Assessing Energy Requirements and Material Flows of Selective Laser Sintering of Nylon Parts

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ABSTRACT

Selective laser sintering (SLS) is a prominent technology for rapid manufacturing (RM) of functional parts. SLS and competitive RM technologies are generally assumed to be more environmentally sustainable than conventional manufacturing methods because the additive process minimizes tooling, material waste, and chemical fluids. A thorough life cycle analysis (LCA) of the environmental impacts of SLS has yet to be published. This study focuses on a section of the SLS part life-cycle. It tracks the nylon powder material flows from the extraction and synthesis of the material to SLS part production. Basic material properties and environmental effects are reported. Estimates of material waste and energy use are also reported and compared with those of injection molding.

MOTIVATION

SLS is a laser-based, additive manufacturing method for creating functional parts. Parts are built from a CAD model, layer-by-layer. The part is built inside a powder bed, and most of this powder can be reused in subsequent builds. The SFF community has identified multiple sustainable advantages of SLS [1]. For example, SLS and other SFF machines reduce transportation and supply chain impacts, as designs can be sent to machines via CAD files and produced on the spot with no special tooling. Quantitative support for many of these hypotheses is not publicly available, and many environmental metrics, such as material waste, toxicity, and process energy use, are not well-known [2]. A 2009 NSF-sponsored workshop identified multiple research needs relating to sustainability, including material performance data and measures of process sustainability in comparison with other manufacturing methods [1]. The research presented in this paper contributes to these needs by providing estimates of the nylon material waste and energy use of SLS in comparison with injection molding (IM).

These estimates will contribute to broader life cycle inventories (LCIs) of SLS and a better understanding of how SLS compares with alternative manufacturing processes. An LCI is an important part of life cycle analysis (LCA), an accepted method for quantifying the environmental impacts of a product or process throughout its life cycle, starting with the procurement of materials and ending with the return of materials to the environment or processing plant [3]. LCI data report energy and material inputs and air, water, and soil emissions and solid waste outputs for each process within the life cycle.

In this research nylon and energy LCI data are collected and interpreted for two stages of a part life cycle: material refining and part manufacture. The energy required to create nylon was included in this study to better evaluate the cost of material waste in the SLS and IM manufacturing processes. Additionally, the energy requirements of SLS and IM manufacturing processes were considered. A full LCI would include additional aspects of these processes, such as chemical inputs and emissions.

SCOPE

A few studies provide data on material and energy use during SLS, but the data are too few to calculate SLS impacts with any certainty. The scope of this research was limited to the available literature and interviews with local service bureaus. Calculations were performed for a section of the SLS part life-cycle; specifically, nylon powder material and energy flows were tracked from the production of the material through SLS part production. Other life cycle stages were not considered. As injection molding (IM) is the biggest competitor for nylon parts, a similar study was performed for IM, and energy values were compared. Metal SLS parts, which are believed to be more sustainable [1], were not considered.

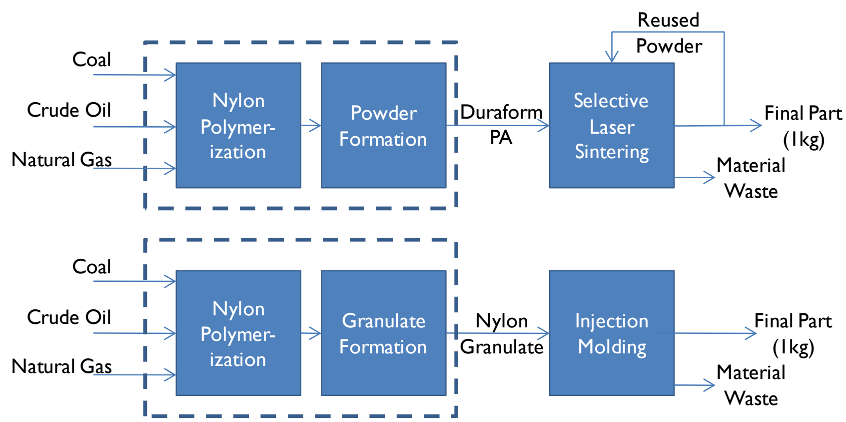

Figure 1: Process Diagrams and Scope of This Study

Figure 1 depicts the gate to gate process being studied. Important parameters are the material yields of the IM and SLS processes and the powder formation process. Electricity is not shown in the flowchart, but was estimated for all processes as well. The following sub-sections describe each of the processes and their possible environmental impacts. These process descriptions are followed by a synthesis of the material and energy use quantities from the literature and a calculation comparing IM and SLS yields.

