DOI: 10.54254/2755-2721/72/20240974

Application and performance analysis of advanced materials in engine lightweight

Zijian Lang[1], Tao Zhang[2,3]

[1]Cranfield University, Bedford, The UK
[2]Beihang University, Beijing, China

[3]langzijian@bjzhc.com.cn

Abstract. This paper discusses the application and performance analysis of advanced materials in engine lightening. Firstly, we analyze the properties of high performance aluminum alloy, titanium alloy and composite materials, including their composition, mechanical properties and high temperature resistance. Then, the practical application effects of these materials in key components such as automobile and aero-engine are analyzed through concrete cases. For example, the introduction of micronutrient and improvements in heat treatment processes have significantly increased the strength and corrosion resistance of high-performance aluminium alloys. Titanium alloy is widely used in the key parts of aero-engine because of its high strength and light weight, which greatly improves the performance of engine. The low density and high strength of the composite make it an ideal choice for reducing engine weight. Finally, we discuss the current challenges and future directions, and explore solutions to reduce costs, improve processing efficiency and develop new alloys, in order to provide guidance and reference for the further development of engine lightweight technology.

Keywords: High-performance aluminum alloy, titanium alloy, composite materials, engine lightweight, performance analysis.

1. Introduction

The pursuit of lightweight engines is crucial for improving the performance of automobiles and aircraft while reducing fuel consumption. This effort has been revitalized by the emergence of advanced materials, opening up new avenues for achieving this goal. High performance aluminum alloys, titanium alloys, and composite materials have great prospects in the field of engine lightweight due to their unique physical and chemical properties. This article aims to explore the material characteristics and performance analysis of these advanced materials, practical application cases, as well as related challenges and development directions. Firstly, a thorough study will be conducted on the composition, mechanical properties, and high temperature resistance of these advanced materials. This explanation will provide valuable information on the inherent characteristics that make it suitable for light engine applications. Then, through the demonstration of specific case studies involving automotive components and aircraft engines, the effectiveness of these materials in practical engineering scenarios will be emphasized. By gaining a deeper understanding of practical applications, the practical benefits of using these materials can be elucidated, thereby affirming their role in improving engine performance. In addition, an analysis will also be conducted on current challenges such as material costs and processing complexity [1]. At the same time, this document will identify future development directions aimed at mitigating these challenges, including measures aimed at reducing costs, improving processing efficiency, and innovating new alloys. Through comprehensive analysis and discussion, this article aims to provide theoretical information and practical references, thereby providing valuable suggestions for the continuous progress of engine lightweight technology.

2. Application of high performance aluminum alloy

2.1. Material characteristics and performance analysis

High-performance aluminum alloys are carefully optimized to improve their lattice structure and strengthen the phase interface. This optimization is achieved through the addition of trace elements such as strontium, zinc and magnesium, combined with advanced heat treatment processes such as solution treatment and age hardening. With these techniques, the alloys show significant improvements in strength and corrosion resistance. For example, 7075 aluminum alloy after T6 heat treatment, its tensile strength can reach 570 MPa, nearly 5 times higher than the strength of pure aluminum. In addition, these alloys also show good fatigue resistance and resistance to stress corrosion cracking [2].

In addition, characterization of microstructure parameters, such as dislocation density and grain size, helps to build mathematical models for predicting the fatigue life of aluminum alloys. These models play a crucial role in accurately predicting fatigue life under different stress levels and environmental conditions. In addition, these models incorporate consideration of environmental factors that affect corrosion resistance [3]. By incorporating environmental corrosion factors into the analysis, these models provide a robust framework for calculating the long-term life and reliability of aluminum alloys. Through such a comprehensive analysis, the inherent characteristics and performance capabilities of high performance aluminum alloy are clarified, which opens the way for its effective application in lightweight engine manufacturing.

2.2. Application case analysis

In a case study of automotive engine piston applications, the use of the new material not only reduced the weight of the piston by about 17% compared with the traditional AA4032 aluminum alloy by using the AA2618 aluminum alloy, and because of its excellent thermal stability and low Coefficient of thermal expansion, it significantly improves the thermal efficiency and power output of the engine. Through the finite element analysis of thermal stress distribution in the piston operating cycle, we found that the stress concentration region of AA2618 alloy piston is about 20% less than that of AA4032 alloy at high temperature and high pressure, this directly reduces the risk of fatigue failure [4]. The application of the mathematical model shows that the fuel efficiency of an engine with an AA2618 aluminum piston is about 5% higher than that of an engine using conventional materials under standard operating conditions, the effectiveness of high performance aluminum alloy in improving engine performance was proved, as shown in Table 1.

