Note on the Rate and Energy Efficiency Limits for Additive Manufacturing

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Summary

We review the process rates and energy intensities of various additive processing technologies and focus on recent progress in improving these metrics for laser powder bed fusion processing of metals, and filament and pellet extrusion processing of polymers and composites. Over the last decade, observed progress in raw build rates has been quite substantial, with laser metal processes improving by about 1 order of magnitude, and polymer extrusion processes by more than 2 orders of magnitude. We develop simple heat transfer models that explain these improvements, point to other possible strategies for improvement, and highlight rate limits. We observe a pattern in laser metal technologies that mimics the development of machine tools; an efficiency plateau, where faster rates require more power with no change in energy nor rate efficiency.

Introduction

A wide range of new additive technologies, sometimes called 3D printing, or more recently additive manufacturing (AM), is having a profound effect on how we make things. The technology can make solid objects directly from a computer description of the part. This eliminates many manual steps in conventional part making and can produce complex geometries that are often very difficult, if not impossible, to make by conventional techniques. These attributes have led to considerable success in the areas of rapid prototyping and tool making.

The main competitive advantages of this technology are: (1) an enormous range of shape complexity, (2) rapid delivery of one-off parts, and (3) deskilling of some of the manufacturing steps. These advantages have led to considerable enthusiasm for this technology, accompanied by significant investments and rapid technology development. But along with these encouraging signs has come speculation about future benefits that are

less certain. Many of these technologies still have well known challenges. These include; (1) slow process rate; (2) poor surface finish and material and dimensional tolerances; and (3) expensive equipment. Other issues that are often mentioned, but are likely to improve over time, are high material costs and limited material choices as well as process stability and automation. The issues of postprocessing and powder management and reuse have received only limited attention and need more discussion. These topics are particularly important for big area additive manufacturing (BAAM; a pellet extrusion type technology for polymers that will be discussed later) that needs significant postprocessing and for reactive powders such as titanium and aluminum and for nonprocessed, but temperature-exposed, polymer powders.

In this article, we focus on process rates for two popular melt processing technologies; laser melting (powder bed fusion; PBF) for metals, and filament and pellet extrusion of polymers and composites, and the companion issue of energy usage. This paper builds upon the work of others who have carefully measured, analyzed, and documented the energy use and time requirements for a variety of AM technologies. These include, in particular, Baumers and colleagues (2010, 2011a, 2011b, 2012, 2017), Faludi and colleagues (2017), Kellens and colleagues (2011, 2014, 2017), Kruth and colleagues (2005, 2010), Schleifenbaum and colleagues (2011), and Buchbinder and colleagues (2011), and their co-workers, as well as many others listed in our references.

We differentiate between different time and rate measures as follows: (1) The *build time* is the total time to produce a raw part without postprocessing. This would include such steps as heating up and cooling down the machine, and printing the part and is discussed in more detail later. (2) The *process time* (or *print time*) represents the core process step of adding material to a solid object. If the process is run efficiently, the process time would constitute 90% or more of the build time (Faludi et al. 2017; Kellens et al. 2011). 3) And, finally, the *manufacturing time* would be the total time to produce a part including the build time and the postprocessing time.

Additive technologies can make one, or a few, parts in a very short elapsed time by avoiding tool making, which can take weeks or months. But if the part can be made by conventional methods, and if large production volumes are needed, then the additive methods cannot compete because they are too slow. The slowness of these processes is related to a fundamental tension between two basic goals: (1) fine features and (2) fast print rate. So far, solutions have favored making small (but not fine) features, at tolerable, but decidedly slow, print rates. A consequence of this selection is long print times.

We argue that the current most commonly employed solution (small features with slow print rates) is fundamentally limited by the details of the heat transfer phenomena that control the melt delivery rate. It appears to us that currently the laser melting technologies, particularly for aluminum alloys, are stalled in the sense that recent rate improvements have not improved energy efficiency, while the polymer extrusion processes recently had a big breakthrough by abandoning small features

and living with significant postprocessing, but increasing the build rate by more than 2 orders of magnitude, while decreasing the energy intensity (not counting postprocessing) by almost 2 orders of magnitude.

The currently slow rates of material processing may be the single most important barrier for the future development of this technology and a dominant feature in the energy usage of this technology.

Overview of Process Rates and Energy Requirements for Manufacturing Equipment

In earlier work (Gutowski et al. 2009; Gutowksi and Sekulic 2011), we have identified a pattern in energy use and process rate that almost all manufacturing process equipment follows. The pattern is seen in figure 1 that plots the average electrical energy used per kilogram (kg) of material processed (joules [J]/kg) vs. the process rate (kg/hr [hour]). The concept behind this plot is relatively simple; most manufacturing process equipment operates within a rather narrow power band, typically between 5 kilowatts (kW) and 50 kW, even though their process rates and energy intensities can vary by 8 or more orders of magnitude. Furthermore, these power requirements can be broken down between constant and variable power components. Processes dominated by constant power requirements tend to fall along the diagonal lines in figure 1. While processes dominated by variable power, that is, with energy requirements that scale with the quantity of material being processed, rather than with the processing time, tend to fall between the two horizontal lines. The lower horizontal line at 1 megajoules (MJ)/kg corresponds roughly with the minimum energy needed to melt 1 kg of iron or aluminum, while the upper horizontal line corresponds to 10 MJ/kg or roughly the minimum energy required to vaporize 1 kg of aluminum. We have added a third diagonal line at 500 watts (W) to this diagram because AM processes, as a whole, tend to have lower power requirements compared to most conventional manufacturing processes. We use the plot here to position additive technologies relative to conventional processes. Metal additive processes are shown in red and polymers in blue. Conventional manufacturing processes, such as machining, injection molding, and the melting step for casting processes, lie to the bottom right of the additive technologies.

