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Additive Manufacturing Overview: The Qualification Pathway

Mary E. Kinsella and Rollie Dutton, Air Force Research Laboratory
Dale Carlson, Air Force Life Cycle Management Center

ABSTRACT

Additive Manufacturing (AM) has evolved from rapid prototyping processes whose capability has been developed enough to potentially produce production parts. AM encompasses a family of processes that produce parts from CAD files, usually in layer-by-layer fashion. Theoretically, AM enables a whole new design realm in which geometric complexity is not a constraint, and material (and thus material properties) can be specifically located where you want it, and not where you don't want it.

In general, AM has the capability to build complex geometries at no extra cost, geometries that often cannot be directly built any other way. AM eliminates the need for expensive and long-lead tooling, and is more cost effective for small lot production. It enables light-weighting through part consolidation and the capability to put material where – and only where – you need it. It enables low cost design iteration, mass customization, and virtual warehousing, on-demand manufacturing, and on-the-spot tailoring (additive features).

However, it is important to note that each processing step affects microstructure, properties and performance. In more traditional processes, such as forging, we understand all process steps and the resulting effects on material and part performance. Due to the fairly recent introduction of AM technologies, data and experience are scarce, and we know little about the relationships between material properties, process parameters, and part performance. We have yet to learn all of the possible defect types and how to detect them. AM processes are currently sub-par in dimensional accuracy and surface finish and anisotropy, especially in non-metal processes, is an issue. Component size is limited, particularly for powder bed processes and robust process control and inspection capabilities are often lacking. As a result process repeatability can be problematical. Finally projected cost savings are often overcome by post-processing requirements.

Currently most efforts are focused on using AM to replace existing parts. The real benefits of AM, however, will only be realized when it is applied to new designs. Along with computational methods, AM technologies enable the unique opportunity to connect material properties with process parameters and part performance. This capability will change the way we do design in the future, no longer constraining us to the properties of existing materials or the rules of existing processes. Once requirements are defined, materials and processes will be tailored to meet them in an efficient and freeform manner.

Adopting such a design system could have pervasive impacts to all industry sectors where the environment changes throughout the component, for example, gas turbine engines or chemical reactors. Potential impacts could include improved thermal management, enhanced energy efficiencies and improved process yields. Defense-related applications include a host of high-temperature propulsion applications including hypersonics as well as lightweight multi-functional components.

Background

Additive Manufacturing (AM) technologies have evolved from rapid prototyping processes, whose history goes back only to the 1980s. Gradually these technologies have been developed to the point where their capabilities are sufficient, in some cases, to produce production parts. This development, along with advancements in personal computers, lasers, and solid modeling, have led to the emergence of AM as a new manufacturing approach enabling a new and innovative way to design and build components and systems. AM encompasses a range of processes that produce parts from CAD files, usually in layer-by-layer fashion. The processes are widely varied and involve materials across the spectrum from polymers to composites to metals (see Table 1).

Process Type	Materials
Powder Bed Fusion	Various
Directed Energy Deposition	Metals
Material Extrusion	Polymers/ Composites
Vat Photo-Polymerization	Polymers/ Composites, ceramics
Material or Binder Jetting	Polymers/ Composites
Sheet Lamination	Metals, Composites

Table 1: AM process categories (as defined by ASTM) and typical materials.

Powder bed fusion is a popular process category for aerospace propulsion applications. In these processes, thermal energy selectively fuses regions of a powder bed. The powders can be metallic or polymer based, and the dynamics of the process are very different depending on the material. It is currently being applied for prototyping, tooling, and non-critical components, and it is under development for some components with complex geometries, such as heat exchangers and fuel nozzles.

Another process category with aerospace propulsion applications is directed energy deposition, in which focused thermal energy is used to fuse materials by melting as they are being deposited. These are processes that use metallic materials, either in wire or powder form. While not typically used to build components directly, extrusion, vat photo-polymerization and jetting processes can be used indirectly for propulsion applications, e.g., for tooling, prototyping, and design iteration.

It is evident from the number of process types and the variety of materials that can be processed that the number of material-process combinations, and thus the number of manufacturing challenges, is broad.

Uniqueness of AM Technology

Theoretically, AM enables a whole new design realm in which geometric complexity is not a constraint, and material (and thus material properties) can be specifically located where you want it, and not where you don't want it. This enables certain capabilities, such as topology optimization, graded materials, and multi-material integration. From this, we can benefit from the use of more organic geometries, the ability to combine electronic function with structure, or to build one part with varying properties.

Another inherent benefit of AM is the ability to manufacture parts directly without the use of tooling. This not only provides lead-time benefits, but also allows for more design iteration at lower cost. Fewer tooling requirements removes the lead time for molds and dies and enables quicker and less expensive design changes. If new tooling is not required, then it is possible to replace parts for which tooling is no longer available. Now replacement parts can be built more "on demand," rather than in large lots of spares that need to be stored, and manufacturing in remote locations becomes feasible.

