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# Review of Current Problems and Developments in Large Area Additive Manufacturing (LAAM)

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## Abstract

Large Area Additive Manufacturing (LAAM), also known as Big Area Additive Manufacturing (BAAM), is a screw extrusion, pellet-fed additive manufacturing technology. The large build area, rapid build speed, and inexpensive pelletized feedstock of LAAM are major advantages over conventional AM methods. LAAM has a large variety of applications in areas including energy, automotive, aerospace, high volume production, and composite molds. However, LAAM is not without its challenges. The largest challenges LAAM faces include mechanical properties, uniformity and precision, and predictability of composite material properties. The goal of this paper is to present current research regarding challenges in LAAM, methods of addressing those challenges, developments, and applications, as well to highlight further research to be done.

Keywords: Big Area Additive Manufacturing, Oak Ridge National Laboratory, Cincinnati Inc, Large Area Additive Manufacturing, Large Format 3D Printing, Hybrid Manufacturing, Functionally Graded Material, Composite Additive Manufacturing

## Introduction

Additive manufacturing (AM) is a method of producing parts by selectively adding material layer by layer. One of the most common AM technologies is fused filament fabrication (FFF), also known as fused deposition modeling (FDM), which creates parts by selectively extruding filament in sequential cross-sectional layers to form a 3D part. This technology makes it possible to create complex geometries unavailable with conventional manufacturing methods without the need for expensive tooling. However, FFF and most other AM technologies are unsuitable for high-volume manufacturing due to slow build speed, low max build volume, and relatively expensive material cost.

Large Area Additive Manufacturing (LAAM) aims to overcome the disadvantages of other AM methods by utilizing a pellet-fed screw extrusion design like that seen in conventional extrusion molding. Much of the research in LAAM comes from Oak Ridge National Laboratory (ORNL) in partnership with Cincinnati, Inc., who developed the Big Area Additive Manufacturing (BAAM) system. LAAM works similarly to FFF in that it takes a CAD model and digitally slices it into cross-sectional layers. Toolpaths are then generated using G-code for the printer to follow, generating each layer sequentially on top of the preceding layer. However, LAAM demonstrates significant advantages over FFF. LAAM can build parts of up to about 8 x 20 feet, many times the max build volume of FFF machines. LAAM nozzle diameters range from .1 to .5 inches, allowing for substantially higher flowrate than other AM machines. LAAM's screw extrusion design allows it to use pelletized feed stock, which reduces material cost by up to a factor of 20 [1]. These benefits make high-volume production using LAAM viable.

LAAM also features the ability to print with composite materials and to use multiple materials during a single print. These capabilities enable the production of high-performance products and cost-effective material design. The applications of printing with composites and multiple materials with LAAM will be explored in this paper.

Despite the benefits of LAAM, it also has its challenges. Large bead width and flowrate results in poor surface finish. The extruded beads tend to be porous, and the circular profile of the beads results in voids between upper and lower portions of beads throughout a single layer, contributing to weaker parts. Parts fabricated using LAAM also exhibit weak interlaminar strength, a problem associated with virtually all AM technologies. Lag time between screw velocity changes and nozzle flowrate results in inconsistent bead widths and a poor z-seam. Further problems include part weaknesses between material changes, anisotropy in composite materials, limited data about material properties, and part/mold precision. The above problems will be discussed as well as solutions presented from various studies.

## Mechanical Problems and Solutions

### Gaps and Voids

LAAM builds objects by extruding material onto a surface or preceding layer. A single layer is created by extruding the outer profile (wall), then filling in the interior space with a preselected pattern such as zigzagging lines. The extrudate lines are known as beads. These beads have a naturally circular cross section, which leaves triangle-shaped gaps between the upper and lower portions of adjacent beads. These gaps result in lower mechanical strength in the X and Y directions.

A solution to the inter-bead gap problem is known as z-tamping [1]. Z-tamping involves attaching a platen around the orifice of the extruder. This platen vibrates at about 20 Hz during the printing process, flattening the bead while it is still hot and pliable. The beads fill in the gaps as warm material is pressed into any nearby vacancies. This process solidifies layers and creates greater cross-layer strength. Duty, et al. found that z-tamping significantly increased the strength in sample parts by about 10% in the x direction and 100% in the y direction.

### Interlaminar Strength

The problem of interlayer adhesion is common to additive manufacturing, and LAAM is no exception. Weak interlaminar bonds are formed as preceding layers cool toward ambient temperature before proceeding layers are deposited. The cooled material does not bond well with the hot, freshly extruded material. Low interlaminar strength corresponds to low strength in the z direction. This problem is exasperated as layer size and layer build time increase.

