Challenges for the Adoption of Metal Additive Manufacturing Based on the Evolution of Polymer Based 3D Printing

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

3D printing can generally be divided into two categories based on what class of material is being processed, namely polymers and metals. The manufacture of polymers layer by layer is generally associated with the terms 3D printing and rapid prototyping. Meanwhile, advocates of metal 3D printing have adopted the term additive manufacturing (AM) to differentiate the process from its polymer-based cousins (Savini & Savini, 2015).

3D printing is not a new technology, with origins dating back to the 1970's and 1980's. The potential for this new technology was quickly realized, and patents began to be filed in the subject area. Chuck Hull patented stereolithography a method by which ultraviolet (UV) sensitive resin was selectively exposed to UV radiation to solidify it into a net-shape. Meanwhile, S. Scott Crump patented fused deposition modeling (FDM), whereby a material is melted and extruded into a specific shape which layer-by-layer creates a final part (Savini & Savini, 2015). Hull and Crump leveraged these patents into the founding of 3D Systems and Stratasys, companies which continue to shape the polymer 3D printing industry today.

Background

3D Systems and Stratasys initially were afforded virtually no competition, as they held patents on all the relevant technologies to create functional products to sell. This of course is as intended. Patents reward risk takers who develop technology by allowing them to make a profit on their designs. However, the lack of competition resulted in 3D printers priced on the order of hundreds of thousands of dollars, relegated to universities and corporations, inaccessible to ordinary consumers. Even so recently as 2009, a 3D printer would cost as much as $50,000, not much different from the 1990's when the first commercial systems became available. However today, you can buy a 3D printer with similar capabilities to one of its older siblings for under $1000, with many more barebones offerings approaching an astronomically cheap $100.

The reason for this incredible price drop lies in the expiration of the patents held by 3D Systems and Stratasys. Around 2010, these patents expired and allowed other companies to join the 3D printer business. Additionally, open-source development of 3D printing hardware and software allowed individuals around the world to make rapid improvements to the technology (Jones et al., 2011; Savini & Savini, 2015). The combination of commercial and open-source community efforts caused the cost of 3D printers to rapidly drop. However, this is all settled history. Why do we care about how this technology developed when we are already past the critical juncture?

Research Question

The answer lies in metal AM. As a virtue of the material, metal AM has the potential to completely change how we manufacture and distribute goods. With metal AM, parts can be made onsite rather than being delivered from a central supplier, easing supply chain issues. The technology can be used for repairing parts like on board submarines which cannot return to port (DebRoy et al., 2019; Dev Singh et al., 2021). It can be used to create custom parts with complex geometries unable to be manufactured with any other method. The use cases for metal AM vastly outpace that of polymer 3D printing due to the material system it operates with.

Metal AM is a much younger technology, and today stands in a similar place to where polymer 3D printing did in 2009. Patents are held by a few companies, and the commercial systems that exist cost anywhere from hundreds of thousands to millions of dollars (Walther, 2015). However, many of the patents relevant to these systems are going to expire in the next few years. By examining how patents and other factors affected the adoption of polymer 3D printing, can we understand what obstacles metal AM may face that could prevent it from reaching similar widespread use?

Approach

To answer this question, I will compare polymer 3D printing and metal AM on the basis of three different criteria. By highlighting the differences between these two processes we will be able to identify what difficulties metal additive manufacturing may encounter as it propagates more widely. Namely, I will compare it on the basis of technical complexity, safety concerns, and product demand.

To understand the difference in technical complexity, I will compare powder-based metal additive manufacturing with polymer FDM, breaking each hypothetical machine into their base components, and comparing the total cost associated with each. For safety concerns, I will identify whether metal AM has any potential safety considerations that exceed that of polymer 3D printing, and what equipment and training would be needed to offset these concerns. Lastly, to understand product demand I will look at what consumers, including large corporations, universities, small businesses, and individuals, currently lack in regard to the 3D printing space and evaluate whether metal 3D printing could fill these needs. Additionally, as part of this analysis I will seek to understand whether certain stakeholders such as the federal government or corporations may take issue with the proliferation of this technology.