PROCESS DESCRIPTIONS AND PARAMETERS

Nylon

Nylons, or polyamides (PA), are manufactured from feedstocks of coal, crude oil, and natural gas. Nylon 6-6 and Nylon 6 are the most common types of PA for IM, but Nylon 12 is most commonly used in SLS. Nylon 6 is created from a single monomer, caprolactam. The carpolactam is most commonly created using a hydrolytic polymerization process, described in Kirk-Othmer [4], using a series of products such as benzene and phenol, that are created from coal, crude oil, and natural gas feedstocks. The creation of laurolactam, the monomer used for nylon 12, is similar to that of caprolactam.

The Plastics Europe [5,6] life-cycle inventories for nylon 6 granulate production were used to approximate the energy embodied in a kilogram of nylon 12. Embodied energy is the energy required to produce a product and differs from the energy content of that product. The available data did not distinguish between fossil fuels used as feedstock for the monomer and fossil fuels used as energy for processing the feedstock. To determine the value of the fossil fuel energy, it was assumed that nylon 12 and its fossil fuel feedstocks contained equivalent amounts of carbon, and that every kilogram of nylon 12 required 0.7 kg of carbon in its fossil fuel feedstock. The remaining mass of fossil fuel inputs were thus assumed to be burned during nylon refining.The final estimate for energy use during nylon manufacture was approximated as 85 MJ per kilogram of nylon produced, using a mix of electricity (5.5 MJ/kg) and the energy stored in fossil fuels (79.5 MJ/kg). Output data suggest that material waste from nylon production is much less than one percent and therefore negligible. This assumption is supported by Kirk-Othmer's discussion of environmental aspects of nylon processing [4].

As depicted in Figure 1, the forms of nylon feedstock used in IM and SLS differ. IM uses nylon granulate, and SLS uses a commercial nylon 12 powder that is created using a precipitation process. As described in US Patent 4,334,056, a mixture of polymerized lauryllactam and caprolactam are dissolved in ethanol, reacted, and crystallized with a temperature- and pressure-controlled process [7,8]. Duraform PA, a common nylon 12 powder used in SLS, contains particles that range in size from 25-92 microns for reliable sintering. The patent suggests that only 2% of particles yielded by this process are outside of the acceptable size range. The patents were not used to estimate the energy use of nylon powder production because industrial systems are generally more efficient than single experiments. It is possible that the value is similar to that of metal powder; creation of metal powder is reported to be about 1MJ/kg [9]. Without energy data for nylon powder production, it was assumed that the 85 MJ/kg value included the creation of granulate and powder (i.e. as the dashed boundary in Figure 1.)

Although nylon production has harmful environmental releases such as nitrogen compounds, nylon itself is not considered a harmful material. With the exception of additives, nylons pose no significant health risks. There may be hazards from heating the monomer; the MSDS sheet for Duraform PA, a commonly used nylon 12 powder, in Appendix A, indicates that the powder should not be heated above 340 Celsius or combined with acids and oxidizing agents. Nylon does not, currently, biodegrade; methods for reformulating nylon to assist degrading organisms have been successful, but not economical [4]. Recycling of nylon is not yet economically viable, as reprocessing often degrades the material. SLS nylon powders slowly experience this thermal degradation as well and are not infinitely reusable in most commercially available forms.

Selective Laser Sintering

SLS, shown in Figure 2, builds parts directly from CAD files using a high-powered laser and a bed of material, usually nylon 12, in powder form. Referring to Figure 2, the SLS machine starts by heating the powder to near melting point. A roller spreads a thin layer of the powder from the delivery bin across the fabrication bed. The laser sinters the layer selectively to match the CAD file's cross-section. The layer-based sintering process continues until the part build is completed. Un-sintered powders provide support for the sintered parts. After the build finishes, the bed is cooled, and the part is removed. Excess powder, or part cake, is separated from the finished parts and reused.

