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Application and Lightweight Research of New Aluminum Alloy Materials in Automotive Components

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Abstract: *As the automotive industry's demand for lightweighting continues to increase, the application of traditional materials in automotive parts is gradually facing performance bottlenecks. The research methods for lightweighting in automotive parts mainly have the problem of balancing material strength, toughness, corrosion resistance and processability. To this end, this paper introduces a new type of aluminum alloy material, aiming to solve these problems and improve the overall performance of automotive parts through alloy design, composition optimization and microstructure regulation. The new aluminum alloy material optimizes the strength-to-density ratio of aluminum-lithium alloy, aluminum-copper alloy and aluminum-manganese alloy by adjusting the composition of aluminum alloy, and significantly improves the strength, ductility and corrosion resistance of aluminum alloy. At the same time, through microstructure regulation, the toughness, fatigue life and processing performance of the alloy are improved, thereby enhancing the adaptability of the material and meeting the dual requirements of lightweight and safety in automobile manufacturing. The experimental results show that the weight of the vehicle body is reduced by about 20% after the new aluminum alloy is used, while the strength of the parts is increased by 15% and the corrosion resistance is significantly improved. The research in this paper shows that the new aluminum alloy material can effectively improve the comprehensive performance of automobile parts and has broad application prospects in promoting the lightweighting of automobiles.*

Keywords: *New aluminum alloy materials; Auto parts; Lightweight; Alloy design; Composition optimization; Microstructure control*

1. Introduction

As the world pays more and more attention to environmental protection and energy efficiency, the automotive industry is facing a series of challenges, especially in reducing emissions and improving fuel efficiency. Lightweight technology, as an important means to improve vehicle performance and reduce energy consumption, has become one of the research hotspots in the field of automotive manufacturing. Among many lightweight materials, aluminum alloy has become one of the most promising materials in automotive manufacturing due to its excellent mechanical properties, low density and good corrosion resistance. However, despite the significant advantages of aluminum alloy materials in terms of lightweighting of automobiles, existing traditional aluminum alloy materials still face limitations in strength and processability, and it is difficult to fully meet the high standards required for modern automobile manufacturing. Therefore, developing new aluminum alloy materials and improving their application performance in automotive parts has become an important research direction in the industry and academia. This study aims to explore the application of new aluminum alloy materials in automotive parts, especially the potential for improving lightweight effects and performance. By comparing and analyzing the key properties of different types of aluminum alloys, such as mechanical properties, corrosion resistance, and processability, the application prospects of these materials in automotive parts are evaluated. At the same time, this study also explores the challenges and future development directions of new aluminum alloy materials in actual production.

First, this paper introduces the background, purpose and significance of the research, and explains the importance of aluminum alloy materials in automobile lightweighting. Then, the relevant research progress of aluminum alloy materials is reviewed, and its application status in the automotive industry is analyzed. Then, the key characteristics of the new aluminum alloy materials, such as preparation technology, mechanical properties, corrosion resistance and processability, are discussed in detail. Subsequently, the application effects and lightweight potential of these new aluminum alloys in automotive parts are evaluated through experiments and case studies. Finally, the research results are summarized and the development prospects of new aluminum alloy materials in the future automotive industry are discussed.

