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Energy Consumption Model for Additive-Subtractive Manufacturing Processes with Case Study

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There has been a growing trend in industry towards the development of integrated manufacturing centers that combine several manufacturing processes, such as the mill-turn center. As additive manufacturing becomes a more widely adopted technology, combining additive with subtractive manufacturing in one machine is a logical evolution to provide the benefits of final parts made from raw materials with the dimensional tolerance and surface finish expected in many applications. An energy consumption model was created that accounted for the energy consumption during primary metal production, deposition, and machining phases of wire-based and powder-based additive-subtractive manufacturing processes. This model was applied to a case study where the energy consumption to produce sub-sized, sheet type, and plate type (size) tensile bars was calculated. It was found that the wire-based process consumed less energy during deposition, whereas powder-based was less energy consumptive during primary metal production and machining. The findings suggest that given the present understanding of the respective technologies' capabilities, the desired final net shape will dictate the preferred manufacturing process with respect to energy consumption considerations.

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NOMENCLATURE

CNC = Computer numerical control
c_p = Specific heat
η = Energy conversion efficiency
GMAW = Gas metal arc welding
LAMP = Laser aided manufacturing process
LENS = Laser engineered net shaping
MIG = Metal inert gas
MRR = Material removal rate
Nd:YAG = Neodymium-doped yttrium aluminum garnet
PMP = Primary metal production
SEC = Specific energy consumption

1. Introduction

1.1 Energy Considerations in the Manufacturing Landscape

The manufacturing sector currently makes up 11% of the U.S. gross domestic product, but consumes 21.5% of the total energy in the country.[1] A review of energy consumption in a variety of manufacturing processes was performed by Yoon et al., 2014.[2] The authors sought to characterize the energy consumption of bulk forming, subtractive, and additive manufacturing processes using the Specific Energy Consumption (SEC), "defined as the energy consumed in the production of a material unit".[2] The SEC is traditionally defined as Joules per unit mass (J/kg) processed for additive and bulk forming processes, whereas for subtractive processes, it is defined as Joules per unit volume removed (J/m^3).[2]

Recognizing the importance of manufacturing in the overall energy consumption landscape, there have been increasing efforts in recent years to make advances in energy efficiency.[1,3,4] This has included pursuits focusing on creating tools to describe the energy consumption in manufacturing processes, as well as those aimed at developing a range of more energy efficient processes and technologies.[5-10]

1.2 Additive Manufacturing

One technology with the potential to improve the energy utilization of the manufacturing sector is additive manufacturing. Additive manufacturing is an all-encompassing title for manufacturing processes

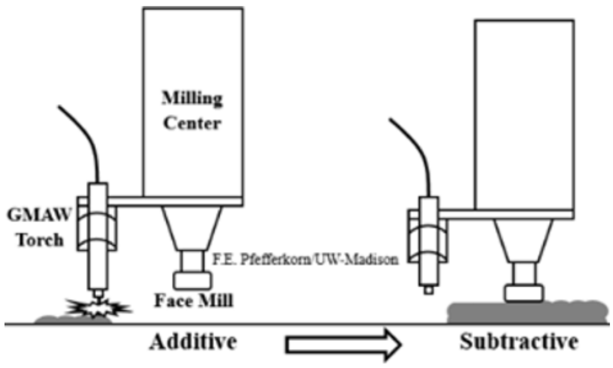

Fig. 1 Simplified wire-based additive-subtractive manufacturing process diagram

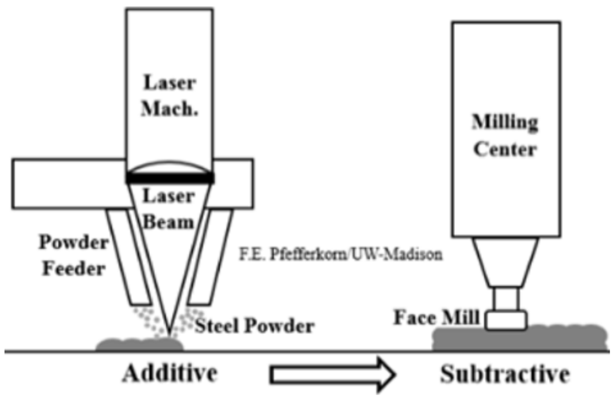

Fig. 2 Simplified powder-based additive-subtractive manufacturing process diagram

that build parts through an iterative addition of material, typically in a layer-by-layer fashion. In the past two decades, additive manufacturing of metals has become an active area of research and production systems are now commercially available.[11] However, the accuracy and surface quality of parts created by these technologies are typically much lower than those produced by machined parts.[12] A combination of additive and subtractive manufacturing processes in a single machine system can address these issues and help realize the raw material to final product goal of a comprehensive manufacturing system.[13] Metal additive-subtractive manufacturing systems have recently been brought to market.[14]

