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THE ECONOMICS OF BIG AREA ADDITIVE MANUFACTURING

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Abstract

Case studies on the economics of Additive Manufacturing (AM) suggest that processing time is the dominant cost in manufacturing. Most additive processes have similar performance metrics: small part sizes, low production rates and expensive feedstocks. Big Area Additive Manufacturing is based on transitioning polymer extrusion technology from a wire to a pellet feedstock. Utilizing pellets significantly increases deposition speed and lowers material cost by utilizing low cost injection molding feedstock. The use of carbon fiber reinforced polymers eliminates the need for a heated chamber, significantly reducing machine power requirements and size constraints. We hypothesize that the increase in productivity coupled with decrease in feedstock and energy costs will enable AM to become more competitive with conventional manufacturing processes for many applications. As a test case, we compare the cost of using traditional fused deposition modeling (FDM) with BAAM for additively manufacturing composite tooling.

Introduction

According to the Wohlers Report, sales of additive manufactured products and services was approximately $4.1B in 2014 and is expected to grow to $21B by 2020.(Wohlers 2015) This is an average growth rate of 39% per year. This corresponds to the recent history from 2010 to 2013 in which the industry experienced a growth rate between 24.1% and 35.2%. However, to put this in perspective, global manufacturing is approximately $12.8T per year suggesting that AM only represents 0.03% of worldwide manufacturing. Optimism suggests that there is room to grow whereas pessimism suggests AM is restricted to niche markets. An analysis of the current economics of AM suggests the latter. However, the authors hypothesize that it could be the former with disruptions in the technology.

As a case in point, (Salmi 2012) provide a case study comparing high pressure die casting (HPDC) to selective laser sintering (SLS) to manufacture an aircraft component. To take advantage of the process, the team redesigned the component reducing the weight by 72% (e.g. the weight of the AM part was 3.6X lighter). An analysis of HPDC identified four primary cost elements: material, tooling, machine cost and labor for pre- and post-processing. In a similar manner, SLS had four primary cost elements: material, machine cost and labor for pre- and post-processing. The fundamental difference between the two manufacturing approaches was the lack of tooling cost for SLS and the production rate (3.6 seconds per part for HPDC versus 13.5 hours for SLS). If cost is the primary metric for comparison, HPDC was $21.29+$21,000/N where $21,000 was tooling cost and N is part count whereas SLS had a fixed cost of $526.31 per part. Therefore, if the production volume is less than 41 parts, SLS is the more economical manufacturing process. At a volume of 41 parts, tooling accounts for 97% of the manufacturing cost in HPDC but decreases as volume increases. For SLS, machine cost per part (e.g. time) accounts for 90% of the total part cost and does not change with volume (see Table 1). Therefore, ***time***, not material or labor, is the most expensive cost of additive manufacturing.

Table 1: SLS Additive Cost Breakdown

	Cost	Percentage
Preprocessing	$8.00	1.5%
Material	$25.81	4.9%
Processing	$472.50	89.8%
Post processing	$20.00	3.8%

(Wohlers 2015) provided a similar case study conducted by Johnson Controls. The part in the investigation was approximately 250 x 120 x 50 mm and is currently manufactured via injection molding (IM) with a production volume of 8500 units per year. The part was redesigned for SLS with no requirements for finishing or post-processing. The unit cost for injection molding was $2.64 whereas it was $39.42 per unit using SLS. In this case, tooling accounted for 25% of the IM part cost whereas material and time accounted for 96% of the cost of the SLS part. Aggressive decreases in material cost and manufacturing time (order of magnitude) show that there is a pathway towards cost competitiveness between additive manufacturing and conventional manufacturing. The critical question is whether these disruptions are theoretically possible. Our hypothesis is yes if there are fundamental changes in both the technology (orders of magnitude increase in speed) and the business models (orders of magnitude drop in material cost).

State of the Art

Table 1 provides a survey of typical build volumes and rates for commercial AM systems. In terms of build rate, extrusion technologies (extrusion, jetting, directed energy) are relatively straightforward to estimate since is it directly related to flow rate of the material. Estimate of production rates for powder bed and vat systems are slightly more complex. The layer time is a function of both fusion and the preparation of the bed (raking and possibly preheating the material). Therefore the majority of industry quoted rates is measured in layer time rather than volumetric rate. In order to provide a rough order of magnitude comparison between technologies, we bound the volumetric rate by assuming between 2% and 20% of the layer volume is fused in powder bed systems.

