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Optimizing quality in precision additive manufacturing: A systematic approach

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Abstract

Precision Manufacturing has significant applications in many advanced technology fields. The development of additive manufacturing (AM) technology leads to numerous possibilities in this area. However, quality control is important in applying precision AM lab research to ready-to-use technologies in industries. This paper reviewed the current precision AM technology and advancement of materials, and then examined the factors that affect the quality aspects of additive manufacturing products, a systematic approach of quality control in AM is proposed and each step in the system was discussed in achieving optimized quality of high precision AM products.

Keywords: precision manufacturing; additive manufacturing; quality control; systematic approach; design for manufacturing

1 Introduction

In additive manufacturing, previous research work focused extensively on material selection, comparison of different process parameter configurations, and effect of those on dimensional accuracy or mechanical performance or mechanical performance with sporicidal design suggestions. Several articles reviewed concentrated on 3D printing applications of a specific material or applications on medical devices. Currently, no study has examined precision AM (additive manufacturing) quality systematically from a comprehensive perspective. However, with the rapid development of AM technology and immediate adoption to industries, a quality system needs to be established to help achieve optimal quality. This research aims to bridge the gap and propose a holistic definition of quality in Precision AM, and provide a systematic approach for quality optimization in precision AM. Furthermore, the study emphasizes feedback in the system and clear communication among designers, technicians, and users on quality outcomes and improvement.

The term precision machining is an elusive concept. It refers to manufacturing parts with extreme accuracy. There are no set tolerance ranges that clearly define a workpiece as high precision. Jobs considered high precision can range from having to consistently hold a 5-micron tolerance for a large batch of parts to parts with tolerances at micron level for a heart valve, to surface finishes of surface roughness of 0.8 microns which match the industry requirements placed on blade machining. Part size and job volumes are determining how challenging a particular tolerance is. Furthermore, high precision measuring systems are needed to verify the dimensional accuracy.

Quality is paramount in manufacturing; however, quality is not all about dimensional accuracy. The focus of the manufacturing stage alone cannot achieve high quality; quality is the outcome that is generated by a whole system, where the feedback is essential in each loop. 3D printing technologies are bringing fascinating changes in manufacturing with the possibility of making high-precision parts under tight tolerances.

2 Advantage of AM in precision manufacturing

2.1 Spatial-free form design

The first and most incomparable advantage is that AM enables intricate designs. Since AM combine materials by addition instead of subtraction, hollow, spatial free-form surfaces are made possible in additive manufacturing. AM can produce complex geometries that are difficult in miniaturized molding or die casting or traditional machining processes. Therefore, traditional, structurally complicated items for the aerospace industry or the automotive industry that heavily rely on their foundry partners to produce prototypes can now have extremely short development cycles. On the other hand, this feature enables medical device manufacturers and aerospace industries to reduce long lead-time of ordering prototypes from their foundry partners.

2.2 Concurrent printing

In AM, three dimensional models are divided into many thin two dimensional layers and were built layer by layer vertically, the feature of concurrent printing makes it possible that multiple parts can be built in one batch, costing little or no extra time. Powder bed fusion and Vat

Photopolymerization technologies can produce the items in one batch with precisely the same quality and features, much faster.

2.3 Near net-shape process

AM is a near-net-shape process, and it does not need to start from an entire piece of material, but instead, products are built by adding the features layer by layer. Therefore, it is a single-step process, no casting, no forging, no CNC machining, etc., fewer operations, less material waste, hence less cost. Furthermore, combined with the advantage of enabling hollow design in the parts, the materials used can even be less, especially for the expensive metal alloy products; finished products can be much lighter, which a promising attribute in aerospace components.

2.4 Single-step manufacturing

Traditionally, material fabrication involves multiple steps, and each of the engineering processes, including cutting and assembly, adds more features to the final product. The fascinating fact about AM is that it is a single step process. There is no need for die casting, forging, cutting, CNC machining, and such. A single-step process means no intermediate stage in between and no work-in-process, and it is much faster to complete and manage the entire manufacturing work. Therefore, the idea of quickly repairing worn or broken gas turbines instead of a full-part replacement can be made possible by using AM.

