Study on Multi-objective Optimization Design of Magnesium Alloy Wheel considered Dynamics and Impact Performance as well as Casting Quality

マグネシウム合金ホイールの動力学・衝撃性能と鋳造品質を考慮した多目的最適化設計

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February, 2020

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Abstract

With the rapid growth of vehicle, a series of social problems such as excessive energy consumption and environmental pollution have emerged. New energy vehicle lightweight is an important way to reduce energy consumption and pollutant emissions. Magnesium and its alloys have a diverse range of markets and applications due to their advantageous characteristics.Combined with characteristics of magnesium alloy and application on the of wheel for research. The main research work include the following aspects:

(1) Lightweight of vehicle is a significant application trends, using topology optimization and magnesium alloy materials is a valuable way. This article design a new model of vehicle wheel and optimize the structure for lightweight. Through measuring and analyzing designed model under static force, clear and useful topology optimization result were obtained. Comparing wheel performance before and after optimization, the optimized wheel structure compliance with conditions such as strength can be obtained. Considering three different materials namely magnesium alloy, aluminum alloy and steel, the stress and strain performances of each materials can be obtained by finite element analysis. The reasonable and superior of magnesium alloy wheel for lightweight design were obtained. This research predicts the reliability of the optimization design, some valuable references are provided for the development of magnesium alloy wheel.

(2) The casting material in this study is magnesium alloy used for wheel lightweight. Analysis of casting process is a very complex issue, this research based on finite element theory and actual production, designed reasonable casting model, instant filling and solidification data were obtained. Aiming at reducing casting defects, process optimization of casting riser structure were designed. Optimized casting process could reduce the probability of defects in castings, improve the quality of castings.Through the simulation and optimization in the casting process, provided a rational design for the casting process. On the basis of the foundation, it has important guiding significance for actual foundry production.

(3) Designing lightweight and comfortable vehicles is a primary aim of the industry. Lightweight wheel designs can have a negative effect on the dynamic impact performance of the wheel; therefore striking a balance between these two factors is a key objective in the design of vehicles. Magnesium alloy wheels were investigated as magnesium alloy has damping performance advantages over some metal materials. Damping test methods were designed to establish the damping performance parameters of the magnesium alloy material. A finite element analysis model of magnesium alloy wheels was established with certain boundary conditions and constraints. The applicability of the model was verified by free modal evaluation of the wheel. Dynamic impact simulation analysis of the designed wheels was carried out and the dynamic speed responses of magnesium alloy wheels under the impact of a dynamic load on the road surface were obtained. Comparing the dynamic impact performance of magnesium and aluminum alloy wheels with the same structure, showed that the magnesium alloy wheel achieved the target weight reduction of 32.3%, however the dynamic impact performance was reduced. In order to realize the lightweight design, the dynamic impact performance of the magnesium alloy wheel should not be inferior to that of the aluminum alloy wheel, therefore the design of the magnesium alloy wheel structure was optimized. The structural design optimization of the magnesium alloy wheel was carried out by defining the structural parameters of the wheel and using the acceleration and shock response of the wheel as the outputs. The optimization of weight reduction and dynamic impact performance of magnesium alloy wheels was achieved.

Consequently, the designed magnesium alloy wheel was shown to have improved ride comfort while satisfying wheel structural performance standards and provided lightweight design.

Chapter 1 Introduction

1.1 Background and significance of the research

Recently，with the developing and various revolutions in vehicle technology，the vehicle has made significant progress in society. Cars and various fuel vehicles have become an indispensable part of people life [1].With the increase of automobile production, fuel consumption, environmental pollution and safety issues have gradually become a problem that can not be ignored. From the perspective of long-term and sustainable development, energy conservation and environmental protection are two major problems that need to be solved in the development of the automobile industry. Major countries and regions in the world have begun to develop pure electric,new energy vehicles such as hybrids.In terms of current economic and technological level,any new energy source is not as economical, efficient and convenient as fossil energy such as oil and natural gas [2-12]. Increasing in human technology, when some technology have been customized and serialized, lightweight technology has become the most important way to solve the two major problems of energy conservation and environmental protection. Building lighter vehicles is one of the most important ways to save energy and protect the environment [13-17]. World primary energy consumption were shown as Fig.1.1.

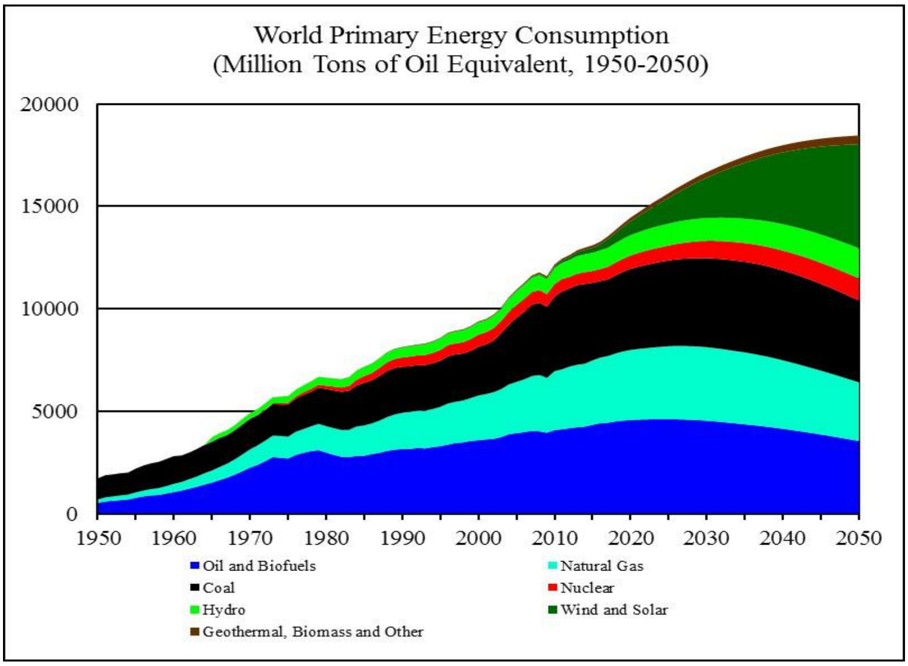


Fig.1.1 World primary energy consumption [18].

The quality of the vehicle has a very important impact on fuel consumption. According to statistics, when the quality of a complete vehicle is reduced by about 10%, when the vehicle is 100 to 120km/h, the fuel consumption per 100 kilometers can be reduced by 0.5 to 0.7L.Therefore, from the perspective of energy saving and emission reduction and fuel consumption reduction, reducing the weight of the car is one of the effective methods [19-20].The main way approach to lightweight the car weight is to reduce the construction of structural parts through the optimization of the vehicle structure and use the lighter materials to manufacture the car structural. Wheels account for a large proportion of the weight of the vehicle, wheel lightweight is an effective way. Lightweight materials such as magnesium alloys are used instead of steel to make wheels weight reduction [21]. Lightweight materials for the manufacture of vehicle structural parts have become the vehicle lightweight industrial technology [22-25]. Lightweight materials were shown as Fig.1.2.

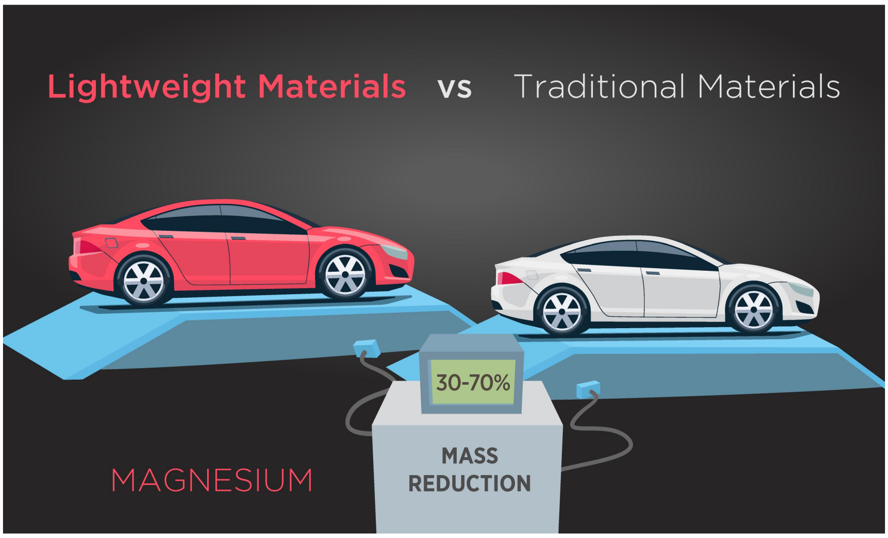


Fig.1.2 Lightweight materials [26].

Manufacturing technology is an integration and paradigm of modern technology and industrial innovation.It is the main symbol of the national manufacturing level.Is the foundation and pillar of national industry [27-28].As a basic industry, casting has a pivotal position in the national economy.Casting products account for a large proportion of mechanical manufacturing products.In the casting process， due to the complexity and invisibility of the molten metal filling and solidification process,the casting process is very complicated [29-30].In traditional production practices, design the casting process need long cycle and high cost with have seriously hindered the rapid development of the foundry industry.The rise and development of the numerical simulation of the casting process overcomes the drawbacks of the traditional production method.It has opened up new avenues for the design of castings. With the rapid development of computer technology, numerical simulation of the casting process (including casting filling, solidification process, shrinkage shrinkage prediction, computer simulation of stress analysis) become one of the frontiers development of the foundry discipline [31-36]. Which has important implications to reduce casting costs, shorten the design development cycle, improving the quality of castings. Therefore, it makes significance to study the casting of the wheel.

In recent years, people have become more and more demanding on driving safety and comfort of automobiles [37-38]. When the vehicle weight is light, it is easy to cause a decrease in comfort.Therefore, the contradiction between meeting the requirements of consumer safety and comfort with the weight of vehicle has become increasingly prominent [39-42].Magnesium alloys are listed as the preferred materials by achieve the weight reduction of vehicles and improve the safety and comfort of vehicles. Magnesium alloy is the lightest metal structural material with good shock absorption performance, high specific strength, high specific stiffness and dimensional stability [43-45]. As one of the most important structural parts on the vehicle, the wheel is subjected to various loads such as impact and vibration during driving, and the force state is complicated. In order to ensure safe service, the materials to be manufactured must have sufficient strength, high plasticity, copper properties and high fatigue strength properties. The use of magnesium alloy wheels can achieve a lightweight body while also improving the NVH effect [46-52].

In view of the current status of the application of magnesium alloy wheel structure design and forming technology, this research summarizes and analyzes the research status of magnesium alloy wheel design and forming technology.Study on the lightweight design and casting forming technology of magnesium alloy wheel structures. The vibration performance of the wheel were analyzed.It has important engineering application value and significance for magnesium alloy wheel.

1.2 Background and development of magnesium alloy

1.2.1 Magnesium alloy development

Magnesium is a typical light metal material. Magnesium is a non-magnetic metal with good thermal conductivity and non-toxicity. It is a close-packed hexagonal lattice, with low density and easy to cut. It has the outstanding advantages of effectively shielding electromagnetic radiation and being easy to recycle. Magnesium is one of the most widely distributed elements in the earth's crust, about 2% of the total crust and 1% of the total amount of seawater, the content is second only to aluminum and iron in structural metallic materials [53-56].Due to the very active chemical nature of magnesium, in nature, magnesium can only exist in the form of compounds, minerals containing magnesium compounds can be found everywhere on land. About more than 1,500 available minerals currently known, there are more than 200 kinds of magnesium minerals, mainly are sulfates, carbonate and silicate.The oceans and salt lakes contain more magnesium than land. Among the more than 10 elements contained in seawater, magnesium ranks third, it is estimated that about 1.3 kg of magnesium per cubic meter of seawater, total reserves of magnesium in seawater are about 2.3×10^{15} t. If calculate 1 million tons of magnesium per year from seawater refining, magnesium can use 230,000 years, that is a very rich resource [57-60].

Magnesium has a very high thermal conductivity, good dimensional stability, excellent energy absorption characteristics and it is a good material for making vibration-damping parts.Magnesium is the easiest to process in metal, and processing equipment is less demanding.Magnesium alloys also have good extrusion properties, form ability and weld ability. In addition, the life of magnesium alloy castings is longer than that of aluminum alloy.The reason is that the thermal fatigue value of magnesium is much smaller than that of aluminum.The use of magnesium and its alloys has increased dramatically over the past decade. Magnesium is a good choice for the most important structural applications. Magnesium supply is shown as Fig.1.3.

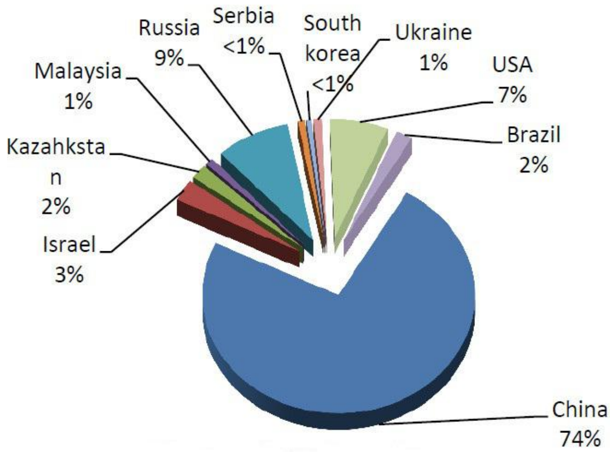


Fig.1.3 Magnesium supply [61].

In 1808, British scientist David used the method of potassium reduction of magnesium oxide for the first time in the laboratory to produce magnesium metal, which created a new era of magnesium.Since then, this metal of magnesium has gradually entered people's field of vision.In the early 1940s, the Pijiang magnesium smelting method was invented by the Canadian Pidgeon [62]. Due to the simple production process and low production cost, the production of raw magnesium was greatly improved, and the industrial production of magnesium and magnesium alloys was a wide-ranging application has laid a solid foundation.The comprehensive mechanical properties of the magnesium alloy material produced by the alloying method are significantly improved, thereby realizing the use of the magnesium alloy material as a structural material, which greatly expands the application range of the magnesium metal.

Germany began industrial production of magnesium alloy materials in 1886, and in 1930 first used magnesium alloy materials in car manufacturing [63]. In 1935, the Soviet Union first used magnesium alloy materials for aircraft production, the Beetle car introduced in 1936 was the first car to use a large number of magnesium alloys to produce car parts. In the engine and transmission system, more than 18kg of die-cast magnesium alloy engine and gearbox housing were used. In 1938, magnesium alloy was first used in the shell of a motorcycle crankcase in Birmingham, England. At present, more and more car and motorcycle parts are being manufactured using magnesium alloys. From the early 1970s to the end of the 1980s, due to the worldwide oil crisis, car manufacturers began to consider the use of magnesium alloys to make cars to reduce the weight of the car and reduce fuel consumption.In the 1990s, due to restrictions on automobile exhaust emissions from environmental protection agencies around the world, magnesium alloying the use of gold in cars has increased dramatically.Since the beginning of the 21st century, in the development of magnesium alloys, research on heat-resistant magnesium alloys, corrosion-resistant magnesium alloys and special-function magnesium alloys has been better developed [64-66].

Due to the outstanding advantages and almost inexhaustible reserves of magnesium and magnesium alloys, magnesium alloy is called “the most promising green material in the 21st century”. Magnesium alloy is the most promising new generation of high performance structural materials to replace steel, aluminum alloys and engineering plastics, it is used in vehicles and instruments such as automobiles and motorcycles. The electronics industry, home appliances, light industry and military fields also have great application potential and prospects, so magnesium and magnesium alloys has been paid more and more attention.

1.2.2 Application of magnesium alloy on the wheel

Magnesium and its alloys were discovered for many years, they have been used in aviation, aerospace, weapons, communications, home appliances, and transportation industries for a long time. With the development of the times, people are paying more and more attention to the development and application of magnesium alloy materials [67-71]. In the 1920s magnesium began to make an appearance in the vehicle industry. The light weight metal began to be used in racing cars to add to their competitive edge. The interest in magnesium use in vehicle applications has increased over the past ten years because of weight and superior performance. Magnesium supply were shown as Fig.1.4.

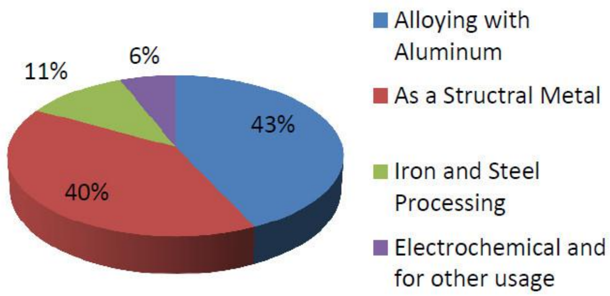


Fig.1.4 Magnesium Usage in different areas [61].

The manufacture of car structural parts from magnesium alloys has many advantages, such as reduce the weight of the car body. The reduction in body weight helps to increase the load capacity and payload of the vehicle. After the weight of the car body reduced, the vehicle energy consumption demand is reduced. Magnesium alloy has high damping coefficient and good seismic performance, that can improve the comfort of driving the car. In view of the fact that magnesium alloy can realize the weight reduction of the vehicle body and reduce the energy consumption of the vehicle and the emission of exhaust gas, the world is competing to develop the magnesium alloy material for vehicles and the application technology research of the vehicle parts forming process.

Germany has always been research in the field of magnesium alloy manufacturing vehicle parts， many company use magnesium alloys on vehicle to manufacture vehicle structural parts. Germany Audi manufactures instrument panels using magnesium alloy die-casting processes. German BMW Motors manufactures engines with magnesium alloys and uses magnesium alloys on the outside of the crankcase [72]. In the 1950s and 1960s, the American vehicle industry also used magnesium alloys to make locomotive parts.Companies such as Ford, GM and Chrysler have also been working on the development and manufacture of magnesium alloy vehicle parts.Typical magnesium alloy automotive parts include clutch housings, steering column frames, intake manifolds, and lighting clamps. Magnesium alloys are also used in the clutch bodies and brake pedal support brackets. GM successfully developed magnesium alloy wheels in 1997, it is of great significance of magnesium alloy application on vehicles [73-75].

The wheel is a component that is loaded between the axle and the tire and consists of a rim and a spoke, where the rim is a component that supports and mounts the tire, the spoke is a component that supported between the axle and the rim. During the driving process, the wheel not only bears its own vertical load, but also bears irregular loads from various directions due to various sudden situations. The wheel is an important safety component in the vehicle driving system. Therefore, its structural performance is also important to consider in the design process.In addition, the wheel belongs to the appearance part of the car. In 2005, Peng Yinghong and others from Shanghai Jiao Tong University conducted a finite element analysis on the low-pressure die-casting of magnesium alloy automobile wheel, predicted the defects such as porosity, and improved the quality of the low-pressure die-casting magnesium alloy automobile by improving the cooling system. In 2007, Canadian scholar Xia Zihui used the finite element method to simulate the forging process of magnesium alloy, and used the experimental flow curve analysis of magnesium alloy AZ80 to simulate the forging process of magnesium alloy vehicle wheel.The effect of friction on the forming of magnesium alloy vehicle wheel were studied. American scholar Shang Roert conducted a bending fatigue analysis on a forged magnesium alloy automobile wheel in 2009, and calculated the fatigue safety factor of each unit. It was found that the fatigue strength at the spokes did not meet the requirements and was optimized by increasing the thickness to meet design requirements.Zhou Zhaoqing of Chongqing University established a model of automobile wheel with magnesium alloy as material, and predicted the fatigue life of the model. On this basis, the design of the wheel was optimized and the weight of the wheel was reduced. In 2009, Tang Hongqiang took the 15-inch model of the automobile wheel as the research object, replaced the material with magnesium alloy, and studied its fatigue performance, and found that the maximum stress in the static analysis is the area with the smallest life.At the same time, he also designed and analyzed the extrusion casting mold of magnesium alloy wheel.With the continuous development of technology, more and more researchers are conducting research on magnesium alloy wheels. Wheel in the vehicle were shown as Fig.1.5.

Fig.1.5 Wheel in the vehicle [76].

In order to meet the aesthetic requirements of the customer, a variety of spoke structures are designed on the basis of meeting the structural performance requirements. The design of the spoke portion of the wheel not only requires aesthetics and novelty, but also has different emphasis on different markets and different regions. Lightweight design of the wheels can improve the fuel economy of the car to a certain extent.Therefore, many wheel manufacturers regard the lightweight design of products as one of the development directions of the enterprise [77-80].

At present, in all cars, the use of magnesium alloy wheels is much less than that of aluminum alloy wheels. It is even rarer in production cars. Generally, it is only used in high-end cars such as Ferrari and Porsche. One of the main factors that restricting magnesium alloy wheels development is the price of the wheels. Magnesium alloy wheels are nearly twice as expensive as aluminum alloy wheels.

Magnesium alloy wheels are has many advantages, it can not only achieve the purpose of lightweight the wheel, but also can improve the ride comfort of the car, with the reduction of raw material prices, the improvement of manufacturing industry and equipment, and the improvement of anti-corrosion technology, the application of magnesium alloys wheel will be more extensive [81-84]. In summary, considering the advantages of magnesium alloy, it is very important to take advantage of magnesium alloy wheel research. Different materials wheel were shown as Fig.1.6.

Fig.1.6 Different materials wheel [85].

Magnesium alloy wheels are lighter in weight and can be reduced by approximately 70% compared to aluminum alloy wheels of the same performance. In addition, the magnesium alloy wheel has other advantages: the vibration damping is good, the magnesium alloy has a high damping coefficient, which is 15 times that of the aluminum alloy. The larger the damping coefficient, the better the vibration damping.The magnesium alloy wheel can reduce the body vibration of components such as engines, transmissions, improves component life and ride comfort. Magnesium alloy good thermal conductivity can release the accumulated heat at the wheel faster, improve the braking performance, and prolong the service life of the wheel.