The first thing to note is that there is quite a range of process types and values for additive processes on the plot. Nevertheless, certain generalizations can be observed. For example, as a group, the additive processes have both smaller process rates (kg/hr) and higher specific energy use, considered as energy intensities (J/kg), than most of the conventional processes. Note that the energy values given in figure 1 are in terms of electricity requirements (J/kg). At the same time, however, there are many other processes that are widely used that have still smaller process rates and larger energy intensities compared to the additive processes. These would include processes used in the semiconductor industry and advanced machining techniques where relatively small quantities of materials are processed.
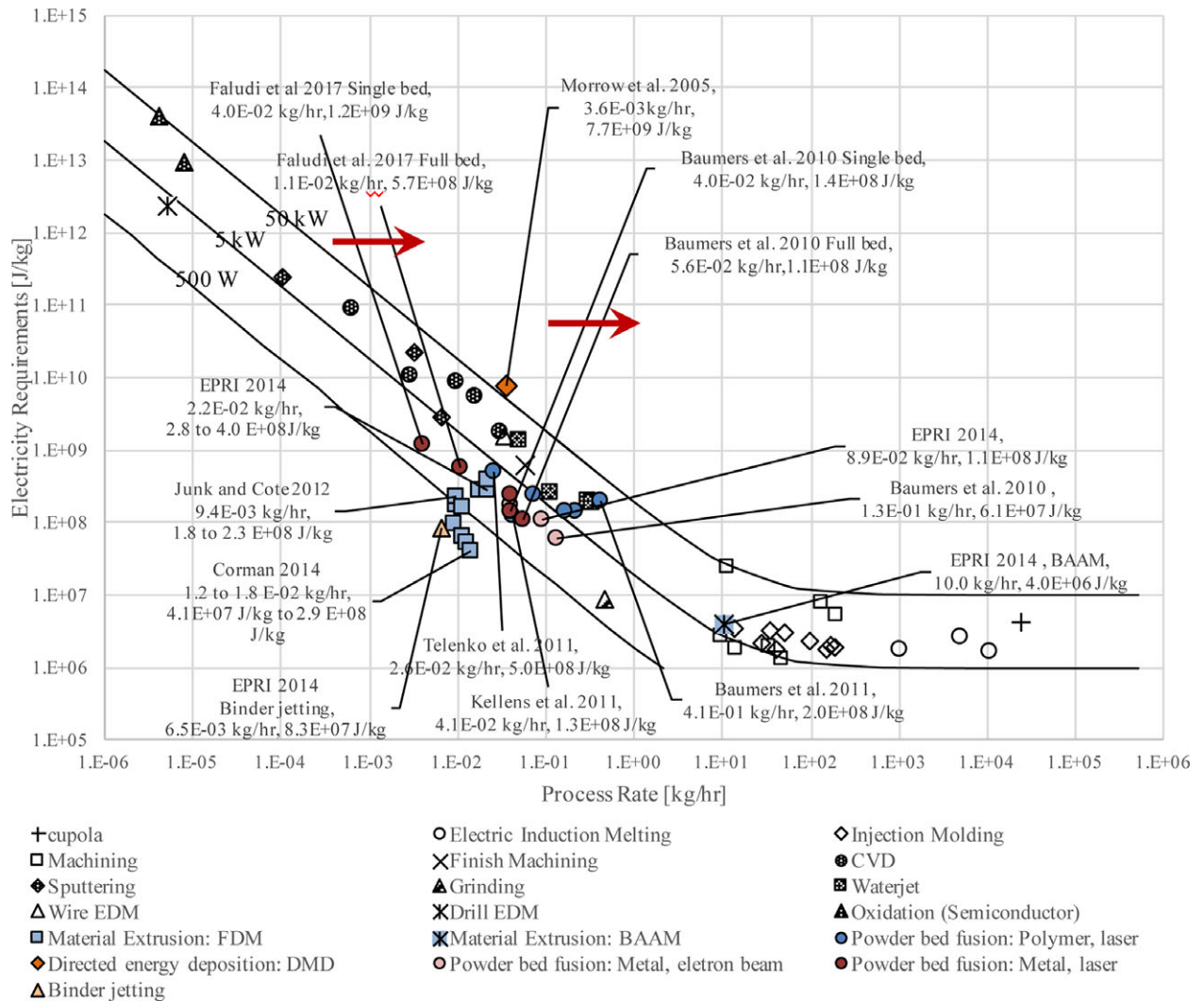
Figure 1 Energy intensity, J/kg (electricity), and process rates, kg/hr for additive equipment (colored data points) compared to other manufacturing processes. Red symbols indicate additive metals, and blue symbols indicate additive polymers. *Note:* EDM is electrical discharge machining, FDM is fused deposition modeling, DMD is direct material deposition, BAAM is big area additive manufacturing, and CVD is chemical vapor deposition. J/kg = joules per kilogram; kg/hr = kilograms per hour.

