DOI: 10.54254/2753-8818/14/20240876

Jet engine blade: Design, material, and manufacturing

Chenghao Liu

School of mechanical aerospace and civil engineering, University of Manchester, Manchester M13 9PL, UK

Chenghao.liu@student.manchester.ac.uk

Abstract. The engine is the most important part of an airplane. Since the blades of an engine are a major factor in jet engine performance, the research of engine blades has always been a hot topic in the field of aerospace. This paper summarizes the research status in the field of jet engine blades. As for the design of the jet engine blade, the design of aerofoil and the geometrical structure of the engine blade is introduced. In the material selection of engine blades, titanium alloy materials, and the application of composite materials are introduced. Electrochemical machining (ECM) and additive technology of engine blades are introduced. The differences between them and traditional casting techniques are compared. The comprehensive analysis shows that the research on engine blades is becoming more and more mature, but there are some challenges in further optimization of manufacturing technology and materials. This paper may offer a reference for the design of jet engine blade.

Keywords: Jet Engine Blade, Electrochemical Machining, Additive Manufacturing.

1. Introduction

Faster modes of transportation will make the planet smaller. Among them, aircraft as the world's highest-speed mode of transportation has a position that cannot be ignored. The engine is the most important part of an airplane. Jet engines are the most widely used in aircraft manufacturing. A jet engine can be viewed simply as a combination of a compressor, combustion chamber, turbine, and nozzle. The blades are present in the compressor and turbine. The blade plays a role that cannot be ignored in the process of suction and ejection of air by the engine. In the compressor, the blades rotate at high speed to draw air into the jet engine. The blades in a turbine drive the compressor through high-temperature gas. Furthermore, the design of the blades has an impact on the performance of jet engines. This is not only dependent on the geometric design of the blade but also affected by the manufacturing process and materials of the blade. Reasonable blade geometry design will reduce blade weight and eddy current formation. Choosing the right material will affect the way the blades are processed and will also extend the service life of the engine blades. The different processing methods are mainly subject to the choice of processing materials. In addition, the production cost and wear fatigue of the blade will be determined by the characteristics of different processing methods. As the research of engine blades has always been a hot topic in the field of aerospace, this paper summarizes the research status in the field of engine blades. Starting with the design of engine blade, this paper introduces the design of the aerofoil of engine blade, and the geometric structure of engine blade is also included. In the material selection of engine blades, titanium and alloy materials, and the application of composite materials are introduced.

DOI: 10.54254/2753-8818/14/20240876

Electrochemical machining (ECM) and additive technology of engine blades are introduced. The differences between them and traditional casting techniques are compared. This paper may offer a reference for the design of jet engine blade.

2. Design of Blade

2.1. Design of Blade

The design of jet engine blades is the design of an airfoil. The working principle of jet engines is to produce pressure differences on both sides of the blade through the high-speed rotation of the blade. When the blade is rotating at a high speed, the flow velocity on the concave surface of the jet engine blade will be lower than that on the convex surface. Based on Bernoulli's principle, a high flow velocity will lead to a low flow pressure. The air in the high-pressure area then pushes the air in the low-pressure area into the engine to create thrust. Moreover, the performance of the blade will affect the working efficiency of the engine. The performance of a jet engine will be affected by the factors such as section of the blade, blade twist, blade chord, and angle of attack of the blade. Therefore, the designer performs a geometric analysis of the blade by using the blade element momentum (BEM) theory. This theory is divided into two different approaches: on the one hand, the aerodynamic forces acting locally on the airfoil need to be taken into account. On the other hand, it is also necessary to consider global changes in momentum [1]. By using BEM theory, the ideal power will be calculated. However, due to the surface resistance, friction, and energy loss of the blade, the actual power is usually less than the ideal power.

Besides the traditional engine blade design, designers have also designed a new design to optimize the working efficiency of the blades. The blades are designed as hollow. Therefore, the internal flow is produced. The benefits of this design are to reduce the weight of the blades and energy consumption. The internal flow is the air flow that enters the hollow structure of the blade from the connection between the root of the blade and the rotating disc, and then flows out from the back edge of the jet engine blade. In addition to the reduction of flow separation, not only the boundary layer on the concave side of the blade is reduced, but also reduction of the factors unfavorable to airflow at the tail end of the hollow structural blade [2].

There is also a method of optimizing the blade called the blade slotting technology. The method is to add a groove in the blade that allows the fluid to flow through. The idea of this design is to control the air flow rate through the slots in the blade to achieve the purpose of the corner separation induced by the shock wave. Due to the blade slotting technology does not require additional energy consumption, it has a lower cost, is more environmentally friendly, and is more reasonable for application [3]. In addition, it is also necessary to increase the heat dissipation efficiency of the blade. To improve the ratio of the thrust and weight of the aircraft and the output power of the engine, the temperature of the engine's air intake should be as high as possible. However, high temperature may lead to ablation of engine blades. Therefore, it is necessary to cool the blades. The cooling method of the blade that is widely used now is the combination of washing and soaking of the blade with the coolant [4]. As for the connection between a single blade and a rotating disc, the dovetail blade is one of the methods, and the dovetail tenon joint at the root of the blade is matched with the groove on the rotating disc to the fixed blade. There are two types of geometry design of dovetail: skewed and straight. Sometimes multiple dovetail tenon joints are used to make the connection stronger.

