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Research on Aluminum Alloy Materials and Application Technology for Automotive Lightweighting

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Abstract: *In recent years, with the rapid development of the automotive industry, cars have gradually been heading towards lightweight structures. Currently, the application of various lightweight metal materials, including aluminum alloys, is becoming increasingly widespread. Aluminum alloys, as a new type of lightweight material for cars, can significantly reduce the weight of vehicles, improve their fuel efficiency, and can be recycled, meeting the energy-saving and environmental protection requirements in our country. Lightweighting is an inevitable trend in the current automotive industry and a major driving force for achieving "dual carbon" goals. With advancements in high-strength lightweight alloy forming and processing technologies, aluminum alloys will have even better processing techniques for automotive lightweighting, and their demand and development prospects for lightweighting will be broader. This paper will focus on aluminum alloy materials required for future automotive lightweighting.*

Keywords: *Automotive Lightweighting, Aluminum Alloy Materials, Applications*

1. Introduction

With the development of the economy and advances in technology, the number of motor vehicles worldwide is increasing, bringing great convenience to people's work and daily lives. However, as the energy crisis in our country becomes more severe, the demand for cars is also increasing. Currently, the automotive industry is moving towards lightweight, energy-efficient, low-carbon, and comfortable vehicles. It is necessary to improve the quality of cars while controlling manufacturing costs. To meet the needs of energy conservation and environmental protection, cars are being developed to achieve lower fuel consumption and higher fuel efficiency. The use of aluminum alloys, which have advantages such as low density, good corrosion resistance, good thermal conductivity, and ease of processing, in lightweight design and development, aligns with the requirements of automotive lightweight design development[1].

2. Overview of Automotive Lightweighting and Aluminum Alloy Characteristics

2.1. Automotive Lightweighting

The lightweighting of automobiles involves reducing the overall weight of vehicles while ensuring their performance, strength, and safety. This allows for increased fuel efficiency, enabling cars to generate more power and ultimately reduce fuel consumption and emissions. The lightweighting of automobiles must prioritize the improvement of stability and performance while implementing effective energy-saving designs and continuous improvements to various components. Lightweighting is a comprehensive advantage that combines various technologies such as design, materials, and manufacturing, improving vehicle performance, optimizing structure, reducing weight, and controlling costs. It is a systematic engineering project that drives the development of the entire automotive industry. There are various approaches to achieving lightweighting, with the most important being the optimization of the body structure, improvement of material utilization, and enhancement of production processes such as laser welding and the development of new materials. Among these approaches, aluminum alloys are highly suitable as lightweight materials for automobiles and can meet the needs of lightweight development in our country's automotive industry [2].

Lightweighting is an important trend in the development of the automotive industry, and its role in energy conservation and emission reduction should not be ignored. It involves reducing the overall weight of vehicles through various means while ensuring their strength and safety. Additionally, the weight of the vehicle is positively correlated with resistance factors such as climbing and tilting, so reducing resistance can enhance performance, decrease fuel consumption, and achieve energy conservation and emission reduction goals. Improving traditional automobiles from the perspectives of processes, materials, and structures to achieve lightweighting has become a hot topic in current research. High strength, long life, and low cost are the goals pursued by the automotive industry. Aluminum alloys have become the preferred materials for lightweighting due to their low density, high thermal conductivity, good corrosion resistance, and energy absorption during collisions. Moreover, their recycling loss rate is only 5%, and they are resistant to corrosion. They have a longer lifecycle, contribute significantly to reducing the consumption of scarce resources, and promote economic, environmental, and energy sustainability [3].

2.2. Aluminum Alloy Characteristics

Aluminum alloys have a low density, high corrosion resistance, good thermal conductivity, high strength-to-weight ratio, ease of processing, and low cost. In terms of density, aluminum has a density of only 2.7 grams per cubic centimeter, which is only one-third of iron, making it a lightweight metal. Most aluminum products are relatively light and easy to work with. In terms of corrosion resistance, aluminum readily forms a dense, stable, and highly oxidation-resistant oxide film on its surface. Therefore, aluminum alloy vehicles have better corrosion resistance than steel vehicles, especially in areas where corrosion protection is not easily applied, making aluminum alloys the preferred choice. They not only improve the appearance of automobiles but also prolong their lifespan, increasing passenger comfort. In terms of thermal conductivity, aluminum has a higher thermal conductivity, approximately three times that of iron, and a high heat exchange rate, making it suitable for heat exchangers and radiators. In terms of strength, although aluminum's mechanical properties are not as good as steel, its strength is higher than that of steel. By incorporating aluminum into other metal materials and subjecting them to heat treatment, higher strength can be achieved. In terms of material processing, aluminum has a lower melting point and good fluidity, making it suitable for processing complex-shaped workpieces. In terms of cost, aluminum is recyclable [4]. Currently, aluminum recycling is widely adopted worldwide, with its usage exceeding 60%. Recycling aluminum can reduce energy consumption by more than 95%, meeting energy-saving requirements effectively. Its application in the automotive industry can save costs on molds and equipment. Additionally, in the production of aluminum alloy frames, aluminum extruded sections with low welding points are commonly used, simplifying the production process and improving assembly efficiency.