There are many small additive machines (mostly filament extrusion polymer based) that operate at relatively low power compared to most of the other processes in the figure. These enter the category of so called "desktop" machines, some as low as 50 W, and would probably not be involved in actual manufacturing.

Note that the main cluster of points for the additive processes is about 3 orders of magnitude smaller in process rate than conventional processes (10^{-1} kg/hr vs. 10^{2} kg/hr) and about 1 order of magnitude lower in power requirements, resulting in an electrical energy intensity that is about 1 to 2 orders of magnitude higher than conventional manufacturing processes (100s MJ/kg vs 1 to 10 MJ/kg).[1] When doing a life cycle assessment of these processes, this puts the energy intensity of the additive processes in the same league as the energy embodied in the materials used, something that is not true for conventional

processes. This is not to say that there are not cases where additive processes would require less energy. This could occur for small part volumes that avoid tooling, particularly when compared to conventional applications with very high "buy to fly" material ratios (Huang et al. 2015; Walachowicz et al. 2017, this issue). These cases are the "sweet spot" for additive technologies, but this sweet spot may remain relatively small compared to the vast array of manufactured parts as long as these low processing rates continue to exist. The consequences of small process rates show up in still other ways that can affect the competitiveness of these technologies. Small process rates mean that attended processes can run up significant labor costs, and that equipment amortization will be over many fewer parts. This can make equipment costs and equipment embodied energy a significant part of the per-part calculation (see Faludi et al. 2017, this issue).

Perhaps the most notable feature for AM technologies in figure 1, however, is a process labeled BAAM at 4×10^6 J/kg and 10 kg/hr. BAAM stands for big area additive manufacturing, a new pellet extrusion process. This process, which is noticeably much faster and less energy intense than the other additive processes, was developed as a collaboration between Oak Ridge National Laboratories and Cincinnati Incorporated and will be discussed later.

Rate Improvements and Limitations

The time steps to make an additive part (after some additional computer-aided design processing) involve the following: (1) machine setup; (2) machine heatup; (3) printing (which involves laser scanning/melting for laser PBF processes) or filament or pellet melting and deposition for extrusion processes; (4) powder recoating for powder processes; (5) cool down; (6) part removal; and (7) postprocessing (typically involving machining and finishing processes). The individual time contribution from each step depends very strongly on how the machine is scheduled. If only a small section of the machine bed is used, the "once per run" steps 1, 2, 5, 6, and 7, and the "once per layer" step 4 can account for a significant proportion of the total run time. But as the machine bed is filled for large runs, these steps diminish in importance and actual printing (step 3) dominates, accounting for more than 90% of the run time. Hence, the difference in time per part between occasionally making one part, to constantly printing a full bed of parts, can be almost a factor of 10 (Baumers et al. 2010; Faludi et al. 2017). So, as we consider the potential transition of 3D printing from prototyping, to additive manufacturing, we assume that many parts will need to be made. In this case, the most dominant time step will be the printing step involving laser heating for metal powder bed processes or filament or pellet heating for extrusion processes, as confirmed by several papers in this special issue (Faludi et al. 2017; Kellens et al. 2017).

Laser Melting

A fundamental limitation to high production rates in these processes is related to management of the heat transfer mechanisms needed to deliver the melt stream to build a part. For a large group of AM technologies, melting is driven by a laser beam scanned across the powder bed surface. The objective is to raise the temperature of the powder bed layer in order to melt and solidify an eventual solid ribbon of material.

The heat must be applied in a way that does not vaporize sizably the surface (leading to significant material loss, especially for metals), nor damage the surface (polymers) while at the same time bringing sufficient thermal energy for melting and heat transfer for propagating to the bottom of the layer so it bonds firmly to the sublayer. The processing parameters are designed such that these conditions can be obtained on a repetitive basis. In practice, the thermal gradient across the layer is managed in metals by initial surface melting followed by rapid capillary advance into the material and in polymers (which are very

poor thermal conductors) by raising the powder bed to a very high temperature, in fact not far below the melt temperature, so that only a small additional increment of heat is required for the subsequent aggregate state (phase) change. Hence, the process is designed such that a new layer is heated rapidly with a constrained temperature gradient across the thickness.

With this process approach in mind, one can estimate the fastest possible delivery rate based upon the ideal assumption that the delivered energy is fully utilized to raise the temperature and melt the ribbon of material. We call this the adiabatic print rate; it comes directly from the conservation of energy principle established by the application of the first law of thermodynamics and conservation of mass. The result, given below, for laser melting suggests methods to increase the print rate and provides a standard of comparison for observing energy efficiency improvements. In practice, other mechanisms could interfere with this ideal rate, such as poor heat transfer, degradation, instabilities, and heat loss to the surroundings, but, in practice, process parameters are adjusted to avoid or at least minimize these interfering phenomena. And, at the same time, the adiabatic rate will provide a useful standard to analyze the progress of energy delivery systems for AM (equation 1).

$$\dot{m}_{adiabatic} = \frac{\alpha P}{c \cdot \Delta T + \gamma} \qquad (1)$$

Note that equation (1) assumes that the solid state material is heated up to the melting point, and subsequently melted only by the absorbed laser delivered heat input, with no heat transfer losses to the surroundings.