2.2. Stress and Strain of Blade

In the design of the engine blade, to explore the fatigue failure interval of the blade, the stress analysis and simulation of the parts under working state is a more effective method. The engine blade is accurately scanned in 3D to carry out modelling of the jet engine blade, and then analyze the section of the blade and the whole part of the blade by the software to find the stress distribution of the engine blade. This is helpful for further optimization of engine blade design, stress analysis and evaluation of faulty engine blades. The dovetail groove is the key part connecting the blade and the rotating disc, which directly affects whether the blade can operate normally, and even whether the whole jet engine

DOI: 10.54254/2753-8818/14/20240876

can work normally. By modeling and simulating the stiffness of the joint of the dovetail head and the dovetail groove, a centrifugal force is applied to the bottom of the dovetail head in the model, which is used to simulate the centrifugal force generated by the high-speed rotation of the blade at work, and the tangential force caused by the strain generated by the high-speed rotation of the disc. While the increasing of the operating temperature, the Young's modulus of the dovetail joint will decrease, and it will then further have the consequence of reducing the stiffness of the dovetail joint [5]. It can be seen from the experimental results that the geometric structure of the studied blade will be more easily destroyed because of the higher friction coefficient [6]. Furthermore, the roughness of different contact surfaces is substituted into the simulation. It can be seen that the slip generated by the contact surface between the dovetail joint and the disc will be smaller because of the increase of the friction coefficient, which is because the increase of the friction coefficient leads to the increase of the friction stress, which further leads to such a result [7]. For the combination of engine blades and rotating discs, the rotating disc is not a standard cylinder but an approximate circular table geometry, and the small diameter side forward. Therefore, for the blade and disc combination, its center of gravity is tilted back. In other words, when it is working, the mass of the rear is higher than the mass of the front, causing the expansion of the front and rear ends of the disc to be different. Therefore, different degrees of expansion will drive the blade to have a significant rotational displacement in the axial direction. Another important experimental result on blade deformation is that a strongly twisted blade will have high warping because of centrifugal force on the blade generated by rotation [7]. Moreover, when a baffle plate is added in the middle of the slot, the improvement effect of the vortex at the end of the blade is better.

3. Material of Blade

To make the designed engine blade become a reality, the selection of materials is one of the important parts. The selection of materials needs to consider the working environment, processing method and energy of the blade. High temperature, high pressure and high-speed rotation are the working environment of engine blades. It is necessary to reduce the mass as much as possible to save energy. Titanium and other alloys are widely used. Titanium has good mechanical properties, physical properties, and easy processing characteristics, so it has a good performance in the manufacture of engine blades. High specific strength, low density and strong corrosion resistance are the advantages of titanium alloys compared with other alloy materials [8]. Titanium alloy also has good tensile strength and yield strength. Some titanium alloys have similar strength compared to some steel, but the mass is much lower than that of steel. Compared with aluminum, titanium has a greater density, but the yield strength of titanium is greater than that of aluminum. The feature of low density also makes titanium more competitive because low density means that the blade can have lower mass, which leads to lower energy consumption. In addition, titanium is also a more active metal. When exposed to air, titanium will oxidize in contact with oxygen in the air, generating an oxide film composed of titanium dioxide on the surface of titanium metal, titanium dioxide also has the characteristics of high-temperature resistance. Furthermore, when the film on the surface of the blade is damaged or scratched, the titanium will be re-oxidized to form a new titanium oxide film to repair itself. The engine blades should be strong enough to overcome failures that may occur when operating under extreme conditions, such as cracking, creep, oxidation, and fatigue. Therefore, the use of alloy materials is very necessary. Superalloys of nickel, cobalt or iron-based alloys are all very suitable [9]. At present, there are still challenges in material selection, which can be further optimized for cost control, weight reduction and aerodynamic efficiency improvement [1]. Due to its excellent strength and lightweight characteristics, composite materials and metal matrix composites are increasingly used in the application of engine blades. New material combinations and further reducing production costs have become new challenges, such as the development and application of carbon fibre and glass fibre composite materials in engines and the improvement of the production and processing methods of existing materials.