Table 2: AM Volumes and Rates

System	Technology	Build Volume (cm x cm x cm)	Build Rate (cm^3/hr)
Arcam Q20	Powder bed fusion	35 dia x 38 tall	20 to 400
Concept Laser Xline 2000R	Powder bed fusion	80 x 40 x 50	10 to 100
SLM Solution 280 HL	Powder bed fusion	28 x 28 x 35	20 to 35
Stratasys 900 mc	Material Extrusion	91 x 61 x 91	10 to 80
ExOne mFlex	Binder jetting	40 x 25 x 25	12 to 260
Stratasys Connex 500	Material jetting	50 x 40 x 20	50 to 500
Optomec MR-7	Direct energy	30 x 30 x 30	20
3D Systems ProX 950	Vat polymerization	150 x 75 x 55	50 to 600
Fabrisonic SonicLayer 4000	Sheet lamination	100 x 60 x 60	500

The rates quoted in Table 1 only consider the manufacturing process. Pre- and post-processing likewise impact total production rate. In the case of electron beam powder bed systems, the unmelted material is lightly sintered and must be mechanically removed, broken down and filtered prior to reuse. Laser powder bed systems do not preheat the powder to the level of the electron beam systems so powder separation is easier. However, the resulting increased temperature gradients result in higher residual stress requiring welding the parts to the start plate and heat treatment prior to part removal. Binder jet systems generate green parts that require sintering in a furnace prior to use. Material extrusion, vat polymerization and material jetting systems produce near net shaped parts but must have support material removed either mechanically or chemically prior to use. Sheet lamination processes are additive/subtractive systems that require machining processes to remove material insitu to the process. The magnitude of post processing varies from process to process. However, in general, the additive process is the main cost element in additive manufacturing and are not currently competitive with traditional manufacturing processes.

Big Area Additive Manufacturing

Conventional fused deposition modeling is based on melting and extruding a filament of thermoplastic feedstock. Prior work shows that the peak flow rate is limited by the rate at which the filament can be melted.(Monzon 2013) Big Area Additive Manufacturing is an extrusion process that uses injection molding material for the feedstock and a single screw extruder for melting and metering the flow rate (see Figure 1). (Holshouser, Newell et al. 2013) A gantry system, commercialized by Cincinnati Incorporated (see Figure 2), moves the extruder in x, y and z directions to build the part. The extruder is capable of delivering 100 lbs/hour of thermoplastic materials from pellet feedstock. The gantry system is capable of achieving 200 inch/sec peak velocities with 64.4 in/s^2 accelerations and position accuracy in the 0.002". As previously reported, the use of carbon fiber reinforcement in the thermoplastic resins increases the part strength and stiffness.(Tekinalp, Kunc et al. 2014) But, just as important, it increases thermal conductivity and reduces the coefficient of thermal expansion relaxing the need for a heated chamber to produce large parts (see Figure 3 and Figure 4). (Love, Kunc et al. 2014) The elimination of the oven significantly decreases the energy intensity (manufacturing energy required per kg of product). As shown in Figure 5, conventional FDM systems with heated chambers have a 100 kW-hr/kg energy intensity. Desktop systems that have similar production rates have a 5.5 kW-hr/kg energy intensity suggesting that the oven accounts for 95% of the energy utilization in FDM production. BAAM further reduces the energy intensity to 1.1 kW-hr/kg by significantly increasing productivity from 1 ci/hr to 2500 ci/hr and manufactured at room temperature.