1.3 Wire-Based Additive-Subtractive Manufacturing

Gas metal arc welding (GMAW), formerly known as metal inert gas (MIG) welding, was developed in the 1950s. The process has traditionally been used to melt and join metals by establishing an arc between a continuously fed filler wire and the base metal. The arc and molten weld pool are usually shielded by inert gases.[15] As illustrated in Fig. 1, researchers have created combined additive-subtractive manufacturing systems by pairing a GMAW-based additive manufacturing process, that deposits a layer of molten wire across a prescribed geometric area, with CNC milling capable of bringing the part to a prescribed shape.[16,17]

1.4 Powder-Based Additive-Subtractive Manufacturing

A powder-based additive-subtractive manufacturing system utilizing laser deposition and CNC milling has been researched by Liou et al., 2007.[18] Named the Laser Aided Manufacturing Process (LAMP), a laser beam creates a melt pool on a surface as powder is injected into the molten pool (i.e., LENS process). The deposition follows prescribed scanning paths to create the desired part geometry. Milling operations bring the part within dimensional tolerance.[18] A simplified diagram of this process is illustrated in Fig. 2.

1.5 Energy in Additive-Subtractive Manufacturing

Due to the infancy of additive-subtractive manufacturing technology, there is currently no literature available on energy consumption in the process. However, energy consumption in additive and subtractive manufacturing systems, separately, has been studied. Research has been conducted on energy consumption of subtractive manufacturing systems (i.e., metal cutting), specifically for milling,[19-23] turning,[21,22,24,25] and drilling operations.[20,25] Additive manufacturing has only recently begun to be studied in this regard, with the literature covering both polymer,[26-28] and metal deposition processes.[26,29-34] A key contribution to the literature was made by Kara et al., 2011, who developed a methodology to model energy consumption of machining operations utilizing an empirical relationship between Material Removal Rate and SEC.[21]

In additive manufacturing of metal alloys, the energy consumption and environmental impact of a powder-based additive manufacturing system were studied by Morrow et al., 2007.[32] The melting efficiency and average energy transfer efficiency of powder-based directed energy deposition technologies such as this have been studied.[31] Also, energy consumed in the conversion of electrical energy from the wall to a laser beam, known as a laser’s wall efficiency, has been reported by Nd:YAG laser manufacturers: the type of laser used in LENS deposition processes.[35]

1.6 Motivation

The objective of this work is to compare the energy consumption along the total process flow of wire-based and powder-based additive-subtractive manufacturing. Additive-subtractive technology is currently in its infancy; therefore it is an opportune time to expand the understanding of these technologies and to gain an understanding of how each can contribute to a more sustainable manufacturing future.

2. Model

The framework for the model used in this study to calculate the energy consumption in producing steel components using wire-based and powder-based additive-subtractive manufacturing was previously presented by Jackson et al., 2016.[36] That model was built utilizing piecemeal experiments done by the authors and data from the experiments of others as reported in published literature.[36] Improvements were made to the model to more extensively capture the available literature and to more rigorously account for the variables impacting energy consumption. The model utilized in the present study accounts for a cradle-to-gate process where the additive manufacturing

