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Review of Additive Manufacturing Materials in the Automotive Industry: Progress, Challenges, and Future Trends

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Abstract. As the automotive industry works more on lighter weight, better fuel economy, and custom design, additive manufacturing shows great promise. The material properties are key to meeting automotive industry needs. This paper reviews the progress of the main additive-manufactured materials in automobiles. In this article, we focus on metal materials like titanium alloy, aluminum and magnesium alloy, and high-performance composite polymers. We compare each material's basic properties, such as strength, heat resistance, weight, and accuracy. This helps to see their engineering value and limits. We also look at current technical challenges like material consistency, process standardization, and scale-up limits. Finally, we suggest future material development and use trends. This work gives a clear view of additive-manufactured materials in automobiles and a basis for later work on material and process improvement.

Keywords: Automotive Industry, Additive Manufacturing Materials, Metal Materials

1. Introduction

The automotive industry has a large impact on the global economy. It is also considered as one of the most influential industries influencing society and individual lifestyles. Traditional manufacturing technologies used in the automotive industry, such as casting and injection molding, rely heavily on subtractive manufacturing processes. In recent years, as the automotive industry moves toward lightweight, high-performance and smart intelligence, the limitations of traditional manufacturing methods in terms of structural complexity, response speed, and material utilization efficiency have become increasingly apparent. Additive manufacturing with its significant advantages in complex structure forming, material utilization efficiency, design freedom and lightweight parts, this technology has brought profound changes to the traditional automobile manufacturing process, thereby changing the production process. With the improvement of manufacturing capabilities and manufacturing quality, additive manufacturing can not only be used for rapid prototyping of automotive parts, but also to produce high-quality end-use parts. In this context, the performance and applicability of additive manufactured materials have become key factors in determining its industrialization process.

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Material properties are one of the key factors that determine whether additive manufacturing can be applied in the automotive industry. In recent years, alloys with aluminum and other metal materials are widely used in industry. However, metals such as titanium are not commonly used. High-performance materials such as Carbon fiber composite and carbon fiber reinforced polymers have been widely used in body structures, suspension systems, energy-absorbing structural parts, heat exchange systems, and interior functional components, demonstrating excellent mechanical properties, heat resistance, and energy absorption capabilities. For example, the titanium alloy Ti-6Al-4V has extremely high specific strength and corrosion resistance. After being processed using SLM and EBM technologies, its tensile strength is increased by up to 25% compared with traditional manufacturing processes, making it suitable for key structural parts with extremely high strength and reliability requirements [1]. Aluminum alloy materials have become one of the most widely used metal materials in body and suspension systems due to their light weight, high strength, good processability, and designability. By regulating the microstructure and composition, product defects such as cracks and pores in the forming process can be effectively alleviated [2]. In terms of polymers and composite materials, multi-material printing technology enables them to be customized into complex honeycomb energy-absorbing structures, reaching an increase to absorb 68% in low-speed collision energy and reduce 70% of peak stress in bumpers, while maintaining lightweight and reusability [3].

Although the application of additive manufactured materials in the automotive industry has made significant progress, there are still many challenges that remain. For example, the difficulty in controlling the residual stress and fatigue life of metal printed parts, the performance degradation of polymers under thermal stability and multiple impact loads, and the lack of full establishment of multi-material integration and industrial standards have all limited its ability to be promoted on a large scale and implemented in engineering. This article explores the various properties of additive manufactured materials, analyzes the advantages and disadvantages of additive manufactured materials in the current automotive field, provides relevant future development directions, and provides a theoretical and basic knowledge for the further utilization of additive manufacturing in the automotive industry.

