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A Comparison of Energy Consumption in Wire-Based and Powder-Based Additive-Subtractive Manufacturing

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Abstract
The objective of this work is to compare the energy consumption associated with the creation of a small volume of steel by wire-based additive-subtractive manufacturing and powder-based additive-subtractive manufacturing. Additive manufacturing is a growing area of research, encompassing many different processes aimed at producing final products. However, many additive processes lack the ability to achieve dimensional tolerance and surface finish required for many applications: *i.e.*, post-processing could be required. Combining additive with subtractive manufacturing in one machine tool enables the production of parts with tighter dimensional tolerances and smoother surfaces. In this work, an energy consumption model was created; it considered the contributions of primary metal production, deposition, and machining when calculating the total energy consumed to create a 100 mm x 100 mm x 1.5 mm volume of steel. It was found that for the entire process chain, the wire-based and powder-based processes consume similar amounts of energy. The greatest difference between the two processes is that the energy requirement for the deposition component during the wire-based process is 85% less than in the powder-based additive process. This finding suggests that from an energy consumption perspective, there is value in wire-based additive-subtractive manufacturing.

Keywords: Energy consumption, additive manufacturing, additive-subtractive manufacturing

Nomenclature

A_e	Depth of Cut
c_p	Specific Heat
L_{fusion}	Latent Heat of Fusion for the Metal
T_{melt}	Melting Temperature of the Metal
T_{room}	Temperature of the Metal before Melting (Room Temperature)

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CAD	Computer Aided Design
CNC	Computer Numerical Control
f	Feed Rate
GMAW	Gas Metal Arc Welding
LAMP	Laser Aided Manufacturing Process
LENS	Laser Engineered Net Shaping
MIG	Metal Inert Gas
MRR	Material Removal Rate
N	Number of Teeth
Nd:YAG	Neodymium-doped yttrium aluminum garnet
RPM	Revolutions per Minute
SEC	Specific Energy Consumption

1 Introduction

1.1 Energy Considerations in the Manufacturing Landscape

The manufacturing sector makes up 11 percent of the U.S. gross domestic product. Energy consumption in the manufacturing sector has decreased by 17 percent from 2002 to 2010 with only a 3 percent decrease in gross output over the same time period, suggesting an improvement in energy consumption per unit of gross domestic output ("Manufacturing Energy Consumption Survey (MECS) - Analysis & Projections - U.S. Energy Information Administration (EIA)," 2013). Over the next 15 years, the manufacturing sector is projected to experience robust growth, but it will require improvements in energy efficiency to prevent the energy demand from bloating during this boom ("Annual Energy Outlook 2014," 2014, "World Energy Outlook 2015," 2015). Previous work to address these concerns has focused on developing a range of more energy efficient processes and technologies as well as tools to describe the energy consumption of manufacturing processes (Dornfeld and Wright, 2007), (Duflou et al., 2012), (Fang et al., 2011), (Haapala et al., 2009), (Linke et al., 2013), (Salonitis and Ball, 2013), (Yuan and Dornfeld, 2009). Also, comparisons of energy consumption between different polymer additive manufacturing technologies have been conducted, providing insights for effective resource utilization and allocation (Clemon et al., 2013), (Jeremy Faludi et al., 2015).

A good comparison of energy consumption in several manufacturing processes has been conducted by Yoon *et al*. (Yoon et al., 2014). The authors sought to characterize the energy consumption of bulk forming, subtractive, and additive manufacturing processes using what is called the Specific Energy Consumption (SEC), "defined as the energy consumed in the production of a material unit." For additive and bulk forming processes, the SEC is traditionally defined as Joules per unit mass of material (J/kg) processed and for subtractive processes, it is defined as Joules per unit volume of material removed (J/m^3) (Yoon et al., 2014).

1.2 Additive Manufacturing

One of the technologies with significant growth potential is additive manufacturing. Additive manufacturing is an all-encompassing title for manufacturing processes that build parts in 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 several production systems have been developed commercially (Frazier, 2014). However, the accuracy and surface quality of parts created by these technologies are typically much lower than what is seen in machined parts (Huang et al., 2013). A combination of additive and subtractive manufacturing processes in a system, would remedy this, and help realize the raw material to final product goal of a comprehensive manufacturing system.

1.3 Wire-Based Additive-Subtractive Manufacturing

Gas metal arc welding (GMAW) was developed in the 1950s, and was formerly known as metal inert gas (MIG) welding. The process that 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 (Kou, 2003). Researchers have developed GMAW based additive manufacturing processes and paired them with CNC milling to create a complete additive-subtractive manufacturing system as described in Figure 1, (Song et al., 2005), (Karunakaran et al., 2010). These systems deposit a layer of molten wire across a prescribed geometric area using GMAW and the layer is then face milled. Upon completion of the appropriate layer depositions and face milling cycles, finishing machining is performed to attain the desired final dimensions. Highly accurate parts with low surface roughness, as well as acceptable density could be produced using these processes. The high deposition rates and ease of implementation are advantages of GMAW based additive manufacturing when compared to laser-based processes (Song et al., 2005), (Karunakaran et al., 2010).