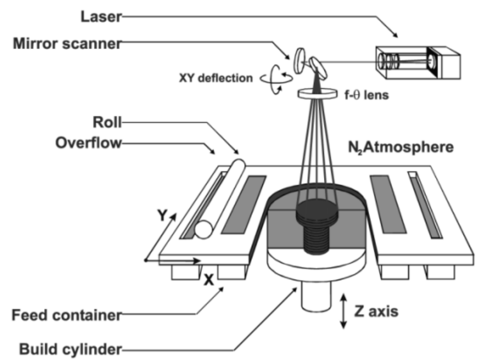

Figure 2: Selective Laser Sintering Machine Schematic [10]

In theory the powder bed, or support, can be entirely reused, but best practice requires that each part bed contain a fraction of virgin material. As mentioned in the previous section, the powders degrade from repeated heating and cooling. For Duraform PA, the manufacturer recommends a 30% virgin mix [11]. Specialized nylon powders, such as glass-filled nylon, might require a mix of 40% virgin powder.

The quantity of powder wasted by SLS operations is not clear. Dotchev and Yussof [11] report an average build density of 12.68% by weight; for every 100kg of powder that experience the thermal SLS process, only 12.68 kg of part are created on average. They tested ten different builds and recorded a range of powder utilization rates from 3-30%. From these experiments they reported that 80-90% of the powder can be reused.

These estimates of material waste were compared with those of a major service bureau. The service bureau reported a 10-15% build density with 10% of part cake (8.5% of total build) lost during the breakout process [12]. The service bureau also estimated that its operations scrap about 40% of excess powder, but that other shops might vary from 1-75%.

A numerical model was used to analyze powder utilization for ten consecutive builds and determine a possible range of yields. Parameters from both sources were tested with 10% loss of part cake and an idealized build density of 28%. These calculations indicated that up to 44% of the material that enters the SLS process might be wasted and that SLS has a likely range of yields from 56-80%.

In addition to powder utilization, it is important to account for energy utilization in the SLS process. Four studies [13-16] exist that report similar power draws, but different specific energy consumptions for the production of SLS nylon parts. The studies measured power draws ranging from three to twelve kilowatts while operating the EOS EOSINT P760, EOSINT M250 Xtend, SLS Vanguard HiQ+HS, and DTM Sinterstation 2500. Specific energy consumption estimates by these sources ranged from 52 MJ/kg to greater than 140 MJ/kg. This energy range stems partly from variations in build density and height. Mognol *et al.* [14] built the same part in multiple orientations and found that difference in build height corresponded to a range of 115-187 MJ. The energy values and build heights reported were not proportional, but the delay required to prepare each layer significantly increased the time and energy required to build the part [14]. It is difficult to prescribe a specific energy consumption constant for SLS, because of the variance in build density and height. Sreenivasan *et al.* [15] reported values that suggest 52.2 MJ/kg can be expected for a realistic part build, and this value was used for the purposes of this paper.

Injection Molding

Injection molding is a common process for producing parts from thermoplastics. The thermoplastic is fed through a hopper into a heated barrel, where it is fed through a nozzle into the cavity of a mold. Pressure is maintained as the material is cooled. After the set cooling time is reached, the finished mold is ejected.

Material waste and part rejects can be a problem for some IM operations. According to the PlasticsEurope data sets in SimaPro and GaBi, IM incurs only a 0.5-0.6% material loss [5,6]. Nevertheless, Olmstead cites a "standard reject rate" of 5% [17]. Michaeli and Greif [18] cite that waste content of material can be 5-50%, presumably by weight. Waste varies by shop and is created during machine start-up, purging, and maintenance. Most IM material can be reused, but the average material loss from these processes is not clear. For this study, a range of material losses, from 1-50% were tested. Energy use for the process was assumed to be 9.9 MJ/kg based on the Plastics Europe databases [5,6]. It is important to note that this value is lower than the averages, 12-19 MJ/kg, reported by Thieriez and Gutowski [19], who utilized environmental impact data from over 100 sources for electrical, hybrid, and hydraulic IM machines. Nevertheless, the Plastics Europe database is a common source for life cycle analysis data regarding refining and manufacture of plastics.

ENERGY AND MATERIAL USE OF SLS AND IM

Energy and material waste estimates were used to compare the efficiency of SLS with IM. Three types of variables were collected. The process characterization, *k*, describes the amount of energy expended in megajoules per kilogram of product output. The variable, *W*, indicates mass. The process characterization, *Y* or yield, indicates the ratio of mass of final product to material feedstock entering the process. The values of these variables are defined in Table 1.