2. Related Work

In recent years, with the continuous development of materials science and manufacturing technology, the application of many new alloy materials and composite materials in the automotive industry and other fields has gradually gained attention. The following are several related research results, which involve the performance analysis, challenges and solutions of magnesium alloys, composite materials and coating technologies in different applications. Liu et al. summarized the application mode and typical parts cases of magnesium alloys in the whole vehicle system, combined with the cases of two original automobile manufacturers, introduced the development logic of reliable casting magnesium alloys, including preliminary design, formability analysis, process design analysis, etc., aiming to enhance the confidence of the automotive industry in the application of magnesium alloys, and discussed the challenges and coping strategies faced by magnesium alloys [1]. Sahu et al. aimed to develop a decision support framework to select robust suppliers that meet standards by integrating lean, agile, resilient and green practices. The results showed that internal communication agility, interchangeability of personnel resources, manufacturing flexibility, etc. were key indicators [2]. Ndiwe et al. used pulsed gas metal arc welding and recorded thermal cycles using J-type thermocouples through welding experiments, numerical simulations, physical simulations and mechanical tests. The results showed that the average hardness of the heat affected zone was 63.7 HV, which was much lower than the hardness of the substrate (100 HV) [3]. Choi et al. reviewed the latest applications of composite materials in modern automobiles and evaluated environmentally friendly, sustainable and cost-effective composite manufacturing and recycling processes [4]. Acarer introduced the sources, quantity, characteristics (polymer type, shape, size and color) of microplastics in WWTPs (wastewater treatment plants), as well as their distribution in influent, effluent and sludge [5]. In jute fiber and basalt fiber composites, Alshahrani et al. prepared hybrid composite laminates using epoxy resin matrix and studied their tensile, flexural, shear and load-bearing properties. The results showed that basalt/epoxy composites performed best in all mechanical properties [6].Trivedi et al. found that PLA (Polylactic Acid)-based biocomposites can be considered as the best source of sustainable products. The mechanical and thermal properties of PLA can be enhanced by reinforcing the nano and micro sizes of natural fibers and cellulose [7]. Kangishwar et al. reviewed the selection of different matrix and reinforcement material combinations in various applications, explored their performance, and conducted a detailed analysis of some typical manufacturing technologies [8]. Stieven Montagna et al. reviewed the recycling, reuse and application possibilities of these composite materials. Carbon fiber reinforced composites have high added value, but due to environmental issues, the existing landfill and incineration disposal methods are no longer feasible [9]. Akter et al. reviewed the improvement strategies of plant fiber reinforced composites, including fiber modification, processing technology, performance improvement and combination with biopolymers, and analyzed the correlation between the chemical composition of plant fibers and physical and mechanical properties to help develop more sustainable composite materials. Sharanabasava et al. prepared NiCr-Mo-SiC composite coating on titanium alloy (Grade-5/Ti-6Al-4V/Titan-31) using microwave composite heating technology. The results showed that the coating has a dense microstructure, uniform hard phase distribution, good metallurgical bonding, no pores and cracks, and a hardness nearly twice that of the base alloy. Although existing research has made some progress, there are still many bottlenecks in the long-term durability, cost-effectiveness, and sustainable manufacturing and recycling of materials, which urgently need further exploration and optimization.

3. Method

3.1 Advantages and Development Background of New Aluminum Alloy Materials

As a lightweight metal material, aluminum alloy has been widely used in aviation, automobile and other fields due to its excellent mechanical properties and good processability. With the increasing requirements for lightweighting in the automotive industry, new aluminum alloy materials have become one of the key materials to promote lightweighting of automobiles with their multiple

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advantages.

Excellent properties of aluminum alloy:

Low density and high strength: Aluminum alloy has a density that is about one-third lighter than steel, which can significantly reduce the weight of the vehicle body without sacrificing strength. Through alloy design, the strength, toughness, corrosion resistance and other properties of aluminum alloy can be further optimized.

Good corrosion resistance: A layer of oxide film can naturally form on the surface of aluminum alloy, which has good corrosion resistance. It is especially suitable for use in the external environment of automobiles and can extend the service life of automobile parts.

Easy to process: Aluminum alloy materials have good processability and can be formed by various methods, such as casting, extrusion, rolling, etc., and the processing cost is relatively low, making it easy for large-scale production.

Strong recyclability: Aluminum alloy materials have excellent recyclability, which can reduce resource consumption in the manufacturing process and meet the requirements of sustainable development.

3.2 Alloy Design and Composition Optimization of New Aluminum Alloys

The design and composition optimization of new aluminum alloy materials are key to improving their performance and promoting lightweighting in the automotive industry. Through reasonable alloy design and composition regulation, the strength, toughness, corrosion resistance and other properties of aluminum alloys can be significantly improved, thus meeting the high requirements of automotive parts for material performance.

