMLS HM is available. Due to the newness of DMLS HM process, powder recycling studies is not yet present and will be good extension of this study. Gas atomized steel powder was used because most of the steel powder production is through water and gas atomization (GA) [22]. The GA process is relatively prevalent powder production method used in additive manufacturing and this is evident from the fact that majority of research studies [2, 6, 12, 12, 23] incorporated gas atomized powder in their evaluation of energy consumption. In addition, powder metallurgy studies [22] related to powder efficiency did not discuss energy consumption during plasma powder production process. In this study therefore, metal powder fabrication methods such as plasma powder production was overlooked to maintain a fair comparison of energy consumption between the processes.

![Figure 4. Geometries and their cross section.](image-url)
The model of carbon emission from energy consumption proposed by Jeswiet and Kara [24] will be used to access the environmental impact of the three processes as shown in Eq. (5).

$$\text{Carbon Emission} = \text{CES}^TM\times \text{E}_{\text{part}}$$  \hspace{1cm} (5)

$E_{\text{part}}$ is total energy requirements to manufacture the desired geometry and CESTM is carbon emission signature for energy. In the USA, an average 0.15 CESTM factor is used [25].

### 2.5.1. Conventional machining

In conventional machining, milling refers to subtractive manufacturing process in which material is removed by a rotating multiple tooth cutter in the presence of cutting fluids to achieve the final surface. Mikron HSM 400 milling is used in energy estimation. Figure 5 shows the fuzzy values for power consumption during a typical machining process, note that tool maintenance is not considered in system boundary of this study.

Gutowski et al. [14] provided the basis for energy requirements in machining operations and Mori et al. [15] expanded his work and introduced concept of idle power and basic power. Diaz et al. [16] found out that during machining operation, tool engages and disengages with material and modelled air cutting time that reduced the overestimation of energy demand. Balogun and Mativenga [17] further improved this model by incorporating works by Gutowski et al. [14], Mori et al. [15] and Diaz et al. [16] and developed an improved and robust model as shown in Eq. (6).

$$E_{\text{CM}} = P_b(t_b + t_r + t_c) + P_r(t_r) + P_{\text{air}}(t_c) + t_c(P_r + P_{\text{cool}} + P_{\text{cutting}})$$  \hspace{1cm} (6)

Here $P_b$ is basic power when machine is turned ON but without feed, cutting and spindle running and is only used to run auxiliary parts of machine such as computer, fan, motors etc. $P_b$ can be estimated experimentally by measuring constant energy consumption during the operation of auxiliary components. The $P_r$ is ready state power when machine is operating but not processing material such as power to bring tool close to cut position with workpiece and $P_{\text{cool}}$ is coolant power used to pump and circulate coolant during cutting. The $P_{\text{air}}$ is air cutting time when cutting tool is not engaged and retracting over the component. The $k$ is specific cutting energy of material and $v$ is material removal rate. The $t_{air}$, $t_c$, and $t_r$ represent air cut time, cutting time and ready state time respectively and can be extracted from machine database. In Eq. (6), $P_b$, $P_r$, $P_{\text{air}}$, $P_{\text{cool}}$ are the constant components of a milling machine. Values of these constants were extracted from Mikron HSM 400 machine as reported by Balogun and Mativenga [17]. Cutting power mainly depends on cutting conditions such as feed rate $f_r$, axial (b) and radial depth of cut (d) and can be estimated using Eq. (7).

$$P_{\text{cutting}} = \text{CWk}v = (\text{CWk})f_rbd$$ \hspace{1cm} (7)

The value of $k$ for stainless steel is 5 Ws/mm$^3$ and it is in the range reported by Kalpakjian and Schmid [26]. The value of $k$ is affected by the interaction of cutting tool and workpiece material. The typical values of $C$ and $W$, as reported by Walsh and Cormier [27] for stainless steel cutting conditions are 1.4 and 1.1 respectively. Eq. (8) is used to estimate the theoretical cutting time of milling operation as follows:

$$t_{\text{cut}} = \frac{L_f}{A}f_r$$ \hspace{1cm} (8)

where $A$ is distance to reach full cutter depth and $L_f$ is length of tool feed.