2.5 Cost-efficient for customization

AM provides an extraordinary advantage of affordability and cost-efficient for customized products. Customized products can be cost-effectively realized by simply inputting customized design files and setting up printing parameters without using additional fixtures and jigs. Low cost and efficiency are critical in the medical industry for making implants, and personalized surgery guides. Therefore, precision AM provides a promising venue for customized implants and other products that are highly needed to be personalized in healthcare.

3 Overview of precision additive manufacturing

AM technologies vary in support mechanisms, material bonding methods, and material supply aspects. Based on the International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) 52900:2015 standard classify AM processes into seven categories:

(1) Binder Jetting (BJ)

(2) Directed Energy Deposition (DED)

(3) Material Extrusion (ME)

(4) Material Jetting (MJ);

(5) Powder Bed Fusion (PBF);

(6) Sheet Lamination (SL);

(7) Vat Photopolymerization (VP).

3.1 Precision AM technologies

Fused Deposition Modeling (FDM) is in the category of material extrusion and is the most common type of 3D printing technology adopted in the consumer market. It is also mentioned as Fused Filament Modeling (FFM) or Fused Filament Fabrication (FFF). This type of material deposition process is similar to applying glue on a surface using a glue gun. The thermoplastic filament made from Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA) is fed to the machine instead of glue sticks made from Ethylene-vinyl Acetate (EVA) copolymers. Fused Deposition Modeling (FDM) method involves supporting structure in printing and needs the removal of the supporting materials as part of the after processing. Fused Deposition Modeling (FDM) is not quite used for precision AM. Even though it is much common in the consumer market for general use, because of the melting filament oozing issue, it is not ideal for accurate and high precision parts building. For example, if Polylactic Acid (PLA) filament diameter of 1.75mm is used, the nominal x-y plane accuracy is only 11 microns. Information on layer thickness can be obtained from the commercial manufacturers of printers, but for dimensional accuracy and the surface characteristics obtained in manufactured components depend on the combination of the printing configurations, with deviations ranging from 16 μm to 36 μm [1].

Stereolithography (SLA) uses a vat of liquid photopolymer resin and a UV laser to build the parts. This method utilizes UV light of a spectrum of 380 to 405 nm wavelength to solidify the liquid resin. The nominal accuracy can reach 45 μm in the x-y plane for vertical Z dimensions less than 150 μm [2].

Digital light processing (DLP) uses a computer-controlled projector to control the shape of the digital light to cure the photopolymer resins. It is used frequently in medical applications because of the relatively good surface finish ability [3] [4]. Moreover, Stereolithography (SLA) and Digital Light Processing (DLP) methods can produce parts that more mechanically isotropy than Fused Depostion Modeling (FDM), especially when a load is applied in different directions to the layers.

Another technique that uses photopolymers is PolyJet technology, which is in the category of binder jetting. It works like an inkjet printer, printing with photopolymer droplets mixed with water-soluble support material, onto the build platform. It has the ability to reach the lower surface roughness of fewer than 10 μm[5].

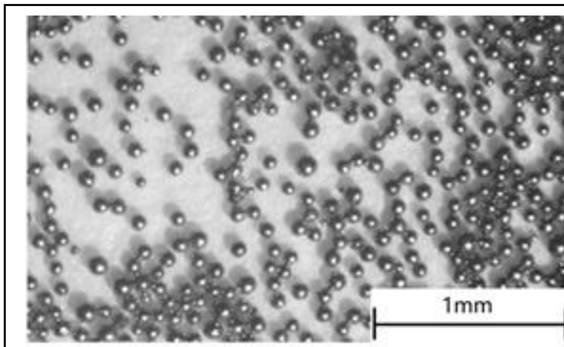

Fig. 1. Titanium Aluminum Vanadium Powder (Ti-6AL-4V). [6]

Selective Laser Sintering (SLS) uses metal powder materials (the metal powders are of sizing 40-110 microns shown in Figure 1) and is a powder bed fusion technique. The computer-controlled laser scans the surface of the powder bed to melt the two-dimensional slice of the CAD file selectively. The laser scanning re-melts some of the previously built layers to ensure strong bonding between layers and overall fully dense components. The nominal accuracy is 60-120 μm, and actual accuracy depends on the configuration of laser power, spot size, scanning speed, scanning pattern, orientation, angle and exposure time, etc.