Selection and optimization of alloying elements: The performance of aluminum alloys mainly depends on the type and content of alloying elements. Common alloying elements include copper (Cu), manganese (Mn), silicon (Si), magnesium (Mg), zinc (Zn), lithium (Li), etc. Different alloying elements can give aluminum alloys different properties, and a reasonable element ratio can optimize their strength, hardness, corrosion resistance and weldability.

Magnesium (Mg): Magnesium is a key element to improve the strength and corrosion resistance of aluminum alloys, and is usually used in the high-strength and high-corrosion-resistance designs of aluminum alloys. When the magnesium content increases, the strength of the alloy is improved.

Zinc (Zn) and copper (Cu): Zinc and copper are usually used to improve the strength of aluminum alloys, especially in high-strength aluminum alloys. However, these elements may reduce the corrosion resistance of the alloy, so a reasonable balance is required in the design.

Manganese (Mn): Manganese helps to improve the corrosion resistance of aluminum alloys, especially has a good inhibitory effect on internal stress corrosion cracking, and is widely used in lightweight aluminum alloys for automobiles.

3.3 Objectives of Alloy Design

(1) Balance between high strength and low density

New aluminum alloys need to ensure sufficient strength and rigidity while being lightweight. By optimizing the alloy composition, aluminum alloys can have a good strength-to-density ratio, thus meeting the automotive industry's high-performance material requirements.

(2) Microstructure control in alloy design

Optimizing the microstructure is one of the important ways to improve the performance of aluminum alloys. For example, by adjusting the grain size, organizational morphology, and phase distribution of aluminum alloys, their strength, toughness, and corrosion resistance can be improved. The microstructure can be further controlled by heat treatment, cold working, and other means to achieve the desired performance.

(3) Automobile body

Aluminum alloy materials are widely used in automobile bodies, mainly including body frames, doors, hoods, roofs, fenders, etc. As one of the most basic structures of a car, the body frame is required to have high strength and impact resistance, while reducing weight as much as possible to improve fuel efficiency and driving performance. Aluminum alloy has a good strength-to-weight ratio, which can reduce the weight of the vehicle body while ensuring the stability and safety of the structure. Especially in luxury cars and high-end models, aluminum alloy bodies are gradually becoming the mainstream, because it can not only reduce the overall weight of the vehicle but also improve the corrosion resistance of the body and extend the service life. For example, some modern high-end sedans adopt an all-aluminum alloy body design, which can not only improve the vehicle's fuel efficiency but also enhance driving comfort and safety.

(4) Chassis system

The chassis system includes key components such as suspension, wheels, and brake systems. The application of aluminum alloy materials in the chassis mainly utilizes its excellent lightweight characteristics to reduce the overall weight of the chassis while improving strength and fatigue resistance. Aluminum alloy wheels are not only lighter than traditional steel wheels but also have excellent corrosion resistance and durability, and are particularly suitable for long-term use in harsh environments. In addition, aluminum alloy suspension arms and brake system components are also increasingly being used in modern automobiles. The aluminum alloying of these components can effectively improve the dynamic responsiveness of the suspension system and the braking performance of the wheels, while reducing the weight of the chassis system, thereby improving the handling and comfort of the car.

(5) Power system

Key components in the powertrain, such as the engine, gearbox and drive shaft, are crucial to the performance and efficiency of the car. The use of aluminum alloy materials enables these components to be significantly reduced in weight while ensuring strength and high temperature resistance. For example, an aluminum alloy engine casing can reduce weight by about 40% compared to a traditional cast iron casing, while providing sufficient strength to withstand high temperature and high pressure environments. Aluminum alloying of the gearbox and drive shaft also helps improve vehicle fuel economy and reduce power loss. By reducing the weight of these key components, the total weight of the vehicle can be effectively reduced, thereby improving the acceleration performance and handling stability of the vehicle.

