ISSN 2706-655X Vol. 7, Issue 1: 14-19, DOI: 10.25236/IJFET.2025.070103

Research on Lightweight Wheel Hub Design and Its Improvement on Vehicle Fuel Economy

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Abstract: *This article focuses on the manufacturing process of lightweight wheel hubs. The innovation of low-pressure and vacuum technology in precision casting improves the quality of car and racing wheel hubs, saving energy and increasing efficiency; Conventional and isothermal forging with strong forging can meet the demand for strong, tough and lightweight wheels for heavy-duty vehicles and high-performance sedans; Integrated spinning process and weight reduction in one, multi pass spinning helps expand the range of new energy vehicles; Additive manufacturing breaks the shackles of design and materials with 3D printing, creating a Xintiandi for aviation and high-end sports cars. These processes empower wheel hub lightweighting from multiple dimensions, promoting the energy-saving and efficient development of vehicles.*

Keywords: *Lightweight wheel hub design; Vehicle fuel; Economic improvement*

1. Introduction

Amidst the thriving development of the automotive industry today, energy crisis and environmental pressure are closely intertwined, becoming key constraints on its sustained progress. Lightweight technology has emerged, providing a glimmer of hope for the automotive industry to break through, and as a key component of vehicles, the lightweight design of wheel hubs has attracted much attention. Traditional wheel hubs often compromise fuel economy due to excessive weight while ensuring vehicle stability and load-bearing capacity. With the leap in materials science, manufacturing technology, and design theory, exploring new lightweight wheel hub designs has become possible. This study focuses on this, deeply analyzing its design path, material selection, and manufacturing process, striving to accurately reveal its outstanding efficiency in improving vehicle fuel economy and injecting new impetus into the development of automobiles.

2. The impact of lightweight wheel hub design on improving vehicle fuel economy

2.1 Material Innovation, Opening the Door to Lightweight Fuel Economy

In the process of wheel hub lightweighting, the replacement of materials plays a cornerstone role. Aluminum alloy has become a powerful alternative to traditional steel materials, with its lower density significantly reducing weight while maintaining the basic strength requirements of the wheel hub. Compared to steel, aluminum alloy has a density of about one-third, which significantly reduces the quality of the wheel hub[1]. The reduced weight of the wheel hub directly reduces the unsprung mass of the vehicle. When the vehicle is in motion, the inertia of the wheel movement decreases, which means less energy needs to be consumed in the acceleration and deceleration process of driving the wheel. For example, in the frequent start stop traffic conditions in the city, lightweight aluminum alloy wheel rims can respond more agilely to power output every time they start, reducing the additional work done by the engine to overcome inertia, and naturally reducing fuel consumption. Magnesium alloy pushes lightweighting to a higher peak, with better specific strength than aluminum alloy, meaning that magnesium alloy wheels can be made thinner and lighter under the same strength requirements. However, magnesium alloys have high chemical activity and are prone to oxidation and corrosion, which puts strict requirements on their processing and protection processes. Once these challenges are overcome, the application of magnesium alloy wheels in vehicles can further optimize the distribution of unsprung mass, improve vehicle handling, and bring greater breakthroughs to fuel economy. When driving at high speeds, due to the smaller moment of inertia of the wheels, the power input required for the vehicle to maintain a constant speed is reduced, and the advantage of fuel

ISSN 2706-655X Vol. 7, Issue 1: 14-19, DOI: 10.25236/IJFET.2025.070103

economy is fully demonstrated in long-distance driving[2]. Carbon fiber composite materials, as a rising star, have made a stunning debut with their ultra-high strength to weight ratio. Its unique fiber weaving structure endows the wheel hub with excellent mechanical properties and can withstand complex stress conditions. From a manufacturing process perspective, carbon fiber can be integrated into complex shapes to avoid weight redundancy caused by excessive connecting components. Despite the current high costs that limit widespread adoption, carbon fiber wheels have demonstrated transformative improvements in fuel economy in pilot applications for high-end and high-performance vehicles. When the vehicle is in motion, the extremely small weight of carbon fiber wheels almost reduces the resistance to wheel rotation, greatly reduces engine load, and significantly improves fuel efficiency, painting an attractive prospect for future automotive energy conservation.