Electron-beam Melting (EBM) technology also belongs to powder bed fusion that uses metal powders as raw materials to build the components. EBM is distinct from Selective Laser Sintering (SLS) since the powders are entirely melted by an electron beam in a vacuum and fused completely. In Directed Energy Deposition (DED), metal wire/powder is combined with an energy source to deposit materials onto a building platform or existing part directly. A nozzle is used to apply metal materials in DED, and it is similar to a continuous welding process, in which environment control of inert gas in the process is essential. Because of the inconsistency of heat transfer in the operations, relatively low dimensional accuracy in EBM and DED can be achieved [7].

3.2 Innovations in Precision AM

The advancement of the materials empowers additive manufacturing with the ability to produce parts with smaller scale dimensions and tighter tolerances. The most studied materials are metallic powders, such as SS316 powder, Inconel 718 powder, Titanium Aluminum Vanadium Powder (Ti-6AL-4V), fiber-reinforced composite, ceramic materials, and biomaterials. For example, parts made from polyether-ether-ketone (PEEK) can be exposed to X-ray and gamma radiation. It is bio-compatible, highly durable, and has an excellent heat resistance property. Therefore, PEEK is widely used as the materials of medical devices, such as prosthetic implant and surgical guides for various surgeries, including neurosurgery, spinal surgery, maxillofacial surgery, and dental surgery, etc.[8]. Figure 2 shows a wax coronary arteries model for metallic stent implant procedure, which was created by MultiJet printing technology that has the highest machine resolution of 16 μm.

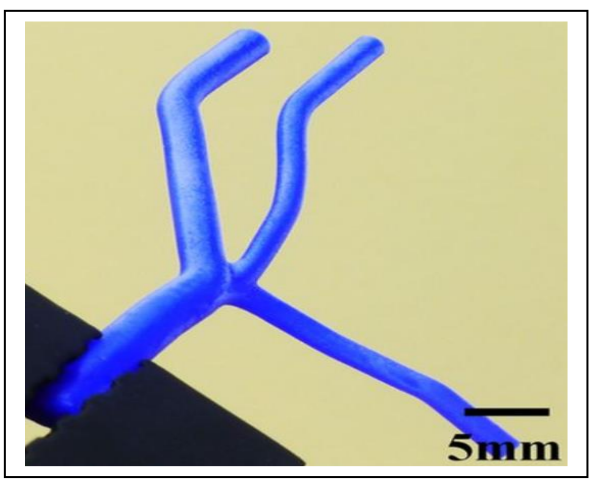

Fig. 2. A 3-D printed coronary arteries model for metallic stent implant procedure. [8]

Ceramic matrix composites have improved corrosion and thermal shock resistance that is needed in aviation and aerospace applications. They can be used in precision AM processes, such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), and Selective Laser Sintering (SLS). However, the parts that come off the 3D printer need to undergo the same secondary processes, such as sintering or firing.

4 Quality in precision additive manufacturing

The quality of final AM products compasses many aspects, yet there are very few studies discussing the overall quality issues in precision AM except for dimensional accuracy and mechanical performance.

4.1 Define Quality in Precision AM

In AM products, the quality outcomes are not considered just for dimensional accuracy, but well-balanced properties of several aspects, including geometric dimensional accuracy, macro and microstructure, mechanical performance, and functional performance. Some of the critical parameters in geometric dimensional accuracy include dimensional tolerance, surface roughness. In the aspect of macro and microstructures, depending on the materials of the parts, the primary quality issues comprise numbers of surface defects, evaluation of porosity, density, texture, grain size, and isotropy. For the parts that are fabricated for industrial or medical use, the mechanical properties of fatigue strength, residual stress, tensile strength, compressive strength, fracture strength are selectively tested to ensure the quality of the parts. The quality standard for mechanical properties ensures the printed parts are structurally stable besides meeting the required geometric specifications and dimensional tolerances.

