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Investigation of Energy Requirements and Environmental Performance for Additive Manufacturing Processes

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Abstract: This paper explores the specific energy consumption (SEC) and environmental impacts for typical additive manufacturing processes. Also, the paper examines the possibility that ensure the product quality while reducing energy consumption with experimental analysis. The results show that (1) the SEC of additive manufacturing processes is related not only to material characteristics but also to the process input parameters; (2) it is possible to increase the energy efficiency without reducing product quality by adjusting the process rate or selecting different materials; and (3) the global warming potential (*GWP*) result of AM processes indicates that the *GWP* is brought about principally by the energy production process. The information provided by this project can also be of benefit to life cycle assessment and other environmental impact assessment related to AM processes.

Keywords: energy consumption; environmental performance; additive manufacturing processes

1. Introduction

By joining materials layer upon layer to build up objects, additive manufacturing (AM) is capable of fabricating complex parts with minimum material waste [1]. Being different from traditional subtractive manufacturing (SM) processes, which construct three-dimensional (3D) objects by cutting material off a solid block of material, AM process always begins with 3D structure modeling and goes through slicing, fabrication and post-finishing [2]. Because of the direct layer-wise fabrication, AM has many competitive advantages including higher material efficiency, more flexible product design and innovation, less material waste, and energy consumption [3]. Therefore, AM is being used increasingly for fabricating end-use products in aerospace, automotive, biomedical, and sporting goods, among others [4].

Nowadays, various kinds of materials can be used in AM processes, including metallic material in LENS and DMD, polymer material in FDM and SLA, and biological material in inkjet printing and micro extrusion. Different AM processes build and eventually consolidate the layers through different methods, but all of them take materials and energy resources as inputs and transform them into required products and wastes. Moreover, the production of material and energy always consumes fuels and natural resources and at the same time, it is accompanied by the generation of negative environmental impacts. Taking LENS process as an example, the process inputs include electricity,

powder material, argon gas, and compressed air and the outputs are fabricated part, waste powder and gases, as shown in Figure 1.

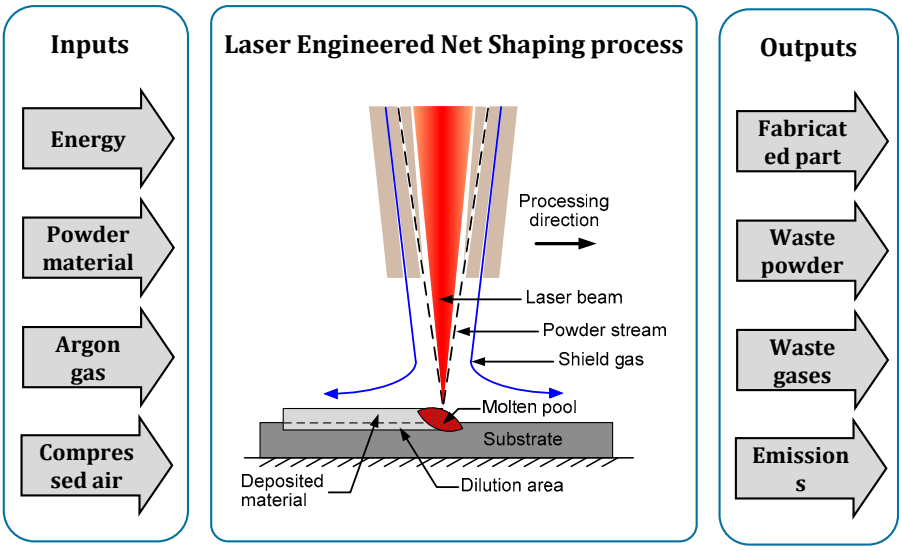

Figure 1. Inputs and outputs of the fabricated part in LENS process.

Currently, manufacturing industries are facing problems of environmental degradation and a lack of resources. Energy consumption and environmental impacts have been paid more attention during the manufacturing processes. As a new emerged technology, the energy consumption and environmental performance quantification are necessary for AM before its extensive industrial application. For a better understanding of the environmental impacts of AM, Luo et al. investigated the energy consumption of three AM processes: SLS, FDM, and SLA. An energy consumption rate (kWh/kg) was used to represent the energy consumption. They found that the energy consumption rate of FDM is higher than that of SLS and SLA for polymeric materials [5]. Similarly, Sreenivasan and Bourell estimated that the mean power consumption for SLS system is about 14.5 kWh/kg [6]. Apart from the investigations on energy consumption rate, previous research also suggested that energy consumption of AM process depends on the build parameters, such as laser power, scanning speed, powder feed rate, part orientation, etc. Mognol et al. estimated the energy consumption of three rapid prototyping systems: Thermojet, FDM 3000, and EOSINT M250. They concluded that the part size, volume of support, and manufacturing time must be minimized to reduce the energy consumption [7]. When compared to the energy consumption of metallic AM processes, Baumers et al. found that the powder density, layer thickness, and input efficiency have a significant impact on energy consumption of SLM and EBM processes [8]. Regarding the building efficiency, Kummailil et al. found that the deposition efficiency related not only on the powder feed rate and layer thickness, but also the energy per unit area [9]. Besides, the effects of build parameters on efficiency and part performance for FDM process were evaluated using design of experiment method [10]. To optimize the efficiency outputs, the maximum layer thickness and low level of infill pattern were recommended.