2. Materials

2.1. Titanium alloy

In additive-manufactured titanium alloy, Ti-6Al-4V is a two-phase material that contains alpha and beta phases. Ti-6Al-4V has a very high strength-to-weight ratio, high heat resistance, and high corrosion resistance. It fits high-end auto parts well. It has a density of about 4.43 g/cm^3. The melting point is about 1650 °C. The beta transition is around 995 °C. The alpha phase structure is hexagonal close-packed, and the beta phase is body-centered cubic [4]. The tensile strength can reach from 900 to 1200 MPa and its yield strength ranges from 800 to 1100 MPa [5]. Its density is only 57% of steel. Titanium alloys maintain stable mechanical properties below 500 °C. These characteristics suit parts like engine rods and turbo blades and other parts that require high load-bearing capacity, high heat resistance, and lightweight. Titanium alloy parts can reduce the weight by 30–50% and can be used to manufacture high-strength and lightweight structures such as chassis reinforcements and battery pack brackets in electric vehicles.

Directed Energy Deposition (DED), Electron Beam Melting (EBM) and Laser Powder Bed Fusion (LPBF) are used to additive manufactured Ti-6Al-4V alloy, which makes it have obvious advantages in the forming of complex structures, but it is also prone to problems such as porosity

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defects, cracks, residual stress, anisotropy and high surface roughness. Porosity defects are caused by the inability of gases in the molten pool to escape in time. Cracks are mainly formed when the thermal stress generated by the rapid cooling process exceeds the material limit, including microcracks and macrocracks, which significantly reduce the strength and fatigue properties of the material. Surface roughness defects originate from the step effect during the stacking process and the adhesion of incompletely melted particles on the surface. Residual stress is caused by the high temperature gradient generated by the intense thermal cycle of the AM process. In particular, laser processes (SLM, DED) are prone to induce high residual stress, causing parts to warp, deform or even crack; the EBM process can effectively alleviate this problem by maintaining a high temperature construction environment (600–750°C) [6].

2.2. Aluminum alloy

Aluminum alloys are already having broad application in the automotive and aerospace industries due to their material properties such as high strength-to-weight ratio, lower density, high thermal conductivity and corrosion resistance. The typical density of aluminum alloys in additive manufacturing is about 2.7 g/cm³, the melting point is about 660 ℃, and the crystal structure is mainly face-centered cubic (FCC) structure. Common additive manufacturing aluminum alloys, such as AlSi10Mg alloy, have a tensile strength range from 300 to 450 MPa, a yield strength range from 250 to 300 MPa, depending on the manufacturing methods. The long-term performance of aluminum alloys is stable at 150 to 200°C, but the mechanical properties drop significantly above this temperature. For example, the strength retention rate of Al-Mg-Si-Sc-Zr alloy at 250°C is only 60% of that at 200°C [2], which limits its application in ultra-high temperature areas such as engine blocks and exhaust manifolds. Due to the good fluidity and low melting range of aluminum alloys, high-precision manufacturing of complex structural parts can be achieved through additive manufacturing methods such as LPBF.

However, additively manufactured aluminum alloys also have obvious defects, such as porosity, cracks, and oxidation. Porosity is usually formed due to gas trapped in the molten pool, and the appearance of cracks is related to the wide solidification temperature range of the alloy during rapid solidification and the accumulation of thermal stress in the solid-liquid coexistence zone [7]. In addition, the oxidation and moisture absorption tendency of aluminum powder may also lead to oxidation defects on the surface of the part and reduce the material properties. By adding other metals such as Sc and Zr or optimizing manufacturing parameters such as power strength, operating speed, preheating time, the forming quality of aluminum alloys can be significantly increased, the occurrence of defects can be reduced, and the mechanical properties and reliability of aluminum alloy parts can be improved.

2.3. Carbon fiber composite

Continuous fiber reinforcement technology is an advanced additive manufacturing process. It uses continuous fibers, such as carbon fiber combined with matrix materials during the printing process, replacing the resin or PLA commonly used in other additive manufacturing processes. By laying continuous carbon fiber bundles layer by layer, the tensile strength can be increased to 480-620 MPa, close to the level of aluminum alloy, but the specific strength is significantly better than steel. It is suitable for high-load components such as brake system brackets and suspension links. The low thermal expansion coefficient of carbon fiber significantly inhibits warping and deformation, which is also suitable for engine peripheral parts.