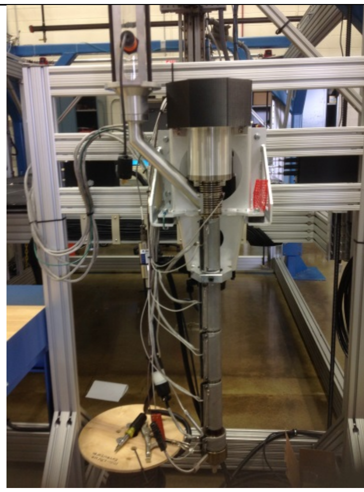

Figure 1: BAAM Extruder

Figure 2: Cincinnati BAAM

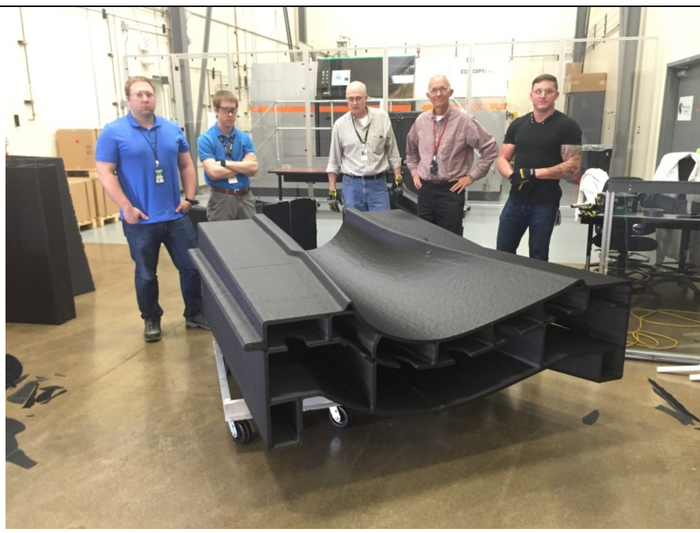

Figure 3: Section of a wind turbine mold

Figure 4: Printed prototype house

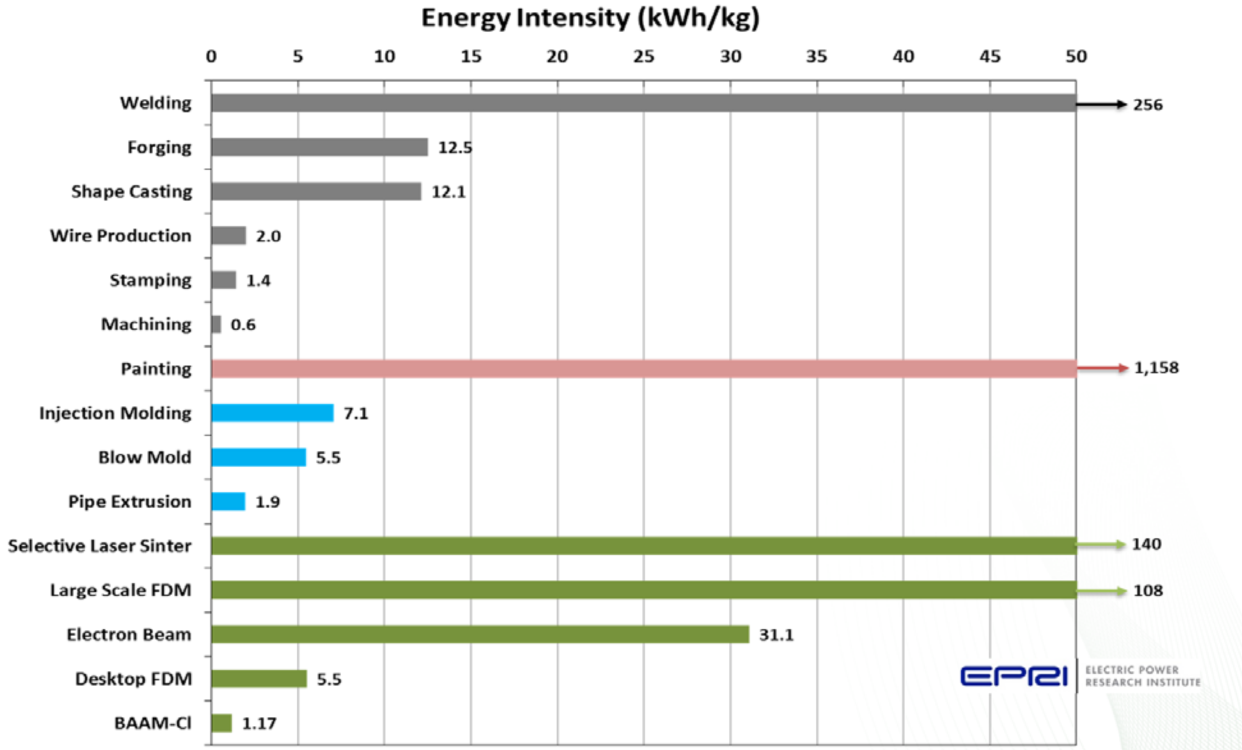

Figure 5: Energy intensity of manufacturing

Therefore, the combination of lower energy intensity, higher productivity and lower material cost suggests that there will be a significant production cost reduction with BAAM when compared to conventional AM systems. As with conventional additive manufacturing, there are four primary costs associated with manufacturing a part: preprocessing (PR), material (M), processing (P) and post processing (PO). The combination of significantly higher production rates with low cost feedstock significantly changes the cost distribution of each of these elements. Preprocessing typically includes preparation of the file (slicing, support, orientation) and preparation of the machine (loading material and file). Material is generally slightly over the volume of the part and includes support material. Post processing includes removal of the part, support, recycling of any material and final finishing (machining, polishing…).

Composite Tooling Case Study

Tooling is the foundation of many manufacturing industries. Molds are used in the aerospace, automotive and appliance industry to shape metal, plastic and composite parts. As an example, the automotive industry generally spends $200M on tooling for each car model. By 2018, tooling for the automotive industry is expected to exceed $15.2B per year. Tooling is generally very expensive ($10K's to $100K's per mold) and long lead (months to years) items. Therefore there is great potential for revolutionizing the tool and die industry through the use of additive manufacturing.

The aerospace industry, due to weight concerns, has begun to migrate from aluminum to carbon fiber composites. The conventional approach for manufacturing composite structures is to layup the carbon fiber, core structure and resin on a mold. The molds and composite materials are processed inside an autoclave to rapidly cure the resins and remove any air. The requirements for the molds are elevated operating temperatures (from 200 C to 375 C), vacuum integrity (15 mbar over 60 minutes) and moderate pressures (100 psi) with tight dimensional tolerances (under 0.005" distortion). A conventional composite tool will cost in excess of $100K (US) and take several months to manufacture. ORNL recently partnered with Boeing, Ford, Techmer and BSF to evaluate the feasibility and economics of using BAAM to