Except for the research on the energy consumption of AM processes, the benefits of AM over SM regarding the energy saving and environmental problems reduction also have been well-documented in previous literature [11–13]. It was reported that AM process could simplify or shorten the energy-intensive processes—such as casting, forging, rough machining, etc.—during the SM; therefore, it will generate less environmental impacts [14]. Comparing the energy demand for AM and SM in manufacturing polymer products, Kreiger et al. indicated that AM could reduce the energy consumption by 41 to 64% due to the direct fabrication [15]. Moreover, it is claimed that AM is a more sustainable option than SM because no specialized tooling or fixtures is required, and AM is

capable of creating on demand parts without need for extra inventory [16]. Additionally, AM could reduce the environmental impact by lessening the transportation and packaging processes [17].

However, the energy consumption and environmental performance of AM technologies is still a matter of debate and being contradictory with the supporters who believe AM is more environmental friendly, there exists different points of view regarding the sustainability issues of this technology. In 2009, a program held by MIT suggested that the energy consumed in DMD process is hundreds of times higher than that of traditional casting and machining process [18]. Similarly, Yoon et al. pointed out that the AM process consumes much more energy than conventional bulk-forming processes [19]. When comparing the environmental impact of AM with that of SM, Faludi indicated that the environmental benefits of AM depend on the manufacturing scale [20]. At mass-manufacturing scale, inkjet printing has significantly worse ecological impacts than SM process. On the other hand, during the material building process in AM, some negative emissions may appear. The emissions of hazardous substances during FDM process have been evaluated in [21], and it was concluded that FDM process using PLA will generate 4.27 to 4.89 $\times$ 10^8 ea/min cartridge. Literature review suggests that different AM processes or different materials used in the same AM process can have different result regarding the energy efficiency and environmental impacts evaluation [22]. As young processes presently on the hype, the environmental effects of components issued from the AM process are not well known due to the lack of investigation.

Energy consumption is an applicable indicator for building efficiency evaluation in AM processes. Previous research has made some progress regarding the energy consumption rate, efficiency, and their relationship with the input parameters. However, there is little research on energy consumption analysis of the metallic and biologic variants of AM. In the present study, SEC was employed to distinguish the energy efficiency for different AM processes. It would be much more effective and efficient to quantify the total energy consumptions once the part volume is given. In more detail, the energy distribution for specific AM process, the SEC under different process rate, layer thickness, energy density, as well as effect of materials on SEC are also investigated. Moreover, this paper studies the relationship of SEC and material property, such as powder size and density, to testify the possibility that acquires desired property with less energy input. In the end, the environmental impacts of different AM processes were quantified and compared based on the result of SEC. The information provided in this paper can be used as references for future study on life cycle analysis and other environmental counting problems relevant to AM process.

2. Materials and Methods

2.1. Definition and Classification

The energy consumption and environmental performance of five specific AM processes were investigated. Considering the characteristics of different AM processes and equipment availability, block specimens (7.62 L $\times$ 7.62 W $\times$ 1.727 H mm^3) were designed for each process. The AM technologies considered, materials used, and corresponding characteristics are summarized in Table 1.

Table 1. Materials and AM processes considered in this study.

	AM Process	Materials	Material Type	Diameter (μm)	Density (g/cm^3)
Metallic material	LENS	Inconel 718	Powders	63.3	8.19
		Stellite 1	Powders	86.7	8.69
		AISI 4140	Powders	68.2	7.85
		Triboloy T800	Powders	81.4	8.64
Polymer material	SLA	Resin	Liquid	NA [a]	1.12
	FDM	ABS	Filament	750	0.9
Bio material	Inkjet Printing	Cell	Hydrogel	NA	NA
	Extrusion	Slginate	Hydrogel	NA	NA

[a] NA means value is not available for specific material characteristic.

The specific energy consumption (SEC, J/cm^3) of the AM process is expressed as energy consumption per unit deposition volume. SEC is a measure for the averaged applied energy per unit volume of the part during the material building process, as shown in Equation (1).

$$SEC = \frac{PT}{V} = \frac{UIT}{V} \tag{1}$$

where P is the input power (W), U is the system voltage (volt), T is the process time (s), I is the current of the system (amps), and V is the volume of the deposited object (cm^3).

2.2. Data Collection

The voltage and current of power supply were measured by a multi-meter (Fluke 289) and a current clamp with 3 KHz bandwidth (Fluke i 410, Fluke Corporation, Everett, WA, USA). The collected data were processed with FlukeView Forms Software version 3.8 (Fluke Corporation, Everett, WA, USA). For each AM process, the current were measured three times for each specimen and an average value was used for SEC calculation. The process time was read off directly from the software and the volume of the specimen was measured by Archimedes' principle. Taking LENS process as an example, the experimental set-up for the energy consumption measurement is shown in Figure 2.