Table 1. Comparison of Automotive Engine Piston Materials and Performance Enhancement

Material Used	Weight Reduction (%)	Thermal Efficiency Improvement (%)	Stress Concentration Reduction (%)	Fuel Efficiency Improvement (%)
AA4032 Aluminum Alloy	0	0	0	0
AA2618 Aluminum Alloy	17	-	-20	5

2.3. Challenge and direction of development

The task of improving the strength reduction of high-performance aluminum alloys at high temperatures is a daunting challenge, forcing researchers to explore new solutions. An important research approach is to enhance the high-temperature capability of alloys by adding rare earth elements. Due to the controlled addition of cerium and lanthanum in aluminum alloys, stable rare earth phases precipitate at grain boundaries. These phases serve as sturdy barriers, effectively preventing dislocations from moving at high temperatures, thereby enhancing the material's ability to resist creep deformation. Meanwhile, coordinated research aims to develop cost-effective alloy formulations and adopt advanced manufacturing technologies. Innovations such as powder metallurgy and rapid laser prototyping are being used to address challenges related to cost control and processing complexity. These forward-looking measures aim to reduce material waste, improve manufacturing efficiency, and allow the production of complex geometric components that traditional methods have not been able to achieve so far. The future development trajectory depends on continuous innovation in alloy design and manufacturing methods [5]. The expected progress is not only expected to expand the application range of high-performance aluminum alloys in high-performance engines, but also to effectively alleviate production costs and efficiency limitations. With the continuous progress of materials science and manufacturing technology, the prospect of achieving technologically advanced and economically feasible solutions for light engines is becoming increasingly bright [6].

3. Application of titanium alloy in engine

3.1. Material characteristic and performance analysis

One of the distinguishing features of titanium alloys is their high strength-to-weight ratio, which means that they can provide greater strength than most metals at the same weight. This is due to the unique crystal structure of titanium alloys and their ability to customize their properties by alloying (adding other elements such as aluminum and vanadium) . For example, $\alpha + \beta$ titanium alloys can achieve a balance between good strength and excellent plasticity and toughness by precisely controlling the ratio of α to β phases. In terms of high temperature resistance, titanium alloys exhibit better performance than aluminum alloys and many steels, maintaining their physical properties at up to 600 ° C. This is due to the very high melting point of titanium alloys (over 1600 ° C) and their ability to form a stable oxide film that protects the material from further oxidation at high temperatures.

Furthermore, by studying the composition and microstructure of Quantitative analysis titanium alloys, researchers have been able to reveal how the elements in the alloys affect their macroscopic properties, such as hardness, strength, toughness and corrosion resistance. Advanced materials analysis techniques such as electron microscopy (EM), X-ray diffraction (XRD) and differential scanning Differential scanning calorimetry (DSC) provide insight into the internal microstructure of titanium alloys, such as grain size, phase composition and dislocation density, which are directly related to the mechanical properties of materials [7]. A mathematical model, such as finite element analysis (FEA) , can be used to predict the behavior of titanium alloy under complex loads, such as high-speed rotation, high-temperature airflow impact, etc. [8]. These models take into account the material's physical properties, geometry, boundary conditions and loading conditions, and can optimize the material design by simulation, reducing the experimental cost and time, improve the performance and reliability of engine components. Table 2 compares the key properties and analysis techniques of titanium alloys, aluminum alloys, and steels.

DOI: 10.54254/2755-2721/72/20240974

Table 2. Comparison of Material Properties and Analysis Techniques for Titanium Alloys, Aluminum Alloys, and Steels

Property	Titanium Alloys	Aluminum Alloys	Steels
Strength-to-Weight Ratio	High	Moderate	High
High Temperature Resistance	Excellent	Moderate	Excellent
Melting Point (°C)	>1600	~660	>1300
Oxidation Resistance	Excellent	Moderate	Good
Alloying Elements	Aluminum, Vanadium, etc.	Copper, Silicon, etc.	Chromium, Nickel, etc.
Microstructure Control	Achievable	Limited	Limited
Material Analysis Techniques	EM, XRD, DSC	EM, XRD, DSC	EM, XRD, DSC
Mechanical Property Prediction	FEA	FEA	FEA