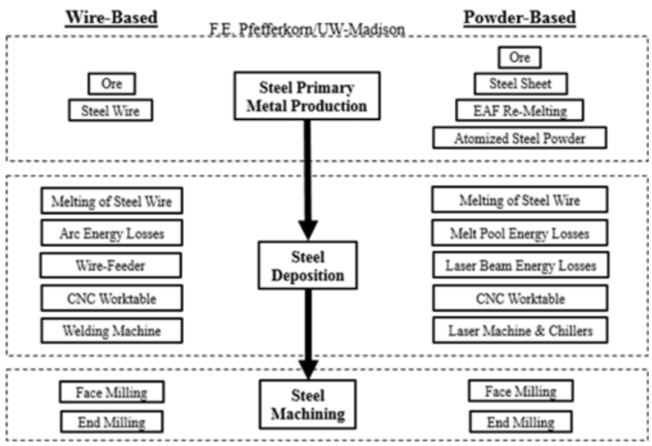

Fig. 3 Process flowchart of energy consumption in wire-based and powder-based additive-subtractive manufacturing

feedstocks are steel wire and powder, and energy consumption to manufacture steel components of specified geometric parameters is calculated. All the elements included in the model's analysis are shown in Fig. 3.

2.1 Primary Metal Production Energy Consumption

Embedded energy is the amount of energy that was consumed during primary metal production (PMP) of the wire and powder feedstock, respectively. The present model calculates SEC for PMP from values reported in published literature and GaBi database software.[36] Although there are large uncertainties associated with GaBi results, other researchers have argued for the validity of using it as a tool in energy consumption analysis of a system.[37,38] An approximate calculation for uncertainty was performed using the standard deviation of the mean and included to fully contextualize the SEC values.[39]

The SEC value found in the literature to produce steel wire from ore was 7.11E+07 J/kg.[36] The data for the GaBi analysis comes from primary data collected from a combination of industrial and public partners. To calculate the SEC, the software considers the embedded energy in creating steel billets in the United States, and then the energy required to roll the billet into wire. The resulting SEC from this analysis is 2.95E+07 J/kg.[40] An average of these two values yields 5.03E+07 2.08E+07 J/kg; this can be multiplied by the deposited mass to find the energy consumption in wire production.

The calculation for the energy consumption embedded in the powder deposited is an average of SEC values in literature and a SEC calculated using the GaBi software and database.[36,40] A three step method of powder production was modeled, where ore is transformed to an intermediate product, specifically, steel sheet or steel billet.[36,40] This method was chosen because the future goal of the model is to be able to estimate the energy consumption in remanufacture of components by directly re-using the material from the original part: i.e., the defective/damaged part would undergo re-melting before being atomized into powder.

An average of six values found in the literature resulted in a total SEC for powder creation of 5.61E+07 J/kg.[36] The GaBi software calculates the SEC for powder creation by considering the energy consumption to produce steel billets in the United States, the energy

Table 1 Wire-based energy consumption distributions

Energy consumption factors	SEC (J/kg)
Theoretical melt energy	1.19E+06
Arc contribution	1.30E+07
Wire-feed contribution	9.78E+06
Machine contribution	7.18E+06
CNC worktable	6.30E+06
Total for GMAW deposition	3.75E+07

required to re-melt the billets using an electric arc furnace, and the energy to atomize the melt into powder. The energy consumption inputs for re-melting and atomization were manually entered from external sources; the GaBi analysis resulted in an SEC of 4.34E+07 J/kg.[36,40] Averaged with the SEC from the previous model, the current model's SEC for powder PMP was found to be 5.02E+07 3.45E+06 J/kg. As with the wire-based process, the mass of the material deposited can be multiplied by this SEC to find the energy consumption in the creation of the powder.

2.2 Deposition Energy Consumption Modeling

The following section details the models of energy consumption in wire deposition through GMAW and in powder deposition through the LENS process.

2.2.1 Wire-Based Deposition Modeling

The energy consumption of GMAW deposition had been characterized in a previous work, but the presented model more precisely accounts for the energy consumption required to operate a CNC worktable during deposition. The previous study found that the average power load experienced during table feeds of a CNC worktable was 1701.44 J/s.[36] To calculate the CNC worktable component SEC, the average power load was divided by the average deposition rate during the GMAW deposition study. The deposition rate was defined as the product of the average travel feed rate, the average bead cross sectional area, and the density of the material, which in this case is steel. A description of the procedure through which the cross sectional area of the deposition was determined can be found in Jackson et al., 2016 and it was assumed that the deposition was fully dense.[36] The density of steel used in this calculation was 7850 kg/m^2. Based on this calculation, the SEC for the CNC worktable, as found in Table 1, was determined.