3. Classification of Aluminum Alloy Applications in Automotive Lightweighting

3.1. Casting Aluminum Alloy

77% of aluminum alloys used in automotive applications are cast aluminum alloys. The results show that cast aluminum alloys have the advantages of stable quality and suitability for mass production, making them widely used in automotive lightweight manufacturing. Currently, cast aluminum alloys are widely used in the production of automotive components such as gearboxes, engine cylinder heads, engine cylinder blocks, wheels, rocker arms, and brake discs. Among them, engine cylinder heads and cylinder blocks require higher corrosion resistance and thermal conductivity, which can be effectively achieved by using cast aluminum alloys. Wheels account for a significant proportion of the overall vehicle weight, making achieving lightweight wheels a priority. In this regard, using casting technology with aluminum alloys can effectively achieve this goal. For light and medium-sized vehicles, using cast aluminum wheels can reduce the weight of the wheels by 30-40% compared to using steel wheels. Additionally, cast aluminum alloy wheels also have the capabilities of high heat dissipation, high strength, high dimensional accuracy, and reducing lateral and longitudinal vibrations [5].

3.2. Deformed Aluminum Alloy

Wrought aluminum alloys exhibit stable performance, high strength, high ductility, uniform composition, and a dense internal structure. They can be divided into two categories: non-heat-treatable

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alloys and heat-treatable alloys. The former includes Al-Si alloys and pure aluminum alloys, while the latter includes Al-Mg-Si alloys and Al-Cu alloys. Currently, wrought aluminum alloys are widely used in automotive structural components, suspension parts, as well as decorative parts such as doors, wheel covers, heat exchangers, shock absorbers, seats, trunks, protective covers, and soundproof covers. Compared to copper heat exchangers, wrought aluminum alloy heat exchangers can reduce weight by 35-45%. In the United States, wrought aluminum alloys account for 60%-70% of the total quantity of heat exchangers, while in European countries, their usage accounts for 90%-100% of the total heat exchanger quantity.

3.3. Foam Aluminum

Aluminum foam is a metallic material with high porosity and high porosity. The product is light in quality, high in strength, good in absorption, good in vibration damping and damping performance. Currently, aluminum foam is widely used in the production of body support parts for automobiles, such as tail girders, buffers and so on. Especially, between the two outer panels, it is necessary to fill the foam aluminum to form a new panel, so as to achieve the purpose of component lightweighting under the premise of ensuring the safety of the component.

3.4. Aluminum-based composites

Aluminum-based composite materials are a type of composite aluminum alloy used in the automotive industry that exhibit high thermal conductivity, high strength, low thermal expansion coefficient, good fatigue resistance, good wear resistance, and high dimensional accuracy. Currently, Japan has already adopted aluminum alloy composite materials in automotive components such as engine pistons. Southeast University in China has developed an aluminum-based composite material for aviation engines, which has a lifespan that can be improved by 3-5 times, significantly enhancing the power performance of aviation engines [6].

4. The Application Advantages of Aluminum Alloy in Automotive Lightweighting

4.1. Good Weight Reduction Effect

Research has shown that there is a significant relationship between car fuel consumption and factors such as vehicle exhaust emissions and vehicle weight. Every 1 kg reduction in car weight can result in a fuel consumption reduction of 0.7 liters per 10,000 kilometers traveled, and a 10% reduction in vehicle weight can lead to a 5%-6% reduction in exhaust emissions. Therefore, the construction of lightweight vehicles has become an important topic for major car manufacturers. The application of aluminum alloys in car production can achieve excellent lightweight structural effects. In particular, aluminum has a density of 2.7 grams per cubic centimeter, which is only one-third of steel. Aluminum alloys are materials with excellent thermal conductivity, second only to copper. Aluminum alloys are corrosion-resistant metals that can naturally form an oxide film on the surface, making them an important material for automotive production.