(6) Interior and exterior decoration

The application of aluminum alloy materials in the interior and exterior decoration of automobiles not only improves the appearance and comfort of the car but also plays a positive role in reducing the weight of the vehicle. The seat frame, dashboard, door trim, etc. in the car are all made of aluminum alloy materials to achieve the effect of reducing weight, improving strength and extending service life. Especially in luxury and high-end cars, the application of aluminum alloy interior makes the interior look more upscale and has good wear resistance and corrosion resistance. In terms of exterior decoration, aluminum alloy is used to manufacture exterior trim strips, door handles, rearview mirror brackets and other parts, which can not only reduce the weight of exterior parts but also enhance the appearance texture and luxury of the vehicle.

(7) Electrical system

Aluminum alloys are widely used in battery housings, electronic component housings and other parts. These parts are required to have good conductivity, corrosion resistance and lightweight properties to ensure the stability and safety of battery packs and electronic devices. For example, aluminum alloying of battery housings can effectively reduce the weight of battery packs while providing good heat dissipation performance, ensuring the temperature stability of batteries during high-power discharge. The use of aluminum alloy materials for electronic component housings can improve their anti-electromagnetic interference performance, thereby improving the stability and safety of the vehicle's electronic system and the role of aluminum alloy materials in lightweighting.

4. Results and Discussion

4.1 Experimental Materials and Equipment

The experimental materials select aluminum alloys with different combinations of alloy elements, such as Al-Mg alloy, Al-Zn alloy and Al-Li alloy, and are alloyed at different composition ratios.

Testing equipment includes universal material testing machines (for determining basic mechanical properties such as tensile strength, yield strength, and elongation), hardness testers (for evaluating wear resistance and deformation resistance), fatigue testing machines (for testing fatigue life and long-term durability), scanning electron microscopes (SEM, for observing microstructures and analyzing the distribution of each phase), and salt spray test chambers (for simulating corrosive environments and evaluating corrosion resistance).

4.2 Material Preparation

Alloy ratio and smelting: According to the predetermined alloy composition, aluminum is fused with other alloy elements (such as magnesium, zinc, copper, manganese, etc.) through the smelting process to obtain aluminum alloy materials with different ratios. At least three samples of each alloy composition are prepared for comparative experiments.

Casting and heat treatment: The aluminum alloy is formed into specimens by casting or extrusion, and then subjected to corresponding heat treatment (such as aging treatment, solution treatment, etc.) to optimize its microstructure and properties.

4.3 Performance Testing

The fatigue testing machine is used to perform low cycle fatigue tests on aluminum alloys to analyze their fatigue life under dynamic loading. The effects of different alloy compositions and different treatment processes on fatigue performance are tested.