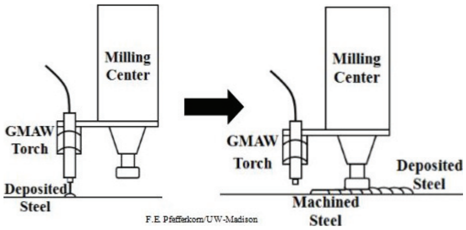

Figure 1. Simplified wire-based additive-subtractive manufacturing process diagram

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*. (Frank Liou et al., 2007). In their machine, called the Laser Aided Manufacturing Process (LAMP), a laser beam creates a melt pool on a surface and powder material is then injected into the molten pool (*i.e.*, LENS process). The deposition follows prescribed scanning paths to create the desired part geometry. Milling operations are then performed to bring the part within dimensional tolerance. It was found that this system was capable of producing parts of surface quality similar to those created in industry through typical machining operations (Frank Liou et al., 2007). A simplified diagram of this process is illustrated in Figure 2.

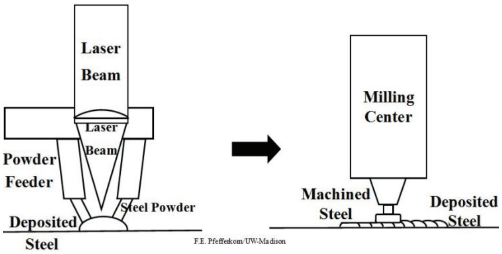

Figure 2. Simplified powder-based additive-subtractive manufacturing process diagram

1.5 Energy Consumption in Additive-Subtractive Manufacturing

Only recently have additive-subtractive manufacturing systems become commercially available and at this time, no literature is available on their energy consumption. However, energy consumption in additive and subtractive manufacturing systems respectively has been studied. A substantial amount of work has been done on the energy consumption of subtractive systems, specifically for milling (Dahmus and Gutowski, 2004), (Diaz et al., 2011), (He et al., 2012), (Kara and Li, 2011), (Li et al., 2013), (Pervaiz et al., 2012), turning (Kara and Li, 2011), (Li et al., 2013), (Mativenga and Rajemi, 2011), (Neugebauer et al., 2011), and drilling operations (He et al., 2012), (Neugebauer et al., 2011). Additive manufacturing has only recently begun to be studied in this regard, with the literature covering both polymer (Baumers et al., 2011a, 2011b), (Bourhis et al., 2013), (Junk and Côté, 2012), (Kellens et al., 2011, 2010a, 2010b), (Luo et al., 1999), (Sreenivasan and Bourell, 2010), and metallic processes (Baumers et al., 2011b, 2010), (Bourhis et al., 2013), (Kellens et al., 2010a), (Morrow et al., 2007), (Unocic and DuPont, 2004).

In subtractive manufacturing, Kara *et al.* have developed a methodology to model energy consumption of machining operations (Kara and Li, 2011). Since the energy consumption of each machine tool is unique to each machine's specific architecture, characterization of several machines' specific Material Removal Rate (MRR) to SEC relationship was performed. They found this relationship can be described mathematically across multiple platforms using the general form in Equation 1:

$$\mathrm{SEC_{machining}} = \mathrm{C_0} + \frac{\mathrm{C_1}}{\mathrm{MRR}} \tag{1}$$

where, $\mathrm{C_0}$ and $\mathrm{C_1}$ are machine specific coefficients and:

$$\mathrm{MRR} = \frac{\mathrm{A_e} \times \mathrm{f}^2}{\mathrm{N} \times \mathrm{RPM}} \tag{2}$$

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.* (Morrow et al., 2007). They found their process to have an SEC of 7.08E+09 J/kg which included the energy of: a 6 kW CO2 laser, a CNC worktable, chillers, powder feeder motors, a computerized control system, and two stress relief treatments that were performed on the tool to prevent it from cracking (Morrow et al., 2007). For the Laser Engineered Net Shaping (LENS) process, another powder-based directed energy deposition technology, it has been found that the maximum melting efficiency is 0.33, and the average energy transfer efficiency is 0.4 (Unocic and DuPont, 2004). Melting efficiency is the efficiency with which energy transferred to the workpiece actually melts the powder to form deposition beads. Energy transfer efficiency is the efficiency of energy transfer from the laser beam source to the irradiated area (Unocic and DuPont, 2004). Energy is also dissipated in the conversion of electrical energy from the wall to a laser beam, and this is called a laser's wall efficiency; for an Nd:YAG laser as used in the LENS process, the wall efficiency has been reported by a laser manufacturer to typically be 0.15 ("Fiber Laser Energy Savings Calculator," n.d.). Unfortunately, at this time there has been no work studying the energy consumption in wire-based additive manufacturing systems.