2.2 Structural optimization, carving out space for improving fuel economy

The structural optimization of the wheel hub is like a precise surgical operation, precisely removing redundancy and enhancing efficiency. Starting from wheel rim design, variable cross-section wheels have become the focus of innovation. Traditional equal section wheel rims often have excessive design in certain areas to ensure overall strength, resulting in material waste and increased weight. According to the force distribution, the variable cross-section wheel rim is reasonably thickened and strengthened in key load-bearing areas, and thinned and reduced in areas with less force, allowing for precise control of the wheel rim weight[3]. This not only maintains or even enhances the reliability of the wheel rim's support for the tire, but also converts the reduced weight into lower energy consumption throughout the vehicle's operation. Taking a common family sedan as an example, the optimized variable cross-section wheel hub can increase the single driving range by several kilometers under comprehensive working conditions compared to traditional designs, and over time, fuel savings are considerable. The spoke design also contains great potential for optimization. The transition from multiple spokes to fewer spokes is a delicate balance between mechanics and aesthetics. Reducing the number of spokes is not a simple reduction, but a rearrangement based on the finite element analysis results of the wheel hub stress. Design the spokes on the main force path to achieve the most effective force transmission with minimal material and avoid unnecessary material stacking. The wheels designed in this way not only showcase a simple and powerful appearance style, but also reduce the ineffective dissipation of energy in the wheel components during vehicle acceleration, braking, and cruising due to weight reduction. Especially in the current pursuit of ultimate endurance in new energy vehicles, optimized lightweight wheel hubs help to more efficiently utilize electrical energy, reduce charging frequency, expand travel radius, and effectively improve the economic efficiency of vehicle operation. Topology optimization technology adds intelligent wings to the optimization of wheel hub structures. By simulating the stress-strain distribution of the wheel hub under various working conditions through algorithms, accurately identifying the areas where the material can be removed and the areas that need to be strengthened. The designed wheel hub structure is not limited to traditional shapes and presents an organic and efficient form. This data-driven design approach unearths weight redundancy hidden in traditional designs and maximizes material utilization. Vehicles with topology optimized wheels have stable improvements in fuel economy, whether in urban congestion or high-speed driving scenarios, allowing every drop of fuel to release maximum energy and drive the vehicle further with less consumption.

2.3 Advanced manufacturing process, forging the cornerstone of high efficiency and energy conservation

The traditional casting process, as a well-established method for wheel hub manufacturing, has the advantages of scale and controllable cost, but it encounters bottlenecks in lightweighting and performance improvement. The internal structure of the wheel hub produced by sand casting is loose and the grain size is coarse. In order to ensure strength, more material allowance must be reserved, which makes it difficult to reduce the weight of the wheel hub. Although low-pressure casting has been improved and can refine grain size and increase density to a certain extent, it still cannot meet the demand of modern vehicles for extreme lightweighting of wheel hubs. The forging process is like precision steel quenching, reshaping the quality and weight of the wheel hub. Under high temperature and high pressure, metal billets are forged by molds, and the internal grains are compacted and refined, resulting in a dense and uniform structure and a significant increase in mechanical properties. This enables forged wheels to achieve higher strength requirements with less material, reducing weight by 15% -20% compared to cast wheels of the same size. After the vehicle is assembled with forged lightweight wheels, the significant decrease in unsprung mass brings about a chain energy-saving reaction[4]. During the acceleration phase, the engine load is reduced, power transmission is more direct and efficient, and fuel is quickly converted into vehicle speed increase, rather than being consumed to overcome heavy wheel hub inertia; When braking, the inertia of the lighter wheel hub decreases, and the energy loss recovered by the braking system is reduced, allowing for more rational recycling of energy and overall improvement of fuel economy. Spinning technology, as an extension and expansion of forging technology, adds a dynamic touch to wheel hub forming. Based on forged blanks, the wheel rim is subjected to high-speed spinning and stretching using spinning equipment. This process is like coating the wheel hub with a tightly fitting "lightweight armor", which not only strengthens the strength of the wheel hub, but also precisely controls the material thickness, further reducing weight. The wheel hub processed by spinning has continuous and complete fiber flow lines at the wheel rim, excellent fatigue resistance, and a balance between durability and lightweight. Applied to vehicles, whether it is frequent acceleration and deceleration during daily commuting or stable cruising during long-distance journeys, fuel consumption is always maintained at a low level, empowering vehicle energy-saving and endurance with exquisite craftsmanship.

