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Additive Design and Manufacturing of Jet Engine Parts

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A R T I C L E I N F O

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A B S T R A C T

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 competed 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.

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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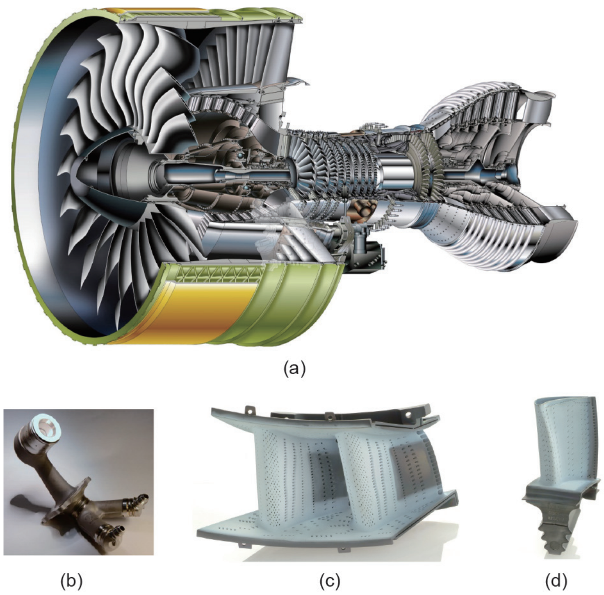

Fig. 1. Jet engine application of AM. (a) Turbo fan jet engine; (b) fuel nozzle; (c) high-pressure turbine nozzle; (d) high-pressure turbine blade.

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 lattice structure, which does not exist in nature. Rather, they are inspired by web-mesh structures such as those in the subsurface of human bone. The web-mesh is distributed irregularly in size and shape, according to its functional requirement. Therefore, one of the challenges in design for AM is the democratization of a web-mesh design with no restriction of shape and/or size of the inner or subsurface web-mesh structure.

There are two challenges in making and analyzing a part with subsurface cellular structures. One is the ability to create an overhang-shaped structure without assistant supports. The other is the affordability of computational cost, which determines how detailed a model can be built for the cellular structure.

Our solution is to create a hollow-sphere finite element, rather than a sphere made of elements. This hollow-sphere finite element, like other types of existing elements, has a geometric specification that is defined by its radius, thickness, and the holes on it. Due to the sphere's symmetrical shape, the constitutive equation of the hollow-sphere finite element is simple. Aside from the many superior mechanical properties of a sphere, the most important reason to use a spherical structure is because it does not require assistant supports for AM. This solution requires a brand new theory, method, and tools, as well as well-trained engineers.

There are two critical challenges for innovative AD and AM. The first challenge is the design of a new part with either a gradient material and/or a subsurface micro-structure; it is necessary that such a part be able to meet the different requirements of a jet engine part. The second challenge is meeting new standards of the regulation codes for both the manufacturing and application of a structure with a gradient material and/or subsurface micro-structures.

Due to disruptive changes in the design domain, with relief being obtained from the traditional constraints of the manufacturing process, engineers have already discovered many innovative designs of structures that can even result in a negative thermal expansion, negative stiffness, negative Poisson's ratio, and more. Furthermore, engineers can proactively design a structure with a desired vibratory mode shape, failure mode, life distribution, and so forth. Based on a typical turbo fan jet engine, we estimate that using AM can result in a huge improvement to an engine, and can increase its efficiency, safety, reliability, and cost-effectiveness (Fig. 2).

For example, a hollow fan blade (Fig. 3) must meet the bird-strike requirement, frequency-tuning requirement, HCF and LCF requirements, deflection requirement, and so forth. The question of how to meet all these requirements in a harmonious way is the objective of the design engineer. Unlike the traditional design method, there is no need to repeatedly pass the design back and forth between the aerodynamic engineer, structural engineer, and manufacturing engineer. Rather, each member of the team can now design a "best" part without being concerned for the constraints from other disciplines, as it is possible to change materials and subsurface micro-structures.