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. With additive-subtractive technology in its infancy, there are significant opportunities to expand development of these two processes. This paper seeks to understand these technologies from an energy consumption perspective to gain an understanding of how each can contribute to a more sustainable manufacturing landscape.

2 Model Methodology

This work has sought to build a model that performs a cradle to gate analysis of the energy that would be consumed in an additive-subtractive manufacturing system used to produce steel components using wire and powder as the input to the additive part of the process. The entireties of the processes included in this analysis are shown in Figure 3.

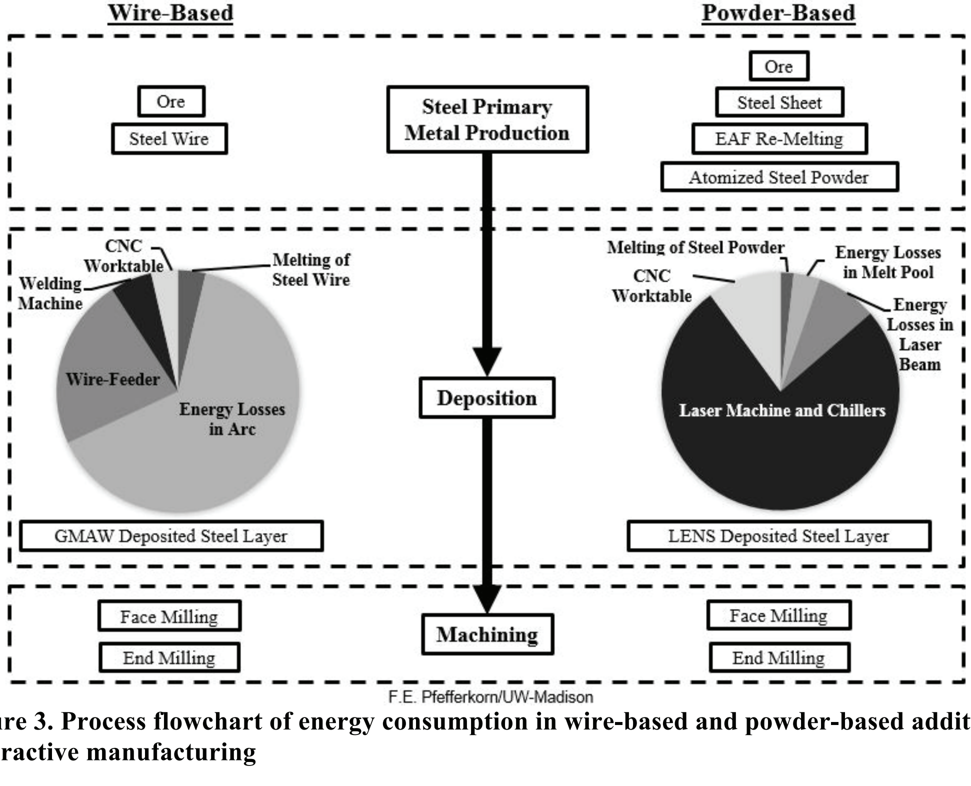

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Figure 3. Process flowchart of energy consumption in wire-based and powder-based additive-subtractive manufacturing

2.1 Wire-Based Energy Consumption

The model attempts to encapsulate the total amount of energy that went into a resulting volume. Therefore, the amount of energy that was consumed in the creation of the wire that was deposited must be considered. This was calculated using a well-established SEC from "The Energy Cost of Automobiles" (Berry and Fels, 1973). The SEC to produce steel wire from ore is 7.11E+07 J/kg; this SEC can be multiplied by the mass of the deposited material to find the overall energy consumption in wire production (Berry and Fels, 1973).

Estimation of the energy consumption in GMAW deposition was enabled through a study of a manual GMAW machine, where the energy consumption was measured during idle, wire feeding, and deposition phases of 5 different welding parameters. This allowed for the contributions of separate components of the total energy consumption to be distinguished. Also, the range of welding parameters allows for an average energy consumption of the deposition process to be estimated. Five different bead on plate depositions were made as summarized in Table 1 and the energy consumption was measured using a power and energy monitor (Fluke 435 Power Quality and Energy Analyzer) with a 4 Hz sampling frequency. The mass of the plate was measured before and after the bead on plate depositions. During testing, the machine was allowed to idle for 60s to reach steady state. Wire feeds were performed by holding down the trigger for approximately 5s while the welding gun was away from the deposition plate, allowing for the basic energy of the wire feeding mechanism to be quantified. Depositions, shown in Figure 4, were then performed.