Where $\dot{m}_{adiabatic}$ = the adiabatic mass process rate (kg/s)

α = laser/material absorption coefficient ($0 \leq \alpha \leq 1$)
P = laser power (W)
c = average specific heat (J/(kg K))
$\Delta T = T_{melt} - T_{start}$ (K)
γ = enthalpy of melting (J/kg)

We define the adiabatic efficiency as the mass rate ratio (or sometimes as the volume rate ratio, assuming constant density, to conform with commonly reported results in the literature), for example (equation 2),

$$\eta_{adiabatic} = \frac{\dot{m}_{actual}}{\dot{m}_{adiabatic}} \qquad (2)$$

Observed Laser-Metal Process Rates

Four strategies have been used in recent years to increase the production rate of laser PBF technologies: higher powered lasers; multiple lasers; heated chamber; and optimized process settings. The success of these strategies will be revealed in the data presented in this section, but in summary, over the last decade, steel powder laser PBF print rates have increased by more than an order of magnitude, ($20\times$), while over a shorter time, aluminum print rates have increased eightfold. Both improvements are due largely to the use of higher powered lasers, but the other strategies, as listed above, were also employed.
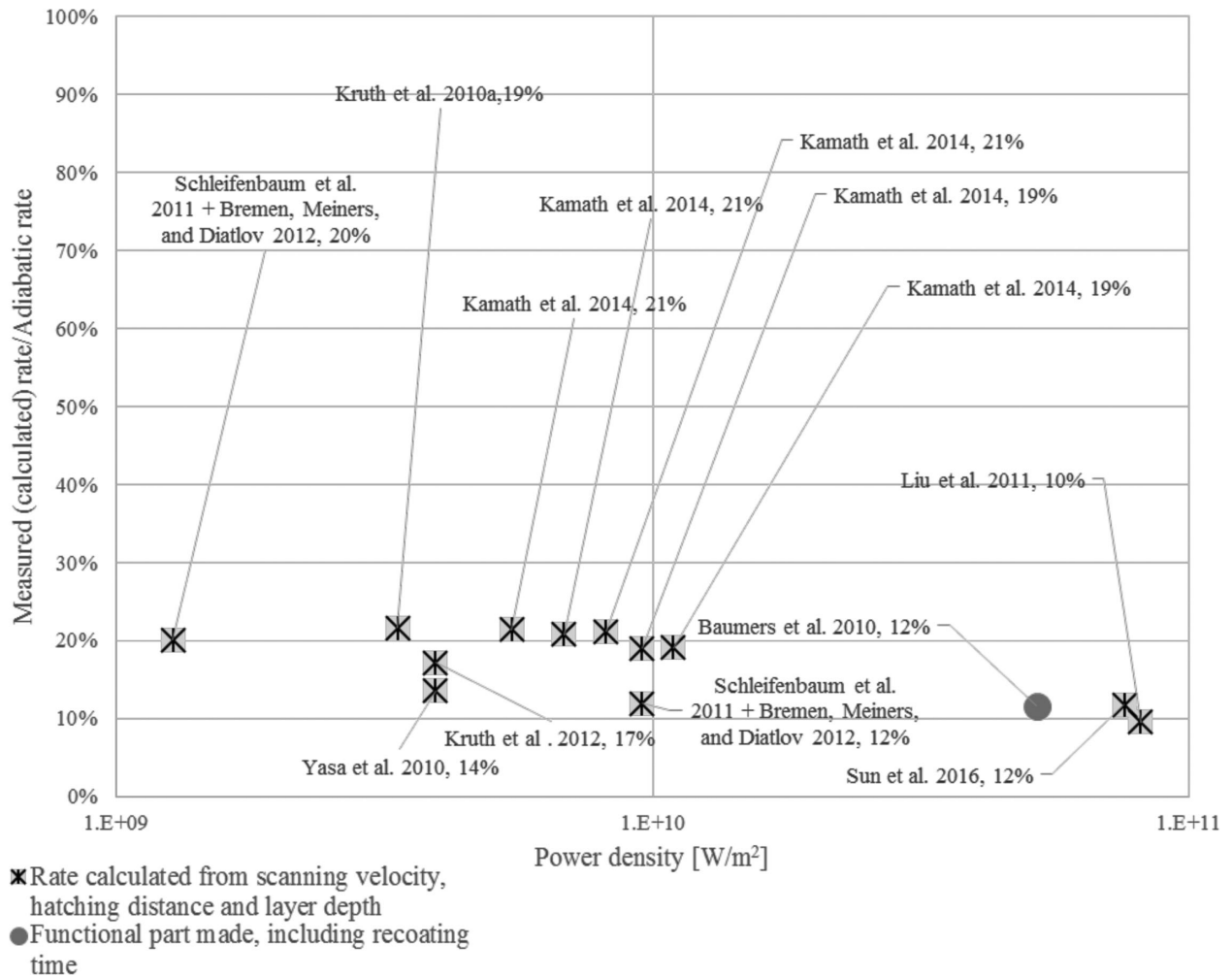
Figure 2 Measured rate/adiabatic rate (adiabatic efficiency) vs. laser power intensity (W/m^2) for steel powders for different additive equipment using larger lasers and defocusing. W/m^2 = watts per square meter.