3.2. Application case analysis

Titanium alloys are widely used in the key high temperature components of aeroengines, such as turbine blades, compressor impellers and engine supports. These components are subjected to extreme temperatures and pressures during engine operation and require high performance materials. Titanium alloys are used not only because they can withstand these harsh conditions, but also because they can significantly reduce the overall weight of the structure. Taking turbine blades as an example, the traditional nickel-based alloy has good high temperature performance, but its high density limits the improvement of engine efficiency. With the introduction of titanium alloy turbine blades, the weight of the components can be reduced by about 10% -15% while the strength and high temperature resistance are ensured [9]. This weight reduction translates directly into increased fuel efficiency and lower launch costs. The application of mathematical model further confirmed the advantages of titanium alloy components in engine:

$$Weight\ Reduction\% = \frac{Initial\ Weight - Final\ Weight}{Initial\ Weight} \times 100\% \tag{1}$$

Where *Initial Weight* is the initial weight of traditional nickel-based alloy components. *Final Weight* is the final weight of the components after replacing them with titanium alloy components.

By simulating engine conditions at different stages of flight, such as temperature and pressure changes during take-off, cruise and landing, researchers can accurately calculate the stress and strain states of materials and optimize component design, reduce weight while ensuring safe operation.

3.3. Challenges and directions

Although titanium alloys show great potential in aero engine applications, there are still some challenges to their wide application. The first challenge is the high cost and complex processing requirements of titanium alloys. Machining titanium alloys requires specialized tools and technologies, such as high-speed CNC machines and specific cutting fluids. In addition, the processing of titanium alloys leads to stress and heat-affected zones, which can compromise the performance of components. In order to overcome these obstacles, researchers are diligently working to reduce the production cost of titanium alloys, improve processing technologies, and innovate new titanium alloy materials [10]. For example, the use of powder metallurgy and 3D printing technology is expected to reduce material waste and production costs, while providing unprecedented design flexibility, simplifying the production of complex shaped parts that were previously impossible to manufacture using traditional manufacturing methods. In addition, the development of a new generation of titanium alloys also uses microalloying technology and surface modification technology to further improve the material properties. The addition of rare earth trace elements can improve the corrosion resistance and high temperature properties of titanium alloys. Surface treatment technologies such as laser cladding and electrochemical deposition can endow titanium alloys with functional coatings such as wear-resistant and heat-resistant, thus extending the service life of components [11].

In short, thanks to unremitting research efforts and technological innovation, the future prospects of titanium alloys in aero engines and other high-performance applications are bright. By addressing existing challenges and advancing materials science and processing technologies, titanium alloys are expected to play a central role in the development of next-generation high-performance engines and other critical applications.

4. Application of composite materials in lightweight engine

4.1. Material characteristics and performance analysis

In the application of composite materials, carbon-fiber-reinforced polymer fiber reinforced polymer (CFRP) is an important lightweight material, and its unique material characteristics play a crucial role in improving engine performance, as shown in Figure 1. First, the extremely low density and excellent specific strength of CFRP allow for significant weight reduction in engine components. Secondly, the high specific modulus and excellent fatigue performance of CFRP make it able to withstand high-strength stress and frequent working cycles, thus improving the reliability and durability of the engine. In addition, the excellent corrosion resistance and abrasion resistance of CFRP also make it have excellent performance in harsh working environment.

Figure 1. A typical structure of carbon fiber reinforced polymer (CFRP) (Source: ResearchGate.com)

To gain a deeper understanding of the mechanical behavior of CFRP, researchers have used Quantitative analysis and mathematical modeling [12]. By analyzing the fiber orientation, fiber sequence and resin matrix, the structural design of the composite can be optimized, and the performance stability and reliability can be improved. The mathematical model can not only predict the stress distribution and strain change of composites under loading, but also evaluate the performance of composites under different load conditions.

4.2. Application case analysis

In modern engine design, composite materials have been widely used in a variety of key components, its performance advantages have been fully developed. Taking the fan blade as an example, the blade made of CFRP material not only has obvious advantages in reducing weight, but also can improve its stability and reliability in high-speed rotation and impact. Through the analysis of practical application cases, it can be found that under the application of CFRP materials, the structure of the fan blades is lighter and more impact-resistant, therefore, the operating efficiency and life of the whole engine system are effectively improved.