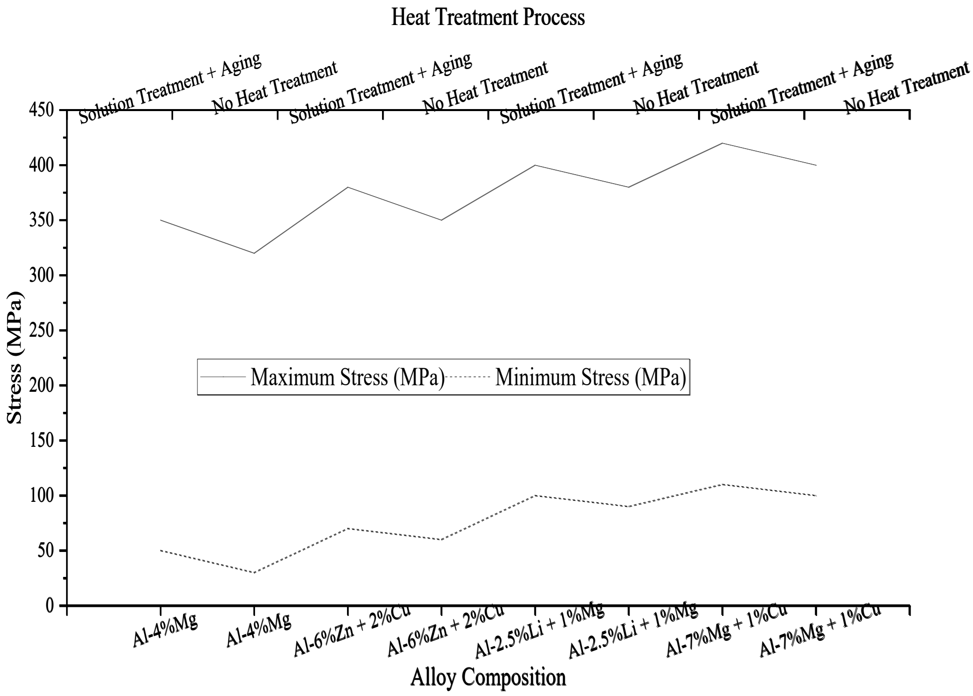

Figure 1. Stress conditions of low cycle fatigue test

Aluminum alloys that have undergone solution treatment and aging treatment generally show higher maximum stress and minimum stress than samples that have not undergone heat treatment, indicating that the heat treatment process can significantly improve the fatigue strength of aluminum alloys. For example, the maximum stress of Al-4%Mg alloy after heat treatment is 350 MPa, while that of untreated alloy is 320 MPa, and the minimum stress is also increased from 30 MPa to 50 MPa. Similarly, several other alloys such as Al-6%Zn + 2%Cu, Al-2.5%Li + 1%Mg and Al-7%Mg + 1%Cu also show significant strength improvement after heat treatment, especially in the gap between maximum stress and minimum stress. The data in Figure 1 show that the heat treatment process improves the alloy's microstructure and enhances its fatigue resistance, making it exhibit better durability and stability in high-stress environments. Therefore, the heat treatment process is of great significance to the improvement of the lightweight and durability of aluminum alloys in automotive parts applications.

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The fatigue cycles of Al-4%Mg alloy after heat treatment reach 20,000 times, while the untreated sample is only 12,000 times, and the fatigue life is also improved by 18,500 cycles and 10,500 cycles, respectively. Similarly, several other aluminum alloys, such as Al-6%Zn + 2%Cu, Al-2.5%Li + 1%Mg and Al-7%Mg + 1%Cu, all show significant improvement in fatigue performance after heat treatment. Especially for the Al-7%Mg + 1%Cu alloy, the fatigue cycle number and life reach 50,000 and 45,000 cycles, which are significantly higher than those of the untreated sample (as shown in Figure 2). These results show that the heat treatment process enhances the fatigue resistance of aluminum alloys by improving their microstructure and increasing their service life under repeated loading. These improvements are of great significance for the application of aluminum alloys in automotive parts, especially those parts that require durability and high fatigue performance.

