Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA27117

The Application of 3D Printing in the Automotive Manufacturing Industry

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Abstract. As the automotive industry continues to evolve toward personalization, lightweighting, and efficient manufacturing, 3D printing technology is increasingly becoming a key technology in automotive design and production due to its advantages in freedom, material utilization, and manufacturing flexibility. This paper systematically summarizes the application paths of 3D printing in typical automotive components such as engines, bumpers, and seats, and also reveal its potential for repairing headlight housings and plastic bumper parts. 3D printing has significantly shortened product development cycles, achieved structural optimization and lightweighting, and demonstrated unique value in personalized. However, it still faces challenges in terms of printing accuracy, material standardization, and process consistency. As well as, this paper further outlines the future development trends in terms of equipment performance, material systems, and process integration, with the aim of providing theoretical support and practical guidance for the deep integration of 3D printing technology into the entire life cycle of automobile manufacturing.

Keywords: 3D printing, automobile manufacturing, automobile repair

1. Introduction

The automotive industry is currently undergoing a period of technological transformation. Consumers are increasingly demanding personalization, lightweight materials, and rapid delivery, driving manufacturers to actively seek new manufacturing processes to respond to the fierce market competition. As a key branch of digital manufacturing, 3D printing technology is being widely used in the automotive industry's research, development, and production processes due to its significant advantages in design freedom, material utilization, and manufacturing flexibility [1].

3D printing technology constructs object structures by layering materials, breaking with the numerous constraints of traditional subtractive manufacturing processes related to molds, processing paths, and material shapes. This enables automotive companies to rapidly transform complex parts from digital models into physical objects, thereby shortening product development cycles and reducing prototyping costs [1]. Especially in advancing the manufacturing of lightweight components, 3D printing can balance structural complexity with mechanical strength, providing a feasible solution for achieving vehicle weight reduction objectives [2].

From its initial use in rapid prototyping, 3D printing has gradually penetrated into the production of end-use components, moving beyond its limitations as a purely experimental technology and

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entering a phase of large-scale application. Some leading automakers have already incorporated this technology into the production of body panels, intake manifolds, customized structural components, and replacement parts for repairs, significantly enhancing their flexibility in responding to market changes [1]. By combining reverse engineering with stereo lithography apparatus(SLA) technology, precise repairs can now be performed on small-batch damaged parts such as plastic housings for headlights, demonstrating significant application potential in automotive after-sales maintenance [3].

Although 3D printing technology demonstrates superiority in terms of material adaptability and the ability to form complex structures, it still faces a series of challenges, including printing accuracy, surface quality, material standardization, and process consistency [2]. In actual production operations, how to reduce manufacturing costs, improving forming efficiency, and achieving seamless integration with existing industrial processes are also key factors constraining its further adoption [1].

This article systematically outlines the specific application paths of 3D printing technology in automobile manufacturing and maintenance. It analyzes the application of 3D printing technology in automobile production and automobile maintenance through actual cases, and dissects its technical advantages and practical obstacles. It provides strategic references and path recommendations for the automobile industry to incorporate 3D printing technology into research and development, production, supply chain, and after-sales service. It has important theoretical and practical value in promoting its deep integration throughout the entire life cycle of automobiles.

2. Automotive parts manufacturing

2.1. Automobile engine

Engine manufacturing technology is directly related to the performance of the entire vehicle and industrial competitiveness. The production of traditional engine parts relies on complex mold design and high-precision machining processes, which are time-consuming, costly, and wasteful of materials. In contrast, 3D printing technology directly constructs the geometry of parts by layering materials, demonstrating significant advantages in terms of increasing manufacturing flexibility, shortening design time, and reducing costs [4].

3D printing technology enables the direct fabrication of complex engine components, marking a breakthrough in the production of structures that were previously difficult to manufacture in a single process. Metal printing technologies such as Selective Laser Melting (SLM) and Laser Direct Melting (LDM) can be used to produce components like engine blocks, cylinder heads, and connecting rods—parts that are subject to complex stress loads and feature intricate shapes. This significantly reduces the number of machining processes required in traditional manufacturing. 3D printing materials made from titanium alloys offer excellent strength and corrosion resistance, making them ideal for producing engine components that require both lightweight and high-strength properties, such as turbocharger brackets and intake manifolds [4-6].

To address the demand for prototyping small-batch, multi-variety engine components, 3D printing demonstrates exceptional flexibility and cost-effectiveness. Its mold-free nature enables companies to swiftly complete prototype manufacturing and structural validation during engine iteration development. This significantly shortens the design cycle [5]. In the design process of engine connecting rods, additive manufacturing has been used to optimize the internal topological structure, reduce overall weight, and significantly improve material utilization and structural strength [7].