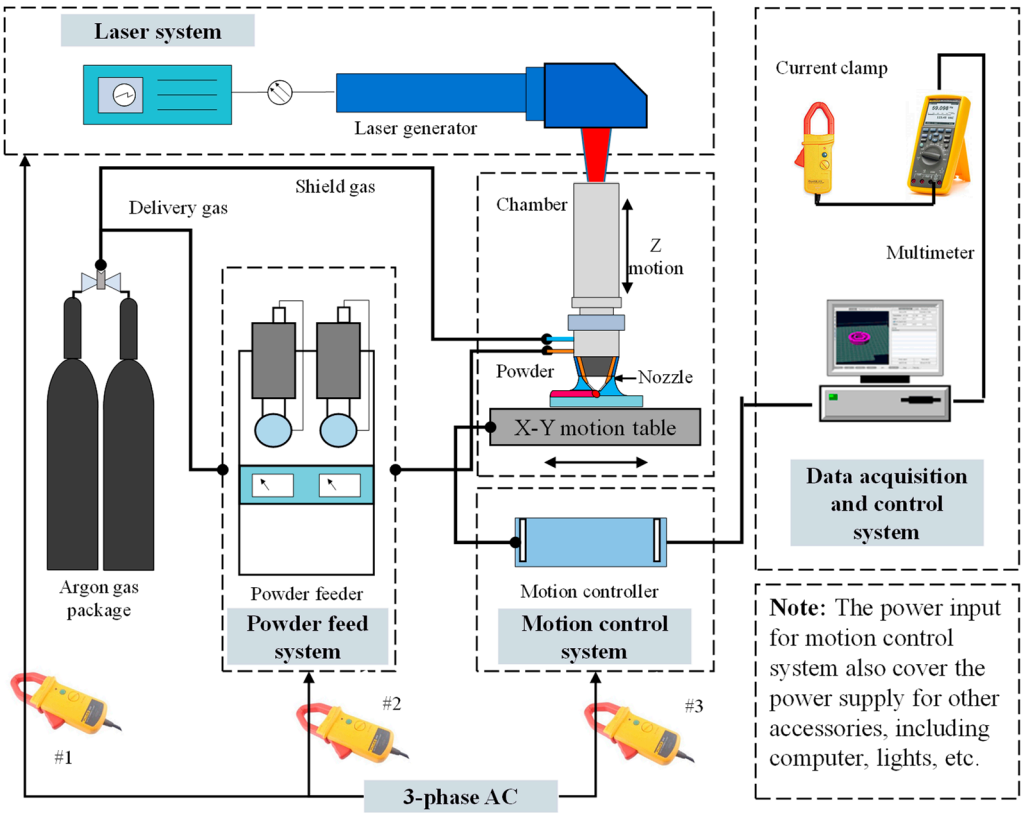

Figure 2. Illustration of experimental set-up for energy consumption measurement for LENS process.

2.3. Environmental Impact Quantification

As a useful tool to evaluate environmental performances, life cycle assessment (LCA) could estimate the cumulative environmental impacts generated from the entire product life cycle [23]. Based on the ISO 14040 and 14044 standards, an LCA consists of the following four components: (i) goal and scope definition; (ii) life cycle inventory analysis; (iii) life cycle impact analysis; and (iv) interpretation [24]. In this study, LCA was used to estimate the environmental impacts resulting from the different AM processes. To simplify the quantification and comparison process, only global

warming potential (*GWP*) was considered as the environmental impact. *GWP* provides a common unit to measure the cumulative effect of greenhouse emissions regarding the global warming and it allows policymakers to compare emissions reduction opportunities across different processes.

The boundary (processes under concern) of the LCA includes: material extraction and energy production, delivery material preparation (powders, filament, etc.), and materials fabrication process. The materials used in the selected AM processes are shown in Table 2. Primary energy including hard coal, crude oil, and natural gas were consumed and greenhouse emissions—such as CO, CO_2, SO_2, etc.—were generated during the raw materials production. For metal powder preparation, atomization process was selected due to the high productivity [25]. In this process, the metallic material was heated until melting point is reached in the smelter. Then, high-speed inert gas (argon) was used to disintegrate the drop flow of metallic fluid. The metal powder was generated after congealing during the flight of metallic fluid. For the selected materials in this study, the energy consumption per unit mass ranges from 0.27 kWh/kg to 0.65 kWh/kg in atomization process [26]. An average value (0.46 kWh/kg) was used in this study. The energy requirement for preparing 1 kg filament of Nylon, ABS and 1kg liquid epoxy Resin was 23.6 kWh [27], 2.22 kWh [28], and 54.492 kWh [29] respectively, which was referred from the previous literature.

The emissions of CO_2, CH_4, N_2O, etc., generated in the raw materials and energy production were obtained from the GaBi software version 6 (Thinkstep, Stuttgart, Germany). The time period used for *GWP* was set up as 100 years. The *GWP* of different AM processes can be calculated by Equation (2).

$$GWP = \sum_{j=1}^{m} EFGWP_j \times g_j \tag{2}$$

where g_j is the environmental emissions, referring to CO_2, CH_4, N_2O, etc., and $EFGWP_j$ is the characterization factor of the substance g_j (kg CO_2-equivalent). Characterization factors were used to convert and combine the environmental emissions into *GWP* impacts.

Table 2. SEC of various AM processes.