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Carbon fiber composites in additive manufacturing have low density. Typical polymers such as Acrylonitrile butadiene styrene (ABS) and Thermoplastic polyurethane (TPU) have a mixed density between 1.05–1.20 g/cm³. The elastic modulus can be significantly increased by adjusting the carbon fiber content. For example, the modulus of 100% CF-ABS reaches 6123 MPa, and the maximum tensile strength is about 47 MPa. After mixing with TPU, the modulus and strength are appropriately reduced, but the toughness is enhanced, which is conducive to the effective absorption of impact energy [3]. Through the fused deposition modeling process, continuous carbon fiber reinforced composites (CCFRC) show obvious advantages in tensile strength and flexural strength, especially in the performance along the fiber direction. The selective laser sintering (SLS) process usually uses short carbon fiber reinforced polymer materials (SCFRC), which can achieve complex and fine structures, but is weaker than continuous carbon fiber reinforced materials in terms of mechanical properties. Additive manufacturing CFRC parts are prone to problems such as high porosity, poor fiber interface bonding, and uneven fiber orientation. Printing parameters such as printing path, layer thickness, and nozzle temperature in the FDM process significantly affect the part porosity and fiber orientation, thereby affecting the mechanical properties [8]..

3. Current challenges and future improvement

Although the application of additive manufactured materials in the automotive industry has made significant progress, there are still many challenges. For example, there are problems with residual stress and fatigue life, insufficient thermal stability, immature multi-material printing technology, and no industrial standards.

Additively manufactured Ti64 has excellent mechanical properties and biocompatibility, since it has low thermal conductivity, easy oxidation and obvious strain hardening characteristics of the material, serious residual stress, pores and poor fusion defects are often generated during the manufacturing process, which have serious effects on fatigue life and structure integrity of the material [6]. Aluminum alloy materials show obvious thermal cracks and porosity problems in additive manufacturing [7]. The residual stress generated in the process of metal printing may affect its long-term performance, and it is necessary to optimize the heat treatment and forming path to control the microstructure. Although the additive manufactured carbon fiber reinforced materials can significantly improve the strength and lightweight of parts, it also faces the problems of poor fiber interface bonding, high difficulty in orientation control and obvious anisotropy of parts, which makes the mechanical properties of parts difficult to stabilize and predict [8].

The physical properties of some materials are significantly reduced in high temperature environments, limiting their application in high temperature components such as engine peripherals. Therefore, how to effectively reduce defect generation, optimize material process parameters and improve matrix interface performance has become a key challenge that needs to be urgently addressed in the current additive manufacturing field. Future research should focus on the following directions: material multifunctionalization, structural control and optimization, development of new composite materials with high strength, corrosion resistance and energy absorption performance to meet the needs of multiple working conditions, and establishment of industrial standards [9].

4. Conclusion

With the continuous maturity of additive manufacturing technology, the application of additive manufactured materials in the automotive industry has moved from the concept verification stage to engineering implementation. The gradual application of materials such as titanium alloy, aluminum

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alloy, carbon fiber composites and high-performance polymers has significantly improved the performance and structural design freedom of key components.

However, additive manufacturing needs to consider the advantages and disadvantages of different materials in terms of material performance. Material consistency control, multi-material collaborative manufacturing and standardization construction are still the key factors restricting its promotion. In the future, through interdisciplinary collaboration and technology integration, additive manufacturing can focus on process innovation to reduce production costs and develop new materials to improve the performance of automotive parts. It is expected to achieve a leap from single performance optimization to system integration design of additive manufactured materials, paving the way for the industrialization of additive manufacturing in the automotive industry and bringing a more efficient, smarter and more sustainable development path. In summary, additive manufacturing is reforming and innovating the entire automotive industry, but its further development still depends on the development of new technologies.

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