During milling operation, cutting fluids allow high speed cutting operations and prolong tool life. In CNC machine, cutting fluid pump circulates the fluid from cutting fluid tank to the cutting zone. Cutting fluid is recycled until it is disposed of after two weeks on average. Assuming a CNC with fluid tank capacity of 250 L, pumps 210 h./2 weeks, then the cutting fluid loss is 250L/(210×60) per minute. The effective loss of cutting fluid due to degradation would be 0.02 L/min or about 20 g/min. The coolant is usually about 75–95 wt.% water. With 85wt% water, the coolant oil loss would be 9g cutting oil/min. Machine

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**Table 1. Geometry dimensions and features.**

| Geometry | Geometry 2 | Geometry 3 |
|----------|------------|------------|
| Solid-Envelope Ratio ($\alpha$) | 0.12 | 0.23 | 0.30 |
| CM stock mass (g) | 4000 | 4000 | 4000 |
| AM mass deposited (g) | 580 | 950 | 1300 |
| DMLS-HM deposited mass (g) | 700 | 970 | 1500 |
| Total volume (mm$^3$) | 62361.5 | 117715.5 | 151833.2 |
| Surface Area (mm$^2$) | 28253.7 | 28444.0 | 27595.8 |

**Table 2. Life cycle inventory of stainless steel 316L.**

| Energy Consuming Processes | Energy (MJ/kg) | Abbreviations | Reference |
|---------------------------|----------------|---------------|-----------|
| Embodied Energy (primary production) | 80 | $E_p$ | [16] |
| Secondary Production (recycled) | 22 | $E_s$ | [16] |
| Forming/Shaping Processes | 20 | $E_f$ | [2] |
| Powder Atomization | 34 | $E_p$ | [18] |
| Conventional Machining | Eq. (6) | $E_{\text{CM}}$ | |
| Metal Additive Forming | Eq. (10) | $E_{\text{AM}}$ | |
| Hybrid Additive Subtractive | Eq. (15) | $E_{\text{HM}}$ | |

![Figure 5. Power characteristic and energy consumption in machine tool.](image-url)
parameters such as cutting speed and feed as recommended by Kalpakjian and Schmid [26] and McCauley and Hoffman [28] have been shown in Table 3. Table 4 shows cutting parameters and energy requirements for the machine.

2.5.1.1. Electron beam melting additive manufacturing. Electron beam melting (EBM) process has been employed in the energy framework. The energy consumption units in an EBM are shown in Figure 6 and the energy requirements for the processes are listed on Table 5. Baumer et al. [12] found energy requirement using the following Eqs. (9) and (10).

\[ E_{AM} = E_{startup} + E_{preheat} + E_{build} + E_{cooldown} \]  
\[ E_{AM} = P_{startup} + P_{preheat} + P_{build} + P_{cooldown} \]  
where \( E_{startup} \), \( E_{preheat} \), \( E_{build} \), and \( E_{cooldown} \) are energy consumption during machine startup, preheating, material deposition and cooldown respectively. It is important to note that time for startup power and preheat is independent of part geometry and can be determined from machine database. Preheat is used to avoid build failure because of the charging of electrons, commonly known as ‘powder pushing’ or ‘powder blowing’. Some studies [29, 30] showed that preheating could increase effective mechanical strength and improve the beam matter interaction efficiency. However, preheating can result to higher energy consumption and lead time as more time and energy are required to preheat, remove the sintered particles from the built surface and it may be difficult to fabricate complex features because of difficulty in eliminating sintered particles from the surface [31].