With AD and AM, a high-temperature, high-pressure, and high-speed turbine blade can be made with much better aerodynamic performance, heat-transfer behavior, and stress distribution than ever before; this will eventually result in an optimized design in terms of performance and cost. For example, with a better design for heat-transfer efficiency (Fig. 4), the cooling structure will be better able to reduce the thermal gradient and temperature; this will enable the material to work within its allowable range. At the same time, due to less material being present and a lower thermal gradient, the structure or part will experience less stress from both centrifugal force and thermal constraint. The advantages of AD include: ① a hellow structure that reduces mass and centrifugal force; ② a better cooling structure that reduces temperature and its gradient for lower thermal stress and higher efficiency; ③ a micro-structure

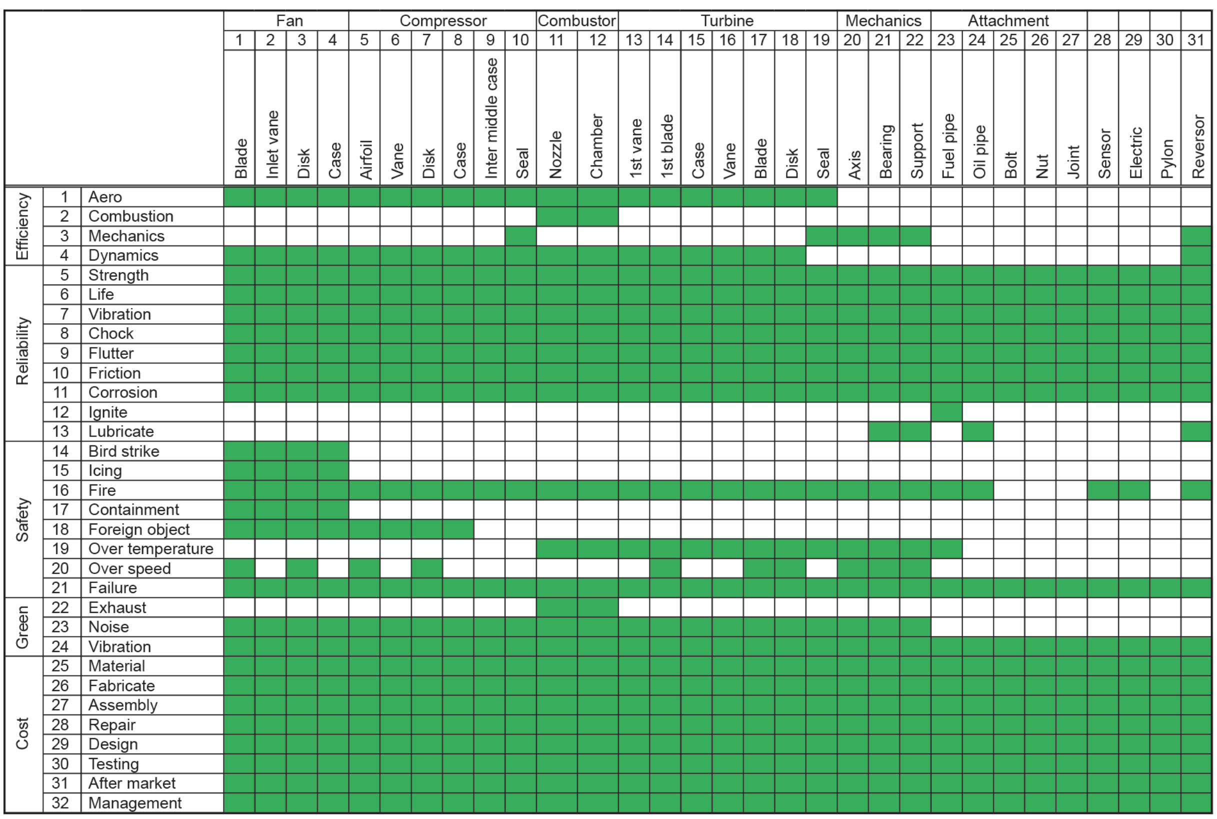

Fig. 2. Value-added improvement for a jet engine through AD/AM. The green blocks in the figure are those with great potential to be improved with AD/AM.

that replaces the single crystal alloy to reduce the cost; and ④ the use of AM to replace precision casting to ensure quality and reduce time to market. In the future, we may not need special high-temperature alloys and special casting processes for a part with a single-crystal metal, the cost of which is very expensive and the quality of which is difficult to guarantee (Fig. 5). It is not necessary to focus on material, because one can arrange the internal micro-structure to reduce the temperature gradient, enhance heat transfer, and reduce mass and stress.