To construct the model, the overall energy consumption of the 5 depositions was divided by the total mass deposited to give the SEC for wire-based deposition. The contributions of each component of the deposition process was then derived from this. The theoretical melt energy SEC was calculated using Equation 3:

$$\mathrm{SEC_{Melt}} = c_p(T_{melt} - T_{room}) + L_{fusion} \tag{3}$$

where c_p is the specific heat for low carbon steel which has a value of 620 J/kg-K, T_{melt}, the melting point of steel, is 1815 K, the temperature of the room during deposition, T_{room}, is 297 K, and the latent heat of fusion for low carbon steel, L_{fusion}, is 2.47E+05 J/kg.

The contribution of the welding machine itself was determined by finding the average base load of the welder and multiplying it by the total time deposition occurred. The wire feeding system's contribution was determined by averaging the energy during the feeding-only phases and assuming the averages to be a component of the deposition unique to their corresponding parameters. These unique components were then averaged and multiplied by the total time deposition occurred. Finally, the remaining energy unaccounted for by the above factors was quantified as the arc contribution. While called the arc contribution, this value encapsulates any energy that goes towards heating or melting of the deposition plate, as well as energy into the melt pool that raises the temperature above T_{melt}, and not simply the losses in energy within the arc. Transforming all these contributions into an SEC for the process was done by matching the energy consumed to the mass deposited during the study, yielding the energy consumption breakdown for the deposition process summarized in Table 1.

The welding in this study was done with a hand triggered welding torch and the travel was controlled by a simple rail guided torch holder. Since the goal of the model is to estimate the energy consumption of an automated process, this method best simulated the physical behavior of an actual automated process. However, such a simple device does not represent the contribution the automated travel of the welding torch will make as part of an integrated additive-subtractive manufacturing machine tool with respect to energy consumption, and instead, the contribution of a CNC table serves as a better model. Therefore, during the machining characterization for this model, the feed energy of the CNC vertical milling machine was monitored in the same manner as the deposition study. A measurement of power load of 8 different table feeds was made and averaged. Since the values did not vary widely, this average gives a good approximation of what a CNC worktable would contribute to the overall energy consumption if the deposition process took place as part of an integrated additive-subtractive system. It was assumed that this load applied across each deposition travel and adding this contribution to the total for GMAW deposition allows for the CNC worktable energy consumption to be captured in the model. The SEC for the CNC worktable is also found in Table 1.

Table 1. Parameters used in GMAW deposition study and energy distribution

GMAW Deposition study (A36 deposition plate)		Energy Consumption Factors	SEC (J/kg)
Machine	Miller Electric Millermatic 252 MIG Welder	Theoretical Melt Energy	1.19E+06
Wire Type	L-56 wire from Lincoln Electric	Arc Contribution	2.08E+07
Wire Diameter	0.89 mm	Wire-Feed Contribution	7.37E+06
Shielding Gas	75% Argon & 25% Carbon Dioxide	Machine Contribution	1.80E+06
Wire Feed Speeds	2.9, 4.1, 5.6, 7.6, 8.6 m/min	CNC Worktable	1.15E+06
Voltage Settings	16, 17, 18, 19, 20 V		
Mass Deposited	0.0748 kg		
Deposition Energy	2.33E+6 J	Total for GMAW Deposition	3.23E+07

The energy estimation in the model for the milling operation in both wire-based and powder-based process paths is based on the machining parameters required for a net shape to be reached after deposition. The model proposed by Kara et al. (Kara and Li, 2011), utilizing Equations 1 and 2 was implemented for the subtractive component. A full factorial experiment at two levels and 3 factors was employed to determine the coefficients in this equation for the in-house vertical milling center (HAAS TM-1 built in 2004). In the model, MRR is the key process variable, but MRR is dependent on several factors including workpiece material, machine tool capabilities, cutting speed, feed, and working engagement. Therefore, cutting speeds, feeds, and work engagements were chosen for 2 different materials, A36 and 6061-T6, with two levels of variance, for a factorial study; each condition was performed twice. Equipment and operating parameters for this characterization are summarized in Table 2. In total, 32, 40 mm long, slot milling cuts were made while the energy consumption was monitored. From the volume of material removed and energy consumption during cutting data, the SEC was calculated. Based on the findings in this study, as seen in **Error! Reference source not found.**, the MRR to SEC relationship was characterized and the energy consumption of the CNC mill can be modeled using Equation 4

$$\mathrm{SEC}_{\mathrm{machining}} = 187.73 + \frac{0.0002}{\mathrm{MRR}} \quad \textbf{(4)}$$

In Equation 4, SEC is in terms of kJ/cm^3 and MRR is in terms of cm^3/s. Once the SEC is determined by the equation, it is converted into J/kg for implementation in the model. Performing this conversion allows direct comparisons to the other components of energy consumption within the model. It is important to note that this SEC only captures energy consumed during the processing period (Kara and Li, 2011).