Two solutions are presented for this problem. The first is a technique called z-pinning [2]. This technique involves extruding “pins” of material aligned to the z-direction throughout a part to increase strength in the z-direction. To accomplish this, a part is printed in a conventional way, except cylindrical voids are left throughout the infill of the part. These voids span about six layers in the z-direction. Upon completion of a layer containing the end of a gap, the nozzle moves to the void and extrudes material into the void to entirely fill it. This is repeated for each pin in a part. Pins are alternately spaced in the z-direction to avoid every pin starting and ending on the same layers and to avoid leaving no reinforcement between pin start and end layers. The study shows that z-pinned parts experienced an increase in tensile strength in the z-direction of about 10% over parts with solid conventional infill and 51% over parts with sparse conventional infill.

Another method of increasing interlaminar strength is to reheat a preceding layer before fresh extrudate is deposited on it. Kishore, et al. [3] use an infrared lamp combined with two pyrometers, one on either side of the lamp, to heat the material above its glass transition temperature just before the extruder passes over it. The two pyrometers allow the temperature of the part to be actively regulated during the printing process. This technique proved effective in improving the interlaminar bond strength of the printed parts by up to twice the strength of unheated parts.

### Surface Quality

A common disadvantage in AM generally is poor surface quality. Layer-by-layer manufacturing of a part results in visible and unsightly layer lines. In the case of LAAM, the large width of extrusion beads results in exceptionally poor surface finish. LAAM part surfaces are inconsistent and ridged. This is undesirable when the aesthetics of a part are a concern and when high surface precision and tight tolerances are needed.

One solution to the surface quality problem is to machine the part after printing. This hybrid manufacturing method was used in the production of a wind turbine mold [4], boat hull [5], and a car body [6]. Advantages of this hybridized additive/subtractive approach to manufacturing is that the strengths of both can be capitalized while minimizing or eliminating disadvantages. Parts can be printed using LAAM, then machined to precise tolerances. Machining will remove the outer ridges and anomalies left from the additive process, leaving a smooth finish behind.

However, machining parts after printing requires additional setup and cycle time. It is therefore suitable for prototyping, but not necessarily for high volume manufacturing. Obtaining high quality surfaces using only the LAAM system without a second process would save time and effort. In this paper, two methods are discussed to accomplish high quality surfaces using LAAM.

The first method to accomplish high-quality surface finish is to use a large diameter nozzle for internal portions or non-essential surfaces of a part and switch to a smaller diameter nozzle where surface quality and tolerance matter [7]. This method maintains the high build rate of LAAM by using the larger nozzle to deposit material quickly. Using a smaller nozzle at the edges and critical features of a part increases the print resolution at those locations.

The study suggests two ways of changing the nozzle orifice diameter mid-print. The first is to use multiple nozzles and alternate or change out nozzles where needed. The second method is to use a multi-orifice nozzle. A patented design for a multi-orifice nozzle uses an internal poppet valve which, in its upper position, allows material to flow around it and through the larger extrusion nozzle [8]. When lowered, the poppet blocks the flow of material through the larger nozzle. Material is then forced through drilled holes in the poppet and out through the poppet's smaller-diameter orifice. This innovation allows the bead width to be changed dynamically throughout the build of a part to increase resolution in critical areas and maximize build rate in non-critical areas.

The second method to accomplish high-quality surfaces is called z-tamping [1]. This technique was discussed earlier in this paper as a means of addressing voids between beads. Z-tamping also positively effects surface finish because inter-bead voids can result in porosity or linear defects on the outside surface of a part. If the part is machined, the voids may be exposed, marring the finished surface. Z-tamping compresses beads directly around the extrusion nozzle as they are deposited, flattening the material and pressing it into nearby pores. Thus z-tamping not only increases the strength, but also the consistency and surface quality of a part.

### Uniform Bead Width and Z-seam

LAAM works similarly to FFF, except that LAAM is scaled up by an order of magnitude and uses a pellet-fed screw extrusion design similar to that used in extrusion molding. This design causes difficulty in maintaining uniform bead width throughout a print. Lag time exists in both extrusion molding and LAAM between screw acceleration and material flowrate at the die or nozzle. As a result, bead or part width is nonuniform during startup and shutdown. For LAAM, beads are also inconsistent when the gantry slows for a change in direction and screw velocity is adjusted to compensate. These inconsistencies around corners cause globs of material and unsightly z-seams to appear on the surface of a part.