However, many unsolved issues are associated with AM, especially for jet engine parts that require the application of subsurface micro-structures and/or gradient materials. It is necessary to develop a corresponding constitutive relation between the load and the structure or material—something that we do not yet possess. Therefore, traditional analysis tools, such as the finite-element method, cannot be adopted to analyze this new type of structure, whether it be constructed of a gradient material or subsurface micro-structure. In addition, no design criteria exist yet for such brand-new structures, and there are no associated airworthiness regulations.

In addition to the abovementioned design and manufacturing issues, and the requirements for new analysis criteria and regulations, the speed of the AM fabrication process is too slow and must be conquered. Nevertheless, the jump from "subtractive"

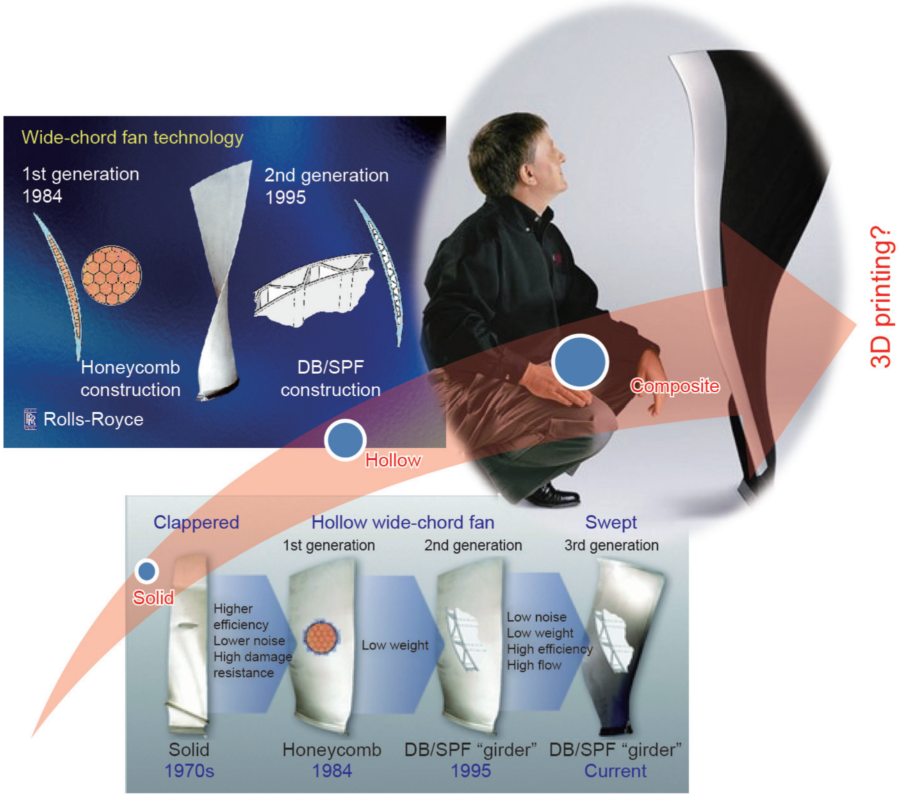

Fig. 3. Current fan blade methodology and futures for fan blade design. DB/SPF: diffusion bonding/sheet superplastic forming.