produce composite tools. A variety of materials were evaluated including PEEK, PEEK, Ultem, Apollo, PPS, PPSF and PPSU. The final material of choice, based on performance and cost, was PPS loaded with 50% carbon fiber. The material cost was approximately $8/lb. The sample tool weighed approximately 65 lbs and took 2 hours to print. Preprocessing time (setting up the machine and slicing the model) was approximately 2 hours. The mold was grown approximately 0.100" over sized and machined using a Thermwood router to the final size. It took approximately 2 hour to transfer the mold to the router and another 5 hours to machine. Assuming labor rates of $50/hr and machining rates of $150/hr, the total tool cost was approximately $1870 (see Table 3). In terms of manufacturing time, from beginning to end, it took approximately 2 days to fully manufacture the mold. In comparison to SLS in the BAAM provides a more balanced distribution of costs. AM machine time is equivalent to material cost and the cost of printing is close to the cost of finishing.

Table 3: BAAM Tool Cost Breakdown

	Time/material	Cost	Percentage
Preprocessing	2 hours	$100	5.3
Material	65 lbs	$520	27.8
Processing	2 hours	$400	21.4
Post processing (labor)			45.5
- Labor	2 hours	$100	
- machine	5 hours	$750	
Total	9 hours	$1870	

A similar analysis can be conducted for the same tool to be manufactured out of PPS on a Fortus 900 mc. First, material cost is approximately $650 for 93 cubic inches of material. The tool has 1725 cubic inches of material bringing the material cost up to $12,018. Production time with 0.020" nozzle will be 460 hours. An industrial FDM system capable of manufacturing this mold will cost approximately $350K with $35K/year service contracts. Assume that the system will be in service for 5 years with a $100K trade in value and a 4% interest rate, the machine will have a monthly cost of $7800. With a machine utilization of 50%, the hourly cost of running the machine, excluding overhead associated with utilities and space charges is $23/hr. Therefore, conservatively assume the total hourly charge rate for an industrial FDM system is $40/hr. This would bring the operating cost of the machine to $18,400 and a total part production cost to $31,368. This is still a very attractive cost for composite tooling but highlights how manufacturing time (460 hours for FDM vs 9 hours for BAAM) and low feedstock cost ($8/lb versus $180/lb) can result in a 17X reduction of AM costs ($31,368 for FDM vs. $1870 for BAAM) and 50X increase in production rate. Figure 6 through Figure 8 show the cost distribution between SLS, FDM and BAAM.