Table 1: Process Characterization Values

Specific Energy Consumption (MJ/kg)			Yield (output/input)			Part Weight (kg)
Nylon	SLS	IM	Powder	SLS	IM	All
k_{Nylon}	k_{SLS}	k_{IM}	Y_{powder}	Y_{SLS}	Y_{IM}	W_{part}
85	52.2	9.9	0.98	0.56-0.8	0.5-0.99	1

Two equations were used to calculate the specific energy embodied in an SLS or IM part. Equations 1 and 2 define the energy required to create a part from IM and SLS, respectively. Both equations are the sums of the energy to make the part during the injection molding process and the energy to make the feedstock entering that process. Equation 2 for SLS includes an additional yield variable for SLS powder production.

$$\boldsymbol{E_{IM} = k_{Nylon} \times \left[\frac{W_{part}}{Y_{IM}}\right] + k_{IM} \times W_{part} \quad (1)}$$

$$\boldsymbol{E_{SLS} = k_{Nylon} \times \left[\frac{W_{part}}{Y_{powder} \times Y_{SLS}}\right] + k_{SLS} \times W_{part} \quad (2)}$$

Because yields for the SLS and IM processes vary, a range of possible yields were tested. For a range of possible IM yields, the SLS yields that consumed an identical amount of energy were calculated by equating equations 1 and 2, as follows in equation 3:

$$Y_{SLS} = \frac{k_{Nylon} \times W_{part}}{\left[E_{IM} - \left(k_{SLS} \times W_{part}\right)\right] \times Y_{powder}} \quad (3)$$

Sample Calculation: $$Y_{SLS} = \frac{\left[\left[85\frac{\text{MJ}}{\text{kg}} \times \left[\frac{1\text{ kg}}{0.5}\right] + 9.3\text{ MJ/kg} \times 1\text{ kg}\right] - (52.2\text{ MJ/kg} \times 1\text{ kg})\right] \times 0.98}{85\frac{\text{MJ}}{\text{kg}} \times 1\text{ kg}} = \mathbf{0.68} \quad (4)$$

Equation 4 is a sample calculation, based on Equation 3, using the baseline data recorded in Table 1. The yield for IM is assumed to be the worst case scenario, 50%, in this calculation. Using these values and energy equations, it is expected that an SLS process meet a yield of 68% to be competitive with IM from an energy standpoint.

The plot in Figure 3 illustrates a number of yields calculated using equation 3. The darker shaded region encompasses the range of possible IM yields, 50-99%. The lighter region encompasses the range of possible SLS yields, 60-80%. Because of the high energy use of the SLS process, five times the energy use of IM, the SLS process is rarely competitive. The feasible range of values requires that IM have a yield below 60% to be competitive with SLS. Even if SLS powder were infinitely recyclable (with a yield rate near 1), SLS cannot compete with the standard reject rate of 5% for IM.