AM Process	Power Type	Materials	Power (w)	Layer Thickness (mm)	Spot Size/Nozzle Diameter (μm)	Energy Density (J/mm^2)	Process Rate (cm^3/s)	SEC (J/cm^3)	Note (Ref.)
LENS	Fiber laser	Inconel 718	350	0.458	400	68.89	1.43×10^{-3}	1.311×10^{6}	[a]
		Stellite 1	350	1.053	400	103.34	1.81×10^{-3}	1.055×10^{6}	
		AISI 4140	380	0.6	400	112.20	1.03×10^{-3}	1.913×10^{6}	
		Triboloy T800	360	1.015	400	106.30	1.72×10^{-3}	1.094×10^{6}	
DMD	CO_2 Laser	H13 tool steel	6000	NA [c]	3500	NA	1.28×10^{-3}	5.974×10^{7}	[b] [30]
DMLS	Fiber laser	Stainless steel	200	0.02	450	56.98	1.60×10^{-3}	2.785×10^{6}	[b] [31]
LMD	Diode Laser	AISI 316 L	2000	0.9	3000	111.11	2.11×10^{-2}	9.478×10^{4}	[b] [32]
SLA	UV light	Resin	NA	0.1	NA	NA	1.44×10^{-3}	5.596×10^{4}	[a]
FDM	Heat	ABS	NA	0.25	250	NA	2.22×10^{-3}	4.327×10^{5}	[a]
SLS	CO_2 laser	nylon	3500	0.15	450	997.15	2.64×10^{-2}	1.556×10^{6}	[b] [33]
Inkjet Printing	Pressure	Cell mixture	NA	0.12	NA	NA	9.05×10^{-10}	1.741×10^{12}	[a]
Micro Extrusion	UV light	sodium alginate	NA	0.15	200	NA	1.59×10^{-4}	4.588×10^{6}	[a]

[a] SEC is calculated by $SEC = UIT/V$, where U, I, T, and V are measured in the Lab; [b] Concluded from previous literature; [c] NA means value not available for specific material characteristic.

3. Results and Discussion

3.1. Discussion of Energy Distribution of AM Process

As a highly collaborative process, AM typically involves several systems, such as energy input system, materials delivery system, motion control system, as well as ancillaries and software. Under a certain process conditions, the proportion of energy consumptions for the modules of powder feed, motion control and accessories can be regarded as constant, however, the proportion of energy consumption during the material fabrication process will decrease with the increase of the process rate. Based on the energy requirement modeling for material removal processin [34], the energy requirement modeling of AM process can be expressed with Equation (3)

$$P = P_{idle} + kv \tag{3}$$

where P is the total power in kW, P_{idle} is the idle power in kW, v is the process rate of materials deposition in cm^3/s, and k is a constant in J/cm^3. Taking LENS process as an example, P_{idle} is the none-load energy consumption, which takes up 20.81% of the total. k is specific energy consumption (SEC) which is closely related to the materials utilized and power source. The energy consumption and distribution of LENS process is shown in Figure 3, indicating that a considerable amount of energy is needed during the startup and maintenance of the equipment, and the additional energy requirement is proportional to the process rate of materials deposition.

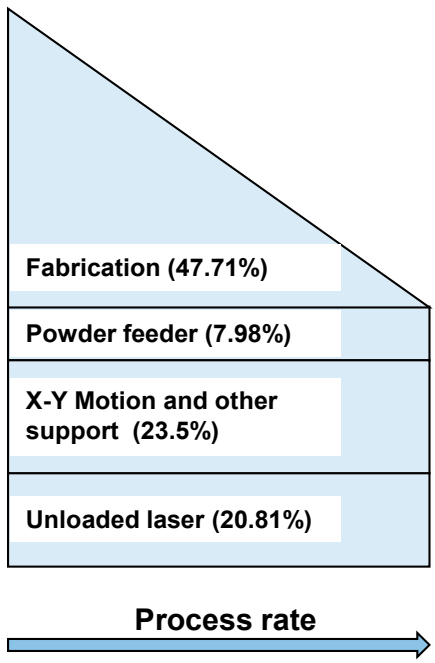

Figure 3. Energy used as a function of production rate for LENS machine. Material: IN718, laser power: 350 W, powder feed rate: 2.5 rpm.

3.2. Discussion of SEC of AM Processes

3.2.1. Result of SEC for AM Processes

Based on Equation (1), the SEC of various AM processes (LENS, SLA, FDM, inkjet printing, and extrusion) was calculated and summarized in Table 2. In order to compare the SEC of different AM processes with different material, the SEC of some other AM processes was referred from the previous publications.

According to the data in Table 2, SEC plot for different AM processes was drawn and illustrated in Figure 4. Generally, the SEC is decreasing with the increase of process rate, and the difference of SEC for different AM processes is as much as seven orders of magnitude. Basically, the SEC of bio materials AM processes is higher than metallic materials, and the SEC of polymer material AM processes is relatively small. Apart from inkjet printing, the SEC for most of the selected AM processes presents a cluster phenomenon. For the polymer materials, it is reported that the SEC of traditional bulk forming process, such as injection molding, is about 6.01×10^3 J/cm^3 [35], which is much less than that of AM processes. For the metallic material, the SEC of subtractive manufacturing processes varies greatly with the different material. The milling and turning processes of AISI 4140 steel were estimated to be 1.45×10^4 J/cm^3 (milling) and 7.1~14.5 $\times 10^3$ J/cm^3 (turning) [36,37] respectively, which only accounts for 0.75% to that of LENS process. Therefore, the traditional bulk forming process for polymer material and subtractive manufacturing process for metallic material are more energy efficient than the corresponding AM processes regarding the SEC when the material preparation process is out of consideration.