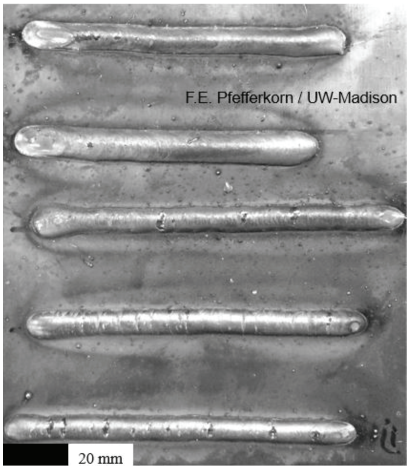


Figure 4. GMAW deposition beads

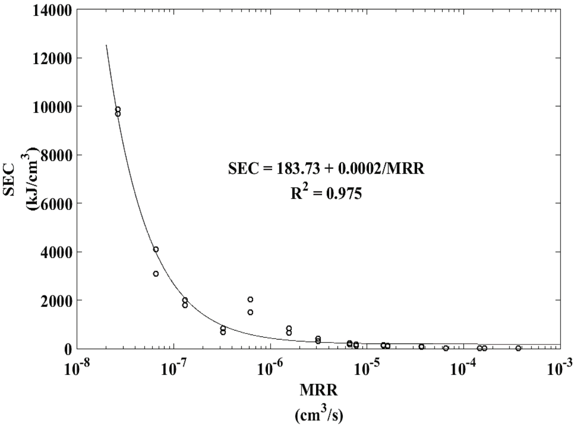


Figure 5. Data and summary of HAAS TM-1 machining energy characterization tests

Table 2. Parameters used in machining study

CNC Milling Machine SEC Characterization		
Machine	HAAS TM-1 3-axis Vertical CNC Mill (Built in 2004)	
Rated Spindle Power	5.6 kW	
Workpiece Material	A36	6061-T6
Tool Diameter	12.7 mm	
Work Engagement (A_e)	A36: 0.1, 0.5 mm	6061-T6: 0.2, 2 mm
RPM	A36: 153, 380	6061-T6: 764, 1910
Feed (f)	A36: .005, .064 mm/tooth	6061-T6: 0.025, 0.038 mm/tooth
Number of Teeth (N)	4	

2.2 Powder-Based Energy Consumption

The first energy contribution for the current energy model comes from the primary metal production of the raw material: *i.e.*, the creation of the powder that is ultimately deposited. This calculation is a three part process modeling an indirect method of powder production. 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.

To calculate the overall SEC, the SEC for several primary metal manufacturing steps were obtained from literature. First, the transformation of ore to steel sheet was averaged from the six values listed in the Handbook of Industrial Energy Analysis to give 5.08E+07 J/kg (Dealy, 1980). Second, the SEC for Electric Arc Furnace melting of the steel plate was taken from the Energy and Environmental Profile of the U.S. Iron and Steel Industry – 1999; all the energy that goes into this melting process is considered and this process was found to consume energy at 6.05E+06 J/kg ("Energy and Environmental Profile of the U.S. Iron and Steel Industry," 2000). Finally, the atomization process from which the powder is formed, is assigned an SEC of 7.00E+04 J/kg; this comes from the Atomization of Melts for Powder Production and Spray Deposition book, and is specifically for iron atomized by water, but for the purposes of this estimation, this value is assumed to be sufficient (Yule, 1994). Summed, these individual SEC values yield the total SEC for powder creation: 5.61E+07 J/kg. And as with the wire-based process path, the mass of the material deposited is multiplied by this SEC to find the energy consumption in the creation of the raw material.

Estimation for the LENS Deposition Energy is based on process efficiencies found in the literature. The first step in estimating the energy consumption of the LENS process was to use Equation 3 to calculate the energy required to melt the deposited mass. Then, using a melting efficiency value of 0.33, which assumes maximum melting efficiency, the amount of energy transferred to the deposition plate and powder was calculated. Dividing this value by the energy transfer efficiency of 0.44 accounts for the energy lost as the beam energy transfers to the irradiated area. Finally, this value is further divided by the wall efficiency of 0.15, yielding the amount of energy a LENS laser would consume.

As with the GMAW deposition portion of the model, since the LENS deposition is modeled as part of an integrated additive-subtractive manufacturing device, this laser would be mounted on a CNC worktable and include a computerized control system. Assuming the power requirements for these components are equivalent to the basic power of a CNC milling machine, which performs the same basic functions, an additional energy consumption value can be added to the overall system. For the model, this SEC is assumed to be 5 times the SEC for GMAW deposition since the literature suggests about 5 passes in LENS are required to build up the amount of material deposited in one pass by GMAW deposition (Manvatkar et al., 2015). Table 3 summarizes all the contributions to the overall LENS deposition SEC.