1.3 Research on magnesium alloy wheel

1.3.1 Magnesium alloy wheel lightweight design

The lightweight of the vehicle is based on the requirements of structural rigidity, strength, durability, vibration noise, passive safety and cost. Through reasonable material selection, optimization of the structure, and reasonable process, the lightweight component will be obtained. Apply reasonable components to the right place at the right time, and fully utilize the functions of bearing, strengthening and energy absorption of various parts of the vehicle. As early as the beginning of the last century, the car involved in motor sport was limited by the Motor Sports Association, which became the world first car lightweight event. This provision also provides a good start for the rapid development of vehicle lightweight in the future. Since then, vehicle parts have begun to develop in a lightweight direction [86-88]. Moreover, more lightweight casting component are beginning to appear on some parts of the suspension and vehicle systems.

Lightweight construction is one of the most important requirements in vehicle development. But how much weight is saved by lightweight construction depends largely on the experience and intuition of the developers and designers.Since the 1970s, with the outbreak of the worldwide oil crisis, with the development of automotive design, manufacturing process technology and automotive materials technology, people began to pay more attention to the research of automotive lightweight technology. Many researchers began to gradually apply to automotive products, the total weight of the car began to appear decreasing year by year. According to statistics, the average total weight of American mid-size cars has been significantly reduced from the early 1980s to the late 1990s.By the end of the last century, the total weight of some cars was controlled at around 800kg or even lower.Among the commercial vehicle series, vehicle lightweight technology has also begun to receive a large number of applications[89-92].

In order to achieve the goal of vehicle weight reduction, the researchers have a variety of ways around the entire design and manufacturing cycle of the vehicle, within the limits of cost and current technical conditions.This includes improving existing materials and processes, using new materials, new structures and so on to achieve lightweight goal of vehicle[93-95]. Mainly through the following ways to achieve vehicles lightweight:

(1) Achieve lightweight with a variety of lightweight materials

The use of new materials to achieve lightweight vehicles requires optimal design of materials, that is, a reasonable match between the materials of the various parts of the vehicle.Since various materials have different properties, these properties may be common properties between different materials, or they may be unique properties of individual materials.Therefore, in the optimization, under the premise of ensuring the structural performance of the structure, how to design multiple attribute variables of different materials for fast and effective optimization is the focus of lightweight material optimization design.The use of lightweight lightweight materials in complete vehicles and components is one of the main ways to reduce the weight of vehicle and components in automotive lightweight design. In particular, with the advancement of material processing technology in the 1990s, materials used in vehicle are pursuing the realization of lightweight components while also moving toward high performance. Vehicle lightweight materials are divided into two types of lightweight metal materials and non-metal materials. Among them, aluminum alloys, magnesium alloys and high-strength steels are light metal materials, and plastics, ceramics and composite materials are non-metallic materials. In fact, due to the large number of applications of non-metallic materials and new materials on automotive parts, traditional metal materials are increasingly moving toward thinner thickness and higher strength. Some suspensions and parts use a large number of alloys, such as magnesium alloys which can greatly reduce the weight. Among industrial materials, magnesium alloy is the lightest material with the lowest density[96-99]. At present, many world vehicle manufacturing company have made magnesium an important strategic material in this century, and have introduced relevant national magnesium materials research plans.

(2) Optimize the structure to achieve lightweight

Optimize the structure of the car, including structural optimization of the body and structural optimization of components such as wheel. The main target of structural optimization is to carry out the structural shape and size design while meeting the requirements of the process.Automotive structure optimization can be divided into size optimization and shape optimization. Among them, the size is optimized for the section and part thickness, and the constraints are generally meet by various performance targets. The shape optimization is to achieve the uniformity of the internal force of the component while reducing the weight of the component. Shape optimization is a kind of numerical optimization method based on the law of biological growth.The basic principle can be described as the gradual increase in the density of the material at the main force-carrying position of the part while the force is being analyzed, while gradually reducing the material at other non-primary forces.The basic principle can be described as the gradual increase in the density of the material at the main force-carrying position of the part while the force is being analyzed, while gradually reducing the material at other non-primary forces. By arranging different materials at different positions, not only the waste of materials can be reduced, the material distribution of the parts is more reasonable, but also the material distribution of the stressed position is strengthened, thereby avoiding the occurrence of high peaks of local stress, and finally achieving the reduction of parts quality. Lightweight of the wheel can also be achieved through structural optimization[100-105].

The advantage of the optimization of the automobile structure is that not only the research and development cost is relatively small, but also the light weight effect is often achieved, which is one of the reasons why the structural optimization is highly valued in many manufacturers.In general, the application of lightweight materials often requires a long development cycle and more research and development costs. In comparison, the weight reduction of the vehicle structure is mainly through structural analysis optimization of the components, improving the structure, making the components thinner, hollow and miniaturized.The structure improvement of vehicle have enabled the lightweight of vehicle.In the early stage of vehicle development, such as the conceptual design stage, and increase the lightweight design optimization of the overall structure or parts, it can achieve less capital investment and shorter development cycle.

At present, technologies such as finite element analysis and computer-aided manufacturing are becoming more and more mature. These technologies bring great convenience and speed to the optimization of vehicle structure for the purpose of weight reduction. If these modern design methods are used reasonably, they can reasonably plan the performance of the vehicle, quickly realize the lightweight design of the vehicle. Through the use of technology and the combination of technology, the entire vehicle development cycle can be used to analyze and calculate the performance of the vehicle, which not only reduces the development cycle, but also saves a lot of development costs.However, in fact, the structure of the whole vehicle and the components such as the wheels are relatively complicated. At present, the lightweight optimization theory has some shortcomings, and the lightweight process often involves the influence of environment and processing.At this time, it is very important for lightweight designers to study the reasonable structural optimization.

The optimization method mainly includes size optimization, shape optimization and topology optimization.

Size optimization: the design variable can represent a structural thickness such as a distributed thickness or a cross-sectional area of a truss model that can be varied.

Shape optimization: the design variable can represent the boundary of the state equation. In this case, the boundary of the considered domain could vary such that some physical quantity is minimized.

Topology optimization: the design variable can represent the connectivity of the domain. It involves features such as number and sizes of holes in the design domain.

Topology optimization as a hot topic of structural optimization is well known for its great flexibility over shape optimization and size optimization. Combining the above advantages, in this study, we use topology optimization for related research.

(3) Lightweight process for vehicle lightweight target

Lightweight process and structural optimization, together with material optimization, complement each other in achieving lightweight design of vehicle [106].When the structure is optimized to achieve the purpose of lightweight parts, the old manufacturing process of the parts and components that are usually designed cannot meet the conditions, but new processing model design or manufacturing processes can meet the conditions. The development of new lightweight technologies can also provide more choices and larger platforms for lightweight structural optimization or new material research. At present, there are two main aspects of the lightweight process, the form ability of parts and the manufacture of parts. Through the study of the process, the purpose of weight reduction can be better achieved.If the lightweight process is considered at the beginning of the product design, not only can there be better structural optimization, but also the structural design and the application of new materials can be more reasonable and feasible, and the purpose of shortening the entire development cycle can be achieved [107-109].

Wheel as an important component of the car, all the interaction forces and moments between the car and the ground are transmitted through the wheels, which directly affect the overall driving stability, safety, reliability, smoothness, traction and appearance of the car. It has a greater impact on the overall energy consumption of the car and the life of the tire. The wheel is usually composed of a rim and a spoke, and the wheel is supported by a rolling bearing on the axle or the knuckle journal. Wheel lightweight research is of great significance to the weight reduction of the whole vehicle.The technical development and research direction of wheel lightweight is to minimize the quality and beautify its appearance while ensuring sufficient strength and reliability. In recent years, the vehicle industry is striving to reduce the weight of some of the wheels through material substitution and structural optimization design. Studies have shown that reducing the weight of the wheel can reduce the fuel consumption of the vehicle more than other components. Because of the wheel has a great reduction potential of quality, the lightweight of wheels is getting more and more attention from car companies. Therefore, in order to better adapt to the trend of lightweight development, it is necessary and meaningful to lightweight the wheels. Combined with lightweight methods for research and design of wheel lightweight is of great significance.

1.3.2 Magnesium alloy wheel casting

In the 1940s, the advent of computers laid a good foundation for the development of finite element simulation technology, and the simulation technology for casting also began to enter the fast lane of development [110-112]. Professor Paschkis of the United States initially took the lead in applying simulation technology to casting, because of the technical level at the time, only a few simple two-dimensional simulations were possible.His research results were elaborated in the major journals of the time.After more than a decade of development, the National Foundry Society in the 1960s conducted a detailed study and published a long-term strategy for the development of numerical simulation technology in casting applications. Many casting experts have participated in the construction and promotion of this project. The most notable of these was Professor Pehike and his team, who conducted extensive simulation analysis and experimental studies to record and organize the parameters of the mold and casting in detail. A large number of experimental studies on the heat transfer coefficient and the filling state simulation of L-shaped and T-shaped castings were carried out. Professor M.C. Flemings proposed that CAE technology can be used to study and predict defects such as cracks, shrinkage and shrinkage, slag inclusions, and dendrite segregation of castings, so that high-quality castings can be obtained by finite element simulation before actual production. Although simulation technology and numerical simulation have made great progress at this stage, there are not many results in the mathematical models and calculation criteria that software calculations can based. For this reason, Pehlke used different types of sand casting processes and die casting discuss the modeling method and calculation process of casting[113-119].

Japan Dazhong Yixiong scholar proposed a new finite element calculation method, which can overcome the calculation error caused by single hexahedral element by performing differential calculation on unstructured and non-orthogonal grid elements. Combining the laminar flow model of the molten metal with the Darcy theorem to simulate the solidification process of the casting, this method can well deepen people understanding of the solidification phenomenon and the solidification essence. The British B. Zhang scholar and his research team worked with a wheel manufacturing company in the United States on a project on the finite element simulation technology for the low-pressure casting process of the wheel.The British B. Zhang scholar and his research team worked with a wheel manufacturing company in the United States on a project on the finite element simulation technology for the low-pressure casting process of the wheel.The main research content is to explore the use of existing numerical simulation technology to replace the actual factory trial production.After completing the finite element simulation, they conducted actual experimental research at the factory, and compared the simulation results with the test conditions, and found the simulated temperature and measured values were basically consistent.The team later carried out practical operations on the problems in the simulation. As a result, shrinkage defects were detected at the intersection of the wheel rim and the spokes. These studies prove that finite element simulation can be used to guide production [120-124].

With the continuous development of science and technology, new magnesium alloy forming processes continue to emerge. At present, the main forming processes of magnesium alloys mainly include casting forming, forging forming and some special methods for preparing and using magnesium alloy component forming processes, such as spray deposition process, powder forging process and the like.Among them, the casting forming process and the forging forming process are the two most widely used forming processes in the field of magnesium alloy product manufacturing. For the magnesium alloy wheel forming process, the forming process used can be roughly divided into a casting process and a forging process. The casting method is currently the most commonly used method for magnesium alloy wheel molding. Magnesium alloy wheel forming casting methods include centrifugal casting, sand casting, high pressure casting, low pressure casting and so on [125-130].

(1) Centrifugal casting method

Centrifugal casting is a technique and method for injecting liquid metal into a mold that rotates at a high speed, so that the molten metal is centrifuged to fill the mold and form a casting. Due to the centrifugal movement, the liquid metal can well fill the mold in the radial direction and form a free surface of the casting, without the core, a cylindrical inner hole can be obtained. It helps to eliminate the gas and inclusions in the liquid metal, affects the crystallization process of the metal, thereby improving the mechanical and physical properties of the casting. Metal filtration, casting temperature, casting speed, solidification under slag, use of paint, casting demolition, casting system, casting quantification, are some process problems that must be determined or solved in centrifugal casting production because they directly affect the quality of the casting. Centrifugal casting is shown as Fig.1.7.

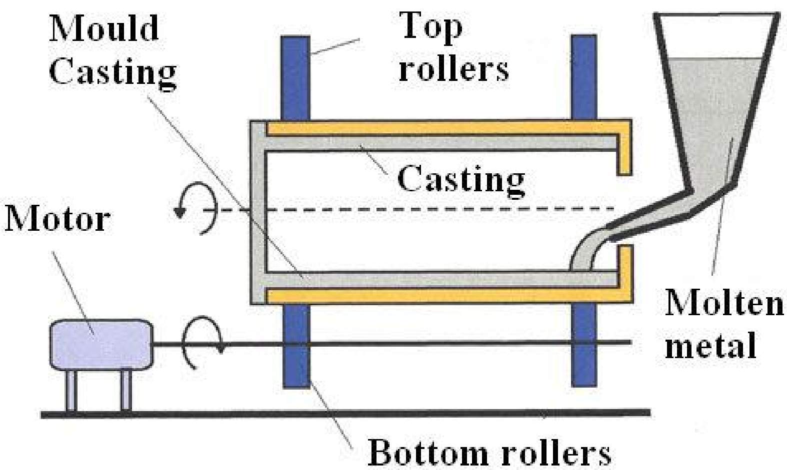


Fig.1.7 Centrifugal casting [131].

The advantage of centrifugal casting is that the feeding conditions are good, the casting structure is dense, and the mechanical properties are good. When the hollow casting is produced, the core can be omitted, so the metal filling ability can be greatly improved when the long tubular casting is produced, the ratio of the wall thickness of the casting to the length or the diameter is reduced, and the production process of the sleeve and the tubular casting is simplified. Disadvantage of centrifugal casting is that free surface roughness in the casting. There are certain limitations when used to produce shaped castings. The diameter of the inner hole of the casting is not accurate, the surface of the inner hole is rough, the quality is poor, and the machining allowance is large.It is not suitable for alloys with large density segregation alloys such as aluminum and magnesium.

(2) Sand casting method

Sand casting refers to a casting method for producing castings in a sand mold. Most alloy castings can be obtained by sand casting. Because the molding materials used in sand casting are cheap and easy to obtain, the castings are easy to manufacture, and can be adapted to the single-piece production, batch production and mass production of castings. For a long time, it has been the basic process in casting production.Sand casting is the most popular and simplest type of casting that has been used for centuries. The main steps include painting, mold, core making, molding, melting and pouring, cleaning. The basic materials for making sand are foundry sand and sand binder.The most common foundry sand is siliceous sand.In order to make the sand mold and core have a certain strength, it will not be deformed or damaged when handling, splicing and pouring liquid metal. Generally, a sand binder is added to the casting to bond the loose sand into a molding sand. The most widely used molding sand binder is clay, various drying oils or semi-drying oils and various synthetic resins also can be used as the molding sand binder. The external sand type used in sand casting is divided into three types: clay wet sand type, clay dry sand type and chemical hardening sand type. Sand casting is shown as Fig.1.8.

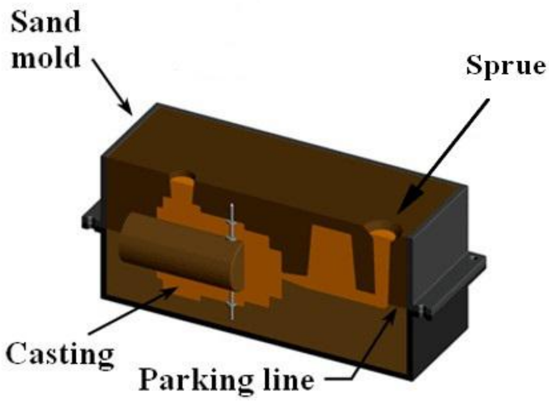


Fig.1.8 Sand casting [132].

The advantage of sand casting is that clay is rich in resources and cheap.The mold has a short cycle, high work efficiency and wide adaptability. Since the molding materials used for sand casting are cheap and easy to obtain, the castings are easy to manufacture, and can be adapted to single piece production, batch production and mass production of castings, for a long time, it has been the basic process in foundry production.At present, internationally, in all casting production, about 60% of castings are produced in sand, and about 70% of them are produced using clay sand. Disadvantage of sand casting is that castings are prone to defects such as sand washing, sand inclusion, and porosity. In this research,we design reasonable wheel casting model to reduce defects.

(3) High pressure casting method

High pressure casting is a casting method in which a molten alloy liquid is poured into a pressure chamber, a cavity of a steel mold is filled at a high speed, and the alloy liquid is solidified under pressure to form a casting. The main features of high pressure die casting that distinguish it from other casting methods are high pressure and high speed. The molten metal fills the cavity under pressure and crystallizes at a higher pressure. The common pressure is 15~100 MPa. The molten metal fills the cavity at a high speed, usually at 10~50 m/s, and some can exceed 80 m/s (the line speed of the cavity introduced into the cavity through the gate) the filling speed of the gate, so the charging of the molten metal The type of time is extremely short, about 0.01~0.2 seconds (depending on the size of the casting) to fill the cavity. High pressure casting is shown as Fig.1.9.

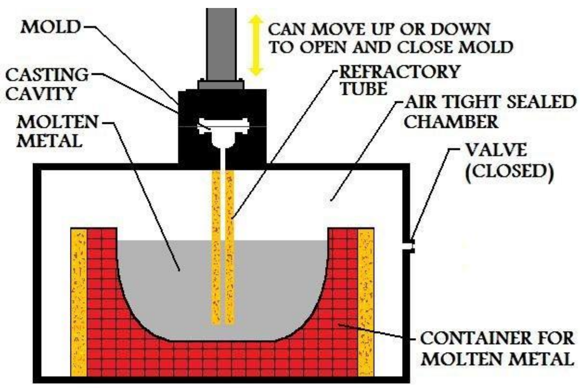


Fig.1.9 High pressure casting [133].

The advantage of high pressure casting is that the product quality is good. The casting size is stable, the productivity is high, and the die casting mold is used more frequently.It can be used directly without machining, or the processing amount is small, so the metal utilization rate is improved. Disadvantage of high pressure casting is that the mold structure is complex, the manufacturing cost is high, and the preparation period is long. Due to the high velocity of the liquid metal filling cavity during the die casting, the flow state is unstable, so the general die casting method is adopted, and the pores are easily generated inside the casting, the elongation is not good, and the heat treatment cannot be performed.For complex castings, high pressure casting is difficult. It is not suitable for small batch production. The main reason is that the die casting type has high manufacturing cost, the die casting machine has high production efficiency, and the small batch production is uneconomical. The equipment and mold cost are high.

(4) Low pressure casting method

Low pressure casting refers to a method in which a liquid metal is filled under a lower pressure ,about 0.02~0.06 MPa and crystallized under pressure to form a casting.The low-pressure casting production process includes metal melting and preparation of molds or molds, preparation before pouring, casting, loose release and removal of castings. Low pressure casting was the first anti-gravity casting technology used in industrial production in the 1940s.Today, low pressure casting is mainly used to produce aluminum alloy and magnesium alloy parts, such as automobile wheels for automobile industry, cylinder blocks for internal combustion engines, cylinder heads, and other castings with complex shapes and high quality requirements. Low pressure casting is shown as Fig.1.10.

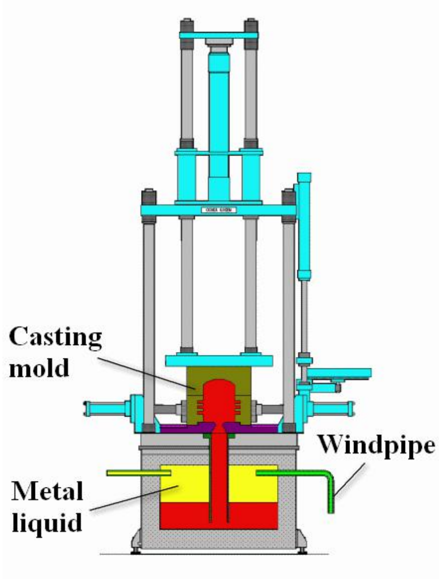


Fig.1.10 Low pressure casting [134].

The advantage of low pressure casting is the liquid metal filling is stable, the defects are few, the equipment is simple, and it is easy to realize mechanization and automation.The bottom injection type filling type, the metal liquid filling type is stable, and there is no splashing phenomenon, which can avoid the entrapment of gas and the flushing of the type wall and the core, and improve the qualification rate of the casting.The castings are dense in structure, clear in profile, smooth in surface and high in mechanical properties, which is especially beneficial for the casting of large thin walled parts.Disadvantage of low pressure casting is long casting cycle, high mold temperature, long solidification time.The degree of freedom of the gate scheme is small. The structure near the gate is thicker and the mechanical properties of the lower profile are not high. Comprehensive and rigorous management such as temperature and pressure are required.

In recent years, some new technologies for magnesium alloy wheel casting have emerged, such as precision punching and forming technology, extrusion casting, warm extrusion method, vacuum tilting method, differential pressure casting and so on. It is of great significance to study the casting process of magnesium alloy wheel.

1.3.3 Dynamic performance research of magnesium alloy wheel

With the development of society and the advancement of science and technology, the world vehicle industry has made remarkable achievements and is moving in the direction of safety, comfort, environmental protection and energy conservation. Nowadays, one of the trends in the development of the world vehicle is safety and comfort. People pay more and more attention to vehicle performance such as driving comfort, safety and economy. The ride comfort is the most direct and superficial experience, which directly determines the user purchase. Therefore, the comfort of vehicles has been getting more and more attention from all companies in recent years. The vibration performance of the vehicle is an important reason that affects the ride comfort of the vehicle. Therefore, the research on vehicle vibration has been paid more and more attention at home and abroad. For the vehicle itself, vibration performance as one of the performance indicators of the car also affects other performances due to various performance effects. During driving, the impact of strong vibration will accelerate the wear of the parts, reduce the fatigue life of the parts, and reduce the handling stability and braking performance of the car. To reduce the impact of vibration, the speed must be slowed down, but the transportation efficiency is reduced. Low speed driving will result in insufficient fuel combustion, which will result in poor fuel economy and poor emissions. For the driver, good vibration performance will make people feel happy and fully enjoy the joy of driving [135-137]. Otherwise, the vehicle constant bumps will make the driver tired and inattentive.

Vehicle dynamics, also known as vehicle dynamics, refers to the dynamics of the vehicle and is a specialized discipline that has developed along with the emergence of vehicles. Strictly speaking, vehicle dynamics includes research related to the motion of vehicle systems, including the two main areas of research, namely the handling stability and smoothness of the vehicle. Vehicle maneuverability mainly studies the yaw, lateral and roll motion of the vehicle. Vehicle ride comfort mainly studies the vibration factor of the body. At present, the research on the mechanical properties of vehicle systems has been perfected and many valuable results have been achieved.