2.2.2 Powder-Based Deposition Energy Consumption Modeling

The LENS deposition SEC was also modified to more accurately account for the energy consumption of the CNC worktable. The model continues to calculate the energy consumption of the LENS process by considering the theoretical energy required to melt the deposited mass (SEC_{Melt}), the melting efficiency (η_{Melt}), the energy transfer efficiency (η_{Laser}), and the wall efficiency (η_{Wall}) which were derived from the experimental work found in both academic and industrial literature.[36] Then, in the same manner as the GMAW deposition portion of the model, the CNC worktable SEC for the LENS deposition was calculated. The average travel feed of the wire-based deposition used in this model comes from a study by Manvatkar et al.[41] and was 8.47 mm/s; the bead cross sectional area

Table 2 Powder-based energy consumption distributions

Energy consumption factor	SEC (J/kg)
Theoretical melt energy	1.19E+06
Melt efficiency contribution	2.41E+06
Laser transfer efficiency contribution	5.40E+06
Machine and chillers contribution	5.10E+07
CNC worktable	9.25E+07
Total for LENS deposition	1.53E+08

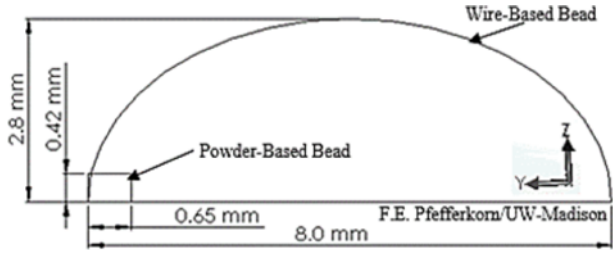

Fig. 4 Powder-based deposition bead cross-section

Table 3 Tensile bar cross sectional areas

	Wire-based	Powder-based
Sub-sized	3.60E-5 m^2	2.83E-5 m^2
Sheet	1.56E-4 m^2	1.23E-4 m^2
Plate	1.60E-3 m^2	1.26E-3 m^2

Note: The tensile bars of each size category would fail under identical tensile loads

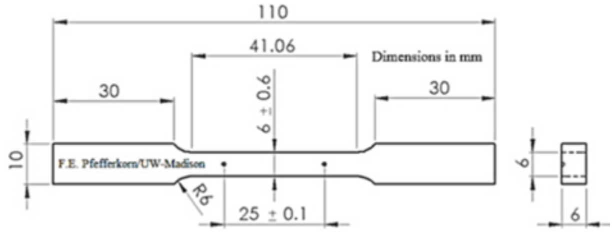

Fig. 5 ASTM E8/E8M - Sub-sized tensile bar specimen

is discussed in full detail the following section. summarizes all the contributions to the overall LENS deposition SEC and Eq. (1) clarifies its calculation.

$$SEC_{\text{Powder}} = \frac{SEC_{\text{Melt}}}{\eta_{\text{Melt}} + \eta_{\text{Laser}} + \eta_{\text{Wall}}} + SEC_{\text{Worktable}} \quad (1)$$

2.2.3 Powder-Based Deposition Geometry Study and Modeling

An understanding of the deposition geometry is key in calculating the amount of energy consumed in the additive and subtractive operations. To this end, literature was found describing the resulting geometry of LENS deposited steel beads.[41] These beads have smaller geometries than found in GMAW deposition; therefore, the initial deposition comes closer to the specified net shape in LENS. Because of this, it was important that the model capture the difference between the two processes in deposited mass, number of passes needed to deposit material, as well as mass removed during machining.

To account for the broad range of possible bead geometries, an average of all the geometries from the study by Manvatkar et al.[41] was taken, and then a single bead cross section was modeled in a simplified form, having the rectangular cross section (0.65 mm × 0.42 mm). For context, Fig. 4 shows a powder-based bead cross section in relation to that of a wire-based bead. Unlike the GMAW bead geometry, the behavior of overlapped beads was not assessed. To extrapolate the single bead cross section for any geometry, it was assumed that a bead width is required to be removed from all 4 sides of the layer, and one layer is required to be removed in height, from the minimum volume possible as governed by the single bead geometry and the prescribed net geometry of the part. This accounts for errors due to the abridged modeling of the overlapped bead geometry.[36]

2.3 Machining Energy Consumption Study and Modeling

The energy estimation in the model for the milling operation in both wire-based and powder-based processes is based on experimental energy consumption characterization of a vertical milling machine.[36]