4.2. Production of materials capable of recycling

Due to its resistance to corrosion during usage, aluminum alloys are metals that are not easily corroded and have a high recycling rate. Throughout the various stages of production, usage, recycling, and processing into aluminum ingots, and further manufacturing into products, the loss of aluminum material is only around 5%. Among various metal raw materials, aluminum has the highest recycling rate. Currently, in most countries worldwide, recycled aluminum is used in automotive production. Additionally, due to its low melting point and good flowability, aluminum can be processed into various parts with complex shapes and forms. This not only benefits the development of the automotive industry but also promotes the recycling and circular utilization of aluminum alloy resources in our country.

4.3. Improved vehicle safety and drivability

The use of aluminum alloys in automotive production enables lightweighting of vehicles without compromising their load-bearing capacity. As a result, the vehicle's center of gravity is lowered, improving ride smoothness and stability. Additionally, vibrations and rotational noise from different parts of the vehicle are reduced. The characteristics of aluminum alloy materials allow them to absorb impact forces during collisions, resulting in deformation and crumpling at the front of the vehicle. This reduces vehicle damage and enhances passenger safety. Furthermore, the adoption of aluminum alloy materials effectively reduces the overall vehicle load and towing load, thereby improving vehicle maneuverability.

5. Aluminum alloy in automotive lightweight application technology

5.1. Casting and molding technology

In the production of aluminum alloys for automotive applications, casting processes play a crucial role. Approximately 80% of automotive aluminum alloys are produced using various casting methods, including precision casting, gravity casting, lost wax casting, low-pressure casting, squeeze casting, and die casting. Among these processes, die casting is the most widely used due to its advantages of low scrap rate, high product quality, and high dimensional accuracy. Extrusion casting is a new process that requires little or no cutting. It yields aluminum alloy components with clear external shapes and dense internal structures. This forming technique is suitable for manufacturing components such as door panels and bumpers.

5.2. Semi-solid molding technology

Semi-solid forming is a novel aluminum alloy forming process for automotive applications, which provides components with shape-forming properties closer to ideal aluminum alloy parts. Prior to forming, aluminum alloys typically undergo solidification and melting processes. During this stage, when the aluminum alloy is in a semi-solid state, it can be more stable and fully utilized during the forming process, resulting in improved formability. This technique is particularly significant for enhancing part accuracy, reducing solidification shrinkage, prolonging part lifespan, and improving mechanical performance. Semi-solid forming is a promising new technology widely used in automotive lightweight components. However, currently, this technology has not yet advanced to the extent of manufacturing large-scale aluminum alloy parts [7].

5.3. Applications of high strength aluminum alloys

High-strength aluminum alloys have higher strength and rigidity, making them suitable for lightweight design and applications in various fields as alternatives to traditional steel or other materials. Here are some common applications of high-strength aluminum alloys: (1) Automotive Manufacturing: High-strength aluminum alloys can be used in various automotive components, such as vehicle body structures, chassis, engine supports, suspension systems, and wheels. They can reduce the overall weight of vehicles, improve fuel efficiency and handling performance, and provide good safety performance in collisions. (2) Aerospace Industry: High-strength aluminum alloys are widely used in the aerospace field, including aircraft fuselages, wings, engine components, flight control systems, and more. By using high-strength aluminum alloys, aircraft weight can be reduced, fuel efficiency can be improved, and the payload capacity and flight performance can be increased. (3) Railway Transportation: High-strength aluminum alloys can be applied in railway transportation for vehicle body structures, carriages, suspension systems, wheels, and more. They can reduce the overall weight of trains, improve operating speeds and energy efficiency, and enhance the stability and smoothness of the vehicles. The application of high-strength aluminum alloys enables lightweight design, reduces energy consumption, decreases environmental pollution, and improves the performance and competitiveness of products in various fields.