Solutions have been explored to address these issues. The first solution is similar to a technique used in extrusion molding where the nonuniform portions of part produced during machine startup and shutdown are simply removed. However, material deposited in a 3D print cannot simply be removed. Instead, material can be redirected during startup/shutdown and later be disposed of. Oak Ridge National Laboratory developed a "posiverter" which opens an exhaust valve through which material can flow during start/stop until steady state flow is achieved, at which point the valve closes, extrusion begins, and the printhead begins moving simultaneously [7]. This technique helps alleviate severe inconsistencies at the z-seam.

The study also discusses the use of a lead filter to modify commands to the extruder when the gantry accelerates or decelerates for a direction change. The study examined the effect of nozzle flowrate latency during screw velocity changes around the corner of a part. This latency causes material to initially glob up as the gantry slows, then thin out as a result of screw deceleration and gantry acceleration. The study developed models to predict the timing necessary to compensate for that latency. Those models are implemented via a lead filter to the machine. The lead filter adjusts the timing of extruder speed changes so that the actual nozzle flowrate corresponds with gantry speed changes. As a result of this study, a consistent bead width around the corner of a part was accomplished.

Another study examines the use of a laser profilometer and a thermal camera to enable real-time defect correction [9]. These tools are used to generate an accurate height map. Then, issues such and underfills, overfills, and low layer time can be corrected in real time. The study found that this technique improved the uniformity and quality of prints. However, wide use of this technique is inhibited by the lack of slicing software integration. Slicing software support for this technique would enable further study.

A final technique used to improve uniform bead width is z-tamping [1], which has been discussed in prior sections. Z-tamping involves a vibrating platen around the extruder nozzle which flattens beads as they are deposited. This technique helps eliminate transients, globs, and voids.

## Understanding Properties of Materials

An important issue in LAAM is knowing the properties of printable materials. Understanding the behavior of parts fabricated using LAAM across various materials is critical to assessing the viability of using LAAM for specific applications. Examples of these applications, such as vehicle bodies, are discussed later in this paper.

Material property data for parts manufactured using other manufacturing methods does not necessarily apply to parts made using LAAM. Therefore, studies have been conducted to better understand the properties of various materials in LAAM, including polymers, composites, and multiple materials. These studies provide data on material properties such as strength and cost and provide comparison tools for material selection. Studies related to the properties of polymers, composites, and multiple material structures will be discussed.

Duty, et al. studied the mechanical behavior of LAAM parts in each of the x, y, and z directions [1]. They found that the porosity between and within beads and weak interlaminar adhesion result in substantially weaker parts. These issues are discussed in detail in section 1.1 and 1.2 of this paper. They also tested and compared ABS and ABS-CF deposits. In terms of stiffness, they found that pure ABS performed quite similarly to the injection mold benchmark in every direction. While CF-ABS was stiffest in the x direction (parallel to the axis of the extruded bead), its stiffness in the y and z directions fell dramatically below the injection molding benchmark to equal the stiffness of pure ABS. In terms of strength, pure ABS was somewhat weaker in each direction than its injection molding counterpart. CF-ABS was somewhat weaker than the injection molding reference in the x direction, but significantly weaker in the y and z directions. CF-ABS even falls below the strength of pure ABS in the y and z directions. This is likely due to high internal bead porosity of fiber-reinforced parts. Optimizing the extrusion process to improve composite material properties is an area of ongoing research.

With respect to cost, Duty, et al. note that the use of pelletized feedstock can reduce the cost of material by a factor of up to 20x over traditional FFF filament. Using pelletized feedstock also opens the material portfolio of BAAM to essentially any of the materials traditionally used in injection molding. Sudbury, et al. also discuss the cost-saving effectiveness of LAAM [10]. Their study involved the fabrication of several sandwich panels of various materials, including ABS, CF-ABS, and functionally graded materials (FGM). FGM is a hybrid material in which material constituents vary gradually over the span of the part, allowing for cost-saving optimization of the properties of the part. The study concludes that FGM allows for a decrease in weight by about 5% and a decrease in cost of about 48%.

Other studies discuss the use of engineering-grade plastics such as polyphenylene sulfide (PPS) [11] and polyether ether ketone (PEEK) [12] in LAAM, as well as fiber-reinforced versions of these materials. These plastics have great potential for use in high-grade applications. However, the properties and classifications of these materials within LAAM is limited. Most published research limits its study of LAAM materials to ABS and fiber reinforced ABS. When properties of other materials are mentioned, the properties often come from injection molding references, not LAAM, which is the case in Sudbury, et al [10]. More research is necessary to effectively expand and classify LAAM materials.