Methodology

As my approach is split into three different criteria on which to compare metal AM with polymer 3D printing, my methodology is also threefold. For the first, we are seeking to understand the costs associated with each technology. As such, I will be looking at the original patents for FDM printing and powder bed fusion (PBF), one of the metal AM techniques at the forefront of development. This will help identify what the original patent holders had in mind as the key components of their inventions. After identifying these key components, I will look to do a cost accounting of these parts as they currently stand, as well as whether we can expect any change in these costs. In terms of safety considerations, I will be drawing from a combination of personal experience with both FDM and PBF, and literature regarding the safe operation of these machines. Lastly, I will analyze whether cheap metal 3D printing would have any demand amongst individual consumers and whether other stakeholders such as companies and governments may take issue to the technology's further spread.

Technological Cost

To describe patents simply, they are a method by which inventors are able to disclose their inventions but exclude others from developing the technology for commercial gain. They are meant to reward innovation and the spread of knowledge without copycats from harming the originators of a technology. As a result, it is not surprising that both the original patents for fused deposition modeling and selective laser sintering (SLS, the first patented form of PBF) are filled with generalities. Scott Crump's original patent for FDM 3D printing, "Apparatus and Method for Creating Three-Dimensional Objects" describes a moveable head that deposits a material to build up a 3D object (Crump, 1992). It does not specify what motion system would be used to move the moveable head and lists a range of materials it could deposit including waxes, thermoplastics, epoxies, molten metals, glass, and more. When describing how it would be controlled, the patents say that "preferably" the movement would be controlled via computer numerical control (CNC). In short, any system that has a head depositing material to make an object would fall under the purview of this patent. The first SLS patent by Carl Deckard is a little more specific. It describes a system where a laser is directed by computer-controlled mirrors onto a layer of powder to selectively sinter a mass, which is then covered by powder deposited in a new layer by an unspecified mechanism (Deckard, 1989). The new powder layer is then sintered to bond it to the previously sintered mass with the process repeating to build up an object. The patent still covers a wide range of materials including ceramics, plastics, metals, and polymers.

Narrowing Things Down

From these two patents, what the critical technologies for operation are for FDM and PBF processes is not immediately clear, besides both requiring a computer-controlled motion system and PBF needing a laser. Part of the issue is caused by the lack of specificity in terms of what material each process works with. For our purposes we will limit FDM printing to polymers, specifically thermoplastics which can be reshaped and reused by heating them up, and PBF to metal powders, with the justification that these are what modern FDM machines work with, and this paper is on the subject of metal AM respectively.

FDM Requirements

These material requirements have obviously impacted the design of modern FDM 3D printers. Thermoplastics take the form of a filament that is pushed through a heated nozzle that moves around and deposits plastic to create a 3D object (Carolo, 2022). Based on this, you would be led to believe that a heated nozzle and a computer-controlled motion system is all you need to 3D print an object with this process, but that is not completely true. Most thermoplastics used in 3D printing end up contracting, which causes the final part to warp and deform, potentially causing complete failure. This limits printing to much smaller objects, or to a few specific materials, limiting the usefulness of FDM greatly. To prevent this warping and print larger parts out of more materials, the temperature of the plastic needs to be carefully controlled. For this reason, Stratasys also patented the use of a heated chamber to regulate the temperature of prints, isolated from the systems electronics, as the heat could damage them (Sertoglu, 2021). The last of these patents only expired in early 2021, so up until recently an alternative solution was needed (Swanson et. al. 2004). In this effort, Chris Palmer invented the heated bed, which heats the surface that plastic is deposited on, preventing severe warping (Sertoglu, 2021). This allowed Stratasys's competitors and the open-source community to expand the list of usable materials and scale up the process, without breaking any laws. To summarize, an FDM printer consists of a motion system, electronics (motors, user interface, and microcontroller), and a few specialized components including the heated nozzle, also called the hotend, and the heated bed. None of these components are particularly complex to manufacture, and as such a cheap printer can cost as little as $100, with the upper end of the consumer market capping out at around $1500. The only major consumable in FDM 3D printer is the filament, which usually costs ~$25 per kilogram which will last 1-3 weeks depending on how often the printer is used (Hullette, 2022).

