

Large Scale Metal Additive Techniques Review

A. Nycz*, A. I Adediran*, M. W. Noakes*, and L. J. Love*

*Manufacturing Systems Research, Oak Ridge National laboratory, Knoxville, TN 37932

Abstract

In recent years additive manufacturing has made long strides toward becoming a main stream production technology. Particularly strong progress has been made in large-scale polymer deposition. However, large scale metal additive has not yet reached parity with large scale polymer. This paper is a survey of the metal additive techniques in the context of building large structures. Current commercial devices are capable of printing metal parts on the order of several cubic feet compared to hundreds of cubic feet for the polymer side. In order to follow the polymer progress path many factors must be considered—potential to scale, economy, environment friendliness, material properties, feedstock availability, robustness of the process, quality and accuracy, potential for defects, and post processing as well as potential applications. This paper focuses on current state of art of large scale metal additive technology with a focus on expanding the geometric limits.

Introduction

Additive Manufacturing (AM) is a fabrication process of creating objects by digitally controlled deposition and bonding, layer by layer, directly from a computer generated model. The first commercial 3D printers appeared on the market in the 1980s [1]. Initially, polymers were the only available materials and the printers were very expensive. Nowadays, home printing enthusiast can purchase AM devices for much less than \$500. In addition, in the 2000s new generations of powder-based printers were introduced. This opened the possibility of fabrication of AM parts using metals and ceramics.

The most common type of polymer AM is Fused Material Deposition (FDM). This process relies on a printing head melting polymer and depositing material bead by bead, layer by layer. Despite the tremendous growth of the market and variety of FDM printer brands, the speed of the deposition hasn't change much until recently. Most common commercial printers can build parts at the rate of 1 inch³/h. The longest axis can reach a few feet [2].

The introduction of the Big Area Additive Manufacturing (BAAM) printer developed at the Manufacturing Demonstration Facility (MDF) of Oak Ridge National Laboratory in cooperation with Cincinnati Incorporated changed the status quo in respect to the size and speed of material deposition. The deposition rate can reach up to 100lbs/h, and the current maximum print envelope is 20x8x6 feet. This allowed for printing parts for new markets such as large tooling and automotive components [3-5]. As a proof of concept several fully functional objects were printed. Among them were vehicles (Strati, Shelby Cobra, Jeep, and Printed Utility Vehicle (PUV)), the Additive Manufacturing Integrated Energy (AMIE) demonstration mobile home, and large scale molds. The new process showed significant savings in energy, cost, and time compared to standard manufacturing methods.

It is believed that the same savings can be achieved developing large scale methods for metal AM. Currently, as in the polymer case, the time to manufacture a large scale, low production volume complex metal part might take months [6, 7]. In addition to time and cost there is also the factor of distance. The production site might be thousands of miles from the application site. It is believed that aviation, construction, mining, shipyards, large machinery and tooling could all be industries benefiting the most from this technology. Therefore, this paper reviews the current metal printing methods in the context of creating large parts.