## Other Applications & Demonstrated Applications for LAAM

This section outlines a variety of useful applications that have been demonstrated for LAAM not otherwise included in the paper.

### Multiple Materials

The use of more than one material in a single print is an area of particular interest in LAAM because it allows for greater flexibility in part design. The flexibility can lead to cost savings and improved material performance. For example, a part that needs enhanced strength in only one region may be printed primarily in ABS, with the critical region being printed in carbon-fiber infused ABS (CF-ABS). This way the part can achieve required strength specifications without needing to print the entire part in a more expensive material.

A problem associated with multi-materialism include poor adhesion between material changes. Discrete material changes between layers results in weak bonding and fracture. Various studies attempting to improve bond strength between layers of differing materials found that single-material parts outperformed multi-material pars with discrete material boundaries regardless of the technique used to improve adhesivity [13]. FGM has the potential to remedy this problem through gradual alterations in material constituents. FGM is discussed already in this paper as a means of reducing cost through optimization of the material constituents of a part. This study investigates a method of accomplishing gradual material transitions. By switching the material feed between 2 hoppers, the study finds a repeatable relationship between distance from hopper switch and weight percent composition of sample material. This allows correct planning and implementation of FGM for a part.

### Molds

A major area of research in LAAM is its use in creating composite parts and molds. The use of composite material in LAAM allows for the fabrication of much stronger parts. Using LAAM to create composite molds is an area of particular interest because it has the potential to lower costs and production time. The following examples demonstrate the applicability of LAAM molds in the energy, construction, aquatics, and automotive industries.

One example of the use of LAAM to produce molds is its use to create wind turbine molds. This project proves the feasibility of using BAAM to produce large structural components in a machining center or even on-site. However, Post, et al. point out that there is a need for continuous fiber filament for high strength applications [4].

Another example of the use of molds in LAAM is provided by NLN, et al [14]. This study uses LAAM to create composite preforms for compression molding. Preforms are printed in the general shape of the finished product and compressed to final shape. The combination of AM and compression molding (CM) allows complex parts to be produced that would be difficult to make using conventional methods.

A third example is the use of LAAM to print forms or molds for concrete structures [15]. The study provides bridge pier cap as an example of structures that could be created using LAAM molds. This study notes that while this process is not as cheap as using wood forms, LAAM forms can handle more complexity.

Other studies feature the use of LAAM to manufacture a boat hull mold [5] and an oil pan [16], demonstrating the applicability of LAAM in the aquatics and automotive industries.

### Automotive

There are numerous demonstrated applications of LAAM in the automotive industry. For example, Cincinnati's Big Area Additive Manufacturing (BAAM) system was used to print a full-sized electric vehicle in two days for less than $4000 [6]. This accomplishment demonstrates the potential of BAAM to manufacturing large products (cars, turbine blades) at a low cost. In a similar study, analytical computation methods are used to simulate printing of a car [17], which is more economical than trial and error. This study shows the benefit of simulation in LAAM to aid in design and planning and further lower costs.

Another demonstration of LAAM in the automotive industry was the experimental production of an oil pan [16]. ABS-CF was used to print a mold for the oil pan. Because too much warpage occurred when attempting to only use one process, a hybridized approach was necessary to achieve necessary tolerances. BAAM was used to create the bulk of the product and a smaller printer was used to create high-detail areas. This study shows the potential of combining several aspects of LAAM discussed elsewhere in this paper, such as composite materials and mold production, to fabricate functional parts quickly and at low cost.

## Conclusion

The large build area and screw-based extrusion design of LAAM enables printing of large parts at a much faster rate than conventional AM methods. However, LAAM encounters problems of porosity, interlaminar weakness, and imprecision in surface finish and bead width. LAAM also faces problems of anisotropy and mechanical weaknesses in composite materials.

Further areas for research include ways to address the porosity, anisotropy, and weaknesses present when extruding fiber-reinforced materials. Composites are extremely useful with LAAM because of their ability to form functional molds and parts. Improving the properties and predictability of composites is therefore a high priority.

Another area for future research is material property classification for LAAM. LAAM is compatible with a wide variety of materials, including many materials used in injection molding. However, material property data is not readily available for those materials when used in LAAM. Understanding the properties of those materials in each of the x, y, and z directions of a printed part will allow for better part design and planning.

Finally, the use of multiple materials in LAAM is an area for future research. Functionally graded materials are more extensively studied in FFF, but their use in LAAM is still limited. Exploring the use of FGM and its applications in LAAM could enable more versatile part design, cost savings, and material properties.

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