It is important to note that the specific cutting energy will be different in machining the powder-based deposition due to different material properties compared to the wire-based deposition (Boothroyd and Knight, 2006). Specifically, parts of mild steel made with wire-based technologies have been reported to have ultimate tensile strengths of 620 MPa, whereas those manufactured through LENS, a powder-based additive technology, are reported to have tensile strengths of 790 MPa (Song et al., 2005). At this time, the model for SEC during machining only considers the MRR. The MRR is reliant on the components of the machining parameters as discussed previously. It is also known that recommended speeds and feeds for the same type of material (*e.g.*, mild steel, aluminum, plastic) fall within a reasonably similar range. This model assumes that while the material properties produced by wire-based and powder-based deposition are different, since they are the same type of material, *i.e.*, steel, identical speeds and feeds can be used for machining in the wire-based and powder-based processes.

Table 3. LENS deposition SEC distribution

Energy Consumption Factor	SEC (J/kg)
Theoretical Melt Energy	1.19E+06
Melt Efficiency Contribution	2.42E+06
Laser Energy Transfer Efficiency Contribution	5.51E+06
Machine and Chillers Contribution	5.11E+07
CNC Worktable	6.70E+06
Total for LENS Deposition	6.69E+07

3 Case Study Comparison

In order to compare the energy consumption between the two process paths, a case study was performed using the SEC values presented in the model. The case study investigates the energy consumed to produce a small volume of steel with the dimensions: 100 mm x 100 mm x 1.5 mm. The overall process of this case study is: first a mass of additively deposited material is defined for both wire and powder-based processes. Then, energy needed to produce (primary metal production) and deposit this mass is calculated for both process paths using SECs developed in the model. Next, the energy of machining the deposition to the specified dimensions in both process paths is calculated. All these values are combined for each process and the overall energy consumption is compared. The objective of this case study is to make a direct comparison of the energy consumption in wire-based and powder-based additive-subtractive manufacturing.

3.1 Deposition Geometry Study

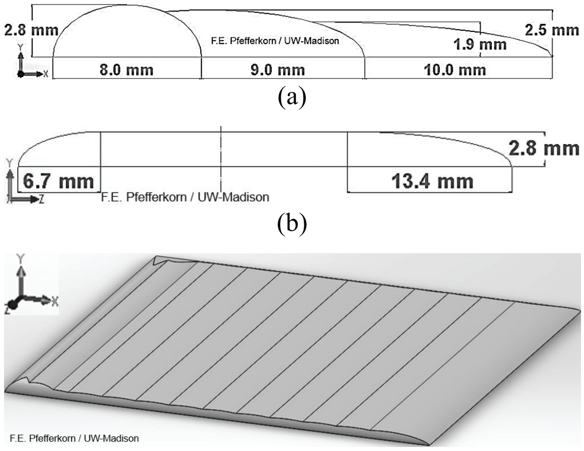
When depositing material in both wire-based and powder-based additive-subtractive manufacturing, the resolution is low compared to the desired net shape. Therefore, in order to achieve a desired geometry, an excess of material must be deposited. A subtractive operation is then performed to remove this excess material and achieve the correct geometry.

A study of GMAW deposition bead geometry was undertaken to determine how much material would need to be deposited and subsequently removed for the layer prescribed for the case study. Key geometric measurements were taken of 5 different welding conditions using a white light focus variation metrology system (Alicona InfiniteFocus) to find an average deposition geometry for a single bead. Then, overlapped beads were studied because when depositing a layer, beads are overlapped to improve the density of the layer. In this study a 7 mm step over was used during deposition of overlapped beads. First, two overlapped beads were measured at different points along the bead path to find an average decrease in height from the first bead to the second, as well as the width of the two beads. Then, 3 overlapped beads were measured and the same key geometric factors where characterized for the third bead. It was found that after three beads, an equilibrium geometry was reached with subsequent beads exhibiting no distinguishable differences; a cross section of the resulting bead geometry can be seen in Figure 6a. Finally, at the beginning and end of the beads, there is a slope of material from the deposition plate to the top of the bead. This slope was characterized by averages of the same 5 beads examined in the single bead deposition study and Figure 6b shows a simplified profile of the slope.

For the LENS deposition, literature was found describing the geometry of steel deposition beads (Manvatkar et al., 2015). It was found that beads deposited through LENS have significantly smaller geometries than found in GMAW deposition, which means the initial deposition is able to come 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 as well mass removed during machining.

The laser beam diameter in the study by Manvatkar *et al.* [45] was 0.9 mm and the geometry of steel deposition beads were studied as the power and scan speed were varied. It was found in the paper that decreasing the scanning speed and increasing the power would increase the bead width respectively, but similar to the wire-based deposition geometry determination, this case study seeks to estimate a generalized geometry. It is important to keep in mind that depending on the laser processing parameters, the resulting bead geometry may change, and in this case study, a simplified geometry is used to determine energy consumption along the path. Therefore, to account for the broad range of possible bead geometries, an average of all the geometries from the study was taken and then simplified so that 5 stacked beads had a rectangular cross section as described in Figure 7a (Manvatkar et al., 2015). Unlike in the GMAW bead geometry, the behavior of overlapped beads was not assessed and the simplified geometry was extrapolated into a square area. The dimensions of the entire deposited area are shown in Figure 7b and were determined by assuming at least a bead width was required to be removed from all 4 sides of the layer; this was done to account for a reasonable error range in extrapolating the bead geometry.