In addition, the application of CFRP in engine cover and other components has also achieved remarkable results. As an external protective structure of engine, the light weight design of engine cover can not only reduce the overall weight, but also improve the overall sealing and thermal efficiency of engine system [13]. Through the analysis of the mathematical model, the reasonable layout and structure design of CFRP material in the engine cover can be determined, so as to maximize its advantages of lightweight and strength, it provides reliable technical support for the improvement of engine performance.

4.3. Challenges and directions

Although CFRP has great potential in engine lightweight, it still faces some challenges in its application. Firstly, the high manufacturing cost of CFRP limits its application in large-scale applications. Secondly, the processing complexity of CFRP materials and the connection technology with other materials still

DOI: 10.54254/2755-2721/72/20240974

need further improvement. To meet these challenges, the future research will focus on reducing the manufacturing cost of CFRP, improving its processing efficiency and developing new connection technology. At the same time, with the continuous improvement of materials science and manufacturing technology, it is expected that more new CFRP materials will be developed to meet the needs of improving engine performance.

5. Conclusion

In summary, the use of advanced materials is the cornerstone of the manufacture of lightweight engines. Through an in-depth study of the inherent properties of high-performance aluminum alloys, titanium alloys and composites, it is clear that they have great potential for improving engine performance and reducing fuel consumption. However, achieving the ultimate goal of engine lightweight requires overcoming challenges such as material cost and machining complexity. With a strong commitment to ongoing technical research and innovation, we remain optimistic about our ability to overcome these obstacles and advance the field of lightweight engine technology, thereby making a substantial contribution to the future of mobility and energy savings. The ideas and perspectives presented in this document can provide guidance and support for the practical application of lightweight engine technology and point the way for future engine engineering development.

References

[1] Martin, J. Hunter, et al. "Additive manufacturing of a high-performance aluminum alloy from cold mechanically derived non-spherical powder." Communications Materials 4.1 (2023): 39.
[2] Rahmani, Mohammad Hossein, et al. "N-doped carbon hollow sphere reservoirs containing Zn2+-mercaptobenzoxazole with pH-responsive function to fabricate a high-performance corrosion protective epoxy coating for aluminum alloy." Corrosion Science 219 (2023): 111202.
[3] Aglawe, Kapil, et al. "Application of aluminum alloys in aviation industry: A review." AIP Conference Proceedings. Vol. 2800. No. 1. AIP Publishing, 2023.
[4] Pesode, Pralhad, and Shivprakash Barve. "A review—metastable β titanium alloy for biomedical applications." Journal of Engineering and Applied Science 70.1 (2023): 25.
[5] Nyamekye, Patricia, et al. "Impact of additive manufacturing on titanium supply chain: Case of titanium alloys in automotive and aerospace industries." Advances in Industrial and Manufacturing Engineering 6 (2023): 100112.
[6] Pesode, Pralhad, et al. "Titanium alloy selection for biomedical application using weighted sum model methodology." Materials Today: Proceedings 72 (2023): 724-728.
[7] Gupta, Munish Kumar, et al. "Comparison of tool wear, surface morphology, specific cutting energy and cutting temperature in machining of titanium alloys under hybrid and green cooling strategies." International Journal of Precision Engineering and Manufacturing-Green Technology 10.6 (2023): 1393-1406.
[8] Ogunmefun, O. Anthony, et al. "A critical review of dispersion strengthened titanium alloy fabricated through spark plasma sintering techniques." Journal of Alloys and Compounds (2023): 170407.
[9] Bhong, Mahesh, et al. "Review of composite materials and applications." Materials Today: Proceedings (2023).
[10] Aziz, Tariq, et al. "Challenges associated with cellulose composite material: Facet engineering and prospective." Environmental Research 223 (2023): 115429.
[11] Talreja, Ramesh, and Janis Varna, eds. Modeling damage, fatigue and failure of composite materials. Elsevier, 2023.
[12] Hasan, Md Munjur, et al. "Sustainable ligand-modified based composite material for the selective and effective cadmium (II) capturing from wastewater." Journal of Molecular Liquids 371 (2023): 121125.
[13] Amor, Nesrine, et al. "A review on computational intelligence methods for modelling of light weight composite materials." Applied Soft Computing (2023): 110812.