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2.2. Car bumper

As the demands for automotive lightweighting, modularization, and safety performance continue to rise, traditional bumper manufacturing methods are no longer sufficient to meet the modern automotive industry's requirements for structural strength, design complexity, and production efficiency [8]. Against this backdrop, 3D printing technology, with its advantages of high design freedom, high material utilization, and short product cycles, has gradually been integrated into the design and manufacturing processes of automotive bumpers, emerging as one of the key technical pathways for structural optimization and lightweight design [9].

As a critical exterior structural component of automobiles, bumper design must balance energy absorption, stiffness, and collision resistance, while lightweighting objectives compel engineers to maintain structural performance despite material reduction [9]. To this end, multiple studies have combined topology optimization with 3D printing technology to achieve both structural simplification and performance enhancement. For example, Li Chulin et al. conducted modal and collision safety simulation analyses on a commercial vehicle bumper using HyperWorks and LS-DYNA, and performed topological reconstruction with the objective of minimizing weighted strain energy. The resulting 3D-printed optimized design reduced weight by 9% while meeting design constraints for stiffness and frequency [9]. Similarly, Chen Junjie et al. conducted multi-objective topological optimization design on the front underbody protection structure of a commercial vehicle, establishing an optimization function with multiple sub-objectives including stiffness and natural frequency. Through reasonable weight allocation and manufacturing feasibility adjustments, they obtained a 2.1 mm thick irregular cross-section main beam, achieving a 4.1% reduction in mass, which has significant implications for thin-walled components such as bumpers [8].

2.3. Car seat

With the widespread promotion of energy conservation and environmental protection concepts, lightweight design has become a key approach to enhancing vehicle performance and reducing energy consumption. As one of the heaviest components in a vehicle, the seat plays a crucial role in structural optimization [10]. Against this backdrop, the development of topology optimization methods and new materials technologies has provided effective solutions for reducing the weight of automotive seats, while the integration of 3D printing technology has further expanded the feasibility of design and manufacturing flexibility [11].

Regarding topological optimization, Ge et al utilized CATIA for modeling and subsequently combined the TOSCA module to conduct topological optimization research on the front seat frame [10]. By setting minimum flexibility as the objective function, structural optimization was implemented. While meeting the strength and stiffness requirements specified in the GB 15083—2006 national standard, the seat frame achieved approximately 4% weight reduction, confirming its feasibility in weight reduction for front seats in passenger vehicles.

Zhang Junyuan et al advocated replacing traditional steel with long glass fiber-reinforced thermoplastic composites (LFT), integrating energy absorption models with topology optimization technology to optimize seat structures under forward and backward loading conditions [12]. By creating simulation models using Hybrid III dummies, the analysis results demonstrated that the LFT seat frame not only complies with the safety standards of GB 13057-2014 but also achieves effective weight reduction.

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3. Automotive parts repair

3.1. Car headlight housing

With the rapid expansion of the automotive aftermarket, traditional automotive repair models are struggling to meet the diverse demands in terms of cost, efficiency, and personalized service [13]. 3D printing technology is increasingly playing a critical role in automotive repair, particularly in the repair of plastic components such as headlights [14].

The greatest advantage of additive manufacturing in headlight repair is its flexible part replication capability. Traditional repairs typically rely on manufacturers supplying original parts. If parts are discontinued or difficult to procure, this can significantly extend the repair timeline. However, by utilizing reverse engineering and additive manufacturing for repairs, 3D scanning can quickly obtain the geometric information of damaged parts, which can then be combined with 3D printing technology to reassemble and produce replacement parts. This achieves an environmentally friendly repair model of "repairing instead of replacing," significantly reducing waiting times and lowering overall repair costs [13,14], as illustrated in Figure 1.

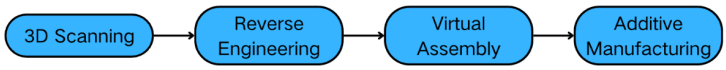


Figure 1. Additive manufacturing process for repairing car headlights

During the actual implementation phase, engineers can use digital modeling of the original vehicle parts to make necessary structural improvements and error corrections based on the scan data, thereby producing replicas with precision matching the original parts during the printing process. This process avoids the high costs associated with mold manufacturing and can accommodate small-batch, customized repair needs, effectively addressing microstructures that are difficult to replicate using traditional injection molding, making it particularly suitable for repair environments with high precision standards.

Additive manufacturing demonstrates significant benefits in terms of environmental protection and resource conservation. 3D printing not only reduces unnecessary material consumption but also extends part lifespan through localized repairs, avoiding the need for complete part replacement. This further reduces resource consumption and enhances the sustainability of repairs. This approach is particularly critical for repairing complex plastic structures and contributes to the green transformation of the entire automotive industry [15].