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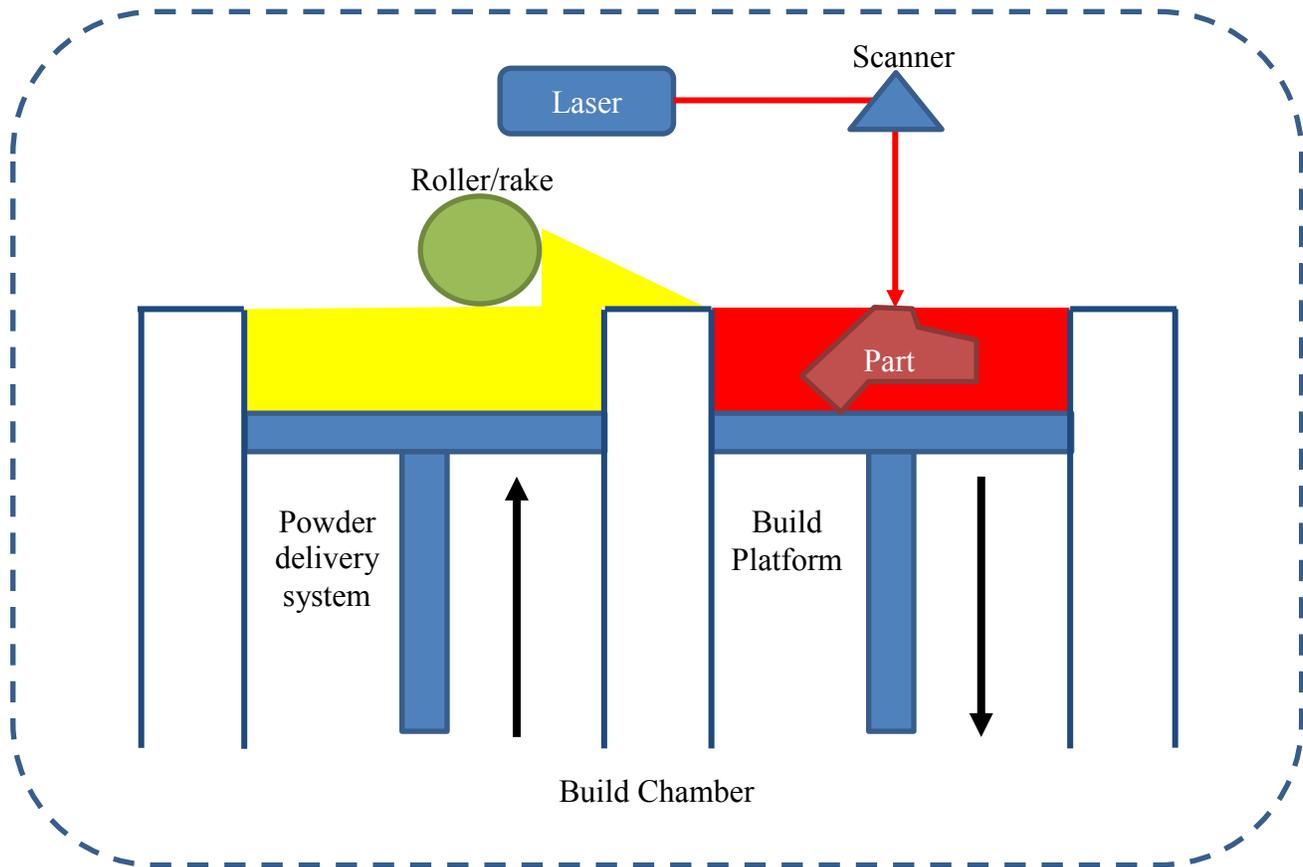


Figure 1. Typical powder bed system.

Defining large scale

In order to consider AM techniques for large scale manufacturing, first the scale has to be defined. Considering the size of machinery and the target industry it is believed the large scale can be defined as parts having its longest axis length at minimum 3-6 ft long (1-2 m).

Most powder bed systems are limited to 500mm in the largest axis (less than 2 ft) [8], while the most common volume is approximately 250x250x300mm.

Another critical factor for printing large scale is the deposition speed. It has to be sufficient to build a part in reasonable time. In order to depict this problem, consider a part of 1ft³ in volume. The deposition rate of powder bed systems is in the range of 1in³. In this case it would take 1728 hours or 72 days of continuous operation to build a part of such volume. Considering the maximum speeds of current selective sintering systems (SLS), which is 2 in³/h, or electron beam melting (EBM) that is 5 inch³/h, the time drops to 14.4 days. These print times do not include any of the typically mandatory pre or post processing [9].

Types of metal deposition techniques

Metal additive methods can be divided into two major groups based on the material delivery—powder beds and direct energy deposition (DED). Based on the energy source the powder bed group can be further divided into laser, electron beam and binder jet. The DED group can be divided similarly into laser, electron beam and arc welding subgroups.