DOI: 10.54254/2753-8818/14/20240876

4. Manufacturing of Blade

In addition to optimizing the performance of engine blades or controlling the cost in the design of engine blades and the selection of engine blade materials, the selection of manufacturing processes can also further reduce costs and improve engine performance. Nickel-based superalloys and titanium alloys are commonly used to make engine blades, which are relatively easy to work with and the structure of engine blades is complex and irregular. Compared to traditional machining methods, electrochemical machining (ECM) and 3D printing are more suitable for the manufacture of engine blade parts that are difficult to cut or cast. ECM requires less thought and design than casting. At the same time, it will not generate defects that may occur during casting, like hot tears, cold shut, incomplete filling, and scabs. Similarly, compared with the reduction processing method, additive technology can not only realize the processing of complex structures more easily but also save material waste. ECM and 3D printing are gradually maturing. The ECM method has unique advantages that are different from traditional processing technology, such as not easily affected by the properties of the processed material, ensuring the integrity of the machining tool, good surface integrity of the machined parts, high processing efficiency, and low processing costs. In the ECM methods, the anode is the workpiece, the cathode is the preforming tool, and then a pulse voltage of 10-40 volts or a direct current voltage is applied to the workpiece and the preforming tool respectively [10]. In particular, when titanium or titanium alloys are used for ECM, titanium forms a dense oxidation passivation layer that inhibits the dissolution process of the material. Therefore, when ECM is performed on titanium alloys, the use of the electrolyte containing halides can effectively avoid the above problems [10]. As for additive manufacturing technology, only Binder Jetting (BJT), Directed Energy Deposition (DED), and Power Bed Fusion (PBF) can be used in the manufacture of engine blades. Specifically, the BJT method deposits a liquid binder on a thin layer of a powdery material, the boundary of which is determined by the geometry of the designed part. The DED method refers to using a concentrated high-energy source such as a laser to melt the material while the material is sprayed by a nozzle and deposited. Not only that, electron beam and plasma arc can be used to melt the material. The principle of PBF method is to fuse a material by melting it with high-energy source which is mentioned before such as electron beam. PBF is the most used AM processing method in the manufacture of blades. It is becoming more and more popular because of its simple process and the wide range of materials to choose from [11].

5. Conclusion

Engine blades have become an increasingly important research field in aerospace engine technology. This paper summarizes the current development of jet engine blades. The airfoil design of different engine blades will bring different effects to the work of engine blades. The difference in processing methods will also have different effects on the stress distribution, anti-wear, and anti-fatigue of the engine blades. Correspondingly, compared with the processing method, the choice of blade material will not only directly affect the choice of processing method, but also affect the blade's ability to withstand wear and fatigue. However, there are still some technical challenges that need to be addressed, such as the fabrication of blades with complex structures the application of new composite materials and the optimization of their processing methods. The research on engine blades has the potential to promote the development of other industries and research areas, the study of engine blades will continue to be an active research area in the future.

References

[1] Leye M. Amoo, On the design and structural analysis of jet engine fan blade structures, *Progress in Aerospace Sciences,* Volume 60, 2013: 1-11.

[2] Matjaž Eberlinc, Brane Širok, Marko Hočevar, Experimental investigation of the interaction of two flows on the axial fan hollow blades by flow visualization and hot-wire anemometry, *Experimental Thermal and Fluid Science,* Volume 33, Issue 5, 2009: 929-937.

[3] Wang H, Liu B, Mao X, Zhang B, Yang Z, Investigation of the controlling mechanisms of blade slotting technology on the shock-wave-induced corner separation, *Aerospace Science and Technology,* Volume 140, 2023, 108491.
[4] Kong D, Zhang C, Ma Z, Liu C, Isaev S.A., Guo T, Xie F, Numerical study on flow and heat transfer characteristics of swirling jet on a dimpled surface with effusion holes at turbine blade leading edge, *Applied Thermal Engineering,* Volume 209, 2022, 118243.
[5] Kang H, Li Z, Liu T, Mei Q, Zhang X, Connection stiffness modeling of rotating dovetailed blade with macro-micro interface topography, *European Journal of Mechanics - A/Solids,* Volume 101, 2023, 105064.
[6] R. Rajasekaran, D. Nowell, Fretting fatigue in dovetail blade roots: Experiment and analysis, *Tribology International,* Volume 39, Issue 10, 2006: 1277-1285.
[7] G. Cesari, F.W. Panella, A. Pirinu, Stress/strain state for critical components of a jet engine aeronautical compressor, *Engineering Failure Analysis,* Volume 116, 2020, 104745.
[8] Hao F, Liu X, Du Y, Mao Y, Chen H, Li S, Wang K, Lei L, Excellent dynamic mechanical properties of a newly developed titanium alloy with bimodal structure, *Journal of Alloys and Compounds,* Volume 961, 2023, 170980.
[9] Mukesh Yadav, Ashwin Misra, Aahan Malhotra, Naveen Kumar, Design and analysis of a high-pressure turbine blade in a jet engine using advanced materials, *Materials Today: Proceedings,* Volume 25, Part 4, 2020: 639-645.
[10] XU Z, WANG Y, Electrochemical machining of complex components of aero-engines: Developments, trends, and technological advances, *Chinese Journal of Aeronautics,* Volume 34, Issue 2, 2021: 28-53.
[11] Francesco Careri, Raja H.U. Khan, Catherine Todd, Moataz M. Attallah, Additive manufacturing of heat exchangers in aerospace applications: a review, *Applied Thermal Engineering,* Volume 235, 2023, 121387.