3.2. Plastic part for car bumper

With the rapid increase in the number of vehicles on the road and the frequent occurrence of traffic accidents, damage to vehicle exterior components such as plastic bumpers has become increasingly common. Traditional repair methods suffer from issues such as low efficiency, inconsistent quality, and limited ability to handle complex curved surfaces. As a new manufacturing technique, 3D printing technology has gradually emerged as a viable solution for repairing damaged bumpers [16].

Automotive exterior components are typically made of plastic materials such as polypropylene (PP), which offer advantages such as lightweight construction, ease of molding, and excellent impact resistance. However, these components are prone to damage in collisions, particularly the front and rear bumpers. Approximately 12 million accidents annually are associated with bumper

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damage. Most repair shops opt to replace the components rather than repair them, leading to the waste of a significant amount of reusable resources and contributing to the accumulation of massive amounts of plastic waste. The environmental burden is increasingly severe [16].

3D printing technology has made significant progress in the field of soft polymer processing, particularly in high-precision modeling of flexible materials and multi-material structure construction. Direct ink writing (DIW) technology, in particular, is widely applicable to high-viscosity polymers and composite materials due to its low requirements for rheological properties. As shown in Figure 6, it can achieve printing operations on complex geometries and porous structures, becoming an important technological foundation for repairing flexible plastic components [17].

The key steps in repair include 3D scanning, data modeling, printing, and bonding. Optical 3D scanning technology can accurately capture data from damaged surfaces and use reverse modeling to highly restore parts. Combining high-performance PETG materials with FDM printing equipment can efficiently complete structural printing, balancing both mechanical strength and bonding performance [16]. The use of 3D printing technology offers significant advantages in reducing repair costs, saving nearly 70%, and producing minimal noise [16].

4. Limitations and future directions

This paper uses multiple specific examples to illustrate the application of 3D printing in the automotive industry. From the perspective of large-scale industrial production, 3D printing technology still faces a series of challenges in terms of technology, economics, and application scope. 3D printing materials are currently limited. The materials used in 3D printing of automotive components primarily include photopolymer resins, ABS plastics, and certain metals. However, printing metal materials that meet automotive safety, strength, and durability requirements still face issues such as high costs and significant performance fluctuations. Automotive manufacturing demands high-volume production and efficiency, yet 3D printing equipment still struggles to meet the requirements of automotive manufacturers for rapid production of large-scale, complex components in terms of printing speed, build volume, and automation levels. Compared to traditional manufacturing technologies, 3D printing lacks industry standards, resulting in poor consistency and reliability of 3D-printed components, making it difficult to replace traditional castings on a large scale.

Despite these shortcomings, 3D printing technology continues to evolve, and its future applications in the automotive industry hold promising prospects. In terms of equipment, next-generation high-power lasers and multi-laser beam systems are steadily improving printing speed and forming accuracy. Control systems are also moving toward integrating visual feedback and machine learning, which is expected to significantly enhance the consistency of finished products. The expansion of material systems is yielding positive results, with the development of new structural metallic materials such as titanium alloys, aluminum alloys, and high-strength steels. These advancements not only help reduce powder costs but also significantly optimize material structure and performance [18].

5. Conclusion

This paper provides a systematic review and case analysis of the typical applications of 3D printing technology in the automotive manufacturing industry, covering the production of key components such as engines, bumpers, and seats, as well as repair processes for components like headlight

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housings and bumper plastic parts. The research findings indicate that 3D printing, with its advantages of high design flexibility, high material utilization, and short manufacturing cycles, not only demonstrates unique value in lightweighting, structural optimization, and personalized customization but also achieves significant results in shortening R&D cycles, reducing production costs, and enhancing supply chain flexibility. Additionally, the repair model combining reverse engineering with 3D printing offers an efficient and environmentally friendly alternative for the aftermarket, contributing to resource conservation and sustainable development.

The analysis in this paper not only provides a reference for the automotive industry to understand and evaluate the application potential of 3D printing technology, but also provides theoretical support and practical guidance for enterprises to formulate technology introduction and application strategies. By revealing current technical bottlenecks and development trends, this study helps to promote the deep integration of 3D printing throughout the automotive lifecycle and provides new pathways for the industry's green transformation and high-quality development.

Looking ahead, with the continuous advancement of high-performance printing equipment, multi-material systems, and intelligent manufacturing technologies, the application boundaries of 3D printing in the automotive industry will be further expanded. From large-scale mass production to complex structural integration molding, from lightweight material development to digitalized end-to-end process management, 3D printing is poised to become a key enabling technology for the automotive industry to achieve flexible manufacturing, green manufacturing, and smart manufacturing, exerting a profound impact on enhancing industry core competitiveness and addressing diverse market demands.

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