



Research
Additive Manufacturing—Perspective

Additive Design and Manufacturing of Jet Engine Parts

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ABSTRACT

The additive design (AD) and additive manufacturing (AM) of jet engine parts will revolutionize the traditional aerospace industry. The unique characteristics of AM, such as gradient materials and micro-structures, have opened up a new direction in jet engine design and manufacturing. Engineers have been liberated from many constraints associated with traditional methodologies and technologies. One of the most significant features of the AM process is that it can ensure the consistency of parts because it starts from point(s), continues to line(s) and layer(s), and ends with the completed part. Collaboration between design and manufacturing is the key to success in fields including aerodynamics, thermodynamics, structural integration, heat transfer, material development, and machining. Engineers must change the way they design a part, as they shift from the traditional method of “subtracting material” to the new method of “adding material” in order to manufacture a part. AD is not the same as designing for AM. A new method and new tools are required to assist with this new way of designing and manufacturing. This paper discusses in detail what is required in AD and AM, and how current problems can be solved.

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The concept of “additive manufacturing” (AM) involves building a part from the microscale to the macroscale. At present, the special geometries of jet engine parts are generally made using traditional subtractive machining methods such as filing, turning, milling, and grinding away material from a block of metal, in addition to traditional casting and forging methods. However, these processes cannot handle structures with sophisticated internal substructures. Precision casting also has constraints when dealing with “ideal” internal structures.

Due to the critical aspect of safety, the primary aspect of efficiency, and the vital aspect of cost, AM is by far the best choice for jet engine parts. As shown in Fig. 1, it is estimated that more than 75% of jet engine parts are suitable for AM application due to their irregular shape and complicated structure. The most important reason for this suitability, however, is that all traditional methods of designing and manufacturing have limitations that make them unable to match the competitive requirements of the materials and processes involved in the manufacture of jet engine parts. Researchers are

still unable to decouple the different requirements from different disciplines; one example involves airfoil tuning, as it is very difficult to meet the different requirements of an optimized design for both aerodynamic and structural integrity.

AM is representative of a step in human evolution, as we transition from making products by forging or cutting away to making products by adding material—a method that is closer to natural processes. The most obvious advantage of AM over traditional manufacturing technologies is its capability to handle very complex shapes, and particularly internal shapes. Another advantage of AM is its ability to save material; as no excess material is wasted in AM, its use is particularly relevant for precious materials. The other unique advantages of AM, such as its use of gradient materials and its ability to combine different materials into a single structure, are not discussed in detail here, as they lack a large enough amount of data to support them thus far.

Aside from material saving and weight reduction, the greatest demands held by customers of air travel and transportation for a jet

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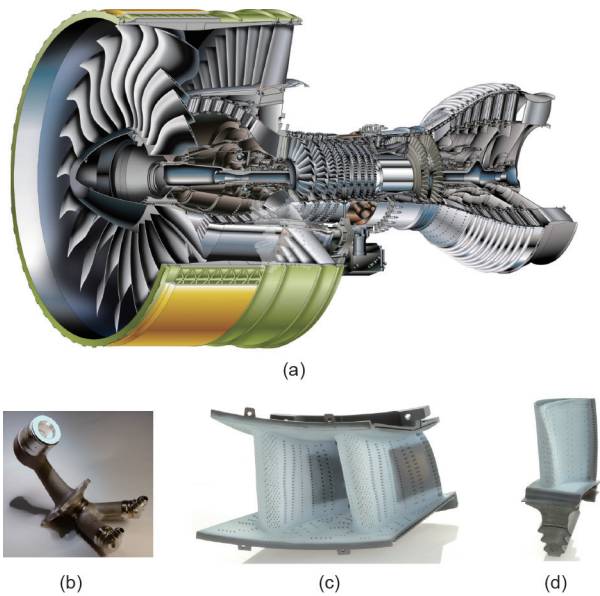


Fig. 1. Jet engine application of AM. (a) Turbo fan jet engine; (b) fuel nozzle; (c) high-pressure turbine nozzle; (d) high-pressure turbine blade.

engine are its safety and efficiency. These characteristics cannot be obtained by simply replacing the conventional manufacturing process with AM, as this transition is a disruptive change in ideology and methodology from “subtracting” to “adding.” The piece-by-piece addition of a material carries many new variables that will actively or passively affect the final product, including: the usage of a single or multiple types of materials; the usage of the same or different conditions in terms of temperature, pressure, or environmental situation; and which and how many chemical elements are present.