CAD models were created for the GMAW deposition layer, as seen in **Error! Reference source not found.**c, and the LENS deposition layer, Figure 7b. This allows the mass of the layers to be directly determined by the software, as well as the mass of material that is required to be removed during machining to reach the desired layer dimensions of the case study. For the wire-based process, the mass of the deposition was found to be 0.187 kg and 0.070 kg of material was removed. In the powder-based process, 0.170 kg was deposited and the mass removed during machining was 0.053 kg. These masses were then applied to the SEC for each process in the wire-based and powder-based paths as discussed in previous sections of this paper.

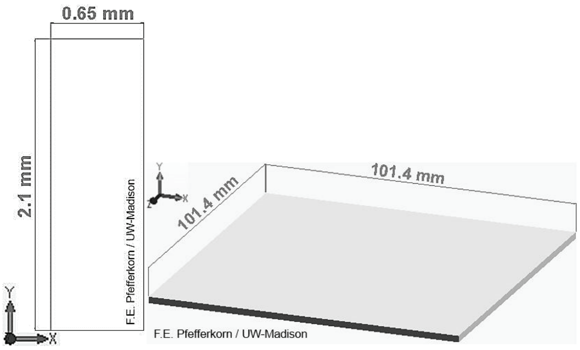


(a)

(b)

(c)

Figure 6. GMAW deposition bead geometry diagrams: (a) cross section of 3 initial beads (b) side profile across bead length (c) CAD model of deposition layer



(a) (b)

Figure 7. Diagrams of LENS deposition geometry: (a) cross section of 5 stacked beads (b) CAD model of deposition layer

3.2 Primary Metal Production and Deposition

In the wire-based process path of this case study, the energy required to produce the mass deposited is accounted for by multiplying the aforementioned SEC for wire creation, 7.11E+07 J/kg, by the mass that was deposited in GMAW deposition, 0.187 kg. The energy consumed in deposition was calculated by multiplying this mass by the SEC for GMAW deposition, 3.23E+07 J/kg. The powder-based path of this case study also determines the energy required to produce the deposited powder, multiplying the mass deposited, 0.170 kg, by the SEC for powder production, 5.61E+6 J/kg. The deposition energy was then determined by calculating the same mass deposited by the SEC for LENS deposition, 6.11E+07 J/kg.

3.3 Machining Parameters

Due to the direct impact of machining parameters on SEC, specific machining parameters were chosen for this case study and are summarized in Table 4. The RPM and feed rate are the general recommendations by the tool's manufacturer for milling steel. As previously discussed, it is assumed in this case study that the composition of the powder-based material is similar enough for the speeds and feeds not to be different when machining the two metals. However, for machining the powder-based deposition, a smaller amount of material is required to be removed and therefore the work engagement is smaller than for the wire-based process. Since work engagement is a component of the MRR, the two machining operations will respectively have different MRR values as summarized in Table 4. Finally, an additional simplification in this calculation is that while there are actually two separate types of milling operations occurring, one is face milling and the other is end milling, it assumed that for both operations, the machining parameters and corresponding MRR will be the same for both operations within the respective process paths.

To determine the energy consumption in machining the wire-based deposition, the SEC was 2.35E+07 J/kg, which was multiplied by the mass of material removed, 0.070 kg. The energy consumption for machining the powder-based deposition was calculated by multiplying that process' SEC, 2.38E+07 J/kg, by mass removed, 0.053 kg.

Table 4. Summary of case study inputs and parameters

	Powder-Based	Wire-Based
Primary Metal Production		
SEC	5.69E+07 J/kg	7.11E+07 J/kg
Deposition		
Machine Type	LENS	GMAW Welder
SEC	6.69E+07 J/kg	3.23E+07 J/kg
Machining		
Machine	HAAS TM-1 3-axis Vertical CNC Mill	
Rated Spindle Power	5.6 kW	
Tool Diameter	12.7 mm	
Work Engagement (A_e)	0.16 mm	0.55 mm
RPM	1528	
Feed (f)	0.06 mm/tooth	
Number of Teeth (N)	4	
MRR	6.57E-05 cm^3/s	2.61E-04 cm^3/s
Machining SEC	2.38E+07 J/kg	2.35E+07 J/kg
Mass Machined	0.053 kg	0.070 kg

3.4 Results and Discussion

Overall, the energy consumption in the wire-based process path was estimated to be similar to the powder-based path as can be seen in Figure 8. This work relies on SEC's from literature that did not report uncertainty, and thus preclude the possibility of a direct uncertainty analysis. Also, it is generally accepted that embedded energy values may vary depending on the reference chosen, but those cited in this study are an effort to provide an appropriate framework for assessing the differences between the two processes. Therefore, the 5% difference between the total energy consumption of the two process paths in this case study is considered an indistinguishable result. Further refinement of the model and case study variables may identify more differences between the process paths. The major components of the case study and their respective values are listed in Table 5 and illustrated in Figure 9.