The powder bed system relies on a complex arrangement of actuated bed, powder delivery, and sintering/melting mechanism (Figure 1). First, a layer of powder is spread evenly onto the bed, and then the energy source melts the desired portion of the powder to form the part. After that, the bed is lowered by one layer height, the powder spread over the bed and the cycle repeats. The deposition chamber might require a precisely controlled temperature, inert gas or vacuum.

Depending on the energy source the powder particles are melted together using a laser beam, electron beam or post cured in an oven. The latter is the case in the binder jet process. During the first phase the powder

is joined together using a binding agent (glue). During the second phase the formed part is cured (sintered) and optionally infiltrated with another material to remove or reduce porosity [10, 11].

In the case of DED methods there are three major energy sources—laser beam, electron beam and arc. The major difference is in the fact that the material is delivered and deposited directly onto the hot spot of a focused laser or arc weld pool. This requires modification of the print head, precise continuous feedstock delivery, and does not have support media for building overhangs.

In case of the arc weld methods the melt pool can be created with different kinds of source types: gas tungsten arc welding (GTAW also known as TIG or tungsten inert gas), gas metal arc welding (GMAW also known as MIG or metal inert gas), or plasma welding (Figure 2).

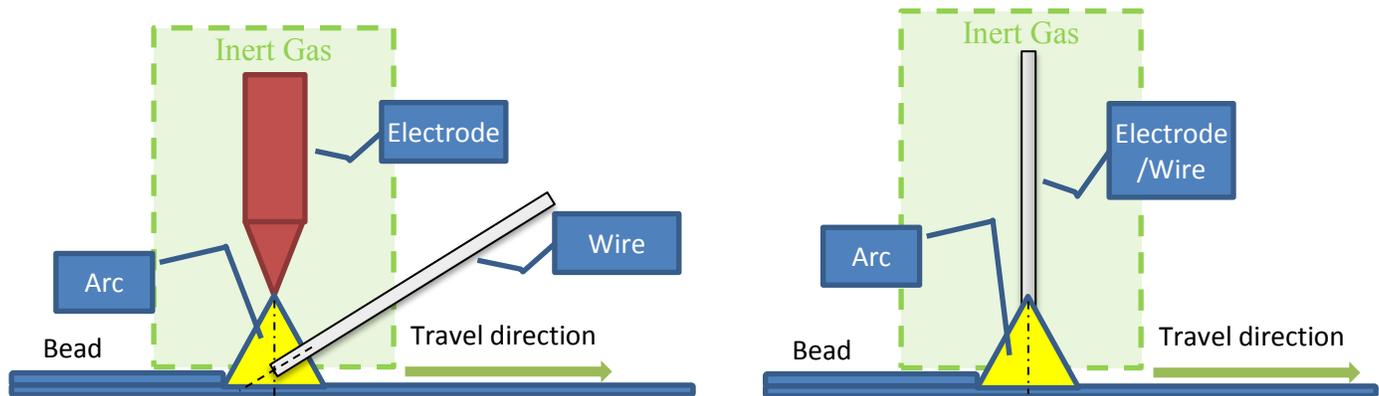


Figure 2. TIG (left) and MIG (right) schematic.

The maximum reported speeds for the DED methods are 5-6 lbs/h (steel) for a laser source and up to 20lbs/h for an EBM source. Arc welding AM techniques, depending on the type, are typically in the range of 5lb/h but can range up to 30lb/h [12, 13].

Considering the DED methods and their maximum claimed deposition speed the time to print a 1 ft³ part would drop by a factor of 10 to 40 and the part could be built in under 24h. One cubic foot of steel weighs about 490lbs (222kg). This is within the low range of many heavy equipment parts [14, 15]. The ability to print multiple cubic foot parts in a reasonable time scale makes large scale AM parts feasible.

Problem discussion

Potential to scale up

In order to build larger parts the current technology geometric limitations must be considered. Powder bed systems are discussed first.

Scaling up a powder bed system requires a larger bed system to produce larger parts. Considering the current size, the powder/part container would have to increase in size at least 2-4 times to start. This would also require a tremendous increase (at substantial cost) in the amount of unused powder in the bed just to fill it up. Although feasible, the scaling does not appear practical. Every increase in size would also introduce mechanical, control or process issues and increase the cost of the printer.

