# Additive Manufacturing in Aerospace: Examples and Research Outlook

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This paper presents an industrial view on the use of additive manufacturing for production of aircraft components, and provides research examples that show the direction of related development. The advantages of additive manufacturing are becoming broadly recognized and the stringent requirements found in the aerospace industry provide the context required to develop these complex processes to the level of robust performance established by traditional manufacturing methods.

**Introduction to Aerospace Requirements for Additive Manufacturing**

Additive manufacturing (AM) processes are unique in their ability to form the final part desired without any intermediate tooling. Additive processes such as Selective Laser Sintering (SLS) begin with a computer generated three-dimensional design of a given part. The part is then digitally segmented into very thin layers, which are selectively solidified in the machine, layer by layer. This ability to "grow" parts allows for designs with such complexity they can not viably be built with other processes. This approach to manufacturing removes the need, cost and delay associated with tooling. Even with increasing rates of aircraft production (1), aerospace companies have numerous parts that are produced in very low quantities which make these tool-less process attractive from an economic perspective (2). The use of AM provides a host of benefits, many of which are being recognized even in general media (3).

From an Aerospace and Defense (A&D) design perspective, the weight of the part is often the deciding design factor for choice of material and manufacturing process use. Also, the uncompromised need for safety in air travel adds a long list of complex requirements, even for the simplest part. To consistently produce parts with identical and understood properties, the material and the process used to form it must be understood to a very high level. This complicated aerospace manufacturing context, which blends low volume economics with acute weight sensitivity and the need for highly controlled materials and manufacturing processes, has lead to the development of knowledge within The Boeing Company required to safely transition Additive Manufacturing from the laboratory and model shop, onto the factory floor.

To begin to understand the foundation of requirements placed on a commercial aircraft part one can look to the United State's Federal Aviation Regulations (FAR), which must be met before a Type Certification can be issued for a given aircraft series, required for entry into service with an airline (4). While this set of regulations is very extensive and detailed, the single most pertinent language within the context of an AM review can be found in Title 14, Section 25, Subpart D, Subsection 25.605; "The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must (a) Be established on the basis of experience or tests; (b) Conform to approved specifications (such as industry or military specifications, or Technical

Standard Orders) that ensure their having the strength and other properties assumed in the design data; and (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service." This brief but clear requirement is one of many that leads to the incredible safety record of commercial air transportation, and also provides the impetus to rigorously study new fabrication methods such as SLS. Each A&D manufacturer will have internal specifications or look to established standards organizations for data that allows accurate design of components from a given material, based on minimum allowable performance. Examples of material performance factors that are considered for even the simplest of components include; specific strengths, fatigue, creep, use temperature, survival temperature, several tests of flammability, smoke release and toxicity, electric conductivity, multiple chemical sensitivities, radiation sensitivity, appearance, processing sustainability and cost.

**Use of Additive Manufacturing in Aerospace**

Within Boeing, both military (5) and commercial (6) programs utilize SLS to produce light-weight, highly-integrated systems and payload components, as seen in Figure 1, that eliminate non-recurring tooling costs and provide for life-cycle production flexability. Since the first implementations on Boeing aircraft, the use of SLS has grown organically within a large number of programs. This is primarily due to its ability to produce thermoplastic parts that are light-weight, non-porous, thin-walled, highly-complex geometrically and do so in an economical fashion. These properties also led to the frequent use of SLS within the burgeoning field of Unmanned Aerial Vehicles.

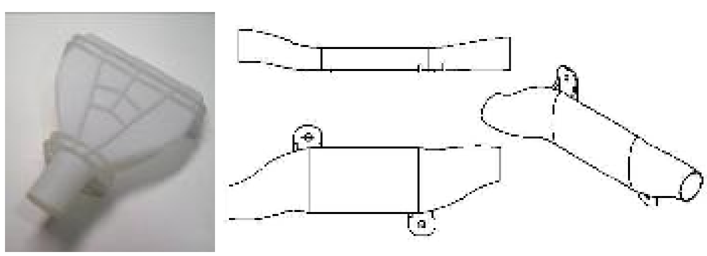

Figure 1. Photograph and illustration of laser sintered air ducts

With weight being a critical factor, the very thin walls and complex designs possible in SLS are attractive for replacement of parts typically made through established processes such as rotational, injection or polymer matrix composite molding. To take advantage of SLS, one must have a firm understanding of the extreme four-dimensional energy input gradients that exist during processing. For example, typical SLS machines use 75 Watt $CO_2$ lasers that have a 500µm spot size. That laser spot moves at up to 10 meters-per-second, over layers of Nylon powder only100µm thick, with each layer being completed in approximately 60 seconds. The thorough description and efforts to simulate the details of the energies present in the SLS process can be found in literature (7). This unique manufacturing context requires that any aerospace company develop in-depth knowledge of the materials and process used, in order to draft commercially efficient specifications.