With AM, it becomes realistic to make a component via a single process involving multiple materials, without the need for any jointing mechanism such as bolts, nuts, and so forth. It is possible, for example, to build a part with different materials that have different mechanical properties in order to meet different requirements at different locations within the part; these differing properties may include strength, frequency, stiffness, high cycle fatigue (HCF) or low cycle fatigue (LCF), corrosion resistance, and creep properties. With AM, it is possible to design a system directly according to end-user requirements, and it is not necessary to compromise due to manufacturing infeasibility. However, jet engine researchers are not yet ready to take advantage of AM’s capability to produce multiple-material structures, especially at the microscale. Thus far, we lack methods, tools, criteria, and standards to analyze such structures. A structure with a gradient material and/or micro-structure on the subsurface can be even more complicated than a composite structure—it is neither homogeneous nor isotropic, and there is no distinguished boundary or interface.

Our current methods of analysis for solid structures, such as the finite-element method or the traditional theories of solid mechanics and material strength, are not applicable to additively designed parts that have gradient materials and/or subsurface micro-structures. Experimental curves such as Hooke’s law, Poisson’s ratio, and S–N curves for LCF and HCF are all based on the “pure” material itself, rather than on the actual structure being assessed; thus, although these methods are widely used today, their results are incorrect and they themselves are out-of-date.

In the past, it was reasonable for researchers to base their judgment regarding a complicated structure on the mechanical properties of the material involved, because they lacked experimental

curves and data for customer-designed structures, powerful computers, the finite-element method, and detecting technology that was able to explore and visualize the inside of a structure. Until now, the popular practice for engineers has been to introduce a “safety coefficient factor” on top of the material’s mechanical properties when a structure is evaluated. However, this practice leads to poor results that either over- or under-estimate the strength or life of the structure, as we lack a standard procedure that can bridge the properties of a material with those of a structure built of that material. This is because the stress/strain of a structure is usually a vector in three-dimensional (3D) space, whereas the mechanical properties of a material are obtained from a standard sample of that material, and are tested with simple stress/strain statuses. As a result, it is necessary to simplify the 3D vector of the actual stress/strain on a structure in order to subjectively come up with a “normalized” number that can be compared with the properties of the material. Along with additive design (AD), this situation must be resolved in order to exploit the full capabilities of AM to build structures; it is a virgin field for researchers to investigate.

For a jet engine, the hollow or inner lattice structure as well as the gradient material are associated with the strength, thermal efficiency, heat transfer and cooling, stiffness distribution, natural frequency, life, and all other structural integration issues.

Unlike traditional design for manufacturing (DFM), designing for function means to optimize a design to make it more efficient and reliable. Engineers cannot usually optimize a part or an engine because they do not have AM capability. The traditional design of a jet engine is a process that compromises among different aspects including the material process, heat transfer, aerodynamics, structural integrity, control, mechanical system, and manufacturing. However, the special capabilities of AM technologies provide an opportunity to change the concept of DFM; by changing engineers’ vision of design, they enable new ways to meet customers’ requirements, with improvements in product performance, efficiency, quality, and costs. These capabilities include shape complexity, hierarchical complexity, assembly complexity, and material complexity.

AD pays attention to hierarchical subsurface porous structural design in order to “proactively” design a part with decoupled relationships between different disciplines. Taking a jet engine as an example, the aerodynamic engineer first creates an ideal shape for the flow path; the structural engineer then takes this ideal shape as the predetermined boundary condition. To meet the requirements for the structural integrity of the part, the structural engineer can keep the ideal shape unchanged but design the subsurface structure by proactively arranging the material distribution and micro-structure.

As jet engine parts have well-defined aerodynamic shapes, for which little topology optimization can be done, their key design requirement is the capability for hierarchical design integration at multiple scales. Thus far, the majority of the jet engine design community is still trapped by the traditional way of thinking: Most engineers are still debating about the mechanical properties of the material, rather than about the properties of the structure itself. Even with AM, most researchers and engineers are still working on how to improve their designs by creating some kind of porous material, rather than a porous structure. The most popular porous material is a lattice material. In order to define a porous structure, it is necessary to design the shape, size, location, and orientation of each void cell. The unit cell concept is very close to the idea of a porous structure. Thus far, only a cellular structure has been used in AM as a hierarchical structure.

The most popular cellular structure is the beam-based lattice structure. This concept is inherited from traditional ways of thinking and practices of topology, particularly those using tools such as finite-element analysis. With AM, however, structural engineers are no longer constrained by artificial types of geometry such as the

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