Table 5. Summary of case study energy consumption results

	Powder-Based	Wire-Based
Primary Metal Production	9.68E+06 J	1.33E+07 J
Deposition	1.12E+07 J	6.04E+06 J
Machining	1.26E+06 J	1.65E+06 J
Total Energy Consumption	2.21E+07 J	2.10E+07 J

Primary metal production is a large component of total energy consumption in both process paths. It can also be seen that the energy consumption of powder production and wire production are relatively close with powder production consuming less energy. The SEC values that determine this result are pulled directly from the literature, however novel wire making processes such as friction stir extrusion, which creates wire from metal chips while staying below the material's melting point, could offer energy savings to the wire production process; especially if a remanufacturing process were to be employed.

The key finding of the case study is that even though less powder is deposited compared to the wire deposition, the powder deposition energy consumption is still greater than for wire deposition by 85%. In Figure 9, it is clear that the greatest difference between the two processes paths is in the deposition component and that from an energy consumption perspective, wire-based deposition is preferred to powder-based. Referring back to the energy consumption factors outlined in Table 1 and Table 3, the energy required to operate the laser (in the powder-based deposition process) by itself is greater than the entire energy consumption of wire-based deposition. However, the lower energy consumption in GMAW deposition cannot be fully capitalized until lower energy methods of producing wire are employed.

Also, it is worth noting that the energy consumption of machining after wire-based deposition is slightly higher than after the powder-based deposition. This is due to the better resolution that can be achieved by the powder-based method; it can come closer to the final dimension during the additive step, thus less machining is required. Advances in deposition resolution for both processes that do not cause a corresponding increase in energy load would reduce the amount of material that must be removed to reach net shape, reducing machining energy consumption and therefore total process energy consumption. This is a valuable area of further research in both process paths.

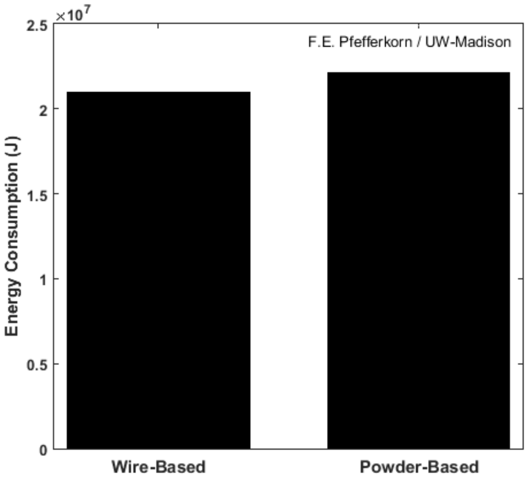


Figure 8. Wire-based (WB) and powder-based (PB) total energy consumption

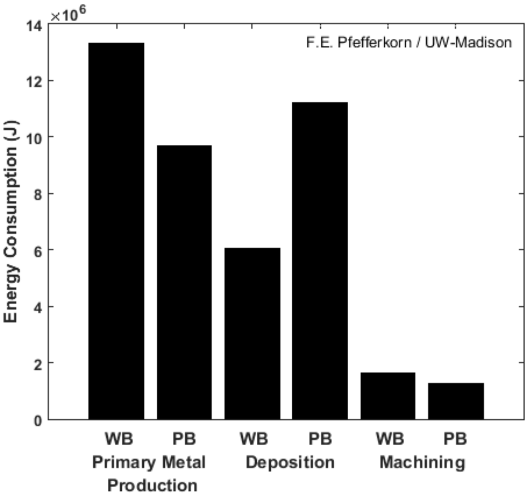


Figure 9. Energy consumption breakdown: wire-based (WB) and powder-based (PB)

4 Conclusions

A model was created to estimate the energy consumption from cradle to gate in wire-based and powder-based additive-subtractive manufacturing processes. The model relied on published SEC values for primary metal production of wire and powder. Deposition process components from the literature and experimentation were utilized to find SEC values for deposition. The SEC of a CNC milling machine was characterized according to published methodology and implemented into the model's accounting for subtractive processing. A case study was conducted using the model's framework to compare the energy consumption between wire-based and powder-based additive-subtractive manufacturing of a 100 mm x 100 mm x 1.5 mm volume. It was discovered that the overall energy consumed in the wire-based and powder-based process paths are similar. While the energy consumption of wire production is greater than for powder, the wire deposition component consumes 85% less than powder-based deposition. This large difference is of great interest moving forward as additive deposition techniques are developed with more consideration for energy consumption. Machining energy in both process paths consumed similar amounts of energy.

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