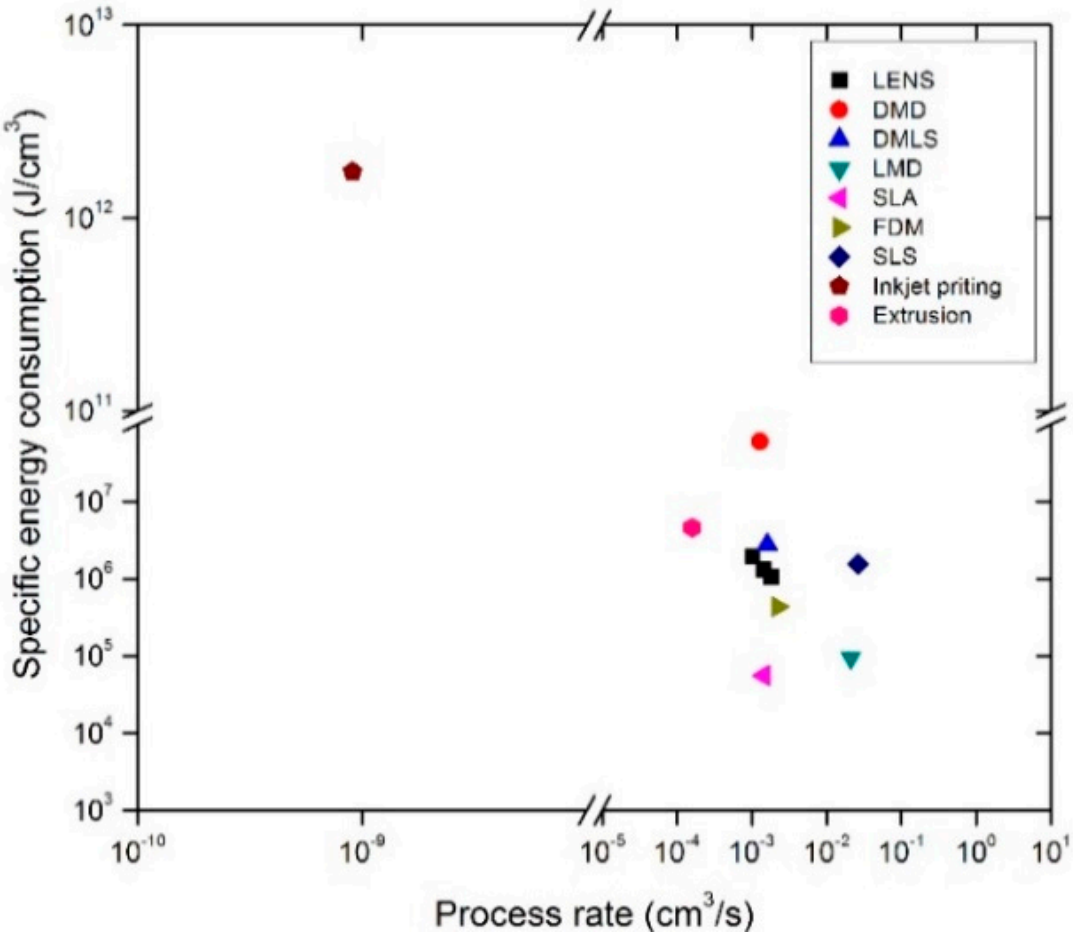

Figure 4. SEC plot for AM processes.

3.2.2. Relation of SEC and Part Surface Hardness

The relation of SEC and materials property (surface hardness) was investigated to examine the possibility that ensure the product quality while reducing the energy consumption. The SEC plot of LENS with Inconel 718 superalloy under different process rate is shown in Figure 5. Although the variation of process rate is small (from 1.15×10^{-3} to 2.38×10^{-3} cm^3/s), the SEC is reduced from 1362.7 J/cm^3 to 677.1 J/cm^3, which is over 50% reduction. Considering that the part surface hardness under different process rate ranges from 221.9 to 238.7 HV$_1$, it can conclude that it is possible to achieve

a satisfied part quality while reducing the energy input. When considering the two factors of energy input and part quality, the parameters of laser power: 275 W, scanning speed: 8.47 mm/s, and powder feed rate: 4 g/min are recommended.