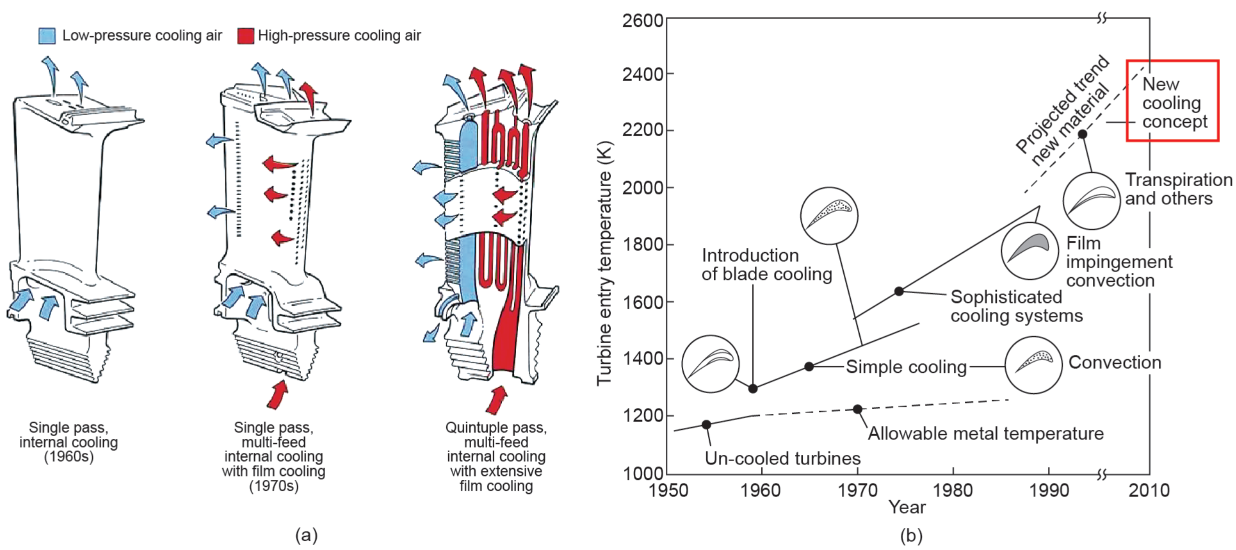

Fig. 4. The use of AD/AM for a better cooling structure of a high-pressure turbine blade [1]. (a) Different cooling mechanisms; (b) development of turbine blade cooling structure.

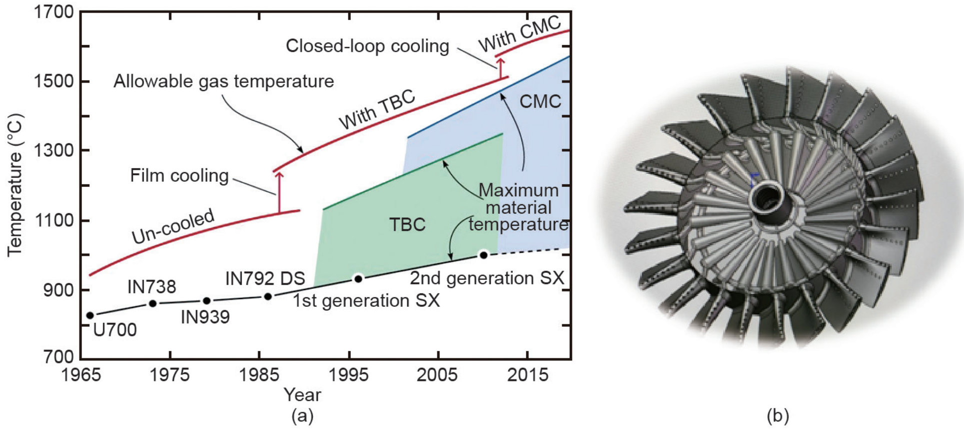

Fig. 5. As shown here using the example of turbine blade design, 3D printing will revolutionize turbine blade design and change our dependence on special materials. (a) The potential of material is limited; (b) cooling structure for intergrated bladed rotor. TBC: thermal barrier coating; SX: single crystal alloy; CMC: ceramic matrix composite.

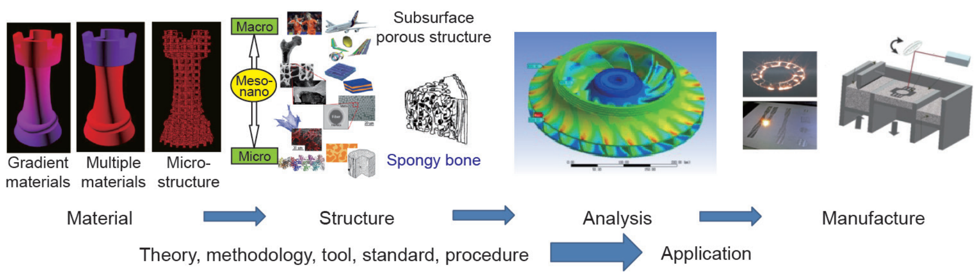

Fig. 6. This new discipline of engineering faces challenges in material, mechanics, mathematics, and physics. AD/AM provides the opportunity to change the world.

to "additive" manufacturing is a revolution in design and manufacturing that will challenge humanity in every aspect of our lives. Those at the forefront of this new revolution will change the world (Fig. 6).

Reference

[1] Lakshminarayana B. Fluid dynamics and heat transfer of turbomachinery. New York: John Wiley and Sons Ltd.; 1996.