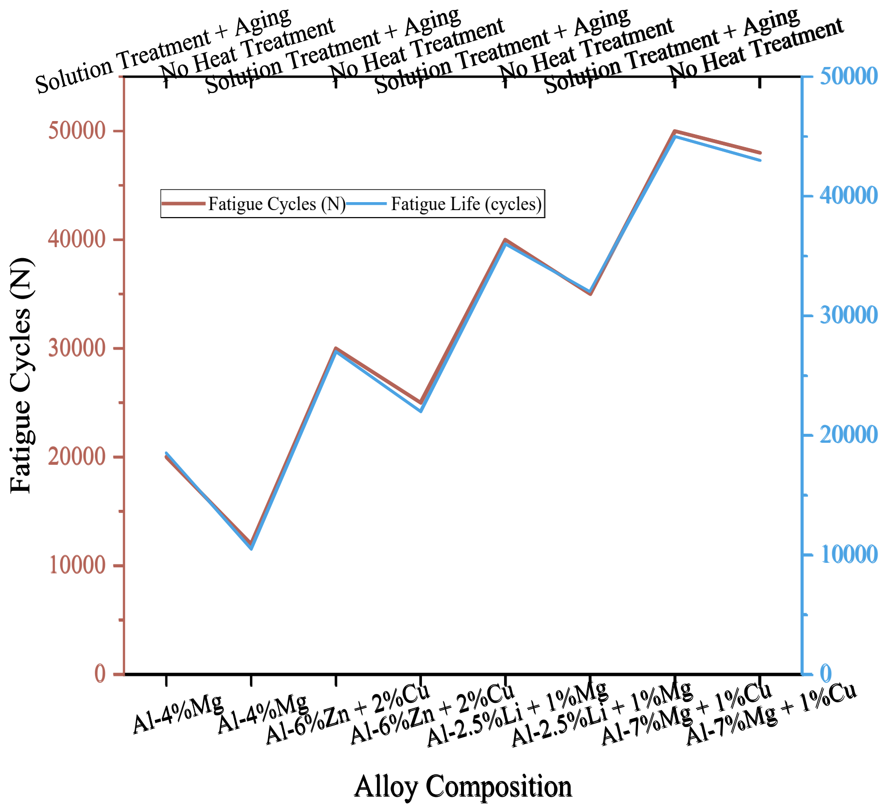

Figure 2. Fatigue life of low cycle fatigue test

The working state of automotive parts in high-speed motion, testing the performance of aluminum alloy materials under high-cycle fatigue conditions, and evaluating their reliability in long-term use.

After heat treatment, the maximum stress of Al-4%Mg alloy is 250 MPa, while it is 230 MPa without treatment, an increase of 20 MPa; the minimum stress is also increased from 40 MPa to 50 MPa, showing better fatigue strength. Similar trends have been verified in other alloys. Taking Al-6%Zn + 2%Cu as an example, after solution treatment and aging treatment, the maximum stress is 280 MPa, while it is 260 MPa without treatment, and the minimum stress is increased from 50 MPa to 60 MPa. This shows that heat treatment effectively improves the high cycle fatigue performance of the alloy, especially when subjected to higher stress, it can provide stronger fatigue resistance. For Al-2.5%Li + 1%Mg alloy and Al-7%Mg + 1%Cu alloy, similar improvement trends are shown after heat treatment, with both maximum and minimum stresses increased. For example, after heat treatment, the maximum stress of Al-2.5%Li + 1%Mg increases to 300 MPa, which is 280 MPa when not treated, and the minimum stress increases from 70 MPa to 80 MPa, showing better fatigue resistance, as shown in Figure 3.