PBF Requirements

PBF technology working with metal powder is similar to FDM 3D printing in that the material is prone to warping, but only because the melted metal becomes so hot that heat cannot be conducted away quickly enough. However, this can be solved simply by printing additional structures to sink heat into or altering the scan path of the laser. More critical to ensuring the quality of the print is regulating the atmosphere of the print environment. At room temperature, most metals are not very reactive, but at high temperatures they become much more prone to oxidation. Oxidation would greatly reduce the mechanical properties of any part printed with PBF in a regular atmosphere. As such, PBF machines need to have a controlled, nonreactive atmosphere, which can be achieved by using an argon atmosphere (Selecting and Delivering Shield Gas in Laser Welding, n.d.). Most industrial machines are sealable and allow the user to pump down the entire built chamber with argon, but this uses much more of the gas, which can cost over $250 per tank. An alternative is to shield only the area being exposed to the laser with a nozzle blowing argon, but this will likely not be nearly as effective at preventing oxidation and may blow away the powder if the gas flow rate is improperly tuned. For this reason, this cost analysis will expect the machine to be in a sealable fully argon environment, with a new argon tank needed every 1-3 weeks for ease of comparison. To build a chamber with gas control, costs should range from around $250 to $500 depending on the size. Another consumable to consider is the powder itself. A common material used for metal additive manufacturing is stainless steel, which costs $90 to $120 per kilogram (Gregurić, 2022; Metal powders for additive manufacturing, n.d.). However, stainless steel is seven times denser than most polymers, so to receive a similar volume to that found on a FDM filament spool, it would cost closer to $735 on average. Still, the critical component that actually enables the printing of metal is the laser. For a laser suitable for AM, prices can range from ~$200 to $250,000 depending on the power required (Fiber Lasers, n.d. ; Fu, 2022). Lower power lasers take longer to melt the metal powders, and therefore extend the time required to print. However, from personal experience, the most time-consuming part of a PBF print is depositing a new powder layer, so a slow scanning speed is not much of a concern, and we can expect to purchase a laser for $200. The mechanical and electrical components of a laser PBF machine are not much different from that of a FDM printer, so to calculate the hypothetical cost of this machine, I will take the middle of the price range of the FDM 3D printers, $800, and by assuming a 50% profit margin on each printer, we can estimate the mechanical and electrical components will cost $400. Adding the cost of the sealed chamber and laser, we can guess that the cost to manufacture a cheap metal 3D printer would be around $1000. Once again, assuming that a commercial venture seeks a 50% profit on each printer, this hypothetical machine would retail for $2000. This number is not particularly offensive, especially to the so called "prosumer" 3D printer market, which can stomach prices up to $10000. However, the consumable costs are much more concerning, coming out to a total of ~$1000 every 1-3 weeks, depending on how often the user prints parts, with most of that cost coming from the price of metal powder. To rephrase, that would be paying the cost of the printer every six weeks at best.

Comparison

On the basis of machine cost, a metal 3D printer is likely more than double the price of its FDM counterpart ($2000 vs. $800), but it is still well within the range of acceptability for many consumers. However, the cost of consumables for a PBF machine is untenable for most consumers. A cheaper alternative to argon could potentially be nitrogen, but stainless steel can become embrittled when exposed to nitrogen at high temperatures (Selecting and Delivering Shield Gas in Laser Welding, n.d.). As such, much more research would have to go into optimizing a specific material for nitrogen atmospheres. Metal powders on the other hand are currently expensive, but as metal AM continues to mature, it is likely that prices will decrease as demand increases and processing technology improves (Dawes et al., 2015). In summary, it is likely still too expensive right now, but there is still potential for the future.