## Examples of Aerospace-Driven Research in AM

In order to build parts with repeatable mechanical properties and dimensional control the temperature distribution across the part building platform must be held at as even a temperature as possible. In order to accomplish this and reduce scrap rates, The Boeing Company and their partners at the University of Louisville and at Integra Services International (Belton, TX) developed a patented method for zonal control of the part bed temperature in SLS equipment (8). The multi-zone, near-IR wavelength heating elements, seen in Figure 2, provide the fast response and spatial resolution required to maintain even part bed temperature. This invention, when paired with real-time infrared imaging provides a significant improvement in thermal control. This level of thermo-spatial control has had to become more advanced than that found in most other thermoplastic processing methods.

Figure 2. MZ heating (left), SLS part bed (center), same parts seen via infrared thermography during laser scanning (right)

Another example of an aerospace driven AM need being met by researchers can be seen in the emergence of flame retardant polyamides. When considering that many polymers are derived from fossil fuel based hydrocarbon feed stocks, the concept of a related chemistry being self-extinguishing when exposed to flame is impressive. That is required, to a greater or lesser degree, of all polymer materials used on the interior of commercial aircraft. To gain the weight and manufacturing benefits provided by SLS on its commercial aircraft, Boeing collaborated with its suppliers to develop the first material that could be laser processed and passed the required flammability tests (9).

## Current Area of Development

Progress has been made to increase the number of AM applications in aerospace, which has identified three new performance challenges for SLS polymer materials. The operating requirements of programs such as F-35 and 787 have put requirements on the AM community to develop materials that can A) operate at higher temperatures B) have significantly better flame resistance and C) offer an adjustable degree of electrical conductivity (10).These new physical performance targets must be met while maintaining as many of the attributes already established by SLS Polyamide materials as possible. Those attributes include mechanical toughness, resistance to chemical attack, ultra-violet radiation resistance, dimensional fidelity, and viable economics. Such a material, if developed successfully, could have a wide range of applications within and beyond aerospace Two of the most notable non-aerospace applications for a new high performance polymers in SLS are the potential use in medicine for implants and devices (11) and low volume automotive production.

As is historically the case when a new technology is enabled and near transition to useful service, numerous parties from many industrialized nations can be seen working on the same technical problem simultaneously. Researchers in the United States, Germany, Japan and the United Kingdom have made the deepest investigations into developing high performance polymers for SLS (12,13). There are many high performance polymers that are attractive for development from a cost perspective, however the cost of testing required by aerospace makes multiple, simultaneous material development efforts cost prohibitive. Because of the known performance of the Polyaryletherketone (PAEK) family of materials, they are viewed as the lowest risk option for current development. The PAEK family includes different chemistries such as Polyetherketone (PEK), Polyetheretherketone (PEEK), and Polyetherketoneketone (PEKK). The choice of a PAEK as the next material family to be developed is based on factors inherent to its chemistry including; very good flammability and chemical resistance, low moisture sorption, good mechanical performance, good resistance to creep and fatigue, it is compatibility with several methods of sterilization and there are numerous material grades and suppliers to choose from.

Due to the comparatively small size of the SLS market and cost of developing new polymer chemistries, raw materials for SLS are typically selected from commercial-off-the-shelf (COTS) grades. These COTS materials have been designed for other applications such as coatings, films or rotational molding. While injection molding and other methods of polymer processing can make use of both heat and pressure to form a part against the surface of a mold, AM processes have to rely primarily on thermal energy input. Viable materials for additive processes must have very specific viscosity and other properties to be successfully processed. To begin generating material performance test data, a processable material form must first be developed.

The development of a viable PAEK-SLS material is an area of competitive, industrial research at this paper's time of writing, so specific information from any one party is generally not published. However the comparison of established, well understood Polyamides (PA) to the PAEK family shows the problem space of engineers working in this field. Table 1 provides comparative thermal properties of lower temperature PA and PAEK materials, as found in literature and manufacturer published information (12, 14).

| Material | Melt Temp °C | Glass trans. temp °C | Specific Heat J/g K | Heat of Fusion (100% crys.) J/g | Thermal conductivity W/m K | Thermal Expansion (ppm / Tg °C) | Specific Gravity g/cc (crystalline) |
|---|---|---|---|---|---|---|---|
| PA | 180-186 | 42-55 | 1.26 | 226 | 0.19 | 85 | 1.03 |
| PAEK | 300-375 | 145-165 | 2.20 | 130 | 0.26 | 60 | 1.30 |

Table 1. Comparison of PA and PAEK family thermal properties

By understanding and comparing the bulk thermal properties of these two material families, one can begin to understand how differently they will behave within the SLS process. One such comparison can be scene when the amount of energy required to heat the material is considered. To process a PA powder, the lower melt temperature combined with the lower specific heat (the amount of energy required to heat a given mass of material one degree Kelvin) indicates that the effort required to achieve a given viscosity with heat input are much lower for a PA than for a PAEK. The PAEK must be heated to twice the temperature just to approach melt, and will require almost twice the energy per degree of heating. This is further complicated in SLS processing, as the transient heating retirements of each layer must not change drastically.