There are many methods in the modeling of vehicle systems. The established vehicle models include plane models and space models.The dynamics of the vehicle system are studied to improve the handling stability and ride comfort of the vehicle and to improve the ride comfort of the rider. Ride comfort of vehicle were shown as Fig.1.11.

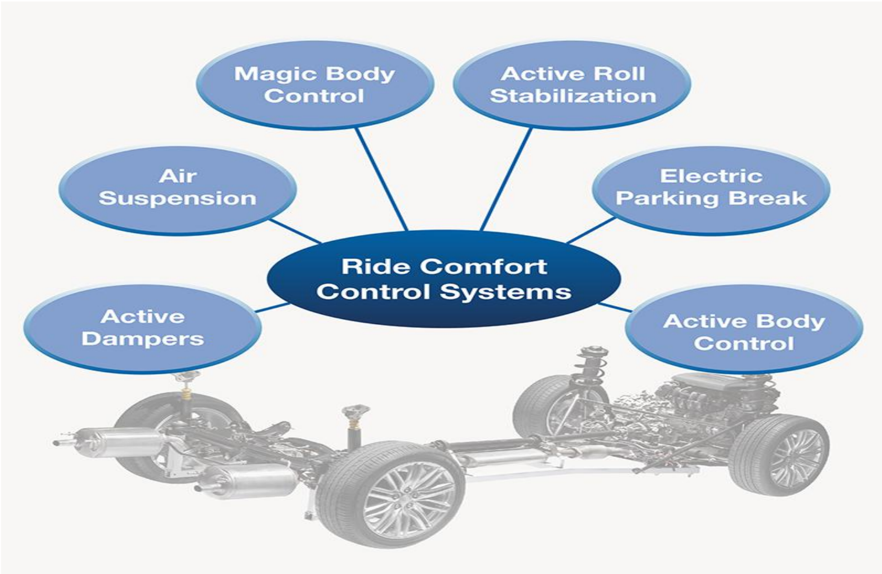


Fig.1.11 Ride comfort of vehicle [138].

Many vehicle industry experts use system dynamics theory and stochastic vibration theory to control vehicle vibration and improve vehicle dynamic design methods. The frequency response function of the vehicle model when the road surface irregularity were used as the input of the vehicle model vibration system is calculated. Some research units include many well-known car production companies, such as GM, Ford, and Toyota of Japan have made a lot of research results around these aspects. When conducting vehicle dynamics studies, the vehicle is usually reduced to a combination of originals such as mass, spring and damping.In fact, on vehicles traveling on uneven roads, the uneven road surface acts as a random stimulus to the vehicle. This random excitation not only causes vibration of the vehicle, but also plays an important role in the dynamic response of the road surface. Especially for transport vehicles with very heavy loads, the dynamic load applied to the pavement structure is one of the important reasons for the early damage of the pavement structure.

At present, the research on the dynamic load applied to the pavement structure under the excitation of the pavement flatness is relatively rare. The dynamics theory is used to study the interaction between the driving vehicle and the pavement structure, and the dynamic response of the pavement under vehicle load and the vibration of the vehicle are calculated. Responsive, establish a relatively complete road system, and propose perfect road and vehicle design parameters, which is currently a hot research topic in the world.

The evaluation of the ride comfort of the vehicle is one of the key contents of the research of the NVH of the vehicle. Many developed countries have studied the comfort evaluation earlier, developed the corresponding standard specifications and applied it in the research and development process of the automobile products, so that they can be sampled. The CAE stage uses the comfort evaluation results to optimize the comfort of the prototype.The evaluation of vehicle ride comfort also can be roughly classified into two categories: subjective evaluation and objective evaluation. The objective evaluation mainly evaluates the ride comfort by measuring the physical quantity such as acceleration, amplitude, speed and frequency of the vehicle vibration. The evaluation method mainly considers the vibration isolation capability of the vehicle, and also considers the sensitivity of the human body to different vibrations. The subjective evaluation mainly reflects the human factors. The driver and passengers experience the comfort of the vehicle through the experience of the vehicle, and use the scoring method to qualitatively evaluate and analyze the comfort of the car without special testing equipment. With the advancement of science and technology and the deepening of theoretical basic research, the research on subjective and objective comprehensive evaluation is now more and more mature.

It is relatively early on the evaluation of comfort. In 1931, Reiher and Meister performed vibration tests on 10 volunteers on a vibration gantry, thus completing a preliminary exploration of the subjective evaluation of comfort. In 1972, Professor Mitschke of Germany proposed to use the root mean square of the longitudinal acceleration of the vehicle and the acceleration root mean square of the driver seat cushion to price the comfort of the vehicle. However, this evaluation method only considers the vibration characteristics of the vehicle itself, and does not take human factors into consideration. In 1986, Prof. Griffin proposed the principle of "total ride value method", on the other hand, this evaluation method is more comprehensive and applicable. After many revisions and improvements, in 1997, the International Organization for Standardization promulgated the latest standards, which clearly defined the measurement methods of the whole body vibrations of the human body under periodic, transient and random conditions.When the vehicle is under long term random vibration and multi-input point axial vibration conditions, the evaluation results using the standard can be better consistent with the subjective feelings of the driver and passenger, and have been widely used. In 2011, Qin Yong and others from Beijing Jiaotong University conducted a comprehensive evaluation of the ride comfort of trains, proposed a comprehensive evaluation model of train ride comfort based on fuzzy analytic hierarchy process. The UK MIRA company has a high reputation in the field of vehicle evaluation and design, and has conducted subjective and objective evaluations for many vehicle.MIRA technicians conducted a subjective evaluation of vehicle ride comfort based on different road excitation.Suzuki of Chiba University in Japan applied a subjective evaluation of vehicle ride comfort using the SD method in psychometric.The method is based on the adjective associated with an evaluation object as a scale benchmark to test the subjective psychological feelings produced by the driver and the passenger after being stimulated by the evaluation object. At present, the SD method has been widely applied to subjective evaluation, attitude survey and other aspects.In order to improve the ride comfort level of vehicles, scholars and enterprise engineering experts from various countries have conducted in depth exploration and achieved certain scientific results [139-145].

Magnesium has very good damping and vibration damping performance. The strength of the magnesium alloy produced has been greatly improved by alloying. Many vehicle parts can use magnesium alloys to get good vibration and improve comfort. Therefore, studying the damping mechanism of magnesium and magnesium alloys and the influence mechanism of alloying on damping performance is an important direction of magnesium alloy material technology research. Since the 1950s and 1960s, a large number of scholars have carried out theoretical research and experimental research on the micro structure, high damping characteristics and damping mechanism of magnesium and magnesium alloys. Some scholars have agreed through a large number of experimental studies that the damping mechanism of magnesium alloys is a dislocation type damping mechanism due to the high density of dislocations contained in magnesium alloy materials, the action of internal stress, dislocations and dislocations. The interaction between the dislocations, impurities and various other defects gives the magnesium alloy high damping properties. Academia has been conducting a lot of research on the dislocation damping properties and mechanism of metal materials, and has achieved certain research results. Many researchers have studied the damping and damping properties of magnesium alloy components and their advantages, and they have obtained a lot of valuable research results.The finite element simulation method is used to verify that magnesium alloy parts have obvious damping and damping performance advantages [146-147].

Because of the good vibration properties of magnesium alloys, magnesium alloy wheels have good vibration performance under reasonable structure.Therefore, even if the vehicle is traveling on more bumpy road conditions, the occupants will have a comfortable driving environment and reduce the pressure on the vehicle damping system.Wheel vibration was shown in Fig.1.12 below.

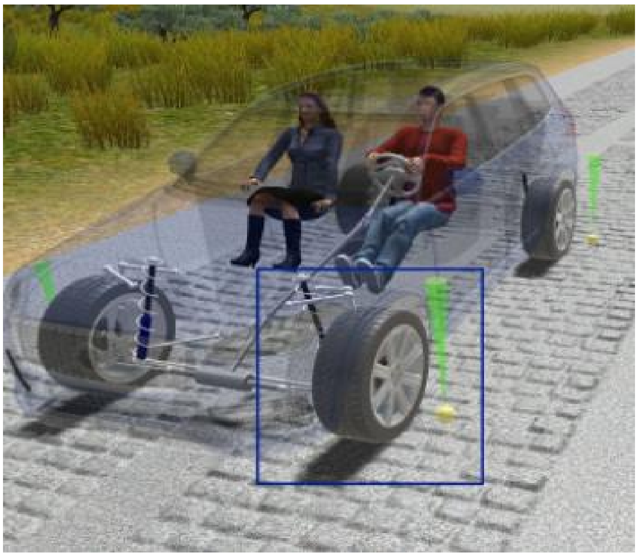


Fig.1.12 Wheel vibration [148].

At the beginning of the 20th century, the aerospace industry began to find ways to determine the natural frequency of the system. They used resonance experiments to determine their natural frequencies [149]. With the development of technology and the introduction of technology, modal analysis is now widely used in various fields of engineering. Modal analysis allows the structural design to avoid resonance, and allows engineers to recognize the structure response to different types of dynamic loads earlier, it also helps to estimate the solution control parameters in other dynamic analyses. Modal analysis is very important in the dynamic design of structures. It is defined as transforming the physical coordinates in the system of differential equations of linear stationary systems into modal coordinates, decoupling the equations into a set of modal coordinates and modal parameters. Describe the independent equations to find the modal parameters of the system. Modal analysis includes analytical analysis and experimental analysis of structural dynamic characteristics. The target of modal analysis is to identify the modal parameters of the system, and provide a basis for structural vibration analysis, vibration fault diagnosis and optimal design of structural dynamic characteristics. By modal analysis of the data obtained during the structural design, the designer can avoid resonance of the structure, as well as knowing in advance the response of the designed structure under different dynamic loads. At present, modal analysis has been widely used in many fields of engineering, and this technology has received high attention in the field of engineering. The modal analysis of the wheel can better understand the dynamic characteristics of the wheel and is of great significance for the research of the wheel.

1.4 The purpose of this research

Through the summary of previous studies, combined with characteristics of magnesium alloy and application on the of wheel for research. The lightweight design of the magnesium alloy wheel were carried out, and the topology optimization method was used to optimize the structure. Design a reasonable magnesium alloy wheel casting model, casting analysis of magnesium alloy wheel. Research on dynamic performance analysis of magnesium alloy wheel.

This article design a new model of vehicle wheel and optimize the structure for lightweight. Through measuring and analyzing designed model under static force, clear and useful topology optimization result can be obtained. Comparing wheel performance before and after optimization, the optimized wheel structure compliance with conditions such as strength can be obtained. Considering three different materials namely magnesium alloy, aluminum alloy and steel, the stress and strain performances of each materials can be obtained by finite element analysis. The reasonable and superior of magnesium alloy wheel for lightweight design can be obtained. This research predicts the reliability of the optimization design, some valuable references are provided for the development of magnesium alloy wheel.

Analysis of casting process is a very complex issue, this research based on finite element theory and actual production, design reasonable casting model, instant filling and solidification data were obtained. Aiming at reducing casting defects, process optimization of casting riser structure can be designed. Reasonable casting process could reduce the probability of defects in castings, improve the quality of castings.Through the simulation and optimization in the casting process, provided a rational design for the casting process. On the basis of the foundation, it has important guiding significance for actual foundry production.

Magnesium alloy wheels were investigated as magnesium alloy has damping performance advantages over some metal materials. Damping test methods were designed to establish the damping performance parameters of the magnesium alloy material. A finite element analysis model of magnesium alloy wheels was established with certain boundary conditions and constraints. The applicability of the model was verified by free modal evaluation of the wheel. Dynamic impact simulation analysis of the designed wheels can carried out and the dynamic speed responses of magnesium alloy wheels under the impact of a dynamic load on the road surface can obtained. The structural design optimization of the magnesium alloy wheel was carried out by defining the structural parameters of the wheel and using the acceleration and shock response of the wheel as the outputs. The optimization of weight reduction and dynamic impact performance of magnesium alloy wheels can be achieved.

Through reasonable research and analysis, a lightweight wheel with reasonable structure can be obtained. Design a reasonable casting model of magnesium alloy wheel combined with magnesium alloy characteristics. Analysis of dynamic performance of magnesium alloy wheel and improve vehicle ride comfort while satisfying wheel structural performance standards.

References

[1] Ratner S. Taxation of Autonomous Vehicles in Cities and States[J]. Stephen Ratner, Taxation of Autonomous Vehicles in Cities and States, 2018, 71.

[2] Ehsani M, Gao Y, Longo S, et al. Modern electric, hybrid electric, and fuel cell vehicles[M]. CRC press, 2018.

[3] Smil V. Energy in world history[M]. Routledge, 2019.

[4] Casals L C, Martinez-Laserna E, García B A, et al. Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction[J]. Journal of Cleaner Production, 2016, 127: 425-437.

[5] Zhili D, Boqiang L, Chunxu G. Development path of electric vehicles in China under environmental and energy security constraints[J]. Resources, Conservation and Recycling, 2019, 143: 17-26.

[6] Zhang L, Qin Q. China’s new energy vehicle policies: Evolution, comparison and recommendation[J]. Transportation Research Part A: Policy and Practice, 2018, 110: 57-72.

[7] Yuan X, Liu X, Zuo J. The development of new energy vehicles for a sustainable future: A review[J]. Renewable and Sustainable Energy Reviews, 2015, 42: 298-305.

[8] Wang Z, Zhou Y. Energy conservation and environmental protection[R]. Working Paper. Beijing: The Energy Conservation Division of the Ministry of Energy Resources, People's Republic of China, 1991.

[9] Rietmann N, Lieven T. A comparison of policy measures promoting electric vehicles in 20 countries[M]//The Governance of Smart Transportation Systems. Springer, Cham, 2019: 125-145.

[10] Ajanovic A, Haas R. Dissemination of electric vehicles in urban areas: Major factors for success[J]. Energy, 2016, 115: 1451-1458.

[11] Apak S, Atay E, Tuncer G. Renewable hydrogen energy and energy efficiency in Turkey in the 21st century[J]. International Journal of Hydrogen Energy, 2017, 42(4): 2446-2452.

[12] Zhang J, Wang R. Research on the Marketing Strategy of New Energy Vehicles in SL Company[J]. American Journal of Industrial and Business Management, 2019, 9(2): 306-314.

[13] Goede M, Stehlin M, Rafflenbeul L, et al. Super Light Car－lightweight construction thanks to a multi-material design and function integration[J]. European Transport Research Review, 2009, 1(1): 5.

[14] Materials, design and manufacturing for lightweight vehicles[M]. Elsevier, 2010.

[15] Joost W J. Reducing vehicle weight and improving US energy efficiency using integrated computational materials engineering[J]. Jom, 2012, 64(9): 1032-1038.

[16] Kirchain Jr R E, Gregory J R, Olivetti E A. Environmental life-cycle assessment[J]. Nature materials, 2017, 16(7): 693.

[17] Riffat S, Powell R, Aydin D. Future cities and environmental sustainability[J]. Future cities and Environment, 2016, 2(1): 1

[18] Tisza M, Czinege I. Comparative study of the application of steels and aluminium in lightweight production of automotive parts[J]. International Journal of Lightweight Materials and Manufacture, 2018, 1(4): 229-238.

[19] Bandivadekar A P. Evaluating the impact of advanced vehicle and fuel technologies in US light duty vehicle fleet[D]. Massachusetts Institute of Technology, Engineering Systems Division, Technology, Management, and Policy Program, 2008.

[20] Basyoni Y I A. Application of Intelligent Transportation Systems (ITS) In Truck Movement in Egypt[D]. Ain Shams University Cairo-Egypt 2012, 2004.

[21] Mutua J M. Use of magnesium alloys in optimizing the weight of automobile: Current trends and opportunities[J]. Sustainable Research and Innovation Proceedings, 2011, 3.

[22] Materials, design and manufacturing for lightweight vehicles[M]. Elsevier, 2010.

[23] Witik R A, Payet J, Michaud V, et al. Assessing the life cycle costs and environmental performance of lightweight materials in automobile

applications[J]. Composites Part A: Applied Science and Manufacturing, 2011, 42(11): 1694-1709.

[24] Das S. The cost of automotive polymer composites: a review and assessment of DOE's lightweight materials composites research[M]. Oak Ridge, Tennessee, USA: Oak Ridge National Laboratory, 2001.

[25] Cole G S, Sherman A M. Light weight materials for automotive applications[J]. Materials characterization, 1995, 35(1): 3-9.

[26] Taub A I, Luo A A. Advanced lightweight materials and manufacturing processes for automotive applications[J]. Mrs Bulletin, 2015, 40(12): 1045-1054.

[27] Hitomi K. Manufacturing systems engineering: A unified approach to manufacturing technology, production management and industrial economics[M]. Routledge, 2017.

[28] Handbook of manufacturing engineering and technology[M]. Springer reference, 2015.

[29] EILOLA J. Method and apparatus for casting prefabricated prestressed concrete products: U.S. Patent 10,280,620[P]. 2019-5-7.

[30] Kumar K, Kalita H, Zindani D, et al. Casting[M]//Materials and Manufacturing Processes. Springer, Cham, 2019: 37-52

[31] Stefanescu D M. Science and engineering of casting solidification[M]. Springer, 2015.

[32] Campbell J. Complete casting handbook: metal casting processes, metallurgy, techniques and design[M]. Butterworth-Heinemann, 2015.

[33] Minamiguchi S, Okamura G, Tsuchiya S, et al. Casting device and casting method: U.S. Patent 10,286,449[P]. 2019-5-14.

[34] Ikeda S, Yamanaka A, Harada Y. Die casting machine and control method of die casting machine: U.S. Patent Application 10/071,418[P]. 2018-9-11.

[35] Cantor B, O'Reilly K. Solidification and casting[M]. CRC press, 2016.

[36] Kermanpur A, Mahmoudi S, Hajipour A. Numerical simulation of metal flow and solidification in the multi-cavity casting moulds of automotive components[J]. Journal of Materials Processing Technology, 2008, 206(1-3):

62-68.
[37] Litman T. Autonomous vehicle implementation predictions[M]. Victoria, Canada: Victoria Transport Policy Institute, 2017.
[38] Bloecher H L, Dickmann J, Andres M. Automotive active safety & comfort functions using radar[C]//2009 IEEE International Conference on Ultra-Wideband. IEEE, 2009: 490-494.
[39] Kaynakli O, Kilic M. An investigation of thermal comfort inside an automobile during the heating period[J]. Applied ergonomics, 2005, 36(3): 301-312.
[40] Takezaki J, Ueki N, Minowa T, et al. Support system for safe driving[J]. Hitachi Review, 2000, 49(3): 107.
[41] Crandall R W, Graham J D. The effect of fuel economy standards on automobile safety[J]. The Journal of Law and Economics, 1989, 32(1): 97-118.
[42] Nader R. Unsafe at any speed: The designed-in dangers of the American automobile[M]. New York: Grossman, 1965.
[43] Mutua J M. Use of magnesium alloys in optimizing the weight of automobile: Current trends and opportunities[J]. Sustainable Research and Innovation Proceedings, 2011, 3.
[44] Joost W J, Krajewski P E. Towards magnesium alloys for high-volume automotive applications[J]. Scripta Materialia, 2017, 128: 107-112.
[45] Du C P, Xu D F. Application of energy-saving magnesium alloy in automotive industry[C]//Advanced Materials Research. Trans Tech Publications, 2013, 734: 2244-2247.
[46] Majka M, Hartnett M. Effects of speed, load and damping on the dynamic response of railway bridges and vehicles[J]. Computers & Structures, 2008, 86(6): 556-572.
[47] Okunribido O O, Shimbles S J, Magnusson M, et al. City bus driving and low back pain: a study of the exposures to posture demands, manual materials handling and whole-body vibration[J]. Applied ergonomics, 2007, 38(1): 29-38.
[48] Barke D W, Chiu W K. A review of the effects of out-of-round wheels on track and vehicle components[J]. Proceedings of the Institution of Mechanical

Engineers, Part F: Journal of Rail and Rapid Transit, 2005, 219(3): 151-175.

[49] Mao Y, Zuo S, Wu X. Longitudinal vibration analysis of electric wheel system in starting condition[J]. SAE International Journal of Vehicle Dynamics, Stability, and NVH, 2017, 1(2017-01-1126): 156-164.

[50] Farahani A M, Balaghi M. CAE Methodology for Optimization of Automotive NVH Performance through Wheel Structure Modifications[J]. American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS), 2018, 39(1): 30-37.

[51] Farahani A M, Heshmatnejad H. Towards Automotive NVH Enhancement: Structural Dynamics Analysis of a Vehicle Wheel[J]. American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS), 2017, 38(2): 51-58.

[52] Gibson A O C, Fujii Y, Nedorezov F, et al. Method and system for reducing driveline NVH: U.S. Patent 9,925,972[P]. 2018-3-27.

[53] Aikawa J K. Magnesium[J]. Western Journal of Medicine, 1980, 133(4): 333.

[54] Mordike B L, Ebert T. Magnesium: properties − applications − potential[J]. Materials Science and Engineering: A, 2001, 302(1): 37-45.

[55] Friedrich H E, Mordike B L. Magnesium technology[M]. Berlin [etc.]: Springer, 2006.

[56] Handbook A S M S. Magnesium and magnesium alloys[J]. ASM international, 1999: 106-118.

[57] Jahnen-Dechent W, Ketteler M. Magnesium basics[J]. Clinical kidney journal, 2012, 5(Suppl_1): i3-i14.

[58] Shigematsu I, Nakamura M, Saitou N, et al. Surface treatment of AZ91D magnesium alloy by aluminum diffusion coating[J]. Journal of Materials Science Letters, 2000, 19(6): 473-475.

[59] Luo A. Processing, microstructure, and mechanical behavior of cast magnesium metal matrix composites[J]. Metallurgical and Materials Transactions A, 1995, 26(9): 2445-2455.

[60] Aghion E, Bronfin B. Magnesium alloys development towards the 21st

century[C]//Materials Science Forum. Trans Tech Publications, 2000, 350: 19-30.

[61] Kumar D S, Sasanka C T, Ravindra K, et al. Magnesium and its alloys in automotive applications－A review[J]. Am. J. Mater. Sci. Technol, 2015, 4(1): 12-30.