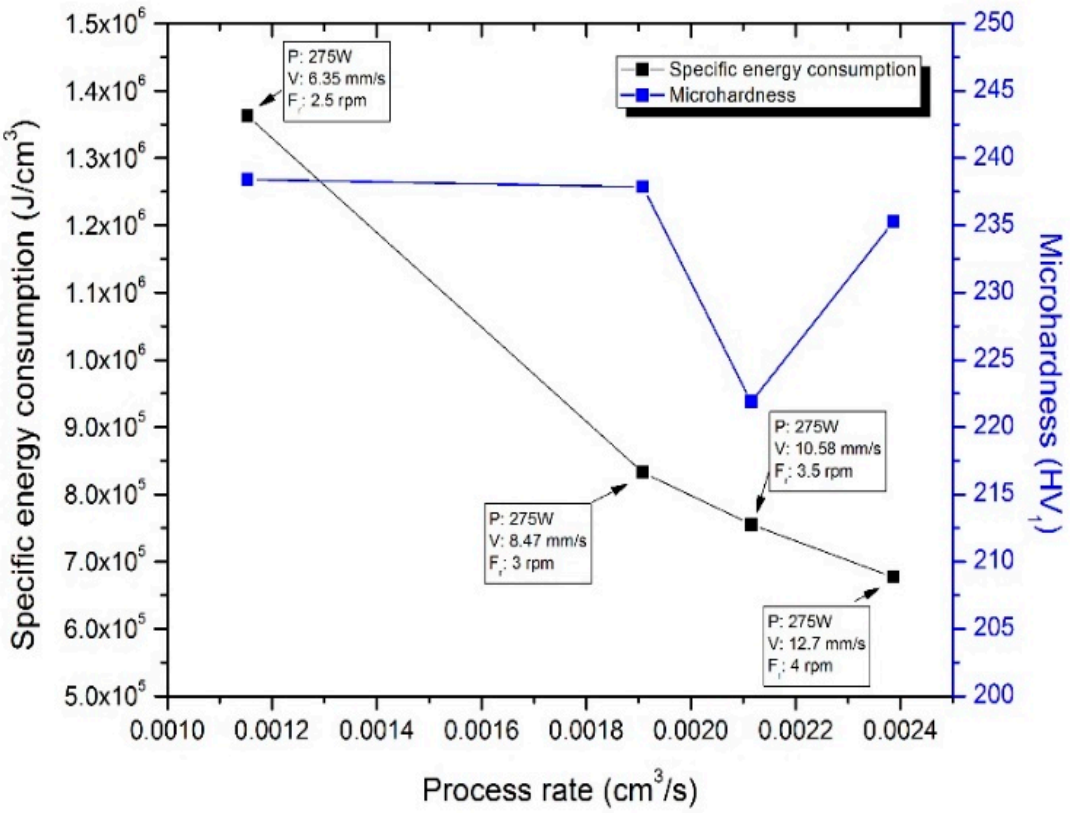

Figure 5. SEC plot for LENS under different process rate (material: IN 718).

3.2.3. Relation between SEC and Metallic Powder Materials

Because different materials have different physical and mechanical property, the best build quality occurs at different parameter combinations. Considering the best final shaping of the fabricated part, the input parameters for each kind of powder is shown in Table 3. The result of SEC for different powders in LENS process is shown Figure 6. It can be found that the SEC of AISI 4140 is highest, followed by Inconel 718, Triboloy 800 and Stellite 1. There are two reasons, for the most part, why the SEC is different: (i) powder characteristics and (ii) input parameters. On the one hand, the higher SEC of AISI 4140 can be partially contributed to the smaller powder size and higher density. More specifically, the energy consumed to heat unit volume by unit temperature, AISI 4140 requires more energy, as can be seen in Figure 7a,b. In addition, the power absorption rate of AISI 4140 is lowest among the selected powders due to the highest thermal conductivity (42.6 W/mK), which causes highest energy requirement. On the other hand, the layer thickness of AISI 4140 is smallest while the energy density is highest during the material deposition process, resulting in the largest number of layers for the unit volume and highest energy input for each layer; therefore, the SEC of AISI is higher than the other materials, as can be seen in Figure 7c,d.

To testify the possibility that acquires desired property with less energy input, the effect of the powders on SEC and part surface hardness was examined and the result is shown in Figure 7. The block part fabricated with Stellite 1 has the highest surface hardness, followed by Triboloy 800, AISI 4140, and Inconel 718, suggesting that it is possible to select powders which can not only cause less energy consumption, but also provide a better part quality, such as Stellite 1 and Triboloy 800.

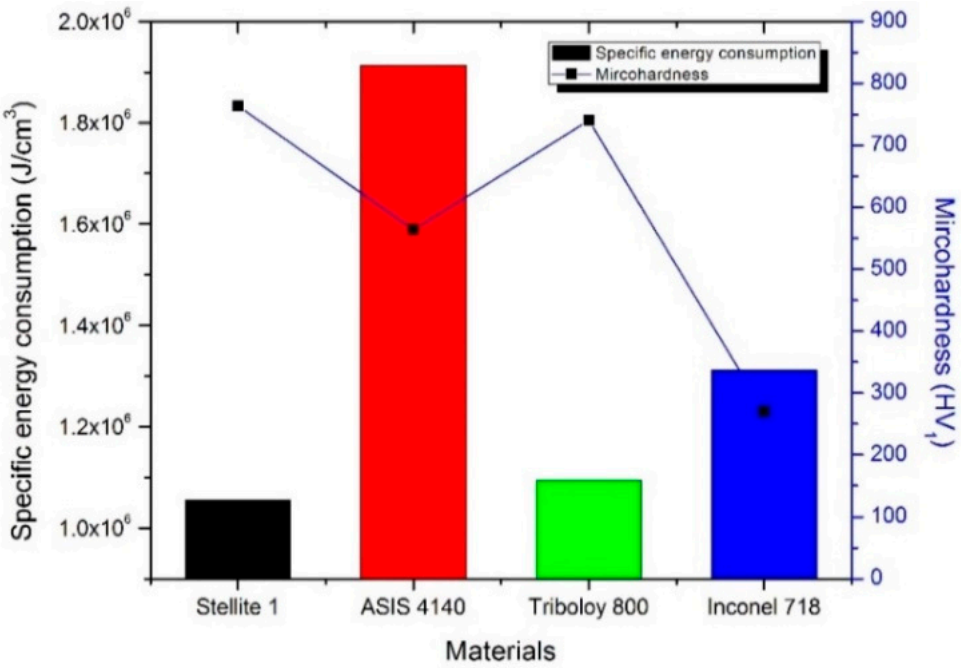

Figure 6. Effect of powders on SEC in LENS process.