Before we get too carried away, however, it is important to note a number of challenges that must be overcome in implementing this new technology. These are best explored in the context of the qualification process.

The Qualification Pathway and Its Technical Challenges

The Air Force process for qualifying and certifying structural components is defined by a number of documents, including the Airworthiness Certification Criteria (MIL-HDBK-516), the Joint Service Specification Guides (JSSG), and the Integrity Programs (MIL-STD-1530C and MIL-STD-3024). Along with materials and processes (M&P) specifications and standards, materials databases, and various documented lessons learned, these documents constitute a well-established approach to ensuring the safety and integrity of AF systems. New M&P technologies intended for transition and implementation must first be qualified according to the guidance and requirements found in these documents. The development of new M&P technologies, such as AM, requires not that we alter the qualification process to accommodate them, but that we determine the best pathway for the new technology through the existing qualification process.

A map of the requirements defined in these documents begins with qualification of the process and continues through qualification of the part. The key requirements for implementing new M&P technologies have been summarized by Lincoln[1] and include: process stability, process reproducibility, characterized mechanical and physical properties, predictability of performance, and supportability

(Table 2). There are challenges for AM at each of these steps, and those challenges constitute the basis of on-going work that aims to reduce the risk of implementation and allow us to leverage the benefits of AM.

Process stability is an often overlooked requirement for qualification of AM. Other processes more familiar to us, such as casting or forging, have long been well established, understood, and trusted – so much so that their stability is taken for granted. AM processes must be developed to that point, but currently are widely variable, with material properties highly sensitive to process conditions. Any change to process parameters has a significant impact on the outcome. These interactions must be better understood, defined, and documented before the qualification process can continue. Furthermore, AM process reproducibility, in general, has not been demonstrated. Due to unstable processes and the sensitive nature of material properties to process conditions, this is proving very difficult to do.

Five Factors Essential to the Aerospace Structural Integrity Program:

- Stabilized material and/or material processes
- Producibility
- Characterized mechanical properties
- Predictability of structural performance
- Supportability

There [is] no attempt to establish a ranking of importance of these factors. A deficiency in any one of the factors could constitute a fatal defect.

Table 2: Key requirements for implementing new M&P technologies [1].

While some characterization of mechanical and physical properties has been accomplished, most of the resultant data are not publicly available. Non-proprietary data are very scarce, and complete characterization is limited to individual companies who are not willing to share the results. Component-level testing has been insufficient to date to achieve predictability of performance. And in-field inspection and/or repair processes are yet to be defined in order to meet supportability requirements.

AM materials (and welding materials) are good examples of process-sensitive materials, i.e., their properties are highly sensitive to processing conditions and geometry. Because of this, every adjustment made to the process causes a different result. In order to have consistent material, therefore, the process must be very tightly controlled and the processing window becomes so small that the result is a point solution. In other words the process is controlled for a very specific part, and no other parts can be built using those same process parameters. This approach is not robust and requires a pretty strong business case in order to be successful.

AM processes have continually changing, local processing environments with changing geometries and processing parameters, which make it difficult to statistically ensure material integrity for design. Compounding these are a lack of constrained process controls; difficult-to-inspect, weld-type defects that form stochastically; post-deposit distortion and residual stresses; and undefined post-processing requirements, including unknown probabilities of detection for non-destructive inspection.

Staged Implementation of AM

Work to resolve many of these issues is underway, but it will not be completed any time soon. The risk in applying AM for applications having any level of criticality is too great at the moment. This has led us to take a more incremental approach to AM implementation. Today AM is in use for some low risk, non-structural parts and for indirect applications, including tooling, fixtures, and design iteration. Indirect applications are proving very effective in reducing lead times and the opportunity space is quite large. In the near future, implementation will include some niche applications, such as non-critical and geometrically complex components, or those with short life or “safe-life” requirements. Later, full-life, non-critical structural applications may be feasible. Fracture-critical hardware or graded materials will not be feasible until the far term.

The Future of AM

While we work through the technical challenges of AM, we keep in mind its real benefits, especially as they apply to new designs. AM is not applicable everywhere: there are technological limitations and business case considerations that must be taken into account. Nevertheless, along with computational methods, AM technologies enable the unique opportunity to connect material properties with process parameters and part performance. This capability will change the way we do design in the future, no longer constraining us to the properties of existing materials or the rules of existing processes. Once requirements are defined, materials and processes will be tailored to meet them in an efficient and freeform manner.

Adopting such a design system could have pervasive impacts to all industry sectors where the environment changes throughout the component, for example, gas turbine engines or chemical reactors. Potential impacts could include improved thermal management, enhanced energy efficiencies and improved process yields. Defense-related applications include high-temperature propulsion applications, such as hypersonics, as well as lightweight multi-functional components.

[1] “Material and Process Technology Transition to Aging Aircraft,” Lincoln, J.W., Proceedings: Aging Aircraft Fleets – Structural and Other Subsystems Aspects, NASA 20010028491, March 2001.