3. Case Study: Steel Tensile Bars

To compare energy consumption between the two processes, a case study was performed. This case study investigated the energy required by each process (powder-versus wire-based) to produce steel tensile bars of three different sizes that would fail under equal tensile load. In other words, the tensile bar geometries were adjusted to accommodate the difference in tensile strength of parts made by powder-based versus wire-based additive manufacturing. The same material, steel, was assumed for all samples. Deposition geometry was used to determine the mass of material required to be deposited and then machined to reach the specified geometry. Then, the energy consumption of PMP, deposition, and machining were calculated using the SEC values from the model. The objective was to make an energy consumption comparison for the case where ultimate tensile load of the resulting steel part is the governing consideration.

3.1 Tensile Bar Geometry Determination

This case study seeks to frame the comparison of energy consumption in terms of a sample part's tensile strength. ASTM E8/E8M is the industry standard for performing tensile tests, hence was referenced to determine the geometry to be modeled. The three sizes of steel tensile bars investigated were: sub-sized, sheet, and plate.[42] It has been reported that steel components have an ultimate tensile strength of 620 MPa in the wire-based process and 790 MPa in the powder-based process.[16] Wire-based tensile bars were assigned the sizes corresponding to ASTM E8/E8M and the cross sectional area for the powder-based tensile bar was determined utilizing Eq. (2):

$$A_{\text{c,powder}} UTS_{\text{powder}} = A_{\text{c,wire}} UTS_{\text{wire}} \quad (2)$$

where, A_c is the cross-sectional area and UTS is the ultimate tensile strength of the material. The cross sectional areas of the tensile bars examined in this case study are summarized in Table 3, and Fig. 5 illustrates the sub-sized tensile bar geometry for reference.

Once the final net shape of the tensile bars was prescribed, the amount of mass required to be deposited was determined based on the

Fig. 6 Top view of deposition passes with material remaining after machining overlaid (not to scale)

powder-based and wire-based deposition geometries, respectively. The mass deposited was then multiplied by the appropriate PMP, and deposition SEC to determine the energy consumed during each respective phase of processing.

This work models the deposition bead geometry of continuous, straight passes. Therefore, all layers of deposition during the part build were considered to have rectangular footprints; the tensile bar shape would be achieved by face milling a flat surface after each layer, and once all necessary layers have been deposited, end milling would bring the bar to its prescribed net shape. This concept is illustrated in Fig. 6; while not to scale, the solid black lines show the deposition rows and the dotted black lines denote material remaining after machining.

3.2 Case Study Inputs and Parameters

In the wire-based process, the energy required to produce the wire deposited was accounted for by multiplying the SEC for PMP of wire by the mass deposited in GMAW deposition. The energy consumed in wire-based deposition of the tensile bars was calculated by multiplying these masses by the SEC for GMAW deposition. To determine the energy consumption in machining the wire-based deposition, the wire-based machining SEC was multiplied by the mass of material removed. Table 4 summarizes these inputs.

The powder PMP SEC was multiplied by the masses deposited during LENS deposition to determine the energy consumed in the creation of powder. Those masses were multiplied by the LENS deposition SEC to calculate the deposition phase's energy consumption. The energy consumption to machine the powder-based deposition was calculated by multiplying that process' SEC by mass removed for each tensile bar size. These inputs are summarized in Table 5.

The machining parameters chosen for this case study mirror those in Jackson et al..[36] As discussed in that work, differences in the machining SEC between the two processes was due to a smaller amount of material being required to be removed from the powder-based deposition; and therefore, the depth of cut is smaller than for the wire-based process. Since depth of cut is a component of the MRR, and SEC is a dependent variable of MRR, the two machining operations will respectively have different SEC values. Finally, an additional simplification in this calculation was performed, even though there are two separate types of milling operations occurring, face milling and end milling, it assumed that the machining parameters and corresponding MRR will be the same for both operations.[36]

Table 4 Wire-based case study inputs and parameters

	Sub-sized	Sheet	Plate
PMP SEC		5.03E+07 J/kg	
Deposition SEC		3.75E+07 J/kg	
Mass deposited	0.108 kg	0.78 kg	10.5 kg
Machining SEC		2.35E+07 J/kg	
Mass machined	0.066 kg	0.448 kg	4.30 kg