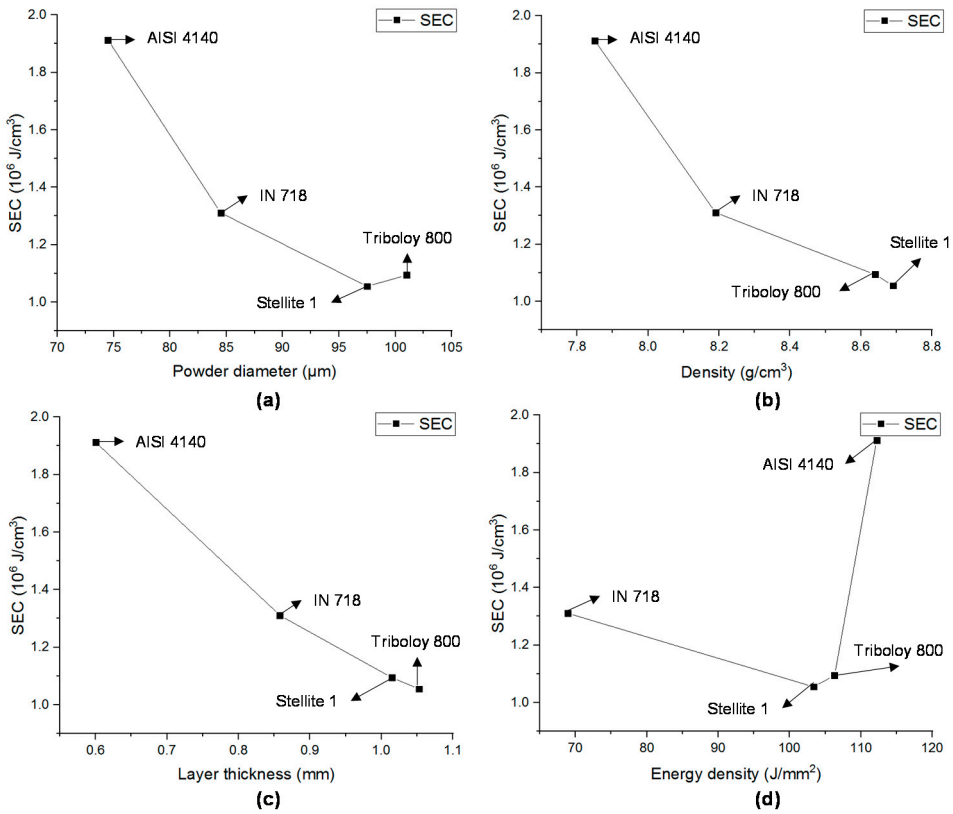

Figure 7. Effect of powder characteristics and input parameters on SEC: (**a**) Powder diameter; (**b**) density; (**c**) layer thickness; and (**d**) energy density.

Table 3. Input parameters selected for each kind of metallic powder in LENS process.

Powders	Laser Power (W)	Scanning Speed (mm/s)	Layer Thickness (mm)	Spot Size (μm)	Hatch Spacing (mm)	Energy Density (J/mm^2)	Infill Patten
Stellite 1	350	8.47	0.458	400	0.305	68.89	Rectangular (45°)
AISI 4140	380	8.47	1.053	400	0.305	103.34	Rectangular (45°)
Triboloy T800	360	8.47	0.6	400	0.305	112.20	Rectangular (45°)
Inconel 718	350	12.7	1.015	400	0.305	106.30	Rectangular (45°)

3.3. Environmental Impacts of AM Processes

Based on the quantification method in Section 2.3, the environmental emissions generated in the processes of materials production, powder/filament preparation, and energy consumption for unit volume (1 cm^3) material fabrication were collected (assuming the materials efficiency is 100%, not including the material recycling process). The *GWP* impact was calculated with characterization and the results are shown in Table 4. Log scale graphic (Figure 8) was used for the direct display of the *GWP* impact result in order for the decision maker to compare more conveniently.

Figure 8 suggests that the final *GWP* impact of AM processes varies due to the different material utilized and energy consumption and it is mainly generated by the energy production process. Along all of the selected AM processes, DMD will contribute the great impact on *GWP* due to the high SEC during the material fabrication process. Because of the lower SEC, the GWP impact of LMD and SLA is relatively less than the other processes. Due to the lack of emission data of bio material production, the *GWP* result is not shown in this figure, however, it can be safely inferred that the *GWP* impact of the extrusion process will be pretty high because of its largest SEC.

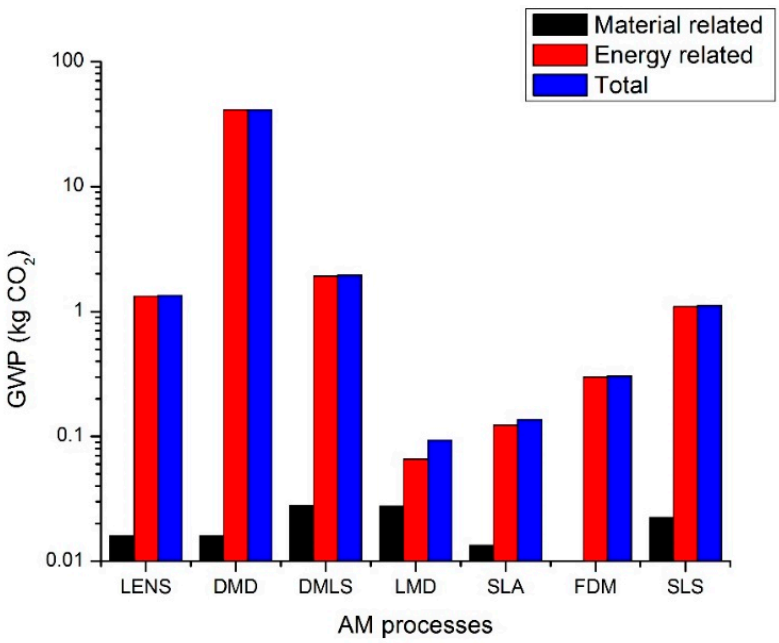

Figure 8. Log scale result of *GWP* impact result of different AM processes.