3. Structural optimization design of 2 lightweight wheel hubs

3.1 Transformation of wheel rim cross-section, the path of precise structural research and efficiency creation

The optimization of the cross-sectional shape of the wheel rim, which is the key part directly in contact with the tire, is the core breakthrough point for lightweight structural design. Although traditional circular wheel rims have simple manufacturing processes and strong universality, they have significant deficiencies in material utilization efficiency. From the perspective of mechanical principles, different parts of the wheel rim are subjected to uneven forces during vehicle operation. The outer edge bears greater lateral and impact forces when turning or crossing hills, while the inner side mainly bears radial pressure. The equal section design ensures the strength at the weakest point and adopts a uniform thickness as a whole, resulting in redundant accumulation of materials in areas with less stress. A new type of variable cross-section wheel rim has emerged, which optimizes the zoning of the wheel rim based on the precise force map simulated by finite element analysis. In areas prone to external stress and impact, increase the thickness of materials appropriately, strengthen the structure, and adopt a trapezoidal or arc-shaped reinforcement design to enhance local bending and impact resistance; The inner part that carries relatively stable radial force is boldly thinned to maintain the required strength with just the right amount of material. This change not only significantly reduces the weight of the wheel rims, but also enhances overall reliability. For example, variable cross-section wheels applied to small SUVs can reduce weight by up to 10% -15% compared to traditional designs. In actual driving, the vehicle's unsprung weight is reduced, the start is light and agile, and fuel consumption is significantly reduced in frequent start stop urban road conditions. For a single commute, if the distance is 20 kilometers and includes 10 traffic light intersections, vehicles with optimized wheels can reduce fuel consumption by about 0.2-0.3 liters compared to the old model. Over the long term, the energy-saving benefits are remarkable[5].

3.2 Reconstruction of spoke layout, a model of integration of mechanics and aesthetics

The spokes connect the wheel rim to the center of the hub, and their layout has a profound impact on the performance, weight, and appearance of the hub. Early multi spoke design pursued visual fullness and stability, with the number of spokes often ranging from 8-10 or even more. However, from a mechanical perspective, having too many spokes can lead to complex force transmission paths, uneven force distribution on some spokes, and unnecessary weight increase. The modern design concept advocates for fewer spokes and larger layouts, using simple lines to outline the aesthetic of power. Based on structural mechanics simulation, accurately locate the main force path of the wheel hub, and place thick and few spokes on it to ensure efficient transmission of force from the center of the wheel hub to the wheel hub. If 5-6 Y-shaped or V-shaped spokes are used, the root of the spokes should be widened at the center of the wheel hub, strengthened at the connection with the wheel rim, and the middle section should be appropriately narrowed to reduce weight, ensuring both strength and weight reduction. This design is applied to new energy cars, effectively reducing the rotational inertia of the wheel hub. When the vehicle accelerates, the motor power does not need to overcome inertia resistance too much, and the conversion of electrical energy into vehicle speed is more efficient. In the endurance test, vehicles equipped with optimized spokes and wheels can increase their range by 5% -8%

ISSN 2706-655X Vol. 7, Issue 1: 14-19, DOI: 10.25236/IJFET.2025.070103

compared to the original model while driving at a constant speed of 60 kilometers, empowering energy efficiency with the beauty of the structure.

3.3 Topology optimization empowerment, intelligent carving of ultimate lightweight

Topology optimization technology injects intelligent genes into the design of wheel hub structures, breaking traditional design thinking patterns. It utilizes advanced algorithms to digitize the stress conditions of the wheel hub under multiple working conditions such as braking, acceleration, turning, and high-speed cruising, and uses massive calculations to find the optimal distribution of materials. In the initial design stage, the algorithm abandons the preset fixed shape and explores freely with the aim of "removing all unnecessary materials". The generated wheel hub structure may seem irregular, but it contains intricate logic. At key nodes around the center hole of the wheel hub and the connection between the spokes and the wheel rim, the material naturally aggregates and strengthens, forming an organic form similar to biological bones; In areas where the force is dispersed and the impact is small, the material gradually becomes sparse, and even hollows appear. Taking high-performance sports car wheels as an example, after topology optimization, the weight is reduced by 20% -25% compared to traditional designs, while the strength meets the strict requirements of extreme driving[6]. When the vehicle is speeding at high speeds, the advantages of lightweight are fully demonstrated, the engine load is reduced, and fuel economy continues to steadily improve in the pursuit of ultimate performance, opening up a new path for structural optimization and energy conservation.