At the same time, using estimates for the physical parameters in equation (1), we noticed that the adiabatic efficiencies of these newer processes have stayed remarkably consistent. The adiabatic efficiency is plotted against laser power intensity (W/m^2 [square meter]) for steel powders in figure 2 and against the laser power (W) for the aluminum alloy, AlSi10Mg, in figure 3. The results show a striking consistency, with steel powder data showing adiabatic rate efficiencies on the order of 20% for power intensities below about 10^{10}W/m^2 and about 13% for higher power intensities up to 10^{11} W/m^2. The aluminum powder data are even more consistent, with an adiabatic rate efficiency around 5% for the entire range from 200 W to 1,600 W. The nominal values used to calculate the adiabatic rates for steel and aluminum are given in table 1, while the data for the actual scan rates are given in tables 2 and 3. The rather low adiabatic efficiencies indicated in figures 1 and 2 are due largely to heat loss to the surroundings, with the much more conductive aluminum powder giving the lowest values.

Keep in mind that the delivered laser power in watts is only a small fraction of the primary power requirements to do the melting. For a larger boundaries perspective, the overall power requirements just to melt the powder would need to include: losses in the laser resonator: due to quantum efficiency being less than 100%, active medium small signal gain saturation, losses due to mirror absorptivity at the wavelength being emitted, output coupling mirror intermediate reflectivity and resonator cavity materials absorptivity (Anderson 1976; Steen and Manzumder 2010; Kannatey-Asibu 2009), and the requirement for a chiller, and losses in the electric grid.

In fact, the overall inefficiency of the laser melting process can be demonstrated by comparing the energy required to laser melt material versus the energy needed to sand or die cast an equivalent amount of material. The example aluminum part presented by Faludi and colleagues (2017, this issue) made on a Renishaw AM 250 with a 200-W fiber laser required 352 MJ$_{elect}$/kg for full bed printing, or 1.06 gigajoules per kg primary energy assuming $\eta_{grid} = 1/3$. Nominal primary energy values for sand and die casting are generally in the range of 10 to 20 MJ/kg (Dalquist and Gutowski 2004a, 2004b). The minimum energy required to melt aluminum from room temperature to the melt
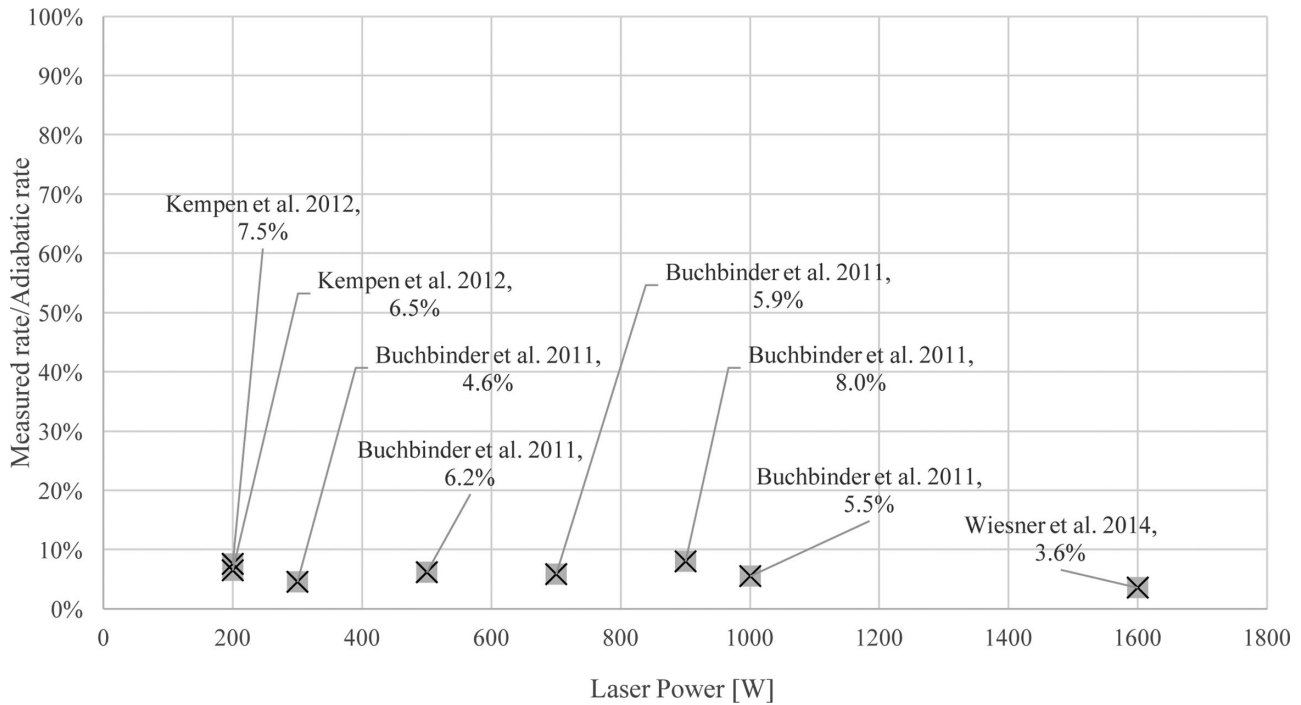
Figure 3 Measured rate/adiabatic rate (adiabatic efficiency) vs. laser power (W) for aluminum powders for different additive equipment using higher powered lasers. See table 2. W = watts.