In AM, challenges often occur in residual stress accumulation caused by rapid heating and cooling processes on a repetitive basis. The uneven heating and cooling not only alters the inside structure but also causes shrinkage which is part of the sources of dimensional inaccuracy. Traditionally, heat treatment is commonly used in metal parts, such as annealing, normalizing, quenching, and tempering, however, for AM parts that have near net shapes and complex geometries that are impossible to implement after process, the heat treatment options are not available and the post-processing has to be very little removal of materials. Last but not least, functional performance such as toxicity, biocompatibility, safety, heat resistance, moisture resistance, and product lifetime are evaluated based on the using environment of the products. Figure 3 illustrates the four aspects of quality outcomes in precision AM.

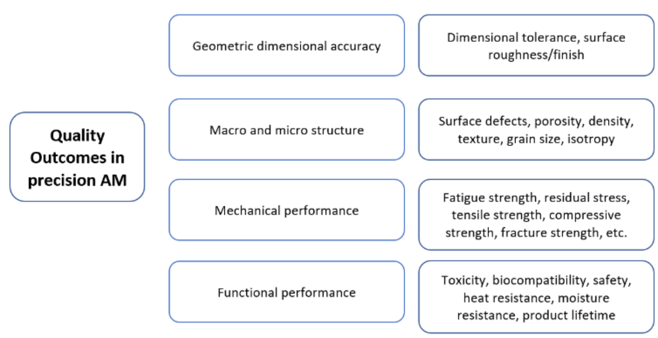

Fig. 3. Four aspects of quality outcomes in precision AM.

Some quality aspects have interrelationship in between themselves. For example, the microstructure of the 3D part would have a significant impact on its mechanical performance. Figure 4 shows the cross-sections of polyether-ether-ketone (PEEK) DFM parts, the arrangement of the melting particles impact the bonding strength of the entire workpiece and significantly affects the compression strength or the elastic modulus. Therefore, safety and product lifetimes can also be increased or reduced accordingly.

Fig. 4. Cross section of a DFM part made of PEEK. [9]

4.2 A systematic approach

Regulations, standards, and guidelines should govern the entire building process to ensure the compliance of relevant policies regarding the specific product category. For example, medical devices that are sold in the US are subject to regulatory requirements issued by US Food and Drug Administration (FDA), particularly for AM products. In 2016, the FDA issued draft guidance on the technical considerations for additive manufactured devices to advise manufacturers who are producing devices through AM technologies. The guidance includes two topic areas: design and manufacturing considerations and device testing considerations. Similarly, in the aerospace industry, the American Society for Testing and Materials (ASTM) provides a series of guidelines including design, materials, quality assurance, performance, etc. for aircraft parts manufacturing.

The delicate nature of precision AM products determines that the subtle change of the manufacturing and using conditions have a minimal influence on the quality and performance of the products that cannot be underestimated. Therefore, climate control such as temperature and humidity, airflow control, shop floor vibration control and power supply disruption control are fundamental in precision AM processes. Airflow control can impact the cooling process especially for the parts with delicate structures, therefore, it should be carefully considered and implemented.

Like any manufacturing process, precision AM needs high-quality materials, which consistently meet the specifications to build constant high-quality devices. Therefore, material quality control should be established and enforced for every batch of incoming materials, such as establishment of specific material requirements, material inspection and testing procedures, and implementation of acceptance sampling plans.

Design plays a vital role in precision AM processes since the digital design is converted to a buildable file that is divided into layers, including additional support material to aid printing. The digital design models are created and validated with pre-specified sizes or matched to the scanned files, such as the anatomy files in healthcare applications.