Table 5 Powder-based case study inputs and parameters

	Sub-sized	Sheet	Plate
PMP SEC		5.02E+07 J/kg	
Deposition SEC		1.53E+08 J/kg	
Mass deposited	0.059 kg	0.368 kg	6.45 kg
Machining SEC		2.38E+07 J/kg	
Mass machined	0.023 kg	0.083 kg	1.32 kg

3.3 Results and Discussion

Manufacturing the sub-sized tensile bar through the wire-based process was modeled to consume 22% less energy than powder-based. For the sheet tensile bar, the powder-based process consumed 3% less than wire-based. The wire-based process consumed 24% less energy than powder-based to manufacture the plate tensile bar. These results can be found in Fig. 7.

The primary reason the energy consumption results do not follow a consistent trend with respect to size of the tensile bars stems from the inherent deposition resolution of each process. All metal additive manufacturing processes deposit more material than will be present in the final part, thus the motivation for additive-subtractive systems. The amount of excess material is determined by the deposition resolution. The resolution of each deposition process, GMAW or LENS, was based on the deposition geometry. When applying the deposition geometry to the prescribed tensile bar sizes, how well the deposition geometry fit to the desired net shape determined how much excess material was deposited. Therefore, the absence of a trend with respect to size of the tensile bars is due to the differences between each process' fitness to each respective size's geometry.

Although the energy consumption of the powder-based process is less than the wire-based to produce the sheet tensile bar, this result is not as definitive as that of the sub-sized and plate samples. It is known that reported embedded energy values have significant variability. The PMP components of the model rely on SEC's from literature and database software that did not directly report uncertainty, however, the range of available data was used to estimate uncertainty. The uncertainty in the reported SECs is large and suggests more work must be done by the manufacturing community to better quantify the energy consumption of these processes. Considering this, the small difference between the overall energy consumption of the two processes for the sheet tensile bar sample is treated as an indeterminate result. More substantial results of this case study can be found by inspecting the energy consumption during the process phases separately, those being PMP, deposition, and machining, as illustrated in Figs. 7(a)-7(c).

An interesting finding in this case study is that for all the tensile bar sizes, the wire-based deposition energy consumption is much less than powder-based even though much more mass is deposited. For example, manufacturing the plate tensile bar requires 39% less powder than wire