Table 1 Parameter values for steel and aluminum powders used to calculate adiabatic print rates

Material	Steel 316L		AlSi10Mg	
Parameter	Value	Reference	Value	Reference
Density [kg/m³]	7,970	IAEA 2009	2,670	EOS material sheet
Heat capacity [J/(kg-°C)]	510	IAEA 2009	963	Touloukian et al. (1970)
Melting temperature [°C]	1,430	IAEA 2009	613	Touloukian et al. (1970)
Plate temperature [°C]	100–300	Baumers et al. (2010)	100–300	Baumers et al. (2010)
Latent heat [J/kg]	273,000	AZO materials data sheet	389,000	Touloukian et al. (1970)
Laser/ material absorptivity	0.64	Tolochko et al. (2000)	0.62	Gestel (2015)

Note: kg/m³ = kilograms per square meter; J/kg = joules per kilogram.

temperature is about 1.4 MJ/kg and will vary slightly from this value depending upon alloy content.

At the same time, what should be noted is that even with significant rate improvements, the adiabatic rate efficiency has hardly changed, and that this implies that the energy efficiency for these processes has plateaued. An energy efficiency, η_{energy}, can be estimated by taking the ratio of the minimum energy input required to melt the part, to an approximation for both the laser energy requirements and the part/chamber preheating using approximate estimates for efficiencies of the subprocesses, including α, which is optimized by matching the laser wavelength with the absorptivity spectrum for the material, assumed to be in the vicinity of 0.6 in our calculations, $\eta_{adiabatic}$, as previously defined and observed to be in the range of 1/20 to 1/5 depending upon the powder; η_{grid}, for the efficiency of the electric grid, we assume 1/3; η_{laser}, as the efficiency of the laser, we assume between 1/5 to ½; and $\eta_{heating}$, as the efficiency of the

heated chamber we assume between ½ and 3/4. The derivation, given in the Supporting Information available on the Journal's website, yields the following approximation for laser melting of metal powders (equation 3),

$$\eta_{energy} \cong \alpha \cdot \eta_{adiabatic} \cdot \eta_{laser} \cdot \eta_{grid} \qquad (3)$$

This result shows the important connection between the adiabatic rate efficiency and the energy efficiency of the thermal energy delivery system and only applies when laser heating dominates over chamber heating as it usually does for the laser melting of metal powders. Hence, a constant absorptivity and adiabatic efficiency with no change in the laser or grid efficiency will result in a constant energy efficiency. In other words, one might be able to increase the print speed with increased laser power, or increased chamber heating for that matter, but these strategies will have to pay the price for increased speed, with additional power requirements. This is very similar to the

Table 2 Measured print rates for steel powders with references

	Machine	Laser	Material	P (W)	Laser spot diameter (mm)	Power density (W/m²)	Measured rate (cm³/hr)	Rate efficiency ratio	Density ratio (vs. bulk material)	Reference
Functional parts (calculation includes recoating time)	AM 250	Yb fiber laser	SAE 316L	200	0.07	5.2E+10	7.0	12%	N\A	Baumers et al. (2010)
	Trumph (not specified)	Not specified	SS 316	200	N/A	N/A	5.0	9%	98.7%	Kruth et al. (2005)
	MCP-HEK (not specified)	Not specified	SS 316	100	N/A	N/A	2.6	9%	99.1%	Kruth et al. (2005)
Pillars, cubes, specimen (data chosen to ensure >99% printed density, calculation includes hatching distance, powder depth, and scanning velocity)	Modified Trumaform LF250	Yb and fiber	Steel 1.2343, 1.2709, 1.4404	1000	1.00	1.3E+09	60.5	21%	>99%	Schleifenbaum et al. (2011); Bremen et al. (2012)
	Concept Laser M2	Yb fiber laser	SS 316L	250–400	0.22	6.8E+09 - 1.1E+10	12.9–23.0	19%–23%	99.13%–99.41%	Kamath et al. (2014)
	SLM 250 HL	Yb fiber laser	SS 316L	380	0.08	7.6E+10	13.5	12%	99.1%–99.2%	Sun et al. (2016)
	Modified Trumaform LF250	Yb and fiber	Steel 1.2343, 1.2709, 1.4404	300	0.20	9.5E+09	10.8	13%	>99%	Schleifenbaum et al. (2011); Bremen et al. (2012)
	Concept Laser M3	Not mentioned, fiber laser from specs	SS 316L	105	0.20	3.3E+09	6.8	23%	98%	Kruth et al. (2010)
	Concept Laser M3	Nd-YAG, fiber laser	SS 316L	100	0.18	3.9E+09	5.2	18%	98.80%	Kruth et al. (2012)
	Customed SLM machine	Nd YAG	SS 316L	100	0.18	3.9E+09	4.1	14%	>99%	Yasa et al. (2010)
	SLM-Realizer 100	Yb fiber laser	SS 316L	50	0.0	8.1E+10	1.4–2.9	10%–19%	99.45%–99.93%	Liu et al. (2011)

Note: Yb = ytterbium; Nd-YAG = neodymium-doped yttrium aluminum garnet; P = power; W = watts; N/A = not available.