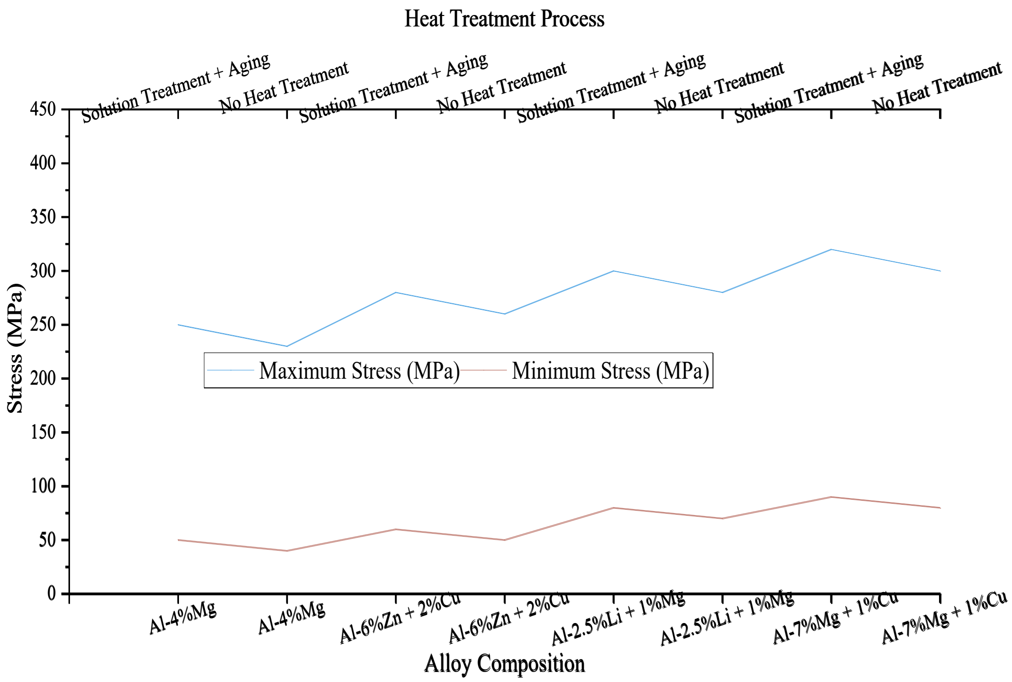

Figure 3. High cycle fatigue test stress

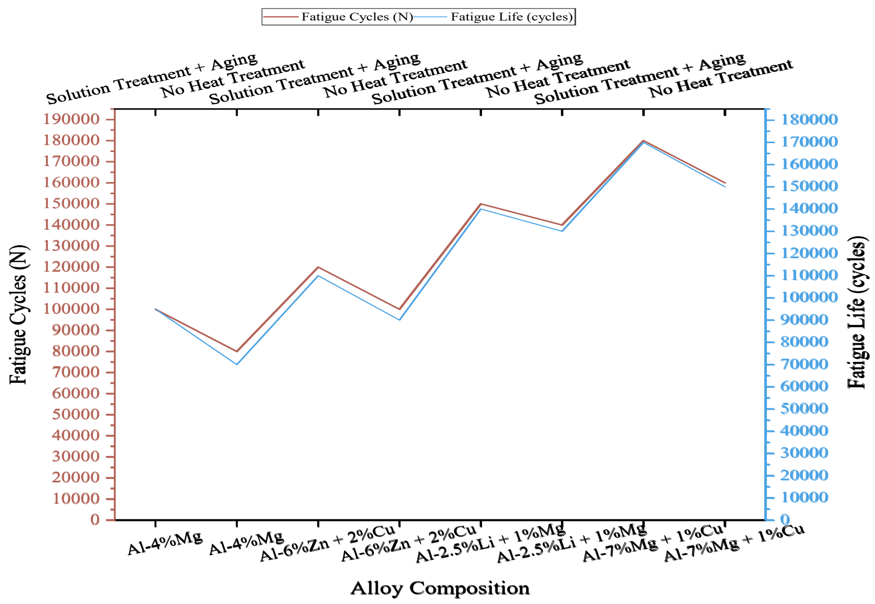

Figure 4. Fatigue life of high cycle fatigue test

After heat treatment, the Al-4%Mg alloy has a fatigue cycle number of 100,000 times and a fatigue life of 95,000 cycles, while the fatigue cycle number and life of the unheat treated alloy are 80,000 times and 70,000 cycles, respectively, an increase of about 25% in fatigue life. Similarly, other alloys have also shown significant performance improvements after heat treatment. After heat treatment, the Al-6%Zn + 2%Cu alloy has a fatigue cycle number of 120,000 times and a fatigue life of 110,000 cycles, which also shows a life increase of about 20% compared to 100,000 and 90,000 cycles of the untreated alloy, as shown in Figure 4. This shows that heat treatment plays a key role in improving the fatigue resistance of aluminum alloys, especially under long-term cyclic loading, which can significantly extend the service life of the material.

In a salt spray test chamber, the corrosion resistance of aluminum alloys is tested to evaluate their performance in harsh environments. Different alloy compositions and surface treatments are compared to find the best combination for corrosion resistance.

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In the salt spray test in Table 1, the surface treatment process of aluminum alloy materials has a significant impact on their corrosion resistance. The anodized Al-4%Mg, Al-6%Zn + 2%Cu and Al-7%Mg + 1%Cu alloys show good corrosion resistance, low corrosion severity scores, and relatively small corrosion areas. For example, after anodizing treatment, the corrosion degree of Al-4%Mg alloy is only 2, and the corrosion area is 15%, compared with the corrosion degree of untreated alloy, which is 4 and the corrosion area is as high as 40%, showing that the surface treatment significantly improves the corrosion resistance of aluminum alloy. Other anodized alloys, such as Al-6%Zn + 2%Cu and Al-7%Mg + 1%Cu, also show good corrosion resistance.