\( P_{build} \) and \( t_{build} \) depends on machine parameters such as scanning speed (S), layer thickness (\( h_{l} \)), beam spot diameter (b) and hatch space being used. Zhang and Bernard [32] introduced theoretical framework to evaluate total build time in AM that takes real time of AM production into context in the estimation. So for a single part manufacturing per build, total build time can be calculated as:

\[ T_{b1} = T_{imp} + T_{l1} + T_{hp} + T_{e} \]  
where \( T_{b1} \), \( T_{imp} \), \( T_{l1} \), \( T_{hp} \) and \( T_{e} \) in Eq. (11) represent total build time, machine preparation time, total layer drawing time, layer preparation time and time for ending operations respectively. Typically, during AM process, machine preparation time and ending operations remain fixed. Fractions of the total time such as \( T_{b1} \), \( T_{l1} \) for single part production can be calculated using Eqs. (12) and (13).

\[ T_{l1} = (Z_{1}h_{l})t_{l} \]  
where \( Z_{1}, h_{l}, \) and \( t_{l} \) denote workpiece height, layer thickness and time for preparation of one layer respectively.

\[ T_{l1} = \frac{V_{n}}{N_{l}d_{l} + d_{h}}S + A_{p}h_{l} \]  
where \( V_{n}, N_{l}, d_{l}, \) and \( d_{h} \) and \( A_{p} \) represent volume of part, number of laser heads, laser diameter, hatching space and surface area respectively.

2.5.1.2. Additive subtractive (hybrid) machining. Since DMLS-HM is a robust combination of additive and subtractive process, theoretically, total energy consumption would be equal to energy consumed during additive process and subtractive process. To find the total energy requirements, both additive and subtractive units have been subdivided into smaller units called energy consuming units (ECU) as shown in Figures 7 and 8.

Basic physics and methodology of theoretical framework of additive and subtractive aligns with energy frameworks developed and employed by Jackson et al. [2] and Peng and Sen [13] for additive subsystems and
Balugen and Mativenga [17] Gutowski et al. [14] for subtractive sub-

system. Energy consumed in additive sub-unit of DMLS-HM can be
calculated using following equation.

\[ E_{DMLS} = P_{basic}(t_{squeezing} + t_{ready}) + t_{sintering}(P_{squeezing} + P_{inert} + P_{sintering}) \] (14)

Since total energy requirements are combination of both additive and
subtractive unit, combining equation [6] and [14] would give Eq. (15)

\[ E_{HM} = P_{basic}(t_{squeezing} + t_{ready}) + P_{air_{cut}} + \alpha_t(P_{tool_{used}} + t_{sintering}(P_{squeezing} + P_{inert} + P_{sintering}) + t_{cool}(P_{milling} + P_{coolant} + P_{basic}) \] (15)

where \( P_{sintering} \) is power requirement during laser exposure, \( P_{squeezing} \) represents power requirement for recoating of layer on build stage, \( P_{basic} \) is machine basic background power for machine auxiliary components like computer, fans, driving motors, \( P_{coolant} \) and \( P_{inert} \) are power requirements to pump coolant and inert gas in chamber respectively, \( n_t \) represents number of tool used, \( P_{tool_{used}} \) represents tool change power and \( P_{milling} \) is power requirement during subtractive operation. Since these values depend on machine being used, power requirement values were extracted from LUMEX 25 DMLS-HM [10] machine data. Total cycle time (\( t_{cycle} \)) can be evaluated using Eq. (16):

\[ t_{cycle} = \frac{V}{Q} \] (16)

where \( Q \) is volumetric built rate and \( V \) is total volume of geometry. For surfaces with lower complexity, a typical range of cutting time is 30–35% [25] and cutting time increases depending on complexity of geometry and desired surface finish. Geometries under consideration are relatively small and simple. So, 30% of cycle time is allocated to milling. Tables 6 and 7 show machine parameters and power requirements used in the study respectively.