In the building process, machine settings are essential to generate the desired results. Different technologies involve different sets of parameters. In Fused Deposition Modeling (FDM), the machine configuration includes infill rate, layer thickness, raster angle, raster width, nozzle diameter, print speed, and bed temperature. In Selective Laser Sintering (SLS), the building parameters are laser power, spot size, scanning speed, scanning angle, scanning overlap, exposure time, point distance, and layer thickness. In Stereolithography (SLA), the building parameters include exposure time, rotation angle, separation slide velocity, approach slide velocity, after exposure time, z-axis over lift, separation z-axis velocity, after separation time, UV wavelength, wait time, overpress velocity, maximum jerk, and overpress return velocity.

After building, cooling, post-curing, cleaning, sterilizing, and other post processes should be kept in the quality control feedback loop. Figure 5 is an illustration of a process flow of precision AM.

Maintenance of the system is also an essential part of the quality system. For example, no matter if it is a laser, digital light projector, or LED, the power decays as time goes by. Figure 6 shows the flow chart of a systematic approach for quality optimization in precision AM, which includes the feedback loop of the entire process.

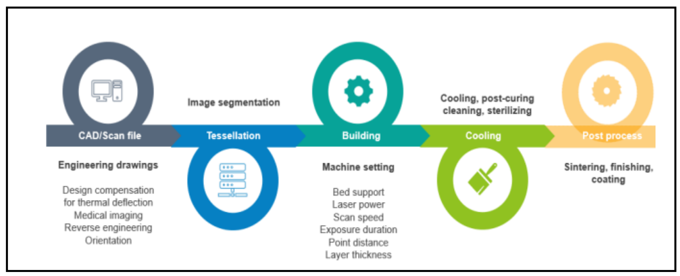

Fig. 5. A process flow of precision AM

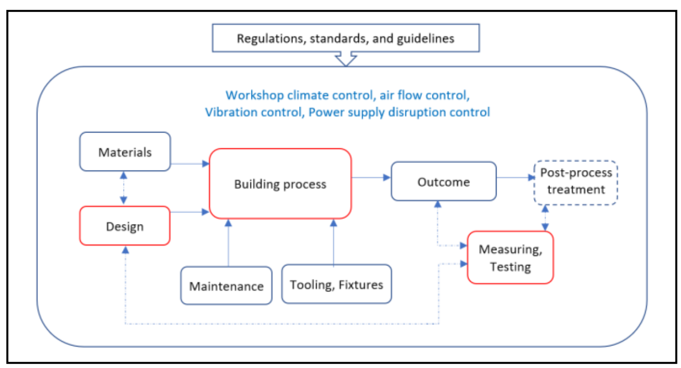

Fig. 6. A flowchart of systematic approach of quality optimization in precision AM.

4.3 Design for quality in precision AM

4.3.1 Two different design types

In dimension driven design, the engineering drawings are converted to STL file that can be read and printed by the machine. The defined features are specified dimensions with tolerances, such as cylinders, planes, fillets, angles, surface roughness, etc. On the other hand, in scan file driven design, 3-dimensional scanning of an existing object or medical imaging is used to generate the STL file. In laser scanning, a laser scanner scans the surface of an object, and the data collected are a point cloud that can create a 3-dimensional surface but cannot show the internal features of the object being scanned. In medical applications, computerized tomography (CT) and magnetic resonance imaging (MRI) modeling is used to obtain the scan files. The choice of scanning method impacts the quality of the data collected [10]. CT obtains the tissues and skeletal body structure less expensive and much faster than MRI, while MRI can provide more details of abnormal tissue images. Furthermore, different segmentation software would also result in a difference in the 3-dimensional models.

4.3.2 Design can mitigate the distortion in precision AM

In precision AM, temperature caused stress is applied continuously to the fusion zone and the entire part. A significant deflection of geometry and deformation in cooling down can occur. In the design phase, the use of an optimum build orientation or different tool path, or global uniform scaling can also be adapted to compensate for the distortion. Pre-distorting for compensation [10] method can reduce distortion to less than 65 μm is applicable to a wide range of AM applications, and is independent of material, process, and equipment. Figure 7 shows the comparison of as-built and distortion inversion for an impeller component.