[62] Shurtleff W, Aoyagi A. History of Soybean Crushing: Soy Oil and Soybean Meal (980-2016):: Extensively Annotated Bibliography and Sourcebook[M]. Soyinfo Center, 2016.

[63] ASM specialty handbook: magnesium and magnesium alloys[M]. ASM international, 1999.

[64] Brown R E. Magnesium wrought and fabricated products yesterday, today and tomorrow[J]. Magnesium technology, 2002: 155-163.

[65] Wilson-Hall J. Reliant Three-Wheelers: The Complete Story[M]. Crowood, 2014.

[66] Tie Tian. Research on Dislocation Damping Mechanism of Magnesium Alloys and Application for Internal Combustion Engine Parts[D]. Jilin University, 2018.

[67] Polmear I J. Magnesium alloys and applications[J]. Materials science and technology, 1994, 10(1): 1-16.

[68] Furuya H, Kogiso N, Matunaga S, et al. Applications of magnesium alloys for aerospace structure systems[C]//Materials science forum. Trans Tech Publications, 2000, 350: 341-348.

[69] Easton M, Beer A, Barnett M, et al. Magnesium alloy applications in automotive structures[J]. Jom, 2008, 60(11): 57.

[70] Blawert C, Hort N, Kainer K U. Automotive applications of magnesium and its alloys[J]. Trans. Indian Inst. Met, 2004, 57(4): 397-408.

[71] Cole G S. Issues that influence magnesium's use in the automotive industry[C]//Materials Science Forum. Trans Tech Publications, 2003, 419: 43-50.

[72] Magnesium alloys and their applications[M]. Weinheim, Germany:: Wiley-VCH, 2000.

[73] Mathaudhu S N, Nyberg E A. Magnesium alloys in US Military applications: Past, current and future solutions[M]//Essential Readings in Magnesium Technology. Springer, Cham, 2016: 71-76.
[74] Blawert C, Hort N, Kainer K U. Automotive applications of magnesium and its alloys[J]. Trans. Indian Inst. Met, 2004, 57(4): 397-408.
[75] Watarai H. Trend of Research and Development for Magnesium Alloys-Reducing the Weight of Structural Materialsin Motor Vehicles[R]. NISTEP Science & Technology Foresight Center, 2006.
[76] Froes F H, Eliezer D, Aghion E. The science, technology, and applications of magnesium[J]. Jom, 1998, 50(9): 30-34.
[77] Lei Yang. The lightweight design and finite element analysis of the magnesium alloy automobile wheel [D]. Shandong University of Science and Technology, 2011.
[78] Xia Z H, Ju F. Finite Element Analysis of the Forging Process of Magnesium Wheels[C]//Key Engineering Materials. Trans Tech Publications, 2007, 345: 1079-1084.
[79] Bhatnagar M. Mathematical modeling of the fatigue life following rim indentation test in aluminum alloy wheels[D]. University of British Columbia, 2010.
[80] ZHANG F, YE J. Application on Numerical Simulation Technology in the Forming Processing of Aluminum Alloy Casting by Die-Casting [J]. Foundry Technology, 2010, 2.
[81] Qiang W, Zhang Z, Zhang X, et al. New extrusion process of Mg alloy automobile wheels[J]. Transactions of Nonferrous Metals Society of China, 2010, 20: s599-s603.
[82] Fujita M, Yamamoto Y, Sakate N, et al. Method of making an article of manufacture made of a magnesium alloy: U.S. Patent 5,902,424[P]. 1999-5-11.
[83] Kulekci M K. Magnesium and its alloys applications in automotive industry[J]. The International Journal of Advanced Manufacturing Technology, 2008, 39(9-10): 851-865.

[84] Kleiner M, Geiger M, Klaus A. Manufacturing of lightweight components by metal forming[J]. CIRP annals, 2003, 52(2): 521-542.

[85] Fraser A. In-wheel electric motors[C]//10th international CTI symposium. 2011: 12-23.

[86] Shinde P, Ravi K, Nehru N, et al. Light Weight BIW Solutions for Improving Functional Properties: A Review[R]. SAE Technical Paper, 2016.

[87] Nyberg E A, Luo A A, Sadayappan K, et al. Magnesium for future autos[J]. Advanced Materials & Processes, 166 (10): 35-37, 2008, 166(PNNL-SA-61445).

[88] Cho K, Sano T, Doherty K, et al. Magnesium technology and manufacturing for ultra lightweight armored ground vehicles[R]. ARMY RESEARCH LAB ABERDEEN PROVING GROUND MD, 2009.

[89] Ma M, Yi H. Lightweight car body and application of high strength steels[M]//Advanced Steels. Springer, Berlin, Heidelberg, 2011: 187-198.

[90] Lyu M Y, Choi T G. Research trends in polymer materials for use in lightweight vehicles[J]. International journal of precision engineering and manufacturing, 2015, 16(1): 213-220.

[91] Materials, design and manufacturing for lightweight vehicles[M]. Elsevier, 2010.

[92] Ballew P D, Schnorbus R H. Realignment in the auto supplier industry: the rippling effects of Big Three restructuring[J]. Economic Perspectives, 1994, 18(1): 2-9.

[93] Witik R A, Payet J, Michaud V, et al. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications[J]. Composites Part A: Applied Science and Manufacturing, 2011, 42(11): 1694-1709.

[94] Sarcar M M M, Rao K M, Narayan K L. Computer aided design and manufacturing[M]. PHI Learning Pvt. Ltd., 2008.

[95] Fenton J, Hodkinson R. Lightweight electric/hybrid vehicle design[M]. Elsevier, 2001.

[96] Atwell Jr R J. Vehicle wheel with balance weights: U.S. Patent 5,350,220[P].

1994-9-27.
[97] Qiang W, Zhang Z M, Zhang X, et al. Precision forging technologies for magnesium alloy bracket and wheel[J]. Transactions of Nonferrous Metals Society of China, 2008, 18: s205-s208.
[98] Deepak S V, Naresh C, Hussain S A. Modelling and analysis of alloy wheel for four wheeler vehicle[J]. International journal of mechanical engineering and robotics research, 2012, 1(3): 72-80.
[99] Yoshimura K. Magnesium alloy wheel for vehicles: U.S. Patent Application 09/171,423[P]. 2001-12-6.
[100] Das S. Design and weight optimization of aluminum alloy wheel[J]. International Journal of Scientific and Research Publications, 2014, 4(6): 1-12.
[101] Mutua J M. Use of magnesium alloys in optimizing the weight of automobile: Current trends and opportunities[J]. Sustainable Research and Innovation Proceedings, 2011, 3.
[102] Riesner M, Devries R I. Finite element analysis and structural optimization of vehicle wheels[J]. SAE Transactions, 1983: 490-507.
[103] Gu Y, Cheng G. Structural modelling and sensitivity analysis of shape optimization[J]. Structural optimization, 1993, 6(1): 29-37.
[104] Zhu Z, Hu J, Sun H, et al. Research on structural optimization of the aluminum alloy wheel[C]//2010 WASE International Conference on Information Engineering. IEEE, 2010, 3: 405-408.
[105] Xiao D, Zhang H, Liu X, et al. Novel steel wheel design based on multi-objective topology optimization[J]. Journal of Mechanical Science and Technology, 2014, 28(3): 1007-1016.
[106] Stapel K, Knauss E, Allmann C. Lightweight process documentation: just enough structure in automotive pre-development[C]//European Conference on Software Process Improvement. Springer, Berlin, Heidelberg, 2008: 142-151.
[107] Heyse J. Spoke, wheel and process for manufacturing a spoke, especially for bicycles: U.S. Patent 7,926,884[P]. 2011-4-19.
[108] Stegemann T, Frings A. Process for production of lightweight sheet-steel wheel

for vehicles: U.S. Patent 6,052,901[P]. 2000-4-25.

[109] Chase L A, Neeb D L, Shea R E. Vehicle wheel construction process: U.S. Patent 6,346,159[P]. 2002-2-12.

[110] Flamm K. Creating the computer: government, industry, and high technology[M]. Brookings Institution Press, 1988.

[111] Oden T. Some historic comments on finite elements[C]//Proceedings of the ACM conference on History of scientific and numeric computation. ACM, 1987: 125-130.

[112] Oden J T. Historical comments on finite elements[C]//A history of scientific computing. ACM, 1990: 152-166.

[113] Ning Li. Numerical Analysis and Die Design Based on Aluminum Alloy Wheel Low Pressure Casting [D]. Tianjin University of Technology, 2018.

[114] Flemings M C, Shiohara Y. Solidification of undercooled metals[J]. Materials Science and Engineering, 1984, 65(1): 157-170.

[115] Mehrabian R, Keane M, Flemings M C. Interdendritic fluid flow and macrosegregation; influence of gravity[J]. Metallurgical and Materials Transactions B, 1970, 1(5): 1209-1220.

[116] Ho K, Pehlke R D. Metal-mold interfacial heat transfer[J]. Metallurgical Transactions B, 1985, 16(3): 585-594.

[117] Pehlke R D, Berry J T. Investigation of Heat Transfer at the Mold/Metal Interface in Permanent Mold Casting of Light Alloys[R]. The University of Michigan, 2005.

[118] Li W M, Jiang Z H, Li H B. Simulation and Calculation to Segregation of High Nitrogen Steels Solidification Process Based on PROCAST Software[C]//Advanced Materials Research. Trans Tech Publications, 2011, 217: 1185-1190.

[119] Xiong C, Ma Y, Chen B, et al. Modeling of filling and solidification process for TiAl exhaust valves during suction casting[J]. Acta Metallurgica Sinica (English Letters), 2013, 26(1): 33-48.

[120] Pattnaik S, Karunakar D B, Jha P K. Developments in investment casting

process–a review[J]. Journal of Materials Processing Technology, 2012, 212(11): 2332-2348.
[121] Wang M Z, Chen G, Zhou Z. Application of Multidisciplinary Design Optimization in the Casting Process Optimization[C]//Advanced Materials Research. Trans Tech Publications, 2014, 936: 1845-1850.
[122] Shuncheng W, Chang C, Kaihong Z, et al. Production of A356 aluminum alloy wheels by thixo-forging combined with a low superheat casting process[J]. China Foundry, 2013, 10(5).
[123] Monroe B K, Kingrey S J, Prieto R A, et al. Method and apparatus for casting a vehicle wheel in a pressurized mold: U.S. Patent 5,896,912[P]. 1999-4-27.
[124] Tang H, Li J, Yang H. Process Optimization of Bimetallic Composite Pipe by Investment Casting Based on ProCAST[C]//Proceedings of the 2012 International Conference on Computer Application and System Modeling. Atlantis Press, 2012.
[125] Ray R, Scott D W. Centrifugal casting of titanium alloys with improved surface quality, structural integrity and mechanical properties in isotropic graphite molds under vacuum: U.S. Patent 6,776,214[P]. 2004-8-17.
[126] Jiang J, Wang Y, Chen G, et al. Comparison of mechanical properties and microstructure of AZ91D alloy motorcycle wheels formed by die casting and double control forming[J]. Materials & Design, 2012, 40: 541-549.
[127] Zheng Shunqi. Study on the modal analysis and casting-extrusion compound forming technology of Magnesium Alloy Wheel [D]. North University of China, 2013.
[128] YU M, CAO W, ZHOU Z, et al. Application of Die-casting Hot Runner System for Magnesium Alloy Based on Numerical Simulation [J]. Hot Working Technology, 2009, 5.
[129] HU Q, LIU B, YU M, et al. Design and optimization of casting system of die casting die for magnesium alloy based on numerical simulation [J]. Die & Mould Industry, 2009, 7(3): 3.
[130] Aghion E, Bronfin B, Eliezer D. The role of the magnesium industry in

protecting the environment[J]. Journal of materials processing technology, 2001, 117(3): 381-385.

[131] http://cxmarketingclients.co.uk/castings/benefits-centrifugal-casting/.

[132] https://www.custompartnet.com/wu/SandCasting.

[133] http://thelibraryofmanufacturing.com/pressure_casting.html.

[134] http://www.osaka-giken.co.jp/lpdc-en.html.

[135] Sun Hongmei. Modal analysis and optimization design of vehicle aluminum alloy wheel [D]. Yanshan University, 2007.

[136] Kiani M, Gandikota I, Rais-Rohani M, et al. Design of lightweight magnesium car body structure under crash and vibration constraints[J]. Journal of Magnesium and Alloys, 2014, 2(2): 99-108.

[137] Zhu W H, Zheng Z X, Feng J Z, et al. Dynamic Design Method for Magnesium Alloys Wheel of New Energy Vehicles[C]//Advanced Materials Research. Trans Tech Publications, 2010, 118: 930-934.

[138] https://ipg-automotive.com/areas-of-application/vehicle-dynamics/ride-comfort-control-systems/.

[139] Lee R A, Pradko F. Analytical analysis of human vibration[J]. SAE transactions, 1968: 346-370.

[140] Arvidsson I, Schmechtig K, Lennartsson B. A simple and efficient description of car body movements for use in virtual prototyping and ride comfort evaluation[R]. SAE Technical Paper, 2000.

[141] Mody P, Rumold W, Attia F, et al. Mojacar and Los Angeles City Traffic Vehicle Testing: A comparison & analysis of subjective ratings and objective measurements[R]. SAE Technical Paper, 2002.

[142] Mansfield N J. Human response to vibration[M]. CRC press, 2004.

[143] Fairley T E, Griffin M J. The apparent mass of the seated human body: vertical vibration[J]. Journal of Biomechanics, 1989, 22(2): 81-94.

[144] Uys P E, Els P S, Thoresson M. Suspension settings for optimal ride comfort of off-road vehicles travelling on roads with different roughness and speeds[J]. Journal of Terramechanics, 2007, 44(2): 163-175.

[145] Gao Y, Tang R, Liang J. Evaluation of vehicle ride comfort based on neural network[C]//Sixth International Symposium on Precision Engineering Measurements and Instrumentation. International Society for Optics and Photonics, 2010, 7544: 754407.

[146] WANG J, ZHAO L, HU Y, et al. Research status and prospect of damping magnesium alloys [J]. Materials Review, 2008, 22(7): 103-106.

[147] Liu C, Ji R, Zhou H, et al. Research and development progress of damping capacity of magnesium and magnesium alloys[J]. Chinese Journal of Nonferrous Metals, 2005, 15(9): 1319.

[148] https://www.tesis.de/en/animations/ride-comfort-analysis-on-a-bumpy-road-with-dyna4-and-ftire/?r=1.

[149] Yan S, He L. Dynamic behavior analysis and structure optimization of magnesium alloy wheel of vehicle [J]. Journal of Fuzhou University (Natural Science Edition), 2014, 42: 584-590.

Chapter 2 Multi-objective Optimization Design of Magnesium Alloy Wheel Based on Topology Optimization

2.1 Introduction

Environmental and resource issues have become the focus of attention around the world. As the automotive industry is increasingly demanding on energy saving and environmental protection, people are taking more attention on the lightweight design of automobiles. In the United States, the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a joint regulation in August 2012[1-2]. This new regulation will be implemented on passenger cars. Improve automobile consumption standard about greenhouse gases and fuels from 2017 to 2025.The emission for combined cars and trucks has to be reduced from 243g/mile in 2017 to 163 g/mile in 2025 according to new regulation. Moreover, the fuel economy must be improved from 36.6 mpg in 2017 to 54.5 mpg in 2025. When designing vehicle products, not only need to reduce energy consumption but also to remain in competition with peers[3-4].According to the data, the automotive own weight is reduced by 10%, and the fuel consumption is reduced by about 6%-8%. Magnesium alloys are considered one of the most promising materials in the 21st century. In the modern design, it is important to improve the efficiency of development and reduce the number of tests. The average use of magnesium in cars has increased from 0.1% (1.8 kg) in 1995 to 0.2% (4.5 kg) in 2007 in the United States according to Refs.[5-6].Using of magnesium material in cars will increase by 15% (about 227 kg) by 2020 based on future vision for magnesium[7].By understanding the efficiency of materials, engineers can gain benefits through magnesium materials when designing wheel[8-10].Wheel is one of the most important parts of a vehicle. To ensure energy efficiency, the wheels must be as lightweight as possible [11-16].

Optimization design is a powerful tool for machinery design, and can produce the best layout of structural design. Topology optimization can provide the first optimized “design concept” of structure material distribution and achieve greater savings and design improvement in size and shape optimizations. Since Bendsoe introduce the homogenization method of topology optimization, topology optimization method has been deeply developed and applied in structural optimization design [17-19]. Zhang carried out the topology optimization of aluminum alloy wheels, the strength and stiffness of the optimized wheels were simulated and analyzed [20]. Hu optimized the aluminum alloy wheel use the wheel rim and flange thickness as the design variables, the maximum stress of the wheel in bending fatigue and radial fatigue conditions as the constraint, and aiming at the smallest wheel quality, the aluminum alloy wheel optimized[21]. Based on the bending fatigue test, Xiao carried out topology optimization on steel wheels, and designed the lightweight design of the wheels with flexibility and modal frequency as the target, and carried out stress analysis and experimental verification[22]. Optimization design is beneficial to the improvement of global wheel performance and wheel lightweight.

Wheel disc and rim are two main parts of wheel. Some parameters of the vent holes such as number, position, and shape which are distributed in the wheel disc can be changed. In this research, a kind of wheel structure is designed, using topology optimization for wheel quality lightweight. The finite element model of wheels are established based on the static force. The rationality and superiority of the designed magnesium alloy wheel are obtained.

2.2 Structure Topology Optimization

In this paper, wheel structure topology optimization method is used to optimize the wheel, which satisfied the lightweight、strength and NVH requirements.

2.2.1 Optimization method

The most common topology optimization is the variable density material interpolation method, which includes SIMP and RAMP[23-25]. The theory of variable density is to convert the discrete optimization problem into a continuous optimization problem by introducing an intermediate density unit.

The SIMP method uses discrete element density as an optimization variable and therefore tends to generate interlaced grayscale images of topological designs. In order to make it manufacturable, three processing steps are required: identify the topology design, smooth the structural boundary, and then realize the parameterization. SIMP method was originally developed independently by Zhou and Rozvany in 1991. Rozvany et al. in 1992 created the term "SIMP".This may be the simplicity of the SIMP approach that makes it widely used and accepted in both industries and in academia. Rietz and Martinez and other researchers discussed some theoretical convergence properties of the SIMP method.The advantages of a slightly modified version of SIMP was discussed by Sigmund in 2007,a minimum stiffness(or other material parameter) that is independent of penalization are included.

An alternative interpolation scheme known as the Rational Approximation of Material Properties (RAMP) were proposed by Stolpe and Svanberg. RAMP model has nonzero sensitivity at zero density. Some numerical difficulties in problems related to very low density values in the presence of design dependent loading could be remedied by RAMP material model.

(a)before optimization (b)after optimization

Fig.2.1 Element model [26].

From the Fig. 2.1, the FE model before optimization were showed by model a and optimal topology configuration were showed by model b . The most commonly used material interpolation model method, SIMP formula is expressed as:

$$E(x_i) = E_{\min} + (x_i)^p (E_0 - E_{\min}) \tag{2-1}$$

Where E_0 is the initial elastic modulus; p is the penalty factor, $p > 1$; $E(x_i)$ is the density value of the material at i .

The theory of variable density is to convert the discrete optimization problem into a continuous optimization problem by introducing an intermediate density unit. In reality, the intermediate density unit is not exist and cannot be manufactured.

Therefore, the intermediate density unit should be reduced as much as possible. The number of which needs to be penalized only for the intermediate density that appears in the design variables.

2.2.2 Topology optimization for wheel structure

In topology optimization, adding draft restraint, circum symmetry beam, minimum unit size and so on. In the wheel optimization, the lightest weight is the optimal design goal. Wheel spokes, disc and rim are main parts of wheel. Several vent holes are distributed in the wheel disc. When designing wheels , Some parameters of the vent holes can be changed. These parameters include number, position, and shape. Many optimization approaches for wheel designs are concerned with size or shape optimizations. Based on topology optimization and the feature of the wheel, this research aims to identify wheel spokes. When doing topology optimization of wheels, optimize the wheel of structure by spokes for lightweight design.

According to the ICM (Independent Continuous Mapping) optimization method proposed by Yunkang Sui and the topology theory, the topology optimization model is established [27].With wheel unit density as design variable, weight flexibility as constraints, the minimum quality is the objective function. Topology optimization objective function is the biggest structural stiffness or the minimum compliance for the topology optimization, constraint is to remove the volume percentage, the topology optimization mathematical model is in the following equation:

$$\begin{cases} Find\ \rho=(\rho_1,\ \rho_2,\ \rho_3,\cdots\rho_n)^T \\ \mathrm{Min}\ \mathrm{C(u)}=F^TU=U^TKU=\sum_{i=1}^{n}(\rho_i)^p u_i^T k_0 u_i \\ \quad Weight=\sum\rho_i v_i\le v_0-\alpha v_0 \\ \quad \varepsilon\le\rho_i\le 1 \qquad (i=1,2,3\cdots n) \\ \quad \rho_i=1 \qquad (i=J_1,J_2,\cdots J_n) \\ \quad F=KU \end{cases} \tag{2-2}$$

In the equation: ρ_i is unit density, P is penalty factor, ε is the lower material density, α is the percentage of the volume of material removal, k_0 is the initial matrix for the structure, k_i is optimized structure matrix, F is the load of unit structure, K is the overall stiffness matrix, U is the displacement vector of unit structure, V_0 is the initial value of volume of material, $C(u)$ is compliance function of structure, $J_1, J_2, \ldots J_n$ are the unit number of optimized unchanged density. Previous studies have shown that optimization wheel structure can be obtained. The optimization flowchart of the wheel is shown in Fig.2.2 below.