| Table 6. Machine parameters DMLS-HM [25]. |
|------------------------------------------|
| Q (mm³/h)                                | 35000 |
| Scan speed (mm/s)                        | 300   |
| Beam diameter (mm)                       | 0.1   |

3. Results and discussion

The total energy consumption from cradle-to-gate for the conventional machining process for geometry 1 with solid-envelope ratio of 0.12 shown in Figure 9 is 327.1 MJ/unit which is highest when compared to 75.8 MJ/unit for EBM and 204.4 MJ/unit for DMLS-HM. This can be attributed to the stock requirement for CM to produce 580g geometry; about 87% of the stock material was wasted in form of chips. However, in the cases of DMLS-HM and EBM processes, material requirement is relatively lower for the final part because both processes form their geometries by building the metal alloy layer by layer with very little waste. Though, DMLS-HM has a subtractive unit integrated with the machine system, its primary purpose is to conduct finish-
operation on the geometry which in turn generates very low amount of chips. Moreover, material requirement may be high in case of CM, but material processing (machining) energy is relatively lower than for EBM and DMLS-HM.

For geometries 2 and 3 with \( \alpha \) of 0.23 and 0.30 respectively, total energy consumption is highest in case of DMLS-HM as shown in Figures 10 and 11 respectively. To produce a part with high volume and large number of layers, EBM required relatively more time for material processing that led to increase in the energy requirements. However, the material requirement was relatively lower than for conventional machining process. The total energy requirements for geometries 2 and 3 for EBM process were 114.3 MJ/unit and 159.1 MJ/unit as compared to 317.5 MJ/unit and 313.7 MJ/unit for CM. As expected, energy requirements in case of CM for geometries 2 and 3 were lower than for geometry 1. This is because geometry 1 required high machining time due to the large cavity feature. But with increased solid to envelope ratio, final geometry was close to stock material and resulting machining time reduced accordingly. The solid-to-envelope ratio, \( \alpha \) has more effect on the energy model of the additive processes (DMLS-HM and EBM) than it does on the subtractive machining (CM) process. The average percentage change in \( \alpha \) resulted to equal percentage change in energy consumption of DMLS-HM and EBM. It had no significant effect on the energy con-
sumption model of the CM process with about 1.5% average change in the energy consumption compared to the major changes in \( \alpha \). The CM process showed dominant energy consumption during the primary pro-
duction stage with an average 70% more than EBM and DMLS-HM pro-
cesses. However, the DMLS-HM was dominant in energy consumption during the shape forming production stage with an average 89% more than EBM and DMLS-HM.

When \( \alpha \) is 0.12, EBM presented lowest energy consumption in the shape forming stage of the production with average of 80% lower energy than DMLS-HM and 2% lower than CM. The EBM’s low energy is attributed to its high process rate. It has been established that energy consumption in AM is influenced by the process rate and that energy efficiency in AM can be improved by increasing process rates [19]. The heat transfer mechanisms required to deliver the melt stream to build a part in AM limits the process rate level that can be achieved. However, due diligence should be paid to avoid sacrificing build quality with too high process rate. The specific energy consumed in CM process is also
highly dependent on the rate of material removal [17]. The finish-machining conducted after fusion of successive ten layers of stainless steel 316L powder will result in additional specific energy consumption by the DMLS-HM process. This explains the higher specific energy consumption during the rough machining with small material removal rate in the CM process. To maintain longer tool life and reasonable parts’ surface finish, the rate of material removal needs to be lower than the EBM process. As a result, the EBM process tend to consume less energy than the CM and DMLS-HM processes as shown in Figures 9, 10, and 11.