3.4 Exploration of integrated molding, seamless construction of lightweight and strong strength

Traditional wheel hub manufacturing often adopts split assembly, where the wheel rim and spokes are formed separately and then assembled. Although it is convenient for production, the connecting parts require additional reinforcement, which increases weight and poses a risk of stress concentration. Integrated molding technology addresses pain points and is committed to creating seamless and coherent wheel hub structures. By using advanced die-casting, forging, or additive manufacturing (3D printing) methods, the wheel hub can be processed from raw materials to finished products in one go. If die casting and forging are integrated, the rough outline is initially formed by die casting, and the key parts are precision forged again using forging molds to refine the grain size, improve strength, and avoid joint gaps. 3D printing relies on the advantage of layer by layer stacking to accurately construct complex internal structures, such as honeycomb shaped and vein like support structures, while reducing weight and ensuring overall rigidity. Applied to light cargo vehicles, the integrated wheel hub, with its structural integrity and load-bearing capacity, is not inferior to traditional wheel hubs, but its weight is reduced by 10% -15%. When the vehicle is running at full load, the fuel economy is significantly improved, and the fuel consumption per 100 kilometers can be reduced by about 0.5-1 liter, reshaping the future of wheel hub lightweighting with innovative technology.

4. Manufacturing process of 3 lightweight wheel hubs

4.1 Precision casting innovation, the lightweight transformation of traditional processes

Casting technology, as the cornerstone of wheel hub manufacturing, has a long history but is constantly innovating under the wave of lightweighting. Although traditional sand casting can meet the basic forming needs, due to its process characteristics, the produced wheel hub is prone to sand holes and pores inside, with coarse grains and loose structure. In order to ensure the strength and safety of the wheel hub, a large amount of material has to be reserved, resulting in a high weight of the wheel hub. Low pressure casting technology has emerged, opening a new chapter in lightweight casting processes. In low-pressure environments, liquid metal slowly and smoothly fills the mold cavity, effectively reducing gas entrapment compared to sand casting, making the internal structure of the wheel hub denser, and significantly reducing defects such as pores and sand holes. This feature endows the wheel hub with higher material utilization, allowing for moderate reduction in thickness and weight optimization while meeting the same strength standards. Taking aluminum alloy wheels as an example, under low-pressure casting technology, the material density distribution is more uniform, the product strength is increased by about 10% -15%, and the weight is reduced by 8% -12% compared to sand casting. Applied to household sedans, the vehicle's unsprung weight is reduced, the handling is improved, and the fuel economy can be reduced by about 0.3-0.5 liters per 100 kilometers under urban comprehensive road conditions, saving energy and increasing efficiency for daily travel. Vacuum

ISSN 2706-655X Vol. 7, Issue 1: 14-19, DOI: 10.25236/IJFET.2025.070103

casting goes a step further by pumping the mold cavity to a vacuum state, completely eliminating gas residue and creating an almost perfect internal structure. Liquid metal is precisely formed without air interference, producing wheels with excellent strength and smooth surface quality, reducing subsequent processing steps. For sports cars and racing cars that pursue high performance and lightweight, vacuum cast aluminum alloy wheels have become the preferred choice. Under the harsh working conditions of high-speed driving, frequent sudden braking, and intense turning, the excellent mechanical performance ensures safety, while the lightweight characteristics help fully unleash the vehicle's power performance, allowing speed and energy efficiency to be perfectly integrated on the track and road.

4.2 Strong Forging Navigation, Performance Driven Lightweight Pioneer

The forging process is like a journey of metal quenching, creating high-performance lightweight wheels. Unlike casting, forging is a plastic deformation process of solid metal billets under high temperature and high pressure, which refines and tightly arranges the internal grains of the metal, forming a continuous and high-strength fiber structure. The wheels produced by conventional forging processes have significant strength advantages and are commonly used in heavy-duty vehicles, off-road vehicles, and other fields that require strict load-bearing capacity. Taking cargo trucks as an example, forged wheels have a 30% -50% increase in fatigue strength compared to cast wheels, and can withstand enormous load pressure and complex road conditions, ensuring driving safety. Although the initial cost is high, from the perspective of long-term use and maintenance, its durability reduces the frequency of replacement, and the comprehensive benefits are considerable. As an advanced method, isothermal forging technology precisely controls the temperature field during the forging process to ensure uniform deformation of the metal at a constant temperature. This overcomes the problem of uneven microstructure caused by excessive temperature gradient in traditional forging, and produces wheel hubs with higher precision and more stable performance. Applied to high-performance sedans, isothermal forged wheels not only reduce weight by 15% -20%, but also improve vehicle acceleration performance and handling sensitivity. When the vehicle starts, the lightweight wheels make power transmission more direct and efficient. When turning at high speeds, precise mechanical response ensures stable driving trajectory, empowering both driving experience and fuel economy.