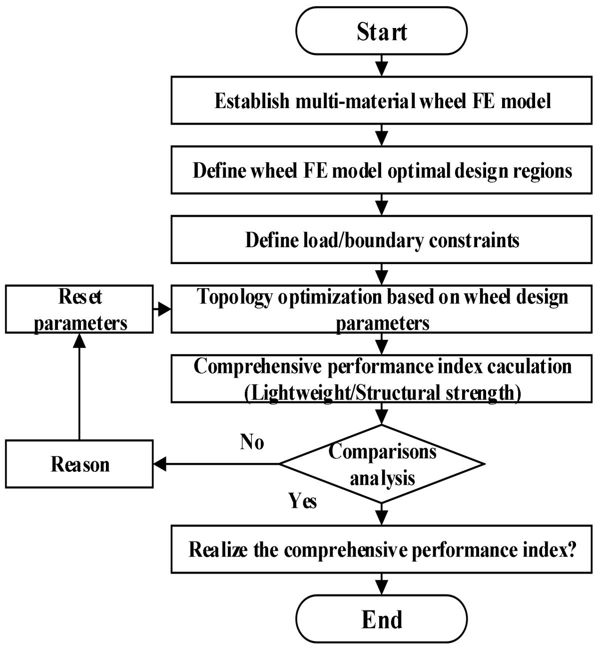
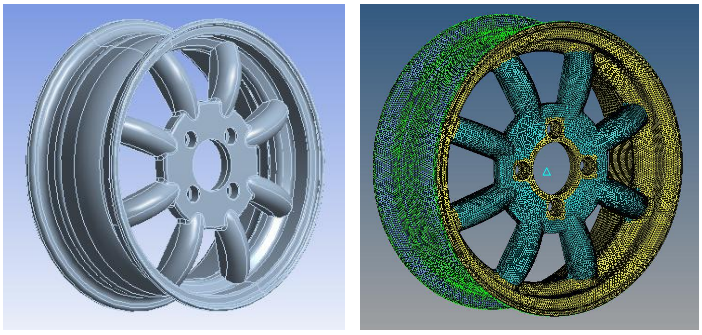


Fig.2.2 Flow chart of the wheel optimization.

2.3 Establishment of wheel model

In modern design, using finite element analysis can be established to determine the strength of the wheel in advance and reduce the test times and cost. Static load while vehicle stops is working conditions of the wheel that should be considered seriously[28-31].Wheel model is shown in Fig. 2.3 below.



(a)3D model (b)FE model

Fig.2.3 Wheel model.

In this research, the gross weight of the vehicle is about 1175kg, load on each wheel is 2937.5N. Two alloy materials are used for the analysis and calculation of wheel as table 2.1 lists.

Table 2.1 Mechanical properties of 2 materials.

Mechanical properties	Aluminium alloy	Magnesium alloy
Density (kg/m³)	2700	1830
Coefficient of elasticity (Mpa)	69	45
Poisson ratio	0.33	0.35
Yield strength (Mpa)	276	160

2.3.1 Verification of finite element model

Model verification is necessary for finite element analysis.The modal analysis result is to analyze the natural frequency, mode shape and other related parameters of the object, these parameters are the essential properties of any object with invariance and stability. Therefore, the finite element model is verified by modal experimental analysis.

Fig.2.4 Modal test.

Table 2.2 Comparison of simulation and experimental data.

Modal	1	2	3
FE analysis frequency/Hz	474.51	480.42	948.03
Modal test frequency/Hz	466	494	954
Error	1.8%	2.75%	0.62%

By comparing the simulation frequency of the FE analysis and modal test frequency, experimentally measured modal parameters and FE analysis results of wheel basic agreement.Wheel finite element model is accurate,can be applied to subsequent in depth finite element analysis.

2.3.2 Structural strength analysis

The static force is intended to detect the wheel performance when the total load of the vehicle compresses the wheel radially. The radial load Fr shall be determined from the equation:

$$\vec{F}_r = K \times \vec{F} \tag{2-3}$$

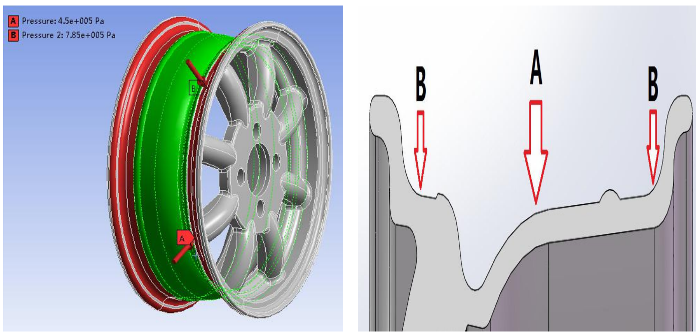
In the equation, $\vec{F}_r$ is radial load (*N*), $\vec{F}$ is maximum rated load (*N*), K is coefficient according to the industrial standards set as 2.25. Radial load is obtained by 6609.4*N*. In this research, using Stearns. J wheel and tire contact research results, the force on the magnesium alloy wheel from the tire can be replaced by the radial force directly on the wheel to simplify the modeling. The calculation formulas W_r , W and W_0 are given by the following equation:

$$W = b\int_{-\theta_0}^{\theta_0} W_r r_b d\theta \qquad (2\text{-}4)$$

$$W_r = W_0 \cos\left(\frac{\pi\theta}{2\theta_0}\right) \qquad (2\text{-}5)$$

$$W_0 = \frac{\pi \cdot b\int_{-\theta_0}^{\theta_0} W_r r_b d\theta}{4br_b\theta_0} \qquad (2\text{-}6)$$

In the equation, W is radial load on the wheel, b is width of the bead seat, r_b is radius of the bead seat, θ_0 is the maximum deflection angle of radial load. In this way, the pressure loaded in the wheel inner ring is 0.45Mpa, the pressure loaded on the rim of the wheel is 0.785Mpa.The load of test model is shown in Fig. 2.5.

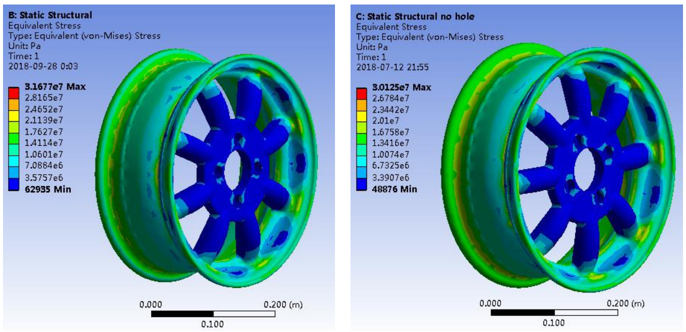


(a) (b)

Fig.2.5 Wheel FE model load.

2.3.3 Results of structural strength analysis

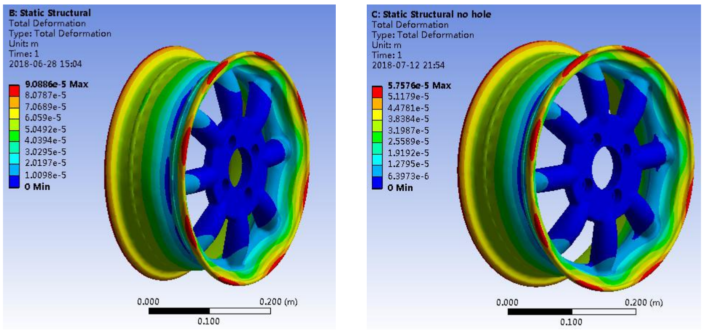
From above loading conditions and finite element theory, in order to realize the lightweight of wheel, meanwhile ensure the strength safety, lightweight material replacement and static analysis are completed. The analysis results were determined and presented in Figs. 2.6-2.7.



(a)Magnesium alloy (b) Aluminum alloy

Fig.2.6 Equivalent Stress of wheel.

Fig.2.6 is the analysis results of equivalent stress between aluminum alloy and magnesium alloy. Through the above comparison, magnesium alloy wheel and aluminum alloy wheel in the same size， magnesium alloy wheel equivalent stress is 31.67Mpa while aluminum alloy equivalent stress is 30.13Mpa, less than the material yield stress.



(a)Magnesium alloy (b) Aluminum alloy

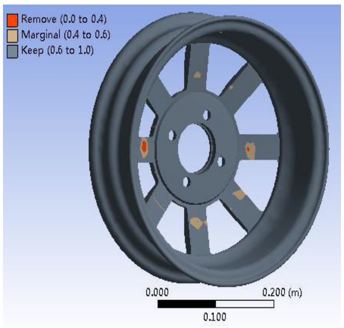
Fig.2.7 Deformation of wheel.

Fig.2.7 is the analysis results before and after wheel optimization. From the above analysis, under the premise of the strength of wheel, the structure optimization of magnesium alloy wheel is carried out. The magnesium alloy wheel deformation is 0.091mm, aluminum alloy wheel deformation is 0.058mm.Magnesium alloy wheel have good strength properties. The optimization effect comparisons were in table 2.3. In radial load, designed wheel model meets strength and other characteristics.Designed wheel can be further optimized.

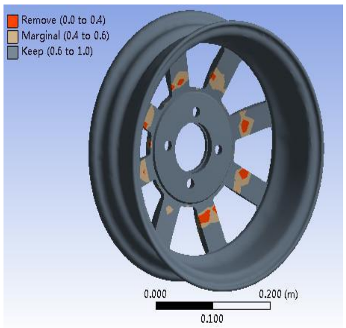
2.4 Optimization of the wheel and results

Based on above optimization theory, structural optimization of wheel were designed.

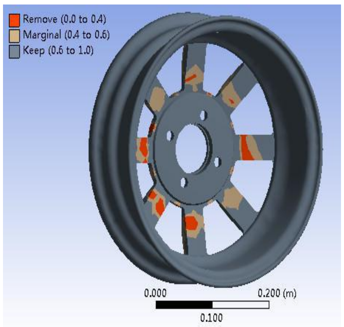
2.4.1 Optimization of the wheel



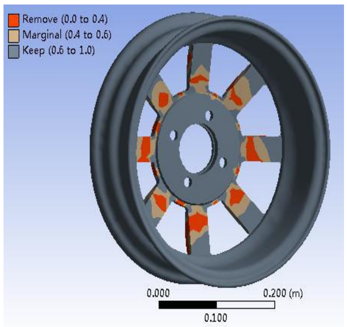
(a)



(b)



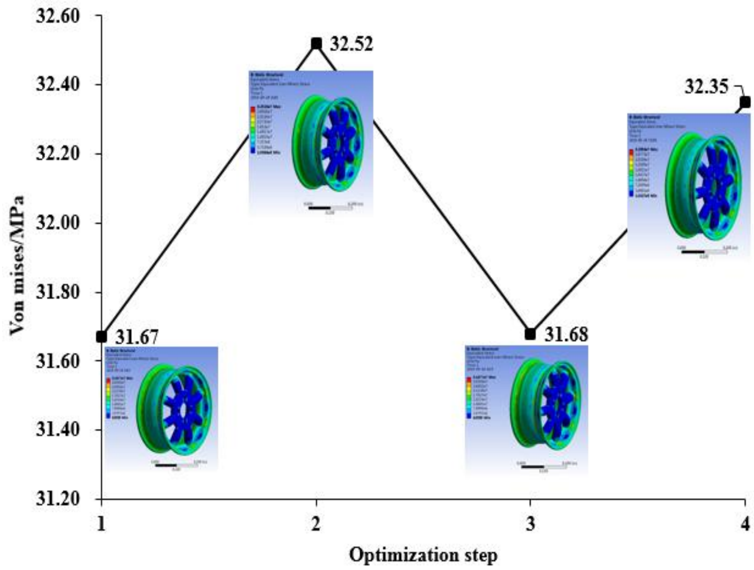
(c)



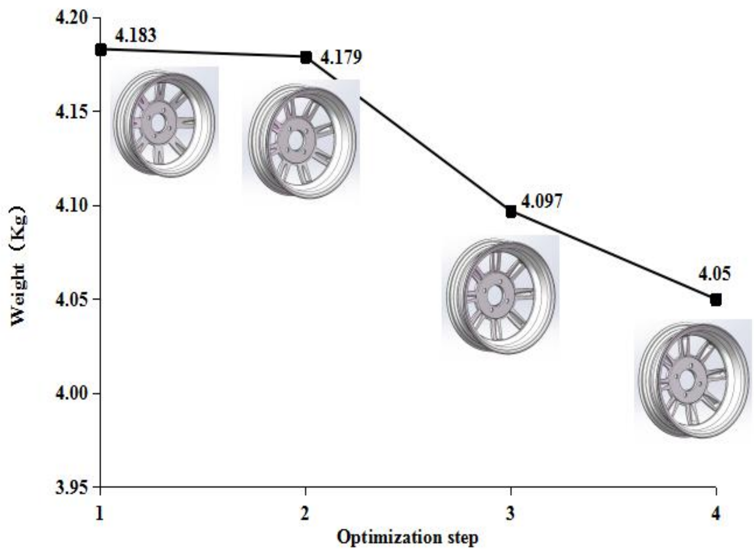
(d)

Fig.2.8 The optimization process of wheel.

Based on above optimization theory and steps, Combine with shape and practicality of structure, Optimization results of the wheel can be done.



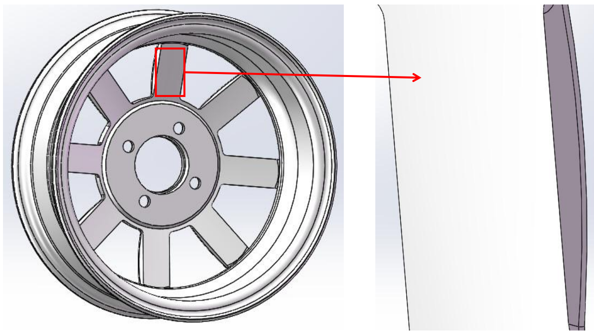
(a) Von mises stress graph



(b) Wheel mass graph

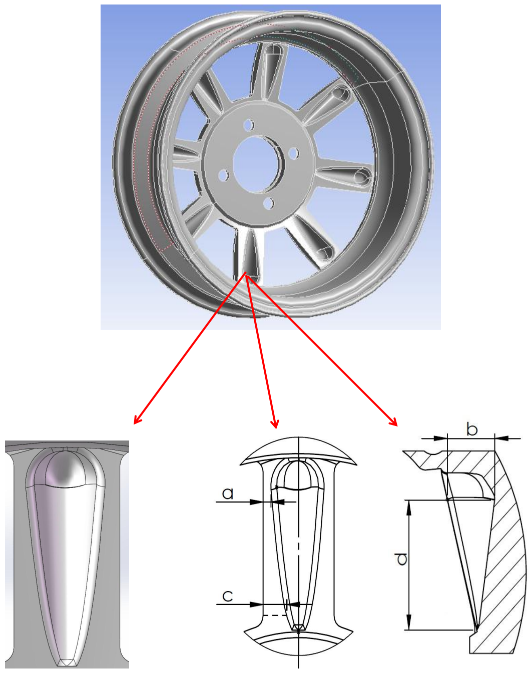
Fig.2.9 Optimization of wheel.

Under the premise of satisfying conditions such as strength， the most remove and optimal model were obtained.



(1)wheel model (2)spoke

(a)Before Optimization



(b)After Optimization

Fig.2.10 Optimization parameters of wheel spokes.

From the FE simulation results concerning the four steps of wheel structure optimization in Figs.2.8-2.10, comparisons among the wheel models can be shown:

(1) Comparisons among the wheel models shown in Figs.2.8-2.9 step 1 and step 4.

By analyzing step 1 model and step 4 model, the stress values for critical locations of wheel under static load, we find that the stress level of the step 4 model is significantly higher than that of the step 1 model.Actual processing can be considered on the wheel basis of topology optimization.

(2) Comparisons among the wheel models shown in Figs.2.8-2.9 step 2 and step 4.

By analyzing step 2 model and step 4 model , the stress values for critical locations of wheel under static load, we find that the stress of the step 2 is 32.52Mpa at the same time, step 4 model is 32.35Mpa. Step 2 stress is significantly higher than that of the step 4 model. Total deformation of step 2 model is 0.022 mm while step 4 model is 0.021 mm.Wheel mass of step 2 model is 4.179kg ,Wheel mass of step 4 model is 4.05kg. Under reasonable stress and strain conditions, wheel model of step 4 is better for optimization target.

(3) Comparisons among the wheel models shown in Figs.2.8-2.9 step 3 and step 4.

By analyzing step 3 model and step 4 model , the stress values for critical locations of wheel under static load, we find that the stress of the step 2 were 32.52Mpa at the same time, step 4 model is 32.35Mpa. Step 2 stress is significantly higher than that of the step 4 model. total deformation of step 2 model is 0.022 mm while step 4 model is 0.021 mm.Wheel mass of step 2 model is 4.097kg ,Wheel mass of step 4 model is 4.05kg. Under reasonable stress and strain conditions, wheel model of step 4 is better for optimization target.

According to the stress, total deformation analysis and optimization step, the most significance model is step 4 model, That is, the spoke reduction of 40% by volume. Combined with the influence of vent holes shape on wheel performance and inner ring of wheel disc influence of wheel structure. The wheel structure after parameter optimization can be done.

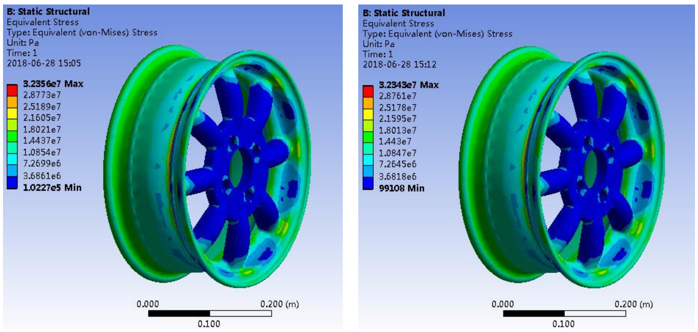
Table 2.3 Before and after parameter optimization (mm).

Wheel optimization parameters	a	b	c	d
Before optimization	6.6	9	14	44
After optimization	4	25	12	55

The more removal of material of optimal topology, the more complex shape of the structure, the smaller size of the spokes, table 2.3 show spokes structure after optimization ,the percentage of material removal of the optimal topology was chose based on the structure and optimization theory.

2.4.2 Results and discussions after optimization

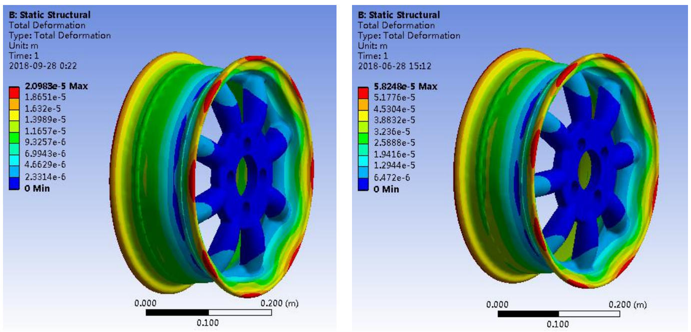
In order to realize the lightweight of wheel, meanwhile ensure the strength safety, lightweight material replacement and further structural optimization are completed. The analysis results of wheel after optimization are presented in Figs. 2.11-2.12.



(a)Magnesium alloy (b) Aluminum alloy

Fig.2.11 Comparison of equivalent Stress.

Fig.2.11 is the analysis results of equivalent stress between aluminum alloy and magnesium alloy. Through the above comparison, magnesium alloy wheel and aluminum alloy wheel in the same size, magnesium alloy wheel equivalent stress is 32.35Mpa while aluminum alloy equivalent stress is 32.34Mpa, less than the material yield stress. Magnesium alloy wheel have good strength properties.



(a)Magnesium alloy (b) Aluminum alloy

Fig.2.12 Comparison of Deformation.

Fig.2.12 is the analysis results before and after wheel optimization. From the above analysis, under the premise of the strength of wheel, the structure optimization of magnesium alloy wheel is carried out. The magnesium alloy wheel deformation is 0.021 mm, aluminum alloy wheel deformation is 0.058 mm.Magnesium alloy wheel have good strength properties. The optimization effect comparisons were in table 2.4.

Table 2.4 Lightweight comparisons (kg).

Lightweight comparisons	Aluminium alloy	Magnesium Alloy	Magnesium Alloy (Optimization)
Weight/kg	6.24	4.23	4.05
Improvement /%	_	35.1	4.4

The optimized magnesium alloy wheel is much lighter than the steel wheel and aluminum wheel, compatible with wheel lightweight design. It makes sense to optimize the wheel with magnesium alloy materials.

The optimization results meets the design target value. Based on topology optimization theory, the wheel optimal structure and key dimensions are obtained while satisfying the performance of the wheel.

Topology Optimization method was efficient and correct, significance for lightweight design of wheels.

2.5 Conclusions

The finite element analysis has been carried out on the wheel. Through the above profound analysis following research results can be acquired：

(1)Using topology optimization for wheel quality lightweight is a useful way. By optimizing wheel spokes to accurate wheel lightweight design.The optimization designed wheel meets the strength condition.

(2)By replacing lightweight materials, compared to aluminium alloy, the weighted reduction is 35.1%. After optimization, the weight of Magnesium Alloy has reduced by 4.4%. Magnesium alloy has a better weight reduction effect, and lightweight materials have effective lightweight means.

(3)According to the analysis results, comparison of wheel performance of different materials, after using the magnesium alloy material for replacement and analyzing of the wheel, the goal of reducing the weight of the automobile wheel can be achieved while satisfying the wheel strength requirements.

References

[1] Morrow W R, Gallagher K S, Collantes G, et al. Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector[J]. Energy Policy, 2010, 38(3): 1305-1320.

[2] Office of Transportation and Air Quality, Regulatory Announcement:EPA and NHTSA Propose to Extend the National Program to Reduce Greenhouse Gases and Improve Fuel Economy for Cars and Trucks, 2011. EPA-420-F-11-038.

[3] Das S. Design and weight optimization of aluminum alloy wheel [J]. Int. J. Sci. Res. Publ, 2014, 4(6).

[4] Joost W J, Krajewski P E. Towards magnesium alloys for high-volume automotive applications[J]. Scripta Materialia, 2017, 128: 107-112.

[5] Pfestorf M, Copeland D. Great Designs in Steel Seminar 2007, American Iron and Steel Institute[J]. 2007.

[6] Ward's Communications, 2008. Ward's Motor Vehicle Facts and Figures 2008. Southfield, Mich.

[7] Cole G S. Magnesium vision 2020-a north american automotive strategic vision for magnesium[C]IMA-PROCEEDINGS-.International Magnesium Association, 2007: 13.