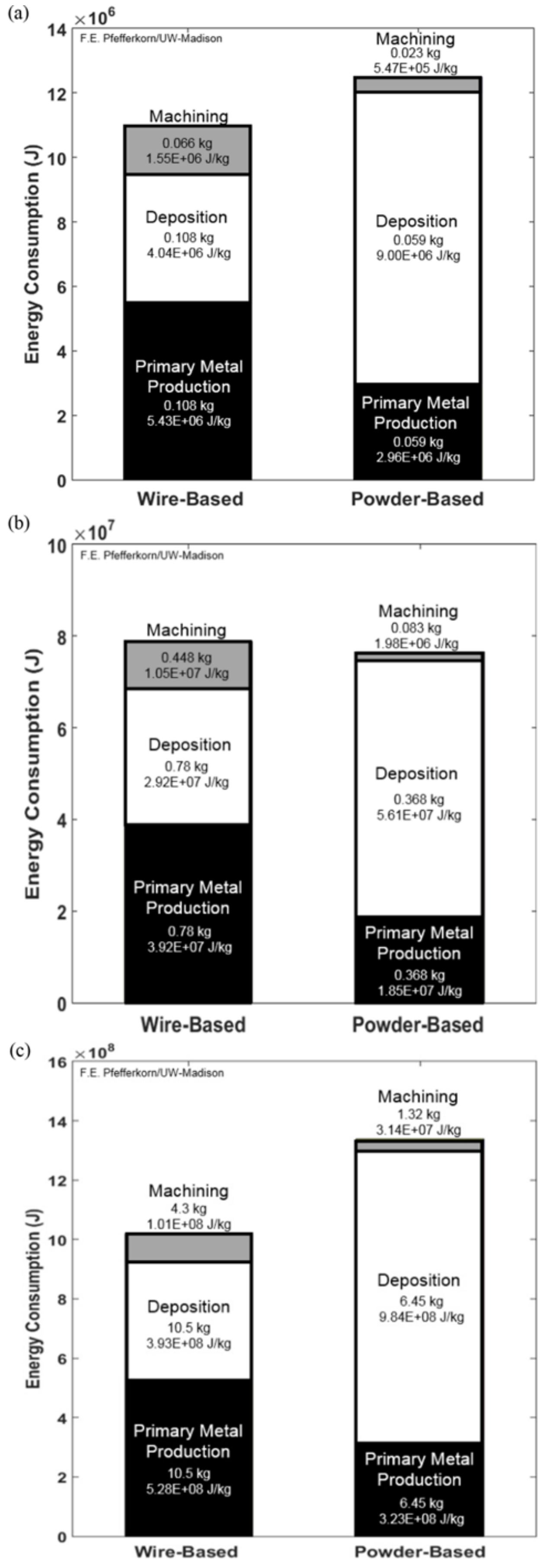

Fig. 7 Case study energy consumption results: (a) sub-sized, (b) sheet, and (c) plate

to be deposited, but 60% less energy is consumed in wire-based than powder-based deposition. This trend is similar for the other two tensile bar sizes. The root of this trend is that the SEC for wire-based deposition is 75% less than the powder-based.

Referring to the powder-based deposition energy consumption components, the two largest contributions are the energy to feed the CNC worktable, and the energy consumed by the laser machine. Due to the fine resolution of the LENS deposition process, it takes a long time and many passes to build up a part. The baseline power load of the CNC worktable is the dominant driver of energy consumption and therefore, the faster material can be deposited, the lower the energy consumption will be. The GMAW deposition process has an SEC that is 26% less than the SEC of the laser machine and chillers component of the LENS deposition process alone.

While the advantages of the GMAW deposition process are clear, the powder-based process consumes less energy in PMP and machining phases of manufacturing. Since the SEC's are similar for these phases, it can be concluded that the difference is due to the resolution capabilities of the two processes. The greater amount of excess mass deposited in the wire-based process contains more embedded energy from the PMP and requires more energy to be machined away.

These findings point to the importance of the deposition phase in understanding the overall process energy consumption. There is a trade-off between the deposition rate and deposition resolution. In this study, the wire-based process has greater deposition rate, hence a lower deposition SEC. The powder-based process has better deposition resolution, which then leads to less processed material overall. This case study sought to identify key drivers of energy consumption in these two additive-subtractive manufacturing processes. To better understand the trade-off found here, future work could investigate the relationship of process parameters and tool paths to energy consumption. This could be used to develop an energy consumption optimization method to determine when one process may be preferred over the other based on the planned G-Code.

The effect on the case study results of equating the tensile bar cross sectional areas by tensile strength was considered. However, the difference in the final tensile bar mass between the two processes was similar across all three deposition sizes, yet the three sizes yield different results. This would suggest that the lower mass of the powder-based part did not substantially contribute to differences in energy consumption seen between the two processes.

4. Conclusions

A model was built to understand the energy consumption in wire-based and powder-based additive-subtractive manufacturing. A case study utilizing this model investigated the energy consumption to produce three different sized tensile bars. The dimensions of the wire-based and powder-based tensile bars were specified to have equal tensile load within each size category, i.e. sub-sized, sheet, and plate. The energy consumption to produce the sub-sized tensile bar with the wire-based process was 22% less than with the powder-based process; for the sheet sized tensile bar, the powder-based process consumed 3% less energy; and the energy consumption in manufacturing the plate tensile bar was 24% less through the wire-based process than the powder-based.

Reviewing the components of energy consumption, the wire-based process is more energy efficient during the deposition phase due to its higher deposition rate and the large energy requirement in the powder-based process to turn electrical energy into laser power. The powder-based process, however, is more efficient in the amount of material it utilizes to create a tensile bar due to its current advantage in deposition resolution. This results in less energy consumed in PMP of the powder as well as in machining the tensile bar to its specified shape. Given these findings, there appears to be a trade-off between speed of deposition and the deposition resolution in determining the more energy efficient means of manufacture. Future investigations could build on this model with data from integrated additive-subtractive manufacturing systems and across a wider array of processing parameters to study how the energy consumption could be optimized to improve efficiency. This could lead to process choosing tools with energy consumption considerations that would aid industry in the pursuit of a more sustainable manufacturing future.

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Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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