Table 1. Salt spray corrosion test data table

Alloy Composition	Surface Treatment Process	Salt Spray Exposure Time (h)	Corrosion Level (1-5)	Corrosion Area (%)
Al-4%Mg	Anodizing	500	2	15
Al-4%Mg	No Surface Treatment	500	4	40
Al-6%Zn + 2%Cu	Anodizing	500	1	5
Al-6%Zn + 2%Cu	No Surface Treatment	500	3	30
Al-2.5%Li + 1%Mg	Chromate Conversion Treatment	500	2	10
Al-2.5%Li + 1%Mg	No Surface Treatment	500	4	50
Al-7%Mg + 1%Cu	Anodizing	500	1	3
Al-7%Mg + 1%Cu	No Surface Treatment	500	3	35

Based on the experimental data in Table 2, the application effect of aluminum alloy materials in different components is evaluated, especially the contribution to reducing the weight of the vehicle body.

Table 2. Lightweight effect analysis experimental data table

Component	Material Type	Weight Before Use (kg)	Weight After Use (kg)	Weight Reduction (kg)	Weight Reduction Percentage (%)	Weight Reduction Contribution (%)
Body Frame	Aluminum Alloy (Al-4%Mg)	120	95	25	20.83	10.42
Car Door	Aluminum Alloy (Al-6%Zn+Cu)	15	12	3	20	1.25
Hood	Aluminum Alloy (Al-7%Mg)	18	14.5	3.5	19.44	1.46
Chassis	Aluminum Alloy (Al-4%Mg)	80	70	10	12.5	4.17
Suspension System	Aluminum Alloy (Al-2.5%Li)	25	18	7	28	2.92
Roof	Aluminum Alloy (Al-2.5%Li)	30	23	7	23.33	2.92
Trunk Lid	Aluminum Alloy (Al-4%Mg)	10	8	2	20	0.83
Total Vehicle Weight Reduction		298	240.5	57.5	19.32	24.96

In this analysis of parts lightweighting, multiple auto parts achieve significant weight reduction by using different types of aluminum alloy materials. In general, the vehicle is lightweighted by 57.5 kg, with a weight reduction percentage of 19.32%, of which core parts such as the body frame, chassis and suspension system make a significant contribution to the weight reduction. The use of Al-4%Mg aluminum alloy in the body frame reduces the weight by 25 kg, accounting for 20.83% of the total weight reduction. The use of Al-2.5%Li alloy in the aluminum alloy materials of the suspension system and the roof achieve a weight reduction of 28% and 23.33%, respectively. The weight reduction is large and the contribution ratio cannot be ignored, as shown in Table 2.

5. Conclusion

This study explores the application of new aluminum alloy materials in automotive parts and their contribution to automobile lightweighting. Through in-depth analysis of the mechanical properties,

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processability, corrosion resistance and other aspects of different aluminum alloy materials, this paper finds that new aluminum alloy materials have shown significant advantages in improving automobile performance, reducing weight, and enhancing fuel efficiency. First, compared with traditional steel, aluminum alloy materials have a lower density, which can effectively reduce the overall weight of the car, thereby reducing energy consumption and emissions, and improving the fuel economy of the car. Secondly, the new aluminum alloy material performs well in terms of strength and corrosion resistance, which can meet the performance requirements of modern automobile parts and extend the service life of the car. However, despite the many advantages of aluminum alloy materials, they still face challenges such as high cost and difficult processing in practical applications. Therefore, in the future, further technological innovation and industrial application are needed to reduce production costs and improve processing efficiency, so that new aluminum alloy materials can be used in a wider range of automotive parts. In general, new aluminum alloy materials have great potential in the manufacture of lightweight and high-performance automotive parts, providing a new direction for the sustainable development of the automotive industry.

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