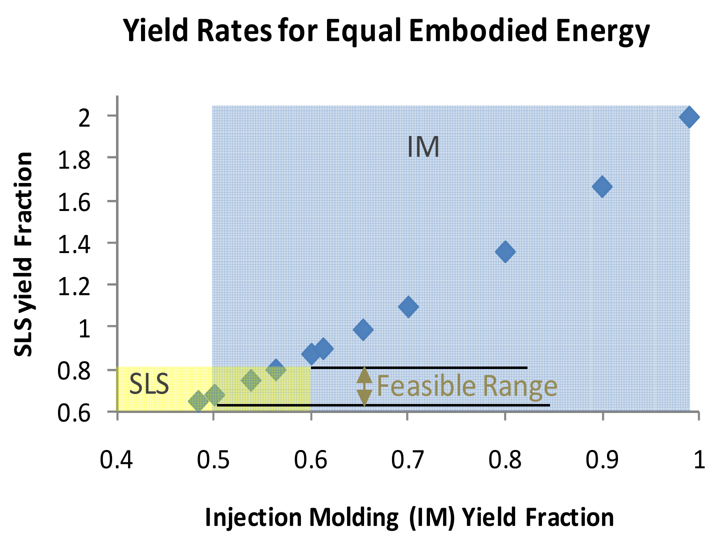

Figure 3: SLS is Only Competitive with Inefficient IM Operations

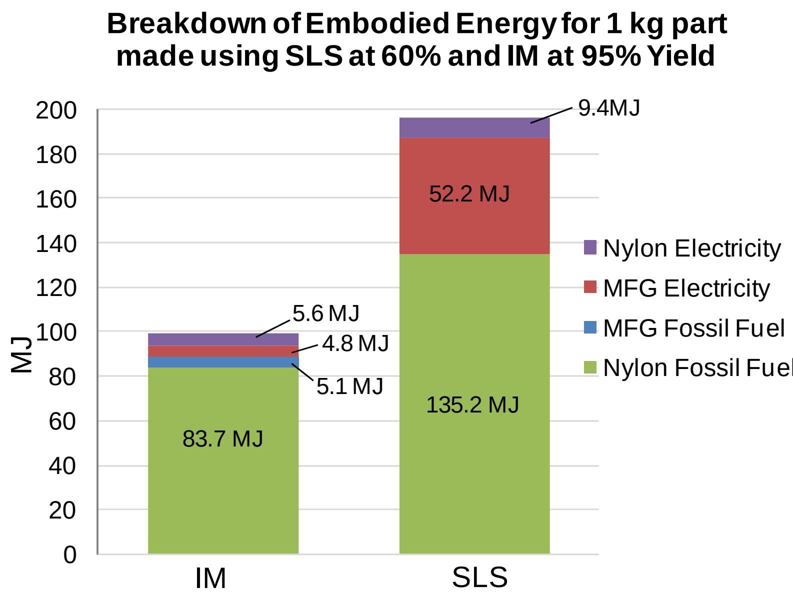

Figure 4: A larger percentage of SLS energy use is electrical energy

SLS is less competitive than IM primarily because it uses more powder and electricity during the manufacturing process. Figure 4 provides a breakdown of embodied energy for representative yields. Overall, the SLS part requires 196.8 MJ while the IM part requires about half of that amount, 99.2 MJ. SLS requires about 1.6 times the energy of IM for nylon production, and 5 times the energy of IM for manufacture. The total embodied energy estimate for an IM part is similar to that reported by Thieriez and Gutowski [17].

It is important to note that these values do not include maintenance and infrastructure costs. Die production, for example, is important in IM operations, but absent from SLS manufacture. The costs of creating and maintaining these machines at difference production volumes also affects their specific energy consumptions. Loughborough University's ATKINS project feasibility study includes a discussion of possible logistical impacts and values [20]. For example, a cost study by Hopkinson and Dickens [21,22] at Loughborough University found that SLS is cheaper than IM at production volumes less than 12,000 units. These cost estimates indicate how the larger supply chain, labor and maintenance costs compare and could indicate their energy requirements as well. Morrow *et al.* [9] compared the environmental impacts of creating tools and dies from machining and Direct Metal Deposition (DMD) and found that about 8 MJ are required to machine a single die, but did not include the extra material costs incurred by this special tooling. It is not obvious how the scaling of SLS and tradition IM operations change their environmental impacts.

CLOSURE

This research quantified the material and energy use of SLS nylon parts and compared these estimates with IM parts. A survey of the literature found loose agreement for the amount of nylon powder wasted during SLS processing and few distinct values for nylon material waste from IM. For these reasons, a variety of possible material yields were calculated and compared.

The results indicate that SLS nylon parts are not as efficient as IM parts when considering nylon material and energy consumed during the material and part production process. It is possible that these findings extend from energy consumption to pollution emissions as well. For example, Thieriez and Gutowski report that most IM emissions occur during material production [19]. Even if the SLS process has fewer on-site chemical emissions than IM, it is probable that emissions from greater nylon manufacture offset this advantage.

Future work could extend this research to a number of areas. Supply chain effects such as reduced transportation and infrastructure costs could make SLS more favorable. These effects could be studied on a large scale with assumptions about the number and locations of available SLS machines. More research comparing metal SLS processing with competitive manufacturing processes, such as machining and die-casting, could provide different insights as well.

Additionally, one of the advantages of SLS is its ability to produce parts that cannot be manufactured using IM. These parts, with optimized geometries, have the opportunity to significantly increase the efficiency of end-use applications. For example, SLS can create honeycomb structures with optimized strength to weight ratios. Identifying and quantifying these kinds of opportunities is an uncharted and promising area of sustainability research.

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