Table 3 Measured print rates for aluminum powders with references

Machine	Laser	Material	P (W)	Measured rate (ccm/hr)	Rate efficiency ratio	Density ratio (vs. bulk material)	Reference
SLM 500 HL	YLR fiber laser	AlSi10Mg	1,600	60.0	3.6%	N/A	Wiesner and Schwarze (2014)
Modified SLM machine	Customized fiber laser	AlSi10Mg	300	14.4	4.6%	95.3%–99.8%	Buchbinder et al. (2011)
			500	32.4	6.2%	95.3%–99.8%	
			700	43.2	5.9%	98.4%–99.8%	
			1,000	57.6	5.5%	~99.5%	
Concept Laser M1	Fiber laser	AlSi10Mg	200	14.8	7.0%	98.5%–99.8%	Kempen et al. (2012)

Note: P = power; W = watts; ccm/hr = cubic centimeters per hour; N/A = not available.

historical development of cutting machine tools. They increased dramatically in cutting speed, by about 2 orders of magnitude over 100 years, due, in large part, to the development of new harder and tougher cutting tools (Kalpakjian and Schmid 2014). However, to take advantage of these new tools, the spindle power was also increased. The end result, in this case, was that the spindle-specific energy requirement converged to a value proportional to the hardness (or ~ 3 × material yield value) of the material being cut, due to the plastic work required. Inefficiency in cutting (due to friction at the tool work piece interface) further doubled this value (Cook 1966; Gutowski and Sekulic 2011). In the case for laser additive processing, the factor is not 2, but 5 to 20, and it appears to have plateaued.

We have further studied the adiabatic rate experimentally, by scanning various metal powders at different rates and with different patterns and have found that, in certain circumstances, one can obtain an adiabatic rate efficiency as high as 40%, but with diminished material quality. We note that these results are very similar to the results of others who have explored the parameter space of scan rate vs. laser power to identify rate limits for laser AM technologies (Kruth et al. 2004; Laohaprapanon et al. 2012; Yadroitsev et al. 2010). It is important to keep in mind that any claim on still higher scan rates would need to ensure that the settings are robust to quality variation. It is reasonable to assume that equipment manufacturers are working at this problem every day.

In spite of these apparent efficiency limits, additive processes can compete with other conventional processes on an energy basis due to other areas of potential efficiency improvements (e.g., due to observed low "buy to fly" material values, or fast turnaround times that avoid tooling for small numbers of parts). But, so far, these apparent "sweet spots" represent only a small fraction of the totality of manufacturing applications.

Observations on Filament and Pellet Extrusion Processes

Earlier in this paper, the significant improvement in print rate and reduction in energy intensity of the BAAM technology, a pellet extrusion technology, was pointed out.

Prior to this breakthrough, however, the print rate of the filament extrusion process had not changed much in spite of many different varieties of machines available. This is shown in figure 1. For example, Corman (2014) shows measurements of four different filament extrusion systems of significantly different power (70 W to 1.4 kW) and size, which indicate almost no change in process rate. All of them used similar filament systems and made parts at the rate of about 10 to 20 grams (g)/hr. Furthermore, since the bigger machines used more power (due to the bigger heated print chambers), they actually had higher energy intensity values compared to the smaller machines, that is, 100s of MJ/kg vs 10s of MJ/kg. These results essentially agree with the other data points provided by (EPRI 2014; Junk and Cote 2012). The lower range of energy use by this technology is quite competitive with injection molding, but the print rates are not. The print rates of 10 to 20 g/hr are roughly 3 to 4 orders of magnitude smaller than injection molding. Unless this rate is improved, it will not be competitive for the vast majority of injection molded parts. Again, a limiting print rate for these machines can be demonstrated by a relatively simple heat transfer model to give insight into how to improve the deposition rate for this process.

Filament extrusion technology works like a glue gun. A solid polymer filament of diameter D (typically 1 to 2 millimeters [mm]) enters a heated die of length L (~20 mm), is heated by conduction from the heated wall, and then exits the die at a smaller diameter d when it is printed. Roughly, d ≈ D/10. This is shown schematically in figure 4. Using a simple approximation, as shown in the Supporting Information on the Web, one can estimate the maximum print rate to be (equation 4),

$$\dot{m} = 2\pi \frac{k}{c} L. \tag{4}$$

In equation (4), k is the thermal conductivity of the polymer filament, and c is the average specific heat. The basic assumption behind equation (4) is that the polymer filament of length L must obtain a sufficiently high temperature by conduction from the heated walls, before it can be advanced and fused to the adjacent layers. A more detailed model for this process is given in Jiang (2017). This result suggests that the print
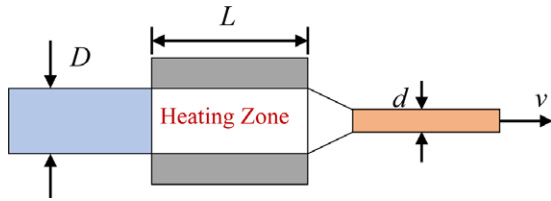
Figure 4 Heating zone for the plastics extrusion process (sometimes called fused deposition modeling [FDM]). The cylindrical filament enters as a solid with diameter D on the left, is heated by conduction from the wall in a zone of length L and exits as a molten polymer of diameter d and velocity v on the right.