6. Application of Aluminum Alloy Materials in the Automotive Industry

6.1. Vehicle body

In the overall structure of automobiles, the weight of the body accounts for about 30%, while fuel consumption directly related to the weight of the body accounts for approximately 70%. This demonstrates the fuel-saving effect of lightweight vehicle bodies, making aluminum alloy materials suitable for automotive production. With continuous advancement in technology, the application of

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aluminum alloys in the automotive industry is expanding. After 1994, Audi introduced two models, the A8 and A2, both made of pure aluminum. The weight of these two models was significantly reduced by approximately 40% compared to traditional vehicles. The A2 weighed less than 900 kg and had an annual production volume of 50,000 units, making it the world's first mass-produced all-aluminum car. The A8 also received widespread acclaim and was considered a major technological achievement. Consequently, major domestic automakers have conducted research and development on aluminum alloys and their applications. Globally, several companies, including Porsche, Volkswagen, and Renault, have jointly launched "lightweight" programs, conducting extensive research on lightweight materials and utilizing composite processes. Based on the Volkswagen 5th-generation Golf, they produced lightweight vehicle structures using various composite materials, with a net weight of 180 kg, resulting in a significant decrease of 101 kg compared to the initial Golf model. The results show that the use of aluminum alloy materials can effectively reduce the weight of vehicles. Furthermore, when used in the same vehicle, aluminum alloys can also improve collision performance. As vehicle bodies account for approximately 30% of the total vehicle mass and fuel consumption accounts for about 70%, achieving body lightweighting can help reduce overall vehicle weight and fuel consumption. The results indicate that aluminum alloy is a feasible material for automotive body production. Taking Audi as an example, aluminum materials were first used for car doors in the 1980s, and in 1994, aluminum body structures were successfully produced, reducing the overall weight of the vehicle by about 40%. Therefore, numerous domestic and international automakers have increasingly applied aluminum alloys to vehicle bodies and conducted extensive lightweight research with various lightweight materials. Consequently, the utilization of aluminum alloy materials in automotive production can effectively reduce vehicle weight.

6.2. Sump

In the development of automotive lightweighting, there is a significant potential for chassis structure optimization, making it relatively easier to achieve the goal of structural lightweighting. Aluminum alloy is a widely used material in automotive suspension systems. For example, Cadillac utilizes an aluminum alloy suspension system, while Ford uses aluminum-made rotors which weigh two-thirds less than iron-made rotors. Despite a slight increase in cost, the lifespan doubles, resulting in overall cost efficiency improvement. Chrysler's "NeodLite" employs aluminum alloy components in its body, effectively reducing the weight of the steering knuckle by 3 kg and the lower control arm and steering knuckle weight by 2.6 kg. It is evident that the use of aluminum alloy materials in chassis production not only achieves the goal of lightweighting but also extends the lifespan of components. In automotive structures, the chassis is the most challenging part to achieve lightweighting, but it is also relatively easier to reach the lightweighting target. Aluminum alloy has been widely applied in the production of automotive chassis. For instance, Ford produces movable wheel hubs that are 63% lighter than track-based movable hubs. Cadillac uses aluminum alloy for various components in its suspension system. Chrysler adopts an aluminum alloy frame that reduces the weight of the steering knuckle by 3 kg, the lower control arm by 2.6 kg, and the steering knuckle by 1.36 kg. Although adopting these measures may increase the production cost of the chassis, it also extends the chassis's lifespan. Therefore, the application of aluminum alloy in body production not only achieves the goal of reducing body weight but also optimizes the performance and extends the lifespan of the body structure.

6.3. Motor

The engine is the most important component in the automotive powertrain system, and its performance directly affects the overall performance of the vehicle, as well as the service life and driving comfort. Aluminum alloy cylinder blocks, cylinder heads, and intake manifolds can reduce the weight of the engine by 30%-40% and improve the compression ratio, reducing thermal load and increasing engine power. To achieve lightweight design, the fundamental goal is to make some components lighter. To achieve weight reduction, it is recommended to use low-strength fasteners and replace steel with aluminum. To meet the requirements of automotive lightweight design, the extrusion casting method is commonly used for the full process design and trial production. Practical results have shown that these measures can meet the requirements for practical application. Currently, major domestic automotive companies commonly use aluminum alloy engine components, including pistons, radiators, connecting rods, and oil sumps. For pistons, most vehicles use aluminum alloy, which reduces the piston's weight and inertia, as well as the crankshaft's weight, improving piston efficiency. Additionally, this material has high thermal conductivity and a small coefficient of thermal expansion, enabling it to maintain good mechanical performance at temperatures up to 350°C. Furthermore, the

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use of aluminum alloy parts reduces vibration, noise, and fuel consumption, resulting in significant improvements. Nowadays, most car manufacturers have adopted aluminum alloys in their engines, including special parts such as oil pans, connecting rods, radiators, and pistons. Among these parts, aluminum alloy is the most commonly used material, particularly for pistons. It effectively reduces the weight of the piston and crankshaft, decreases inertia, and improves utilization efficiency. Its excellent thermal conductivity and low coefficient of thermal expansion also allow it to maintain good mechanical performance at high temperatures, up to 350°C. Additionally, other aluminum alloy engine components contribute to reducing vibration frequency, decreasing operational noise, lowering fuel consumption, and reducing weight.