Table 4: FDM Tool Cost Breakdown

	Time/material	Cost	Percentage
Preprocessing	2 hours	$100	3.2
Material	65 lbs	$12,018	38.3
Processing	460 hours	$18,400	58.7
Post processing (labor)			2.7
- Labor	2 hours	$100	
- machine	5 hours	$750	
Total	9 hours	$31,368	

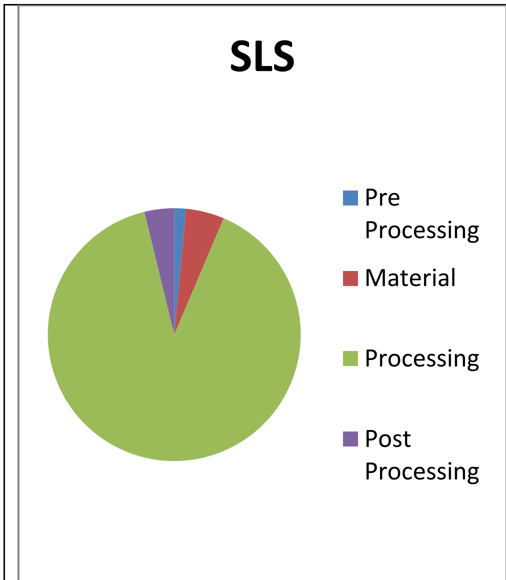

Figure 6: Cost distribution of SLS

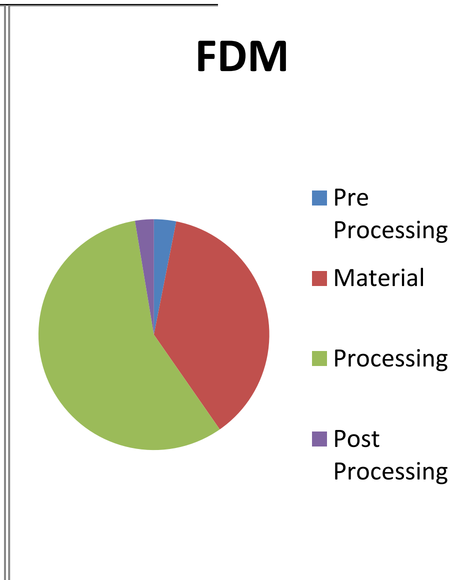

Figure 7: Cost distribution on FDM

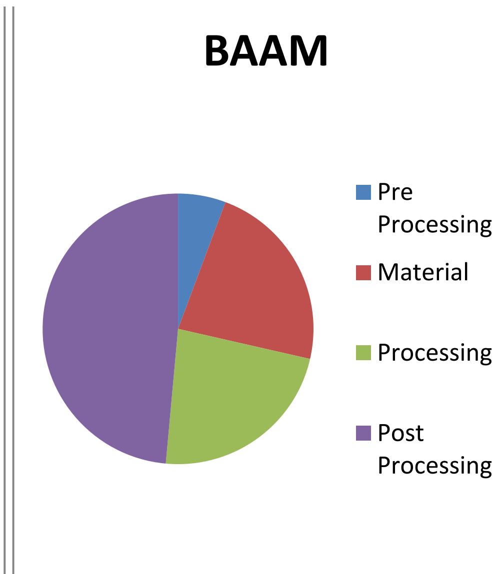

Figure 8: Cost distribution on BAAM

Conclusions

While additive manufacturing has tremendous potential, current performance metrics in size, speed and cost limit applications. One of the primary cost elements in AM is time on the machine. Recent efforts in polymer extrusion show that changing from fiber to reinforced pellets can significantly increase production rate and part size while simultaneously reducing cost. As an example, we show how BAAM can result in a 17X reduction in manufacturing cost and 50X reduction in manufacturing time for the composite tooling industry. Future work is exploring other tooling applications such as stretchform, hydroforming and stamping. Each process will have material performance requirements.

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