Table 4. Result of *GWP* during AM process.

AM Process	Items	Quantity (kg)			Characterization Factor [a]	*GWP* Result (kg CO_2 eq)		
		Material Production	Material Preparation	Energy Consumption		Materials Related	Energy Related	Total
LENS	CO_2	1.59×10^{-2}	2.36×10^{-4}	1.25	1	1.60×10^{-2}	1.32	1.34
	CH_4	6.70×10^{-6}	4.74×10^{-7}	2.51×10^{-3}	25			
	N_2O	1.63×10^{-8}	3.13×10^{-9}	1.66×10^{-5}	298			
DMD	CO_2	1.58×10^{-2}	2.35×10^{-4}	3.91×10	1	1.59×10^{-2}	4.12×10	4.12×10
	CH_4	6.65×10^{-6}	4.71×10^{-7}	7.85×10^{-2}	25			
	N_2O	1.62×10^{-8}	3.11×10^{-9}	5.17×10^{-4}	298			
DMLS	CO_2	2.62×10^{-2}	2.42×10^{-4}	1.82	1	2.78×10^{-2}	1.92	1.95
	CH_4	3.20×10^{-5}	4.85×10^{-7}	3.66×10^{-3}	25			
	N_2O	2.91×10^{-6}	3.20×10^{-9}	2.41×10^{-5}	298			
LMD	CO_2	2.60×10^{-2}	2.40×10^{-4}	6.20×10^{-2}	1	2.77×10^{-2}	6.56×10^{-2}	9.33×10^{-2}
	CH_4	3.19×10^{-5}	4.83×10^{-7}	1.25×10^{-4}	25			
	N_2O	2.90×10^{-6}	3.18×10^{-9}	8.21×10^{-7}	298			
SLA	CO_2	1.21×10^{-2}	8.02×10^{-2}	3.66×10^{-2}	1	1.34×10^{-2}	1.23×10^{-1}	1.36×10^{-1}
	CH_4	3.51×10^{-5}	1.61×10^{-4}	7.35×10^{-5}	25			
	N_2O	1.23×10^{-6}	1.06×10^{-6}	4.85×10^{-7}	298			
FDM	CO_2	3.35×10^{-3}	1.55×10^{-3}	2.83×10^{-1}	1	3.70×10^{-3}	3.00×10^{-1}	3.04×10^{-1}
	CH_4	1.29×10^{-5}	3.12×10^{-6}	5.69×10^{-4}	25			
	N_2O	9.56×10^{-8}	2.06×10^{-8}	3.75×10^{-6}	298			
SLS	CO_2	1.84×10^{-2}	1.77×10^{-2}	1.02	1	2.24×10^{-2}	1.09	1.11
	CH_4	3.74×10^{-5}	3.57×10^{-5}	2.04×10^{-3}	25			
	N_2O	1.04×10^{-5}	2.35×10^{-7}	1.35×10^{-5}	298			

[a] Characterization factors are cited from IPCC 2007 [38].

4. Conclusions

Energy consumption and environmental impact analysis of AM are challengeable and necessary. It will not only affect the strategy formulation but also the technologies development within the industry. In this paper, the SEC and environmental impacts for a wide range of AM processes have been investigated. With selected geometric and materials properties, the paper also studied the relationship between SEC and material characteristics as well as process input parameters. The main conclusions are as follows:

(1) The SEC and environmental intensity for AM processes were related not only to material characteristics but also to the process input parameters. For LENS process, materials with smaller powder size and higher density as well as a smaller layer thickness and higher energy density will cause a higher SEC.

(2) By adjusting the input parameters, it is possible to increase the energy efficiency without reducing the product quality. When considering the energy input and part quality, the parameters of laser power: 275 W, scanning speed: 8.47 mm/s and powder feed rate: 4 g/min are recommended for Inconel 718 in LENS process.

(3) For the environmental impact quantification, the *GWP* impact result of AM processes indicates that the *GWP* is brought about principally by the energy production process. DMD will contribute the great impact to *GWP* due to the high SEC, and LMD and SLA will bring about relatively less *GWP* than the other processes.

Although AM is considered more environmentally friendly than SM due to advantages—such as less waste, no specialized tooling, life cycle reduction, etc.—more efforts should be made to explore the overall environmental impacts of AM, especially under different experiment conditions. The information provided by this paper can be of benefit to life cycle assessment and other environmental impact assessment related to AM processes.

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Nomenclature

AM	additive manufacturing
DMD	direct material deposition
DMLS	direct material laser sintering
FDM	fused deposition modeling
LCA	life cycle assessment
LENS	laser engineered net shaping
SLA	stereolithography
SEC	specific energy consumption
SLS	selective laser sintering
SLM	selective laser melting
EBM	electron beam melting
PLA	polylactic acid
ABS	acrylonitrile butadiene styrene

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