[8] Liu J, Ma Y. A survey of manufacturing oriented topology optimization methods[J]. Advances in Engineering Software, 2016, 100: 161-175.

[9] Deaton J D, Grandhi R V. A survey of structural and multidisciplinary continuum topology optimization: post 2000[J]. Structural and Multidisciplinary Optimization, 2014, 49(1): 1-38.

[10] Wang C Q, Wang D F, Zhang S. Design and application of lightweight multi-objective collaborative optimization for a parametric body-in-white structure[J]. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of automobile engineering, 2016, 230(2): 273-288.

[11] Marin L, Kedziora S. Design of Automotive Road Racing Rim with Aid of Topology Optimization[R]. Faculty of Science, Technology and Communication University of Luxembourg, 2016.

[12] Das S. Design and weight optimization of aluminum alloy wheel[J]. Int. J. Sci. Res. Publ, 2014, 4(6).

[13] Singh D P K, Mallinson G D, Panton S M. Applications of optimization and inverse modeling to alloy wheel casting[J]. Numerical Heat Transfer: Part A: Applications, 2002, 41(6-7): 741-756.
[14] Satyanarayana N, Sambaiah C. Fatigue analysis of Aluminum Alloy wheel under radial load[J]. International Journal of Mechanical and Industrial Engineering (IJMIE), ISSN, 2012 (2231-6477): 1-6.
[15] Rozvany G I N. A critical review of established methods of structural topology optimization[J]. Structural and multidisciplinary optimization, 2009, 37(3): 217-237.
[16] Rozvany G I N. Aims, scope, methods, history and unified terminology of computer-aided topology optimization in structural mechanics [J]. Structural and Multidisciplinary Optimization, 2001, 21(2): 90-108.
[17] Hirano A. Study on Wheel Stiffness Considering Balance between Driving Stability and Weight [J]. SAE International Journal of Commercial Vehicles, 2015, 8(2015-01-1755): 205-212.
[18] Kumar C P V R, Meher R S. Topology Optimization of Aluminium Alloy Wheel [J]. International Journal of Modern Engineering Research, 2013, 3: 1548-1553.
[19] Miller W S, Zhuang L, Bottema J, et al. Recent development in aluminium alloys for the automotive industry [J]. Materials Science and Engineering: A, 2000, 280(1): 37-49.
[20] Hu J H, Liu X X, Sun H X, et al. Development and Application of Light-Weight Design of the Aluminum Alloy Wheel[C]//Applied Mechanics and Materials. Trans Tech Publications, 2013, 310: 253-257.
[21] Praveen P, Gopichand D. Geometrical Optimization and Evaluation of Alloy Wheel Four Wheeler [J]. International Journal of Research and Innovation Volume No: I Issue No.: III, 2014.
[22] Xiao D, Zhang H, Liu X, et al. Novel steel wheel design based on multi-objective topology optimization[J]. Journal of Mechanical Science and Technology, 2014, 28(3): 1007-1016.
[23] Gersborg-Hansen A, Bendsøe M P, Sigmund O. Topology optimization of heat conduction problems using the finite volume method[J]. Structural and multidisciplinary optimization, 2006, 31(4): 251-259.
[24] Chang K H, Tang P S. Integration of design and manufacturing for structural shape optimization [J]. Advances in Engineering Software, 2001, 32(7): 555-567.

[25] Chen J, Shapiro V, Suresh K, et al. Shape optimization with topological changes and parametric control [J]. International journal for numerical methods in engineering, 2007, 71(3): 313-346.

[26] Sui Y K, Ye H L. Continuum topology optimization methods ICM [J]. 2013.

[27] Adigio E M, Nangi E O. Computer Aided Design and Simulation of Radial Fatigue Test of Automobile Rim Using ANSYS [J]. Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN, 2014: 2278-1684.

[28] Van Dyk B J, Edwards J R, Dersch M S, et al. Evaluation of dynamic and impact wheel load factors and their application in design processes[J]. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2017, 231(1): 33-43.

[29] Ganesh S, Periyasamy D P. Design and analysis of spiral wheel rim for four wheeler [J]. The International Journal of Engineering and Science (IJES), 2014, 3(4): 29-37.

[30] WANG L, CHEN Y, WANG C, et al. Simulation and Test on Aluminum Alloy Wheel Rotary Fatigue Life [J]. Journal of Nanjing University of Science and Technology (Natural Science), 2009, 5: 005.

[31] Papadrakakis M, Lagaros N, Plevris V. Multi-objective optimization of skeletal structures under static and seismic loading conditions[J]. Engineering Optimization, 2002, 34(6): 645-669.

Chapter 3 Casting Design and Optimization of Magnesium Alloy Wheel

3.1 Introduction

Environmental and resource issues have become the focus of attention around the world, lightweight vehicles will be the direction of future development with energy saving.The wheel plays an important role in vehicle lightweight design and manufacturing. Magnesium alloy are very meaningful materials for wheel lightweight design research with low density and suitable strength mechanical properties.Topology optimization is to find the optimal distribution and structure of materials in the design area,then optimize the structure for lightweight design[1-4].Sourav Das et al [5] carried the design of aluminum alloy wheel for automobile application which is reference to optimization of the mass of the wheel for lightweight.

Recently, casting and forging techniques have been improved, and the corrosion resistance of magnesium has also been improved.In view of the casting process for magnesium alloy wheel, with the analysis of the technological characteristics of magnesium alloy,casting simulation analysis of the lightweight designed wheel were significant.The casting of the wheel is an element that must be considered in the design of the wheel.Casting is an important basic process and technology in the field of machinery which is widely used in production, transportation, national defense, social life and other aspects[6-8].Common casting methods are centrifugal casting,sand casting,high pressure casting,low pressure casting and so on[9-15].The advantage of centrifugal casting were that feeding conditions are good, the casting structure is dense, and the mechanical properties are good.The disadvantage of centrifugal casting were free surface roughness in the casting, it is not suitable for alloys with large density segregation alloys such as aluminum and magnesium.The advantage of high pressure casting were that the product quality is good, casting size is stable,the productivity is high and the die casting mold is used more frequently.The disadvantage of high pressure casting were the mold structure is complex, the manufacturing cost is high, and the preparation period is long. The advantage of low pressure casting were that the liquid metal filling is stable, the defects are few, the equipment is simple, and it is easy to realize mechanization and automation.The disadvantage of low pressure casting were long casting cycle, high mold temperature, long solidification time, degree of freedom of the gate scheme is small.The advantage of sand casting were that clay is rich in resources and cheap,the mold has a short cycle, high work efficiency and wide adaptability.The disadvantage of sand casting were castings are prone to defects such as sand washing, sand inclusion, and porosity.In this research,we use sand casting for wheel casting ,we design reasonable model to reduce defects.In this way,we can make better use of sand casting advantages and avoid its disadvantage.The finite element simulation of the wheel can significantly reduce the time and cost required to complete the wheel design[16-18].

In this research, the design and model of wheel based on weight optimization were studied and structural analysis were carried out. Compared to the standard value by changing different materials. In addition, from the simulation output and weight optimization, we recommend designed magnesium alloy suitable for lightweight design and better casting performance.Through research on magnesium alloy materials and casting properties, analysis of magnesium alloy wheel casting were done. Based on finite element theory and actual production, we designed reasonable casting model, instant filling and solidification data were obtained.Through the optimization in the casting process, provided a rational design for the casting process.By comparing the model before and after optimization to get the optimal casting model.The actual casting of the wheel were simulated and well casting model were obtained.On the basis of the foundation, it has important guiding significance for actual foundry production.

3.2 Theory and method

Wheel is an important structural component of the vehicle suspension system that supports static and dynamic loads during vehicle operation. Safety and economy are the main concerns of the design. Style, weight, and manufacturing performance are also technical issues associated with wheel design[19-22].In this study, a wheel structure was designed using topology optimization to achieve lightweight wheel quality. Finite element model of the wheel were built based on static force.The rationality and superiority of the designed magnesium alloy wheels were obtained.

3.2.1 Wheel casting theory

In this research, the gross weight of the vehicle is about 1175kg, load on each wheel is 2937.5N.AZ91 magnesium alloy,6061-T6 aluminum alloy and SPFH540 steel were used for material analysis.Alloy materials were used for analysis and calculations as listed in table 3.1.

Table 3.1 The properties of aluminum, steel, and magnesium.

Material properties	Aluminum (6061-T6)	Magnesium (AZ91)	Steel (SPFH540)
Density (kg/m^3)	2700	1830	7850
Modulus of Elasticity (GPa)	69	45	210
Poisson ratio	0.33	0.35	0.3
Yield strength (GPa)	0.276	0.16	0.355

(a) Mechanical properties of aluminum, steel, and magnesium.

Material	Magnesium (%)	Aluminum (%)	Zinc (%)	Manganese (%)	Silicon (%)	Iron (%)	Other elements (%)
Magnesium (AZ91)	Remainder	8.3-9.7	0.35-1.0	0.15-0.5	0.1 max	0.004 max	0.3 max

(b) Composition of Magnesium alloy

Material	Aluminum (%)	Silicon (%)	Iron (%)	Copper (%)	Magnesium (%)	Zinc (%)	Other elements (%)
Aluminum (6061-T6)	Remainder	0.4-0.81	0.7 max	0.15-0.4	0.8-1.2	0.25 max	0.15 max

(c) Composition of Aluminum alloy

The AZ91 magnesium alloy and 6061 aluminum alloy thermomechanical treatment characteristics were considered.The thermal properties of AZ91 magnesium alloy were: melting temperature, ~533°C; specific heat capacity, 1020 J/(kg·K); thermal conductivity, 51 W/(m·K). The thermal properties of 6061 aluminum alloy were: melting temperature, ~585°C; thermal conductivity, 151–202 W/(m·K); specific heat capacity, 897 J/(kg·K). These properties combined with the material properties to influence our findings.

Study on the material properties of magnesium alloys. The phase diagram is a diagram showing the crystallization process of each alloy in the alloy system. The phase diagram of alloy is shown in Fig. 3.1.

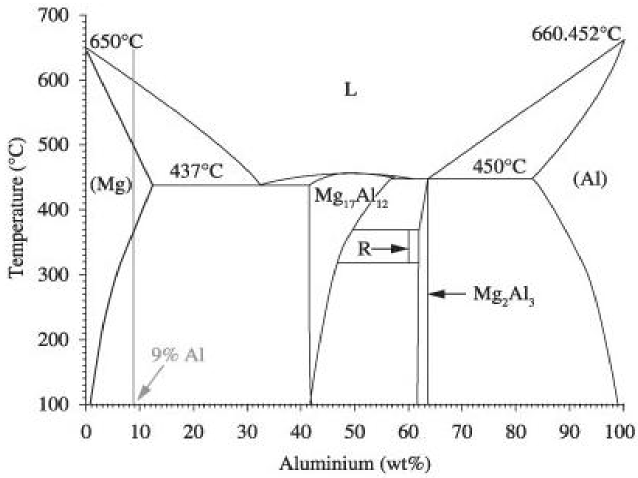


Fig.3.1 Phase diagram of alloy [23].

The reaction is a simple schematic diagram of the range and change law of the phase and structure of the alloy under equilibrium conditions. Relationship between system state, temperature, pressure, and composition[24-25].The study found that the liquidus temperature of the AZ91D magnesium alloy is 595℃, the solidus temperature is 470 ℃. The average free-line shrinkage of this alloy is 1.572%. When cooling and solidifying, it tends to solidify by volume, and it is easy to form a coarse dimorphic eutectic structure.Casting shrinkage can be calculated by the following equation:

$$\eta = (\rho_S - \rho_L) / \rho_S \times 100\% \tag{3-1}$$

In the equation，ρ_S is the solidus temperature T_S respectively density, ρ_L is the liquidus temperature T_L respectively density.

It is an important part of solidification theory to study the process of metal transition from liquid to solid from the perspective of heat transfer. The solidification process begins with the heat transferred from the liquid metal. The solidification state of a casting section at a certain instant is determined by the crystallization temperature range of the casting alloy (determined by the composition and content of the alloy) and the temperature field on the casting section at that moment.

The distribution of the isotherm on the fracture surface, the progress of the solidification front, and the determination of the solid phase rate during the solidification of the casting can not only analyze the location of shrinkage, and crack defects, provide a basis for process design, but also calculate the cooling rate Temperature gradient G, and solidification rate R, and G / R, can predict the solidification structure morphology and properties of castings. The molten metal is poured into the mold, the mold absorbs heat, the molten metal cools down, and the mold heats up. The temperature of a certain point in the metal and the mold changes over time. The heat transfer during solidification is unstable heat transfer. Temperature is the culvert of time and space.

$$T=f(X;Y;Z;t) \tag{3-2}$$

In the equation: X, Y, Z is the position, t the is time. For homogeneous, isotropic objects, the relationship between temperature and time and space can be expressed by a differential equation:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+q=c\rho\frac{\partial T}{\partial t} \tag{3-3}$$

$$q=\rho L\frac{\partial f_s}{\partial_t} \tag{3-4}$$

In the equation: λ is thermal conductivity,T is temperature, c is specific heat capacity, ρ is the density of the material, t is time, əT / əx is temperature gradient in x direction, q is heat released per unit volume of object per unit time, f_s is solid phase rate, L is latent heat of solidification. The equation reflects the conservation of energy in the heat conduction process. The terms in parentheses on the left side of the equation are the components of the heat flux density on x, y, and z coordinates.

$$q_x=\lambda\frac{\partial T}{\partial x};\quad q_y=\lambda\frac{\partial T}{\partial y};\quad q_z=\lambda\frac{\partial T}{\partial z}; \tag{3-5}$$

After further analysis, we can get:

$$k_0=\frac{c_s}{c_L} \tag{3-6}$$

$$m = -\frac{T_L - T}{c_L - c_0} \tag{3-7}$$

$$f_s = \frac{c_L - c_0}{c_L - c_s} \tag{3-8}$$

In the above three equation: k_0 is the distribution equilibrium coefficient, c_s is the solute concentration in the solid phase, m is the liquidus slope, c_L is the bath mass concentration in the liquid phase, T_L is the liquidus temperature, T_s is the solidus temperature.Then by the above equation can obtain the following equation:

$$f_s = \frac{T - T_L}{(1\text{-}\mathrm{k}_0)(c_0 m + T - T_L)} \tag{3-9}$$

The sum of the three terms is the increase or decrease in heat flux density per unit volume.In solidification characteristics of sand casting. Through the temperature field, the thickness of the solidified layer and the solidification time can be obtained. So the heat entering the sand mold is only the latent heat of solidification released by the solidification of the metal.

$$\rho_s LR - \lambda_s \frac{\partial_T}{\partial_x} = 0 \tag{3-10}$$

In the equation: R is solidification speed, L is latent heat of solidification, S is thickness of solidified layer. Assuming no overheating, the temperature of the metal is T_M, we can obtain:

$$\int_0^s L \rho_s ds = (T_0 - T_M)\sqrt{\lambda_m c_m \rho_m / \pi} \int_0^t \frac{dt}{t} \tag{3-11}$$

$$\frac{V}{A} = \frac{2}{\sqrt{\pi}} \left(\frac{T_M - T_0}{\rho_s L} \right) \sqrt{\lambda_m \rho_m c_m} \sqrt{t_f} \tag{3-12}$$

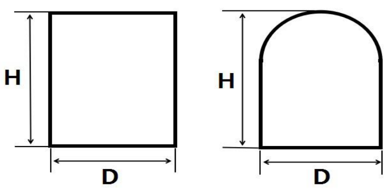
$$t_f = C \left(\frac{V}{A} \right)^2 \tag{3-13}$$

In the equation: V is the volume of the casting, A is metal and mold interface area, T_M is the temperature of the metal. λ_m is metal thermal conductivity, c_m is metal specific heat capacity, ρ_m is the density of the material. t_f is the entire solidification time, C is solidification constant, L is latent heat of solidification.

The dynamic viscosity of magnesium alloys is relatively low and with good fluidity and filling ability, therefore, most magnesium alloy products are obtained by casting methods.In order to improve the quality of magnesium alloy wheel sand casting, magnesium alloy wheel numerical simulation have been carried out.

3.2.2 Casting model optimization

When the liquid metal is poured into the mold, during the solidification and cooling process, liquid shrinkage and solidification shrinkage will occur. If these shrinkages are not supplemented by liquid metal, the addition of metal will cause shrinkage and shrinkage in the final solidified part of the casting, thereby reducing the mechanical properties of the casting and even causing waste.Therefore, when designing the casting process, a riser optimization is often used to eliminate shrinkage to obtain high-quality castings[26-28].Different riser and size is shown in Fig. 3.2.



(a) (b)

Fig.3.2 Different riser and size.

The structural parameters of the riser can be summarized as the bottom dimension D, riser height H. For better calculation and design, were chose Fig.3.2 (a) in this research. According to the above structural parameters, the design variables are:

$$Y = [Y_1, Y_2]^T = [D, H]^T \tag{3-14}$$

On the premise of ensuring the quality of castings, the riser volume should be reduced as much as possible, so that not only can save metal materials, but also obtain better economic benefits.So the objective function is:

$$\min f(x) = V \tag{3-15}$$

The solidification time of the riser should be greater than or equal to the solidification time of the casting.The effect on the solidification time mainly depends on the volume V and the surface area S of the casting. Their relationship is usually expressed by the modulus M, which is:

$$M = \frac{V}{S} \tag{3-16}$$

In order to ensure that the riser solidifies later than the casting, general requirements:

$$\begin{cases} M_r \geq 1.2M_c \\ g_1(Z) = 1.2M_c - M_r \leq 0 \end{cases} \tag{3-17}$$

In the equation: M_r is modulus of riser, M_c is modulus of casting model.The riser also shrinks.Therefore, riser volume must be greater than the volume of the casting and the riser itself. In order to ensure that the casting will not produce shrinkage, considering that the riser itself is also solidifying and the influence of various external factors, it is not possible to use all risers for filling. That is, to multiply the filling efficiency, so we can get the equation:

$$\begin{cases} V_r\eta \geq \varepsilon(V_r + V_c) \\ g_2(Z) = \varepsilon V_c - (\eta - \varepsilon)V_r \leq 0 \end{cases} \tag{3-18}$$

In the equation: V_r is riser volume, V_c is casting deflated portion volume, ε is total volume shrinkage of metal during liquid and solidification, η is feeder efficiency of riser.The height of the riser must not be too low, usually desirable as:

$$\begin{cases} H \geq 1.4D \\ g_3(Z) = 1.4D - H \leq 0 \end{cases} \tag{3-19}$$

In summary, the mathematical model of this optimization design can be described as:

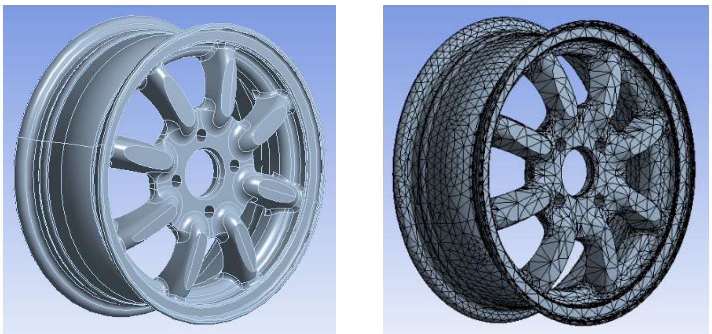
$$\begin{cases} \min f(x) = V \\ Y = [Y_1, Y_2]^T \\ g_I(Z) \leq 0 \quad (I = 1,2,3) \end{cases} \tag{3-20}$$

After the type, shape, and position of the riser are determined, the size of the riser can be designed.The number of risers varies, it also has a great influence on the quality of castings.Combined with the shape and size, continue to optimize the number of riser, we can get the most suitable wheel casting model.

3.3 Wheel design and casting analysis

3.3.1 Wheel lightweight design and establish the wheel casting model

The static force is intended to detect the wheel performance when the total load of the vehicle compresses the wheel radially.Therefore,static force analysis should be performed on the product to ensure the standard of the design.Combining the theory of force analysis of the wheel and the actual situation, the strength performance of the wheel were analyzed. In this way, the pressure loaded in the wheel inner ring is 0.45Mpa, the pressure loaded on the rim of the wheel is 0.785Mpa.Wheel rotary table were constrained,The designed wheel and FE model of wheel is shown in Fig. 3.3.



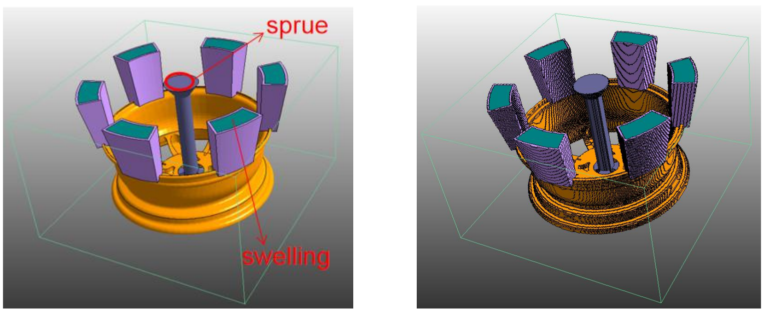
(a) 3D model (b) FE model

Fig.3.3 Wheel model.

Based on above loading conditions and finite element theory, the corresponding performance of the wheel were obtained.From the static FEM analysis results,magnesium alloy wheel equivalent stress is 48.7Mpa while aluminum alloy equivalent stress is 48.4Mpa, magnesium alloy wheel equivalent stress is less than the material yield stress.The magnesium alloy wheel deformation is 0.58mm,aluminum alloy wheel deformation is 0.18mm. Magnesium alloy wheel have good strength properties.The estimated maximum displacements are still considered acceptable for this kind of application.Designed magnesium alloy wheel can reduce the weight by 32.3% compared to the aluminum alloy wheel.The wheels meet lightweight target and meeting wheel performance, provided the basis for casting simulations.

Analysis of casting process were research based on finite element theory,with instant filling, volume and temperature distribution data at the end of filling were obtained.Casting process and liquid metal flow,heat transfer and mass transfer processes are closely related,witch is a non-constant flow process with heat loss and solidification, can be described by mass conservation and momentum conservation equations.The heat exchange between the molten metal and the mold during the filling process and solidification process can be described by the heat balance equation.