A second comparison is the ratio of specific heat to the heat of fusion (the energy flux exhibited in the transition from solid to liquid, and vise versa). In the SLS process, the polymer powder is heated in stages from ambient conditions to very near the melt point. PA has a lower ratio of specific heat to heat of fusion than the PAEK family of materials (1.26/226 compared to 2.20/130). This is important as, despite best efforts, there is some gradient of energy input and temperature across the building area at any given time. If a material has a very gradual transition into melt, such as fully amorphous polymers, it can be difficult to feed smoothly onto the machine's part building area.

This ratio of specific heat to heat of fusion gives indication of how easy a given material can be heated to near the melt point, across the whole part bed, without fusing particles together. The closer to the melt point the material can be feed in the machine, the lower the energy input requirements are on the laser for heat input that transitions the material into the melt region. The lower the requirement put on the laser for energy input, the lower the risk of polymer degradation is. This is because within the $CO_2$ laser spot there is a roughly Gaussian distribution of energy, the peak of which can cause degradation.

Also tied to this comparison is the speed at which the laser draws each layer of the part. With a given energy input requirement put on the laser per the above comparison, the layer can be drawn with faster or slower laser scan speeds. The scan speed effects the overall per-layer time which in addition to the proportion of pre-heat to laser energy required, results in a variable temperature distribution and cooling rate across a part's cross section, per given layer. If too long a time has passed between the start and stop of a given layer and too high of an energy demand is put on the laser, sections of that layer will have cooled faster than others, and in turn shrunk non-uniformly. Dimensional distortion can result if too high a cooling gradient exists relative to recrystallization temperature, thermal conductivity, coefficient of thermal expansion and a host of other material factors.

A thorough description of the interaction between just the properties shown in Table 1 is beyond the scope of this paper, but the three examples give a window into the problems currently being solved by AM researchers. Thankfully, despite all of these complexities, multiple parties are reporting success with the processing of PAEK materials via SLS, as can be seen in Figure 3.

Figure 3. Examples parts of PEAK materials processed via SLS

**Moving Forward**

Beyond new higher performance polymers, numerous research frontiers exist within additive manufacturing. Separate from the specific material development identified above, AM equipment must transition from comparable low reliability laboratory grade equipment to hardened, cost effective, high-temp industrial grade machines. The AM industry can look to its predecessors in injecting molding and CNC machining for examples of how to establish new manufacturing technology and the supporting business case. The unique material requirements posed by AM processing have, during the technologies infancy phase, tied machine manufacturers to material and even part sale activity. While this has provided a good revenue source to support the new companies, it has also impeded new applications by making new material development difficult for all but the largest of users and material companies. This dependence on material and part sales, and non-productive patent litigation, has also distracted the machine manufacturers from improving upon their equipment with an eye towards higher volume, economical industrial manufacturing. Equipment manufacturers such as Toshiba, Haas Automation, MAG, Husky and Arburg do not rely on material or part sales to bolster their equipment business, and if the AM industry is to grow successfully it might look to their business models and history for reference.

Beyond polymers the use of metals in AM for aerospace is equally as complex and exciting. Leading the way in direct metal part manufacturing have been engine manufactures. While direct part manufacturing is a highly dynamic field, the leveraging of AM's ability to create highly complex shapes is very applicable to tooling, for both metal and composites components. New tooling focused machines, processes and materials are being actively developed that leverage the process benefits of AM, while delivering the performance of cast metals (15) or long fiber reinforced composites (16).

Independent of material or processing conditions, the analysis of complex geometries that can be built only with additive methods is also an active and important area of research. Even with material test data generated, the types of structures that AM can build, such as the trussed airfoils seen in Figure 4, are difficult to analyze for predictive behavior. This field of study is generating new software tools for generation and predictive analysis of complex structures, such as three dimensional trusses (17).

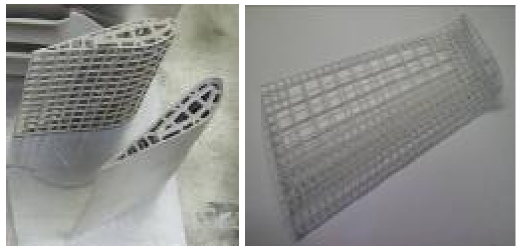

Figure 4. Two complex truss examples that indicate the difficultly of predictive analysis

These descriptions of current research areas, along with examples such as Boeing's use of SLS on commercial and military aircraft, show that the aerospace industry has the opportunity to lead, and responsibility to contribute to, this revolutionary field of manufacturing technology.

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