DED AM systems might require a vacuum chamber like EBM technology. Although it is possible to make the vacuum chamber progressively larger, similarly as in the case of powder beds this has practical limits. Other system such as laser-based might require an inert gas environment. This requirement is not as restrictive as vacuum since, the most common inert gas, argon, is readily available, low cost, heavier than air, non-toxic, and the infrastructure to create the inert environment is not as complex.

The arc welding methods (TIG, MIG) require only a protective envelope of inert gas flow around the arc and the deposition area. This is achieved through the use of an integrated torch containing electrode, cooling, and shield gas. It is a mature system, and the torch does not have to get substantially larger to build bigger parts. In order to make larger parts in this case, a large gantry system or robotic arm or a system of robotic arms is needed. If the base plate for the part to be built is mounted on auxiliary axes, any range of motion axis limitation can be removed. There are therefore no tight geometric limitations on the maximum size of the part [8].

Economy

When considering the economy of these technologies three factors should be considered—feedstock cost and availability, invoice price, and cost of operation.

The two major feedstock types are powder and wire. Wire is cheaper than powder for all metal types. Its price can lower by as much as 50%. The latter is the steel wire case. In addition, there are hundreds of types of wire available compared to tens of types of powder [16].

The prices of commercial metal 3D printers start at about 100k\$ - \$500k\$. The larger the printer build volume, the more it costs [17].

One of the most important factors often missed is the ability of the device to pay for itself which manifests in the printing speed. The more parts it can manufacture per unit of time, the faster it pays for itself. In a case of a very efficient process/device the invoice cost of the printer becomes a secondary factor [18-20].

Feedstock, environment and safety

Additional critical aspects also include the environment and safety. Metal powders can be dangerous to humans and the environment. By nature very small particles can be harmful to breathe, and some can be toxic as well. The powder also poses a fire and explosion danger; handling, processing, and storing can be an issue [21-23]. In contrast, wire under normal conditions is safe to handle and does not pose any direct danger.

The metal AM process itself may create dangerous fumes that will require air filtering and conditioning. Systems for air purifying are well understood and can be applied for a reasonably low cost compared to the price of the printer.

Energy efficiency

Energy efficiency is becoming a serious issue in the 21st century. Climate change concerns, pollution, and the cost of energy are driving development in energy efficient manufacturing methods. In general AM is considered more efficient than traditional methods in many applications. The three major energy sources for metal AM have drastically different energy efficiency levels. The laser source has a reported 2-5% efficiency while EBM can reach up to 15-20%. Arc welding technology can be as efficient as 90% [24-26].

Accuracy

Laser and electron beam powder beds offer the most precise types of metal part fabrication. Print resolution is typically $\pm 0.1\text{mm}$ to $\pm 0.2\text{mm}$ [9]. The DED methods offer precision an order of magnitude worse. The faster the process and the higher the deposition rate the lower the precision it offers. On the other hand, most parts require some post processing (machining) anyway. Precision may not therefore be as critical.

Other factors

There are additional factors to consider when looking for the metal AM process of the future. Among them are mechanical part properties, residual stress or porosity/voids. The robustness of the process also plays a key role in its efficiency. The time required to start a print job and retrieve the part after printing might be significant. The required skills and training of the operators might become a cost and time factor as well.

Conclusions

Large scale AM is still in its infancy. There are a few commercial devices focused on very narrow applications that have a large profit margin. None have yet achieved widespread use. Based on this study it appears that arc welding methods may have the best potential to scale up. However the technology requires substantial further development and refinement.

Laser and electron beam applications of DED have proven high deposition rates but are fairly limited when it comes to scaling up with EBM being the tougher case. Powder bed technologies offer high precision but low deposition rates with limited potential to build large parts at reasonable cost and in reasonable amounts of time. Based on price, availability, and ease of handling the preferred type of metal feedstock seems to be wire instead of powder.

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