Magnesium alloy casting has a narrow crystallization temperature range, high melting point and poor fluidity.For unsteady flow calculations with free surfaces,the key is to determine the position and movement of the free surface.We also needed to deal with the boundary problem such as free surfaces.The shrinkage rate is large and easy to oxidize, so the casting system is required to have a simple structure and a cross-sectional area,making the filling fast and smooth, and has a suitable liquid surface rising speed.Therefore, the components of the gating system are selected as shown in Fig.3.4 below.



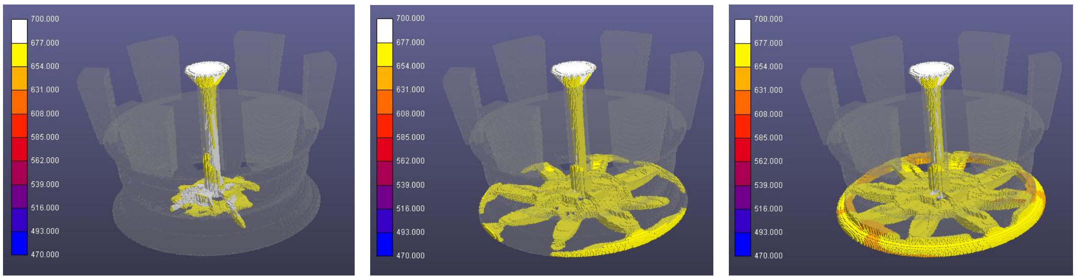
(a)3D model (b) meshed model

Fig. 3.4 Casting system design.

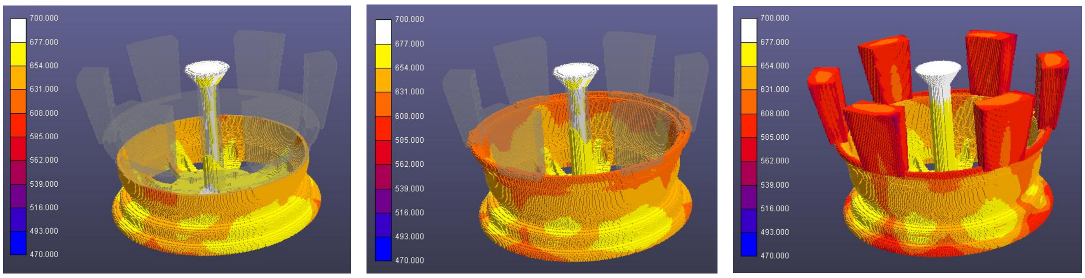
Because of sand casting, it is sufficient to set the thickness of the sand layer directly.The meshed grid size is 2, total number of grids is about 10 million.Here we set the thickness of the sand layer to 40 cm and the gate surface to the gravity direction.Set all parts to the solution range.The simulation process of magnesium alloy wheel is analyzed.In the simulation calculation process, ambient temperature: 25^{o}C, casting speed 1 m/s, time step size 0.001s,starting with the top casting method, gravity acceleration 9.8m/s^2.The magnesium alloy solution is injected into the sprue, first entering the spokes and filling along the rim.Setting up the sensor in the wheel to get the relevant casting information.

3.3.2 Wheel filling and solidification analysis

Based on the casting theory wheel casting model.Use anysolver for calculate,set reasonable debugging and design to get the results.The analysis results were shown in Fig.3.5.



(a) 0.5s (b) 1.5s (c) 2.5s



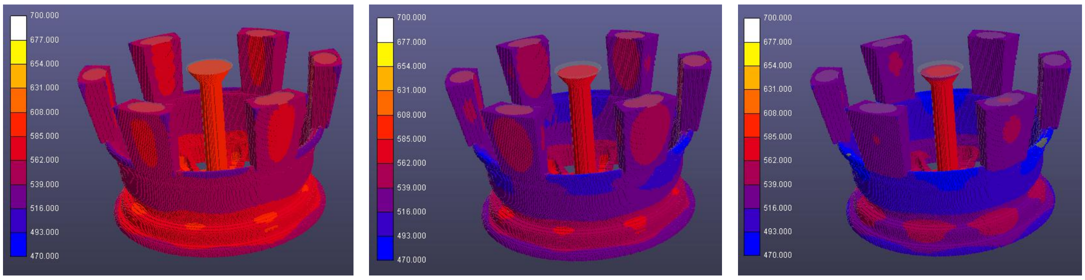
(d) 4.5s (e) 6.0s (f) 11s

Fig.3.5 Temperature of wheel filling.

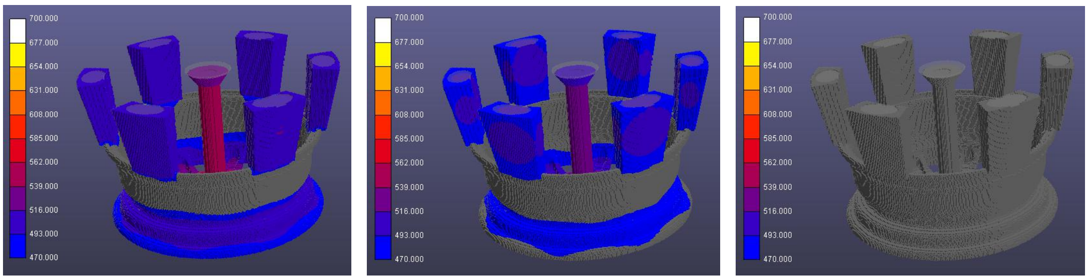
From the casting analysis results,magnesium alloy wheel casting characteristics were obtained.Designed magnesium alloy wheels can be processed under the corresponding strips. In the simulation analysis, the filling process needs 11s.As can be seen from the figure,there were no shortage of castings in the castings.The molten metal fills the cavity smoothly,finally the riser filled.Through sand casting analysis,we can know the filling situation at different times.The temperature of the structure can also be obtained at different times.Then we can make different runners and different flow rates to get a reasonable filling condition.Make guidance for casting simulation analysis.

By the details of the casting, we can get the different characteristics of wheel parts.At the time of 6s, the wheel rim almost completely filled. Red circle in the above figure were prone to have temperature unevenness and defects.The spokes of the wheel with high temperature.The flow state and temperature field distribution of the molten metal in the casting filling process of the wheel model at a certain casting speed were simulated.The distribution data of the temperature at the end of filling were obtained,provides accurate initial conditions for further casting solidification process.

The solidification process of the casting were accompanied by complex phenomena such as changes the temperature of the liquid metal and changes the flow area.The solidification process was a very unstable process.Defects such as shrinkage, under fill and cold insulation of the casting were directly related to this process. By the solidification process simulation of the casting, we can predict the position of shrinkage .The analysis of the solidification process of the casting were shown in Fig.3.6.



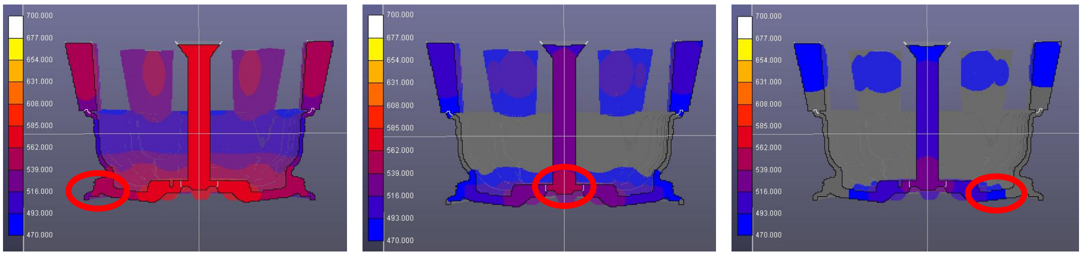
(a) 25% (b) 45% (c) 55%



(d)75% (e) 85% (f) 100%

Fig.3.6 Wheel solidification analysis.

In the solidification analysis, the solidification process needs 526s.In the time of 41s, 83s, 110s, 187s, 239s and 526s, the solidification process were 25%, 45%, 55%, 75%, 85% and 100%. Through the details of the casting, we can get the different characteristics of wheel parts.In 110s in the above figure,blue part were prone to have temperature unevenness and defects.Through solidification analysis,we can know the solidification situation at different times.The temperature of the structure can also be obtained at different times.Then we can make reasonable setting of simulation conditions in combination with the casting solidification process of the wheel, make guidelines for the actual production processing.Temperature section of casting wheel solidification were shown in below Fig.3.7.



(a) 31s (b) 156s (c) 257s

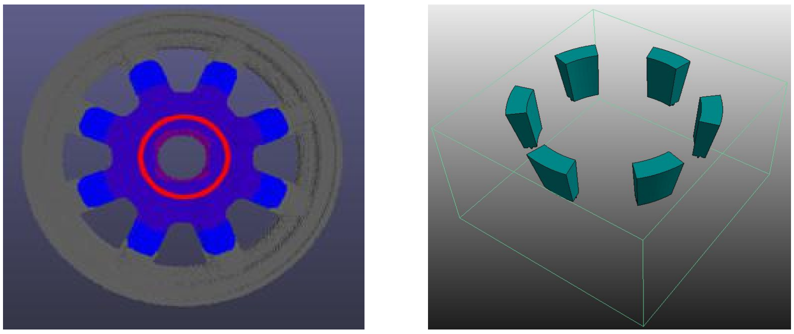
Fig.3.7 Temperature section of wheel solidification.

Through the details of the wheel solidification, we can get the different characteristics of wheel solidification. In the time of 97s, 239s and 318s, the solidification process were 50%, 85% and 95%. At the time of 318s, the wheel rim almost completely solidified.As can be seen from the figure,there were no shortage in the castings.Red circle in the above figure were prone to have temperature unevenness and defects.These places should be pay attention during production.The fluctuation of the molten metal during the wheel solidification process were observed.The flow state and temperature field distribution of the molten metal in the casting solidification process of the wheel model at a certain casting speed were simulated.The distribution data of the temperature at the end of solidification were obtained,provides accurate initial conditions for further numerical simulation and production.

3.4 Casting optimization of the wheel

3.4.1 Optimization of the wheel casting model

By simulating the filling and solidification process of the original casting model, it is necessary to do casting optimization and reduce the shrinkage defects[29-31].The simulation results of the initial process can be seen. The temperature in the middle of the wheel disc were prone to have temperature unevenness and defects.Aiming at reducing defects, process optimization design of casting riser structure.Reduce the probability of defects in castings, improve the quality of castings.Casting optimization were shown in below Fig.3.8.

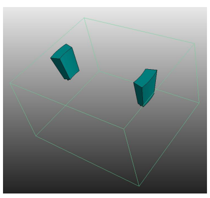
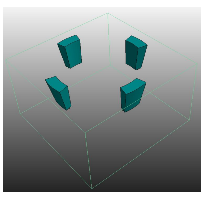
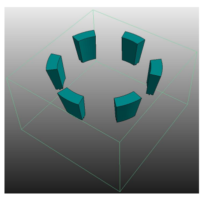
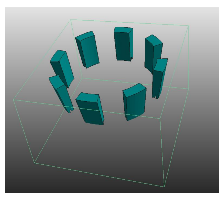


(a)Target: Reduce shrinkage (b) Method: Improve riser

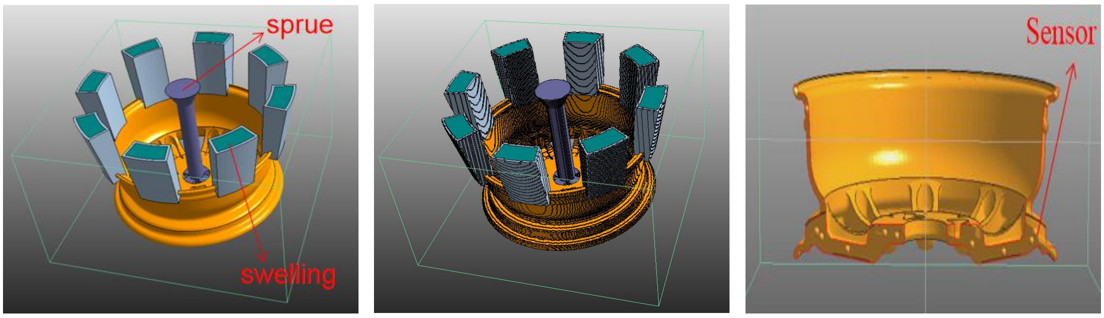
Fig.3.8 Casting optimization.

The models of the optimized wheel casting designs combined with structural design criteria and related parameters are shown in Table 3.2.

Table 3.2 Different wheel casting Riser.

Wheel casting				
Riser amount	2	4	6	8
Casting design				

Through analysis and comparison, better casting model were obtained.Therefore, the components of the gating system are selected as shown in Fig.3.9 below.

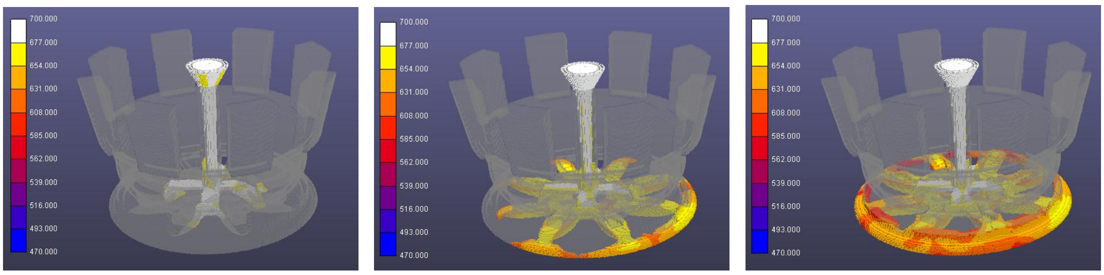


(a)3D model (b) meshed model (c) sensor

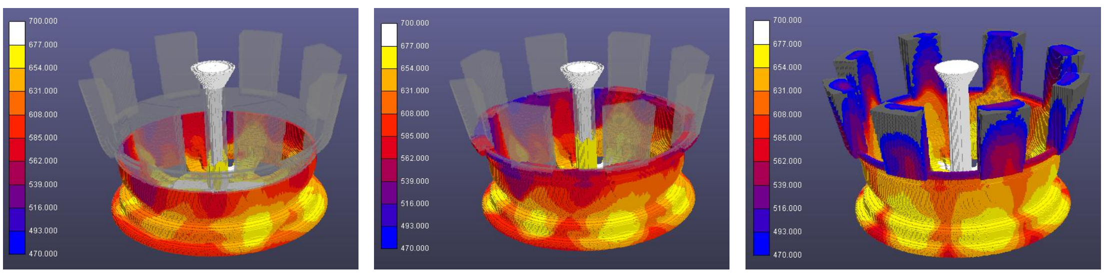
Fig.3.9 Casting system design.

3.4.2 Wheel casting analysis

By the same way and conditions, it is sufficient to set the thickness of the sand layer directly.The meshed grid size is 2, total number of grids is about 10 million.Here we set the thickness of the sand layer to 40 cm and the gate surface to the gravity direction.Set all parts to the solution range.The wheel is filling from top to bottom. The gravity casting process is carried out without any external force. The same method were used to obtain the simulation characteristics of filling and solidification.The analysis results were shown in Fig.3.10.



(a) 0.5s (b) 1.5s (c) 2.5s

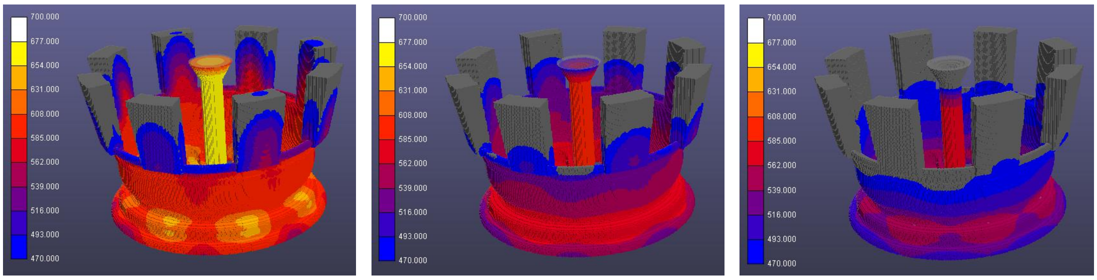


(d) 4.5s (e) 6.0s (f) 11s

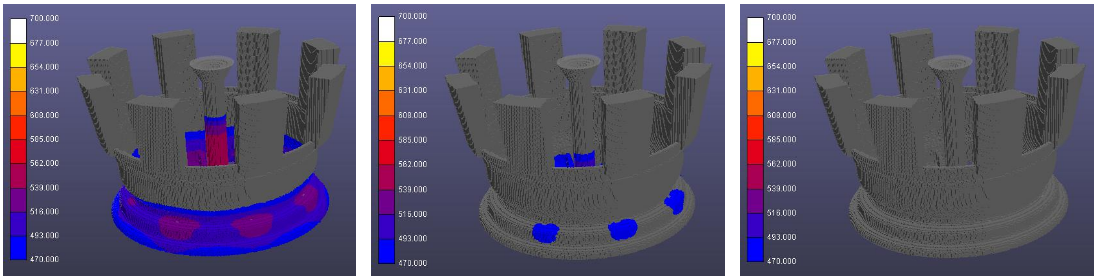
Fig.3.10 Temperature of wheel filling.

By casting analysis results, optimized magnesium alloy wheel casting characteristics were obtained.Designed magnesium alloy wheels can be processed under the corresponding strips. In the simulation analysis, the filling process needs 11s.As can be seen from the figure,there were no shortage of castings in the castings.The molten metal fills the cavity smoothly,finally the riser filled.Through sand casting analysis,we can know the filling situation at different times.The temperature of the structure can also be obtained at different times.Then we can make different runners and different flow rates to get a reasonable filling condition.Make guidance for casting simulation analysis.By the details of the casting, we can get the different characteristics of wheel parts.At the time of 6s, the wheel rim almost completely filled.The spokes of the wheel with high temperature.The flow state and temperature field distribution of the molten metal in the casting filling process of the wheel model at a certain casting speed were simulated.The distribution data of the temperature at the end of filling were obtained,provides accurate initial conditions for further casting solidification process.

Using the same method, we analyzed the solidification of the wheel casting.By the solidification process simulation of the casting, we can predict the temperature and other details.The analysis of the solidification process of the casting were shown in Fig.3.11.



(a) 35% (b) 55% (c) 75%

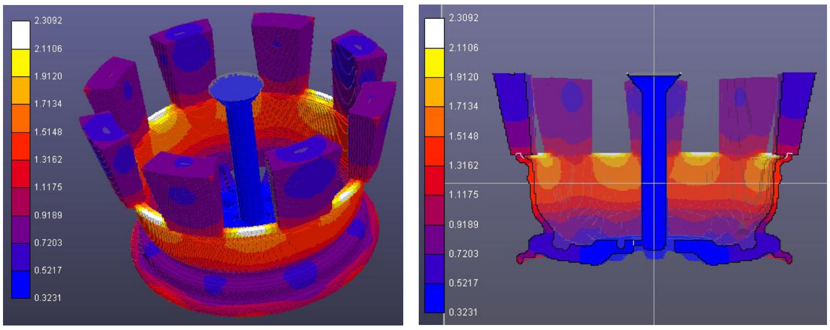


(d) 85% (e) 95% (f) 100%

Fig.3.11 Wheel solidification analysis.

In the solidification analysis, the solidification process were 35%, 55%, 75%, 85%, 95% and 100%. Through the details of the casting, we can get the different characteristics of wheel parts.At the percentage of 95% in the above figure,blue part were prone to have temperature unevenness and defects.Through solidification analysis,we can know the solidification situation at different times.The temperature of the structure can also be obtained at different times.Then we can make reasonable setting of simulation conditions in combination with the casting solidification process of the wheel.

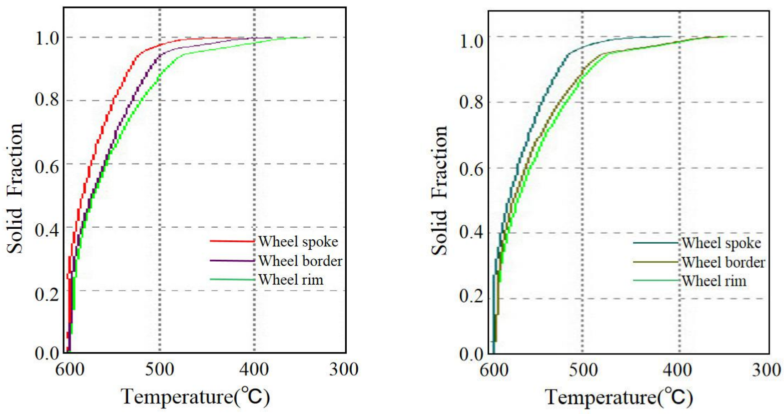
Through the analysis of shrinkage during solidification, we can get wheel solidification shrink.The fastest shrinking place is 2.3092C/s.Through the analysis of the cooling rate in different shrinkage analysis, we can get the defects easily during the solidification process. Wheel solidification shrink were shown in below Fig.3.12.



(a) (b)

Fig.3.12 Wheel solidification shrink.

Through the details of the wheel solidification, we can get the different characteristics of wheel solidification. At the percentage of 95%, the wheel rim almost completely solidified.As can be seen from the figure,there were no shortage in the castings.After optimization, the defects are significantly reduced.Reasonable casting model could be obtained by optimized model.Wheel solidification process were shown in below Fig.3.13.