6.4. Wheel

In the overall structure of a car, the wheels play the role of bearing the weight of the vehicle and providing driving force. There are generally three ways to make the wheel hub lighter: reducing the size of the hub, using lighter materials, and improving the manufacturing process. Additionally, the excellent thermal conductivity of aluminum alloy improves the braking performance of the car. Furthermore, its weight is only about 30% of ordinary carbon steel. Moreover, due to its low inertia resistance during high-speed rotation, it reduces the friction of the tires, thus reducing fuel consumption and increasing driving safety. In terms of the entire vehicle, the weight of the wheels accounts for about 70% of the vehicle's weight. By reducing the weight of the wheel hub, the overall weight of the vehicle can be reduced. Additionally, aluminum alloy wheels have advantages such as corrosion resistance, shock absorption, and durability. Lightweight treatment of the wheel hub can make the car more lightweight. Using aluminum alloy to manufacture wheel hubs can reduce the weight of the hub and save energy. For every 1 kg reduction in the weight of the wheel hub, the car's fuel consumption can be reduced by 800 kilometers per liter of gasoline, thereby reducing fuel consumption and carbon emissions, achieving low-carbon environmental goals. Furthermore, aluminum alloy wheel hubs have good corrosion resistance and durability [8].

6.5. Suspension system

Suspension system is a set of devices installed between the chassis and wheels of a vehicle, used to support and connect the body and wheels, while absorbing vibrations and shocks caused by road unevenness. Its main function is to provide ride comfort, ensure vehicle stability and improve handling performance. In the automotive suspension system, aluminum alloy materials have several common applications. (1) Shock Absorbers: Shock absorbers are crucial components of the suspension system used to reduce vibrations and bumps during vehicle operation. Aluminum alloy is widely used to manufacture shock absorber casings and other structural parts due to its excellent strength, corrosion resistance, and lightweight nature. It helps reduce the unsprung mass of the vehicle, leading to improved suspension system performance. (2) Suspension Arms: Suspension arms connect the wheels to the vehicle's chassis and control the wheel's movements. Aluminum alloy materials are often chosen for manufacturing suspension arms because of their good corrosion resistance, rigidity, and lightweight properties. The use of aluminum alloy suspension arms can reduce the overall weight of the suspension system, improving responsiveness and stability. (3) Control Arms: Control arms play a role in linking the wheels and the vehicle's body structure, controlling the motion of the wheels. Some vehicles utilize aluminum alloy for manufacturing control arms due to their high strength and low density. This helps reduce the weight of the suspension system while enhancing vehicle handling performance. (4) Sway Bars: Sway bars (also known as stabilizer bars) are used to connect different parts of the suspension system, assisting in lateral force absorption and supporting the vehicle's suspension movements. Aluminum alloy sway bars offer good rigidity and strength while being lightweight, contributing to weight reduction of the entire suspension system. The application of aluminum alloy materials in the suspension system allows automotive manufacturers to achieve weight reduction, improved performance, increased driving comfort, and handling capabilities. Simultaneously, it helps to lower fuel consumption and carbon emissions. The use of aluminum alloy brings about better lightweight effects and overall performance for automotive suspension systems.

7. Conclusion

In short, with the continuous progress and development of China's economy and society, environmental and energy issues have become increasingly serious. In this context, the automotive

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industry must prioritize lightweight design, energy efficiency, and environmental friendliness by optimizing and transforming technologies. In automobile design, it is necessary to use aluminum alloy to achieve weight reduction, lower fuel consumption, reduce carbon emissions, and improve corrosion resistance, shock absorption performance, and durability of vehicles. Lightweight design of automobiles is an important direction for future automotive research and manufacturing. Currently, many countries around the world have made significant achievements in automotive lightweight design and successfully applied aluminum alloy materials to achieve weight reduction. However, research on aluminum alloy materials for automotive lightweight design in China is still in its early stages, and there is still a significant gap compared to advanced levels in foreign countries. Therefore, automotive manufacturers must strengthen research on lightweight technologies and methods for aluminum alloy vehicles.

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