The effect of solid-to-envelope ratio, \(\alpha\) on energy consumption and carbon emission of the three processes CM, EBM, and DMLS-HM are shown in Figures 12, 13, and 14 respectively. The solid-to-envelope ratio has statistically significant effect on energy consumption and carbon emission without sign of interaction effect between them. Evaluation of total energy consumption and carbon emission of the processes showed that DMLS-HM had highest carbon emission during the cradle-to-gate production phases with an average of 80% more than EBM and CM processes. The CM was dominant in the carbon emission during the primary production stage with an average of 70% more energy than DMLS-HM and EBM processes. There exist very strong correlation between the performance measurements (energy consumption and carbon emission) and solid-to-envelope, \(\alpha\) and this can be useful in design phase to optimize product design for sustainable manufacturing.

Table 8 shows that in published literature, SEC for SS 316L lies within range of 83–140 MJ/kg for SS 316L when processed through selective
laser melting. Baumer et al. [29] reported higher energy consumption per kilogram of material deposited and lower process rates values. SEC is also influenced by capacity utilization of built table as reported by Liu et al. [37]. It is possible that SEC for [29] is higher because of poor utilization.

In a typical manufacturing operation, built rate of EBM is kept higher than SLM. So, if SS 316L is to be processed using EBM process for relatively low solid-envelope ratio, it is expected that SEC for material processing (ignoring embedded energy EPS) values would lie in the range of 20–40 MJ/kg as calculated by theoretical framework. Because of high specific heat (0.5263 J/g·°C) of Ti–6Al–4V, more energy will be required to melt To-6Al–4V compared to same amount of SS 316L (0.26 J/g·°C) material. No published data on the processing of SS 316L using EBM and DMLS HM was found.

4. Conclusion

Analytical model of energy consumption for direct metal laser sintering hybrid milling (DMLS-HM) process was developed and used to evaluate total energy consumed during manufacture of stainless steel 316L parts of different solid-to-envelope ratio, $\alpha$. The cradle-to-gate life cycle inventory (LCI) of the DMLS-HM was compared to those of conventional machining and electron beam melting (EBM) used to produce the same part geometries. It was found that $\alpha$ will have more impact on the energy model of the additive processes than on the subtractive machining process. On average, the percentage change in $\alpha$ is equal to the percentage change in energy consumption and carbon emission of DMLS-HM and EBM. The CM
process had little average change of 1.5% compared to the major changes in $\alpha$. The DMLS-HM process shows dominant energy consumption during the primary production stage with an average 84% more than EBM and CM processes. However, the CM was dominant in energy consumption during the shape forming production stage with an average 70% more energy than DMLS-HM and EBM processes. The energy and carbon emission values estimated with the developed analytical models were not verified empirically but are within the range of reported data in the literature for the processes considered.

![Figure 13. Effect of solid-to-envelope ratio, $\alpha$ on energy and carbon emission of electron beam melting.](image1)

![Figure 14. Effect of solid-to-envelope ratio on energy and carbon emission of DMLS-HM.](image2)

Table 8. Energy Consumption during Fabrication of Materials Using AM process.

| Machine           | Process | Material | Specific Energy Consumption (MJ/kg) | Resource Consumption | Reference |
|-------------------|---------|----------|-------------------------------------|----------------------|-----------|
| MTT SLM250        | SLM     | SS 316L  | 112–140                             | n/a                  | [33]      |
| MTT SLM251        | SLM     | SS 316L  | 83–108                              | n/a                  | [33]      |
| CONCEPT LASER M3 LINEAR | SLM | SS 316L  | 423–588                             | n/a                  | [34]      |
| CONCEPT LASER M3 LINEAR | SLM | SS 316L  | 96.8                                | Nitrogen: 3.5m$^3$/h; 20.4% waste powder | [35]      |
| Arcam A1          | EBM     | Ti-6Al-4V| 60                                  | 1 L/h Helium         | [12]      |
| Arcam A1          | EBM     | Ti-6Al-4V| 61.0–177.0                          | n/a                  | [34]      |
| Arcam             | EBM     | Ti-6Al-4V| 375                                 | Argon gas: 5.5m$^3$/h | [36]      |
Declarations

Author contribution statement

Emmanuel Ugo Enemuoh: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Nabeel Ahmad: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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