Safety Considerations

If metal AM is to take a similar path to polymer 3D printing and expand to individual user's homes, safety is a major issue to take note of. In FDM printing, the concerns are relatively minor. The user can get minor burns if they touch the nozzle or heated bed while printing, and airborne particulates released by the polymers during printing can have long term health effects, but this can be mitigated by placing the printer in an area with adequate ventilation (Parenti, 2022). The printer can also be a potential fire hazard, but this is not an issue as long as it is not placed near flammable items.

Metal PBF is different from FDM 3D printing in that it can be hazardous even before starting a print. This is the result of the material being used. Metal powder is potentially flammable and/or explosive, it is a respiratory, skin, and eye irritant, and burnt powder can be carcinogenic if not captured by a filter. Additionally, exposure to the laser can blind or burn the user (DebRoy et al., 2019). From personal experience working in a lab with PBF machines, whenever we handle metal powder outside of sealed metal bottles, we are required to wear respirators, long sleeves, and safety glasses to prevent exposure. The machines we use additionally are completely enclosed during operation with laser safe glass enabling monitoring of the print progress from the outside without risking exposure to the laser. These additional safety requirements compared to FDM 3D printing may additionally hamper the adoption of these machines by individual users, and instead make them more suited for laboratory or industrial settings.

Demand vs. Resistance

I am likely to be biased, but as someone who owns several FDM 3D printers, I will speak on behalf of individual consumer demand of metal AM. Polymer 3D printing is very useful, but it is still limited due to the material and the resolution of what can be printed. Plastic 3D printed parts have both limited strength and the tolerances that can be held are good, but not anywhere near what can be produced with laser PBF processes, as someone who has worked with those machines. If there was a cheap PBF machine that was safe to operate on the market today, I would purchase it, even if it could only produce small parts. The ability to make custom metal parts on demand in my own home would justify the purchase immediately to me, and I think others out there would agree.

Still, even if there was consumer demand for metal 3D printing, there would likely be resistance to widespread adoption. 3D printing in general has already sparked concerns about patent and copyright infringement, as with a 3D model anyone can print an object (Bechtold, 2016; Malaty, 2017). For example, Honda in April 2022 sought the removal of all 3D models containing the word Honda from the model sharing repository Printables (List, 2022). Most of the models in question were small replacement parts for things like car door handles, but if that would warrant that sort of response from an international corporation, how would they react to people 3D printing replacement parts for engines out of metal? Another party which may prevent the adoption of metal 3D printers for individuals is the US government, which has expressed concern that metal 3D printing could be used to make unregistered guns (Walther, 2015). This is likely a non-issue as 3D printing a gun is much more difficult than getting one through legal or illegal means, but just because an issue does not really exist does not make it impossible to pass legislation on it (Hamilton, 2021). There is definitely the potential for opposition to metal AM, but I expect it to be more reactive than proactive. Until a metal 3D printer makes it into many people's homes there is no actual problem to oppose.

Conclusions

Metal AM and polymer 3D printing have similar origins as technologies initially inaccessible to the general public due to restrictive patents. Despite this, I am not sure that metal AM will find a similar path to its polymer-based cousin. Demand for technology is there, and opposition is absent right now. Additionally, the safety concerns are real and important to address, but it should be noted that other 3D printing processes, notable SLA which uses toxic resins to print require similar safety practices to metal AM (Kočí, 2022). The limiting factor is cost, specifically the cost of consumables for printing like argon and metal powder. The second is likely to decrease in cost over time, but without major research developments the first will always be a major recurring cost associated with the process, unpalatable to most individual consumers. However, this is likely less of an issue for smaller organizations which may see the value of metal AM, and not be put off by the lifetime costs associated with a machine. So maybe we won't ever see metal 3D printers in the home, but maybe they'll be a common sight in garages and other workspaces. Either way, the potential for technology is there, and with the right push here and there, I see a bright future for it.

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