4.3 Sublimation of Spinning Process, Exquisite Integration of Forming and Weight Reduction

Spinning technology is an innovative highlight in lightweight wheel hub manufacturing, which is based on secondary processing of forged or cast blanks, giving unique advantages to the wheel hub. The principle is to use spinning equipment to make the high-speed rotating wheel hub billet tightly adhere to the inner wall of the mold, and gradually apply pressure to the wheel rim through the roller, causing plastic flow and thinning. In terms of wheel rim reinforcement, the spinning process has a significant effect. After spinning treatment, the fiber flow lines of the material at the wheel rim are rearranged along the direction of rotation, forming a tight structure similar to a "spiral armor", greatly improving the fatigue resistance and strength. Compared to simply forging the wheel hub, spinning the wheel hub can increase its strength by 10% -15%, while further reducing its weight. For new energy vehicles that pursue ultimate endurance, spinning process wheels are assembled. In the energy recovery and power output links, due to the reduced rotational inertia of the wheels, the efficiency of electric energy utilization is significantly improved, and the endurance mileage can be increased by 5% -8% under standard operating conditions, expanding the travel boundary with exquisite craftsmanship. Multi pass spinning technology maximizes precise control. Through multiple spinning operations with different parameters, differentiated treatment is achieved for different areas of the wheel hub, such as increasing spinning passes and pressure in the outer strengthening zone of the wheel hub, and appropriately reducing them on the inner side, while optimizing strength and weight. This refined processing is suitable for various vehicle needs, from small sedans to large SUVs, all of which can rely on customized spinning wheels to explore the maximum potential for fuel economy and performance improvement while ensuring driving safety.

4.4 Breakthrough in additive manufacturing, a new chapter of lightweight design freedom

Additive manufacturing, also known as 3D printing, opens up a new dimension for lightweight wheel hub manufacturing. It breaks free from the mold constraints of traditional subtractive manufacturing and builds wheel hub entities layer by layer based on digital models. From the perspective of design freedom, 3D printing allows for the creation of complex internal structures such as biomimetic honeycombs and lattice structures. These structures maintain or even exceed the

ISSN 2706-655X Vol. 7, Issue 1: 14-19, DOI: 10.25236/IJFET.2025.070103

load-bearing capacity of traditional wheel hubs through clever mechanical design while reducing weight. Taking aerospace applications as an example, 3D printed titanium alloy wheels adopt honeycomb shaped internal support, which reduces weight by 30% -40% compared to traditional forged wheels of the same strength, greatly reducing aircraft load and bringing a leap to aviation fuel economy. In terms of material selection, 3D printing is compatible with a variety of high-performance materials. In addition to common alloys, it can also handle special materials such as ceramics and composite materials. For high-end sports cars with urgent demand for lightweight, 3D printed carbon fiber reinforced composite material wheels are used. With the ultra-high specific strength of the material and the precise molding of 3D printing, extremely lightweight and tough wheels are created. When the vehicle is in motion, the extremely small moment of inertia enables rapid acceleration and braking response, and fuel economy still performs well in high-performance driving, reshaping the lightweight wheel hub manufacturing pattern through technological innovation.

5. Conclusion

In the field of lightweight wheel hub manufacturing, precision casting utilizes technological innovations such as low pressure and vacuum to optimize the quality of wheels for household cars to racing cars, and improve fuel economy and performance; Strong forging uses conventional and isothermal forging to create strong and lightweight wheels for heavy-duty vehicles and high-performance sedans; The spinning process integrates the advantages of forming and weight reduction, and the multi pass spinning is suitable for multiple vehicles, helping to extend the range of new energy vehicles; Additive manufacturing breaks through design and material limitations with 3D printing, opening up new opportunities for aviation and high-end sports cars. In short, each process empowers wheel hub lightweighting from different dimensions, driving vehicles to move forward in an energy-efficient and efficient manner.

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