rate for filament extrusion can be limited by heat transfer.[2] The thermal conductivity of polymers is well known to be small, and so it can dominate many rate phenomena during processing. For example, the cooling rate, and hence the cycle time, for injection molding is generally controlled by heat conduction through the polymer.

Interestingly, to a first approximation, the filament diameter drops out of the mass process rate estimate in equation (4). Hence, printing thicker filaments will not increase the mass printing rate because you are proportionally slowed by thermal diffusion. However, a longer heating zone L (and therefore more cumbersome print head), and more conductive polymer (perhaps filled with a conductive filler like carbon fibers), would help. Also, important would be to decouple the thermal diffusion scale length from the print ribbon length scale. This is something that the single barrel melt extruder does for the new pellet extrusion technology called BAAM. In fact, BAAM does all three of these when compared to fused deposition modeling (FDM); it employs a longer heating zone, a more conductive material, and viscous heating—a bulk heating mechanism.

The BAAM technology abandoned the filament approach, and replaced the print head with a conventional single-barrel melt extruder. Such a machine is feed using (less expensive) pellets, is more than an order of magnitude longer than the conventional filament extrusion print head (L in equation 4), and employs a much more favorable melting geometry compared to the filament approach (Tadmor and Gogos 2006). Jiang (2017) has performed a detailed analysis of this process, which indicates that the use of viscous heating, as well as heat transfer from the barrel wall, greatly enhances the melting process. All of these factors contributed to the very significant increase in process rate and reduction in energy intensity in spite of using higher power compared to conventional filament extrusion technologies. At the same time, while the longer extruder helps to increase the rate, it also makes the print head much bulkier, limiting feature detail, and of course the output is much coarser (with surface features on the order of 1 centimeter), leading to a much poorer surface finish and very significant postprocessing. That is, while the details have not yet been shared, it seems apparent that these large parts, after being printed, are likely loaded into a large machine tool, probably five axis, and machined to get the fine surface finish often displayed on the final

parts. Other possible required steps could be heat treatment, and hand surface finishing, but as far as we know, the details for the required postprocessing have not yet been revealed.

Nevertheless, the new pellet extrusion technology both increases the process rate, by more than 2 orders of magnitude, and decreases the electricity requirement per kg by about 2 orders of magnitude when compared to the filament extrusion technology. Hence, in terms of the two parameters this paper is focused on—process rate and energy intensity—the BAAM technology is a clear breakthrough, demonstrating new thinking and creative use of existing technology. At the same time, there is more to learn about this technology, and we look forward to more detailed reports concerning the stability and strength of the printed structures, and the extent of postprocessing required.

Conclusions

Additive technologies have revolutionized how we can make physical objects. They have shown steady progress as they have transitioned from physical object prototyping, to functional prototyping, to one-off parts, and to tooling inserts. Currently, they are being considered for parts that channel gases and liquids through complex flow paths in high-temperature environments. Applications include aerospace and engine parts like fuel mixing heads and diffusion burners, and tooling applications such as injection molding dies. In these applications, additive technologies can replace complex operations, machining hard materials often with high "buy to fly" ratios. These applications seem very attractive for additive processes and have a very real chance to make better performing parts, in less time and using less material and energy. We expect this trend to continue with still more new application.

Nevertheless, in spite of these successes, additive technologies have very real limits to their performance and without additional innovation and development will not come close to many of the premature announcements concerning their future possibilities. In this paper, we focus on one of the major barriers in the way of the transition from prototyping to manufacturing; the very slow print rate. This obstacle alone could eliminate AM from serious consideration for most parts that are manufactured today. At the same time, this challenge is known in the industry and many capable engineers and scientists are looking hard to cross this barrier. We hope that this paper will bring attention to these challenges.

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Notes

1. Kellens and colleagues (2017) report a range of measured electrical energy values for various commercial additive technologies ranging from 51 to 1,247 MJ/kg with many of the same references that we use here.
2. Note that a major difference between laser processes and extrusion processes is that fast and complex pattern scanning with lasers is possible due to the use of galvanometers, while fast scanning of extruders is impeded by the inertia of the mechanical positioning mechanism. The result is that part complexity has almost no effect on the process rate for laser processes, but can noticeably slow down extrusion processes for complex shapes. See Baumers and colleagues (2017) and Go and colleagues (2017).

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes (1) derivation of energy efficiency equation (4) and maximum rate for filament extrusion equation (5) and (2) derivation of scaling law for filament extrusion.