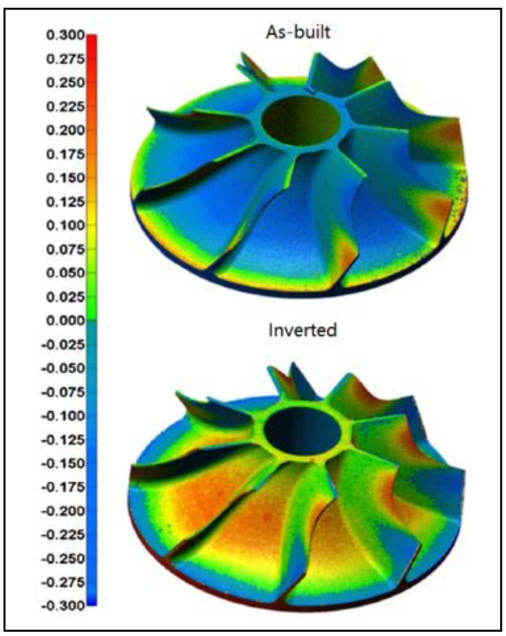

Fig. 7. Pre-distorting in design for compensation, deviations in mm. [10]

4.3.3 Other design for manufacturing (DFM) issues

The DFM issues in precision AM is as critical in any of the design issues in manufacturing. Like any other manufacturing methods, AM has constraints on the parts that can be printed. Therefore, it is essential to consider the limitations of part design that may cause quality deficiency in the early stages of building. For example, using support structure is recommended for building overhangs for wall angles above 45 degrees; vertical pins at the end should be avoided to ensure the layers of material are sufficiently bonded, or adding fillet design at the base of a pin to make the part strong in structure and mechanically durable. Other standard practices include a building orientation plan to reduce build time, increasing heat convention to optimize surface finish, avoiding warping by using a brim or raft, providing extra supporting structure for heat dissipation to prevent rapid cooling, etc.

4.4 Quality control feedback in precision AM

Quality outcomes are the ultimate result of precision AM processes, however, it is well understood that each stage in the manufacturing system has elements that can affect the quality outcomes. From the macro aspects, ambient environment, including temperature, humidity, vibration control, and power supply disruption control have an overall impact on the product quality. On the other hand, any of the phases in the manufacturing system, from the early material inspection, to building configuration in machine setting, to the later measurement and testing stage can give input of the quality outcomes of the products. Therefore, an effective and efficient feedback mechanism needs to be established in the entire system. Firstly, the feedback needs to be in a timely manner. It is critical to make records of the building parameters so that raw material lot numbers, building files, and testing results, etc. can be tracked and resolved in a timely fashion. Secondly, quality feedback information should be presented in a positive manner to different parties. Suppliers, designers, engineers, technicians, and personnel involved in the precision AM process need to work closely as a team and provide each other improvement information through effective communication channels. Lastly, quality standards in each of the four categories of geometric dimensional accuracy, micro and macro structure, mechanical performance, and functional performance can be defined, so that quality control has objective goals to achieve in the process of continuous improvement.

5 Conclusion

Precision AM technologies have promising application prospects in many manufacturing industries, such as automotive, aerospace, and healthcare sectors. AM has many advantages over traditional precision manufacturing technologies in free form design, material efficiency, less processing steps, and less cost for customization. Innovations in materials facilitate the application of precision AM, however, quality control is a concern for many emerging precision AM technologies. In this research, the concept of quality in precision AM was defined, and then a systematic approach of quality control was proposed including the regulations, environment control, material control, design, building processes, maintenance, tooling and fixtures, measuring and testing, and potential post-process treatment. This paper discussed two types of design files driven by dimension and scan file respectively, and distortion mitigation in the design stage, other DFM issues were also mentioned to address the quality issues that might occur in precision AM. Quality control feedback mechanisms were identified to ensure timely feedback between each stage and that communication among precision AM team members happens in a positive and effective manner.

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