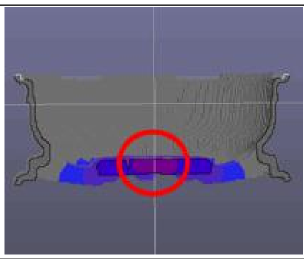
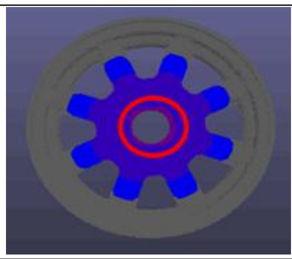
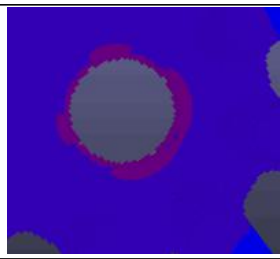
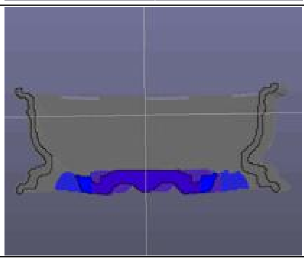
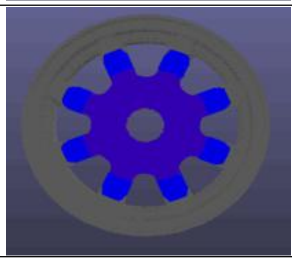
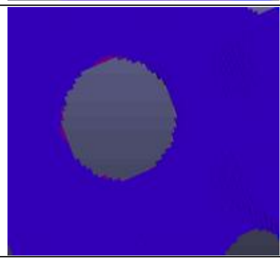


(a) 8 riser (b) 6 riser

Fig.3.13 Wheel solidification.

The solidification process affects subsequent process performance, performance and life,it has very important research significance. From solidification analysis of AZ91D magnesium alloy, a solid solution starts to form and heat is released at the same time.As the solidification progresses sensor, the wheel spoke first tend to stabilize, then the wheel border tend to stabilize, at last wheel rim tend to stabilize. From cooling rate of casting model, analysis of different cooling rate positions can obtain the solidification characteristics of each part.Comparison of wheel casting model were shown in below Table 3.3.

Table 3.3 Comparison of wheel casting model.

Comparison			
Original design			
Final design			

Through the simulation in the casting process, a rational casting model is established for the casting process.Combined with above analysis results and compare the casting models,red circle in the original design were prone to have temperature unevenness and defects,the final design model have fewer uneven temperature and fewer defects. In the solidification analysis, the solidification process before optimization needs 526s,the optimized solidification process needs less. Compared with the different casting processes, the magnesium alloy wheel final
design casting process reduced the time. By redesign riser model to get the suitable casting model,target of reduce shrinkage were obtained.Comparing the model before and after to get the optimal casting model.Optimized magnesium alloy wheel casting model were shown to have better casting performance than original design while meeting casting criteria. Therefore, in addition to studying the casting and materials characteristics, it is critical to optimize the weight of magnesium alloy wheels and the wheel casting process performance.

3.5 Conclusions

In summary of the detailed researched, the results of the simulations led to the following conclusions:

(1) This research design a new model of magnesium alloy wheel.Topology optimization were used to ensure the wheel lightweight design,designed magnesium alloy wheel were 32% lighter compared to aluminum alloy wheel. Using finite element analysis for performance of the wheel strength and modal correlation analysis,magnesium alloy wheel better performance were proved.

(2) Casting of magnesium alloy wheels is a complicated process.Through the simulation in the casting process, a rational casting model is established for the casting process.The rationality of lightweight design of magnesium alloy wheels and casting model were verified. By simulation analysis of the wheel casting,the distribution data of different parts of the wheel at different times were obtained. By optimization of the casting model to get the final suitable casting model.Comparing the model before and after optimization to get the optimal casting model.

Our study opens avenues for the next generation of wheel design and casting. The actual casting of the wheel castings were simulated and the change law were obtained, which also played an exemplary role in the engineering application of numerical simulation technology and production.

References

[1] Messana A, Sisca L, Getti C M, et al. Design, Optimization and Manufacturing of an Aluminum Wheel Rim for the IDRAkronos Vehicle Prototype[J]. 2019.

[2] Loi C Y, Choy H Y. Modelling and Fatigue Analysis of Automobile Wheel Rim[C]//2019 5th International Conference on Control, Automation and Robotics (ICCAR). IEEE, 2019: 696-701.

[3] Mandage A P, Sharma M H, Rayate A K, et al. Fatigue Life Estimation of an Aluminium Wheel Rim Using Finite Element Analysis[J]. 2016.

[4] Deaton J D, Grandhi R V. A survey of structural and multidisciplinary continuum topology optimization: post 2000[J]. Structural and Multidisciplinary Optimization, 2014, 49(1): 1-38.

[5] Das S. Design and weight optimization of aluminum alloy wheel[J]. International Journal of Scientific and Research Publications, 2014, 4(6): 1-12.

[6] Wang Y, Li D, Peng Y, et al. Numerical simulation of low pressure die casting of magnesium wheel[J]. The International Journal of Advanced Manufacturing Technology, 2007, 32(3-4): 257-264.

[7] Zhao M J, Wu Z L, Chen Z R, et al. Analysis on flow control forming of magnesium alloy wheel[C]//IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2017, 170(1): 012006.

[8] Jiang J, Wang Y, Chen G, et al. Comparison of mechanical properties and microstructure of AZ91D alloy motorcycle wheels formed by die casting and double control forming[J]. Materials & Design, 2012, 40: 541-549.

[9] Aguilar J, Schievenbusch A, Kättlitz O. Investment casting technology for production of TiAl low pressure turbine blades–process engineering and parameter analysis[J]. Intermetallics, 2011, 19(6): 757-761.

[10] Gao J W, Wang C Y. Modeling the solidification of functionally graded materials by centrifugal casting[J]. Materials Science and Engineering: A, 2000, 292(2): 207-215.

[11] Dabade U A, Bhedasgaonkar R C. Casting defect analysis using design of

experiments (DoE) and computer aided casting simulation technique[J]. Procedia CIRP, 2013, 7: 616-621.

[12] JIN X, LI S, LIU X, et al. Numerical simulation of a die casting magnesium wheel [J]. Ordnance Material Science and Engineering, 2005, 2.

[13] Bouzakis K D, Maliaris G, Tsouknidas A. FEM supported semi-solid high pressure die casting process optimization based on rheological properties by isothermal compression tests at thixo temperatures extracted[J]. Computational Materials Science, 2012, 59: 133-139.

[14] Guo Z, Saunders N, Miodownik A P, et al. Modelling of materials properties and behaviour critical to casting simulation[J]. Materials Science and Engineering: A, 2005, 413: 465-469.

[15] Motoyama Y, Takahashi H, Inoue Y, et al. Development of a device for dynamical measurement of the load on casting and the contraction of the casting in a sand mold during cooling[J]. Journal of Materials Processing Technology, 2012, 212(6): 1399-1405.

[16] Zhao G, Li X Z, Xu D, et al. Numerical computations for temperature, fraction of solid phase and composition couplings in ternary alloy solidification with three different thermodynamic data-acquisition methods[J]. Calphad, 2012, 36: 155-162.

[17] Dabade U A, Bhedasgaonkar R C. Casting defect analysis using design of experiments (DoE) and computer aided casting simulation technique[J]. Procedia CIRP, 2013, 7: 616-621.

[18] Ravi B. Casting simulation and optimisation: benefits, bottlenecks and best practices[J]. Indian Foundry Journal, 2008, 54(1): 47.

[19] Deepak S V, Naresh C, Hussain S A. Modelling and analysis of alloy wheel for four wheeler vehicle[J]. International journal of mechanical engineering and robotics research, 2012, 1(3): 72-80.

[20] Han S L, Yang L, Wang G S, et al. Innovative design and static analysis of magnesium alloy automobile wheel[C]//Applied Mechanics and Materials. Trans Tech Publications, 2012, 120: 85-88.

[21] Yildiz A R. Optimal structural design of vehicle components using topology design and optimization[J]. Materials Testing, 2008, 50(4): 224-228.

[22] MARIN L, Kedziora S. Design of Automotive Road Racing Rim with Aid of Topology Optimization[R]. Faculty of Science, Technology and Communication University of Luxembourg, 2016.

[23] Westengen H. Magnesium alloys for structural applications; recent advances[J]. Le Journal De Physique IV, 1993, 3(C7): C7-491-C7-501.

[24] ZHANG Z, YANG G, YANG Y, et al. Research on Characteristics of Cooling and Solidification of AZ91D Mg-alloy [J]. Hot Working Technology, 2010, 1.

[25] Davis T A. Development of novel grain refiners for AZ91D magnesium alloys and their effect on hot tearing[D]. University of British Columbia, 2019.

[26] HU Q, LIU B, YU M, et al. Design and optimization of casting system of die casting die for magnesium alloy based on numerical simulation [J]. Die & Mould Industry, 2009, 7(3): 3.

[27] Mangoyan O. Method and System for Casting Metal: U.S. Patent Application 15/331,336[P]. 2018-4-26.

[28] Sun D, Qi W, Yang X, et al. Simulation and Optimization for Casting of Boom Stand Based on AnyCasting[C]//IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2019, 493(1): 012116.

[29] Lewis R W, Manzari M T, Ransing R S, et al. Casting shape optimisation via process modelling[J]. Materials & Design, 2000, 21(4): 381-386.

[30] Tavakoli R, Davami P. Optimal riser design in sand casting process by topology optimization with SIMP method I: Poisson approximation of nonlinear heat transfer equation[J]. Structural and Multidisciplinary Optimization, 2008, 36(2): 193-202.

[31] Kong L X, She F H, Gao W M, et al. Integrated optimization system for high pressure die casting processes[J]. Journal of materials processing technology, 2008, 201(1-3): 629-634.

Chapter 4 Optimization of Magnesium Alloy Wheel Dynamic Impact Performance

4.1 Introduction

Recently, with the increasingly stringent regulatory requirements for energy conservation and emission reduction, there has been a significant increase in the use of magnesium as a structural material because of the lightness of magnesium alloys. Magnesium alloys are structural materials with favorable properties such as low density, high specific strength, high specific stiffness, good vibration dampening characteristics, and excellent castability, and have been extensively studied. The use of magnesium material in cars will increase by 15% (~227 kg) by 2020 based on future projections for magnesium[1-2]. In addition, magnesium alloys are well known damping materials[3-6]. Therefore, magnesium alloys are very attractive for application in the automotive industry for the development of lightweight automotive vehicles to meet energy saving and environmental protection requirements.

The finite elements method is currently one of the fastest developing and most popular numerical methods used in the aviation, automotive, shipbuilding, manufacturing, and electrotechnics industries[7-10]; many contemporary industrial fields; and also modern technologies supported by computers[11-12]. The demand for ride comfort has also increased, therefore numerous studies have focused on its improvement[13-15]. Modal correlation is now a well-established discipline and the finite elements method is an equivalent way of assessing modal models and describing the dynamic behavior of a system. Studies have shown that the density of mobile dislocation and dislocation movement influence the damping capacity of magnesium and magnesium alloys, and the mobile dislocation movement under stress dissipates a large amount of the vibration energy, making it an important source of the high damping capacity of magnesium alloy[16-20]. Ji-Hun Bae[21] studied a wheel with high damping capacity without compromising it structural stiffness.

In this work good damping capacity was demonstrated for AZ91 magnesium alloy. Theoretical models were applied and experimental results showed damping with nonlinearity characteristics. The rational testing and characterization of the damping capacity of AZ91 magnesium alloy carried out in this research demonstrates the damping advantages of magnesium alloys. The favorable damping characteristics of AZ91 magnesium alloy were demonstrated through the comparison of AZ91 magnesium alloy, 6061-T6 aluminum alloy, and SPFH540 steel. The wheel responses for different materials and damping ratios were evaluated. Design optimization is a powerful tool for machinery design, and can produce the best blueprint for structural design. In this work, the wheel structure topology optimization method is used to optimize the wheel design, to satisfy the lightweight and dynamic impact performance requirements. The structure of the wheel spokes was altered in combination with the characteristics of structural damping, to design different wheel structures, and the vibration damping performance was analyzed. Consequently, the designed magnesium alloy wheel was shown to have improved ride comfort while satisfying the requirements of wheel structural performance standards and lightweight design.

4.2 Dynamic impact theory and method

In this study, AZ91 magnesium alloy, 6061-T6 aluminum alloy, and SPFH540 steel were used for material vibration analysis. Analysis and experiments were also carried out to analyze the damping ratio and the material damping mechanism. Three materials were used for the analysis and calculations as listed in table 4.1.

Table 4.1 The properties of aluminum, steel, and magnesium.

Material properties	Aluminum (6061-T6)	Magnesium (AZ91)	Steel (SPFH540)
Density (kg/m³)	2700	1830	7850
Modulus of Elasticity (GPa)	69	45	210
Poisson ratio	0.33	0.35	0.3
Yield strength (GPa)	0.276	0.16	0.355

(a) Mechanical properties of aluminum, steel, and magnesium

Material	Magnesium (%)	Aluminum (%)	Zinc (%)	Manganese (%)	Silicon (%)	Iron (%)	Other elements (%)
Magnesium (AZ91)	Remainder	8.3-9.7	0.35-1.0	0.15-0.5	0.1 max	0.004 max	0.3 max

(b) Composition of Magnesium alloy

Material	Aluminum (%)	Silicon (%)	Iron (%)	Copper (%)	Magnesium (%)	Zinc (%)	Other elements (%)
Aluminum (6061-T6)	Remainder	0.4-0.81	0.7 max	0.15-0.4	0.8-1.2	0.25 max	0.15 max

(c) Composition of Aluminum alloy

The composition of the AZ91 magnesium alloy and 6061 aluminum alloy and their thermomechanical treatment were considered. The thermal properties of AZ91 magnesium alloy were: melting temperature, ~533°C; specific heat capacity, 1020 J/(kg·K); thermal conductivity, 51 W/(m·K). The thermal properties of 6061 aluminum alloy were: melting temperature, ~585°C; thermal conductivity, 151–202 W/(m·K); specific heat capacity, 897 J/(kg·K). These properties combined with the material properties to influence our findings[22-27].

Magnesium alloys are light metal materials. The damping of magnesium and AZ91 magnesium alloy at room temperature is primarily dislocation damping. Currently, a classic theory to illustrate the dislocation damping mechanism is the Granato–Lücke dislocation damping theory[28-29]. Numerous researchers have tested the damping properties of various magnesium and magnesium alloy materials with different structures (such as porous structure), and have obtained a variety of performances related to damping. The examples also include the damping material for performance research such as vibration and frequency response[30-35]. The performance test data characteristics are essentially in line with the G-L dislocation pinning theory model.

The vibration system can vibrate according to its natural frequency when the object leaves the equilibrium position under the action of external force, and no longer requires the role of an external force. This vibration that is not under the action of an external force is known as free vibration. The period of free vibration is called the natural period. The frequency at which vibration is free is called the natural frequency and is determined by the conditions of the vibration system, independent of amplitude. When the frequency of the driving force is equal to the natural frequency of the object, the amplitude reaches the maximum, which is the resonance.

In a damped free vibration system, the vibration equation of the system can be calculated. The forced vibration equation under the simple harmonic excitation of the single degree of freedom system is as follows:

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{4-1}$$

In the equation, f(t) is the force acting on the system, m is mass, c is viscosity, and k is the spring constant. Performing the Laplace transform on both sides of the above equation gives:

$$m(s^2 + cs + k)X(s) = F(s) \tag{4-2}$$

In the equation： $s = \delta + jw$ is the Laplace transform factor;

$X(s) = \int_0^{\infty} x(t)e^{-st}dt$ is the transformation of displacement response;

$F(s) = \int_0^{\infty} f(t)e^{-st}dt$ is the transformation of f(t).

$$Z(s) = ms^2 + cs + k \tag{4-3}$$

It has a stiffness property known as the system dynamic stiffness. The reciprocal is known as the transfer function. Combined with the above equation, H(s) can be expressed.

$$H(s)=\frac{1}{ms^2+cs+k} \quad ,H(s)=\frac{X(s)}{F(s)} \tag{4-4}$$

For the actual vibration system, the transfer function is the ratio of the vibration system measuring point x(t) and the system incentive point f(t). Using jω instead of s does not lead to loss of information useful to the system. Therefore, Fourier transforms are performed on both sides of the equation to obtain:

$$X(w)=H(w)\cdot F(w) \tag{4-5}$$

The velocity transfer function and acceleration transfer function of the system are available:

$$H^V(w)=\frac{X(w)}{F(w)}=\frac{jw}{k-w^2m+jwc} \tag{4-6}$$

$$H^A(w)=\frac{X(w)}{F(w)}=-\frac{w^2}{k-w^2m+jwc} \tag{4-7}$$

The material properties were studied based on the theory related. Combination with the attenuation waveform to obtain vibration characteristics, allowed the ratio of the absolute values of two adjacent amplitudes in a half cycle to be calculated. The ratio of the absolute values of two adjacent amplitudes was the waveform attenuation coefficient. Curves of free decay vibration are shown in Fig.4.1, the damping ratio ξ can be calculated using the following equation:

$$\zeta=\frac{1}{2\pi}\log_e\frac{a_n}{a_{n+1}} \tag{4-8}$$

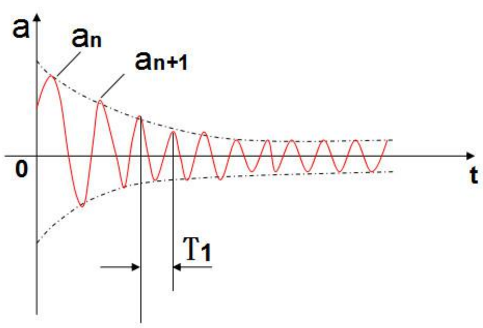


Fig.4.1 Curves of free decay vibration.

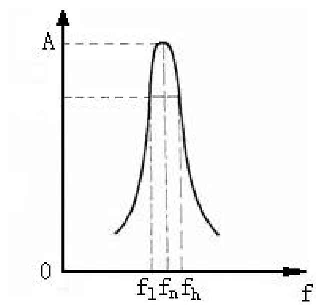


Fig.4.2 Diagram of resonant peak.

The frequency-sweeping method is also used for testing the damping of material, as shown in Fig.4.2. When the frequency-sweeping method is used for testing the damping of material, a resonance peak appears near the resonance frequency and related parameters can be calculated.

4.3 Establishing the wheel dynamic impact model

4.3.1 Wheel dynamic impact model

The wheel spokes, disc, and rim are the main parts of a wheel. When designing wheels, safety and engineering standards must be considered. Design optimization is a powerful tool for machinery design, and can establish the best method for structural design. In wheel design and optimization, the lightest weight is the optimal design goal[36-38]. The wheel structure was optimized based on optimization theory. Wheel models are shown in Fig.4.3.

(a) 3D model (b) FE model

Fig.4.3 Magnesium alloy wheel.

In order to estimate the damping performance of the wheel, a vibration test was carried out. The use of experimental modal analysis methods to identify modal parameters of mechanical components with complex structures is also important for understanding their dynamic characteristics. It is possible to obtain modal parameters such as the natural frequency of the complex structure in the free state and the constrained state, as well as the corresponding mode shapes, and the results of the experimental analysis are extremely accurate. Analysis of the performance of the designed wheel was carried out in addition to the analysis of the materials and the vibration characteristics of the wheel.

4.3.2 Material properties

In the damping test, the impact load is imposed on the test specimen and the waveform of the free decay vibration is obtained. The damping test of the different materials is outlined in Fig.4.4 below.

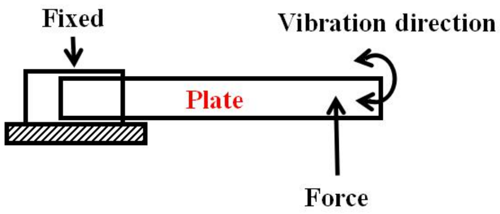


Fig.4.4 Damping verification plate.

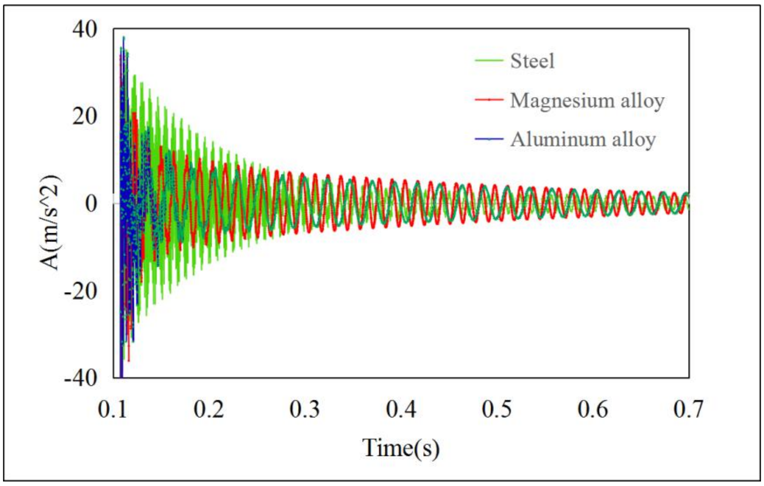
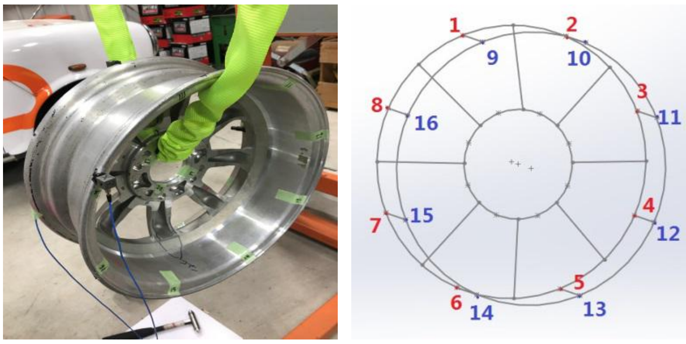


Fig.4.5 Vibration amplitudes of magnesium alloy, aluminum alloy, and steel.

Based on the vibration results data for the damping ratio in Fig.4.5, and combining the two methods, the damping ratio of the AZ91 magnesium alloy was calculated to be ~0.01081, the damping ratio of 6061 aluminum alloy was ~0.00695, and the damping ratio of SPFH540 steel was ~0.00471. Comparison of the damping ratios shows that the AZ91 magnesium alloy had the best damping characteristics.

4.3.3 Wheel dynamic impact analysis model verification

Model verification is necessary for finite element analysis. A vibration test was carried out in order to estimate the damping performance of the wheel. Free suspension is more repeatable than using a flexible support, as it does not introduce the vibration of the supporting gantry or the surrounding experimental environment. The wheel structure as a whole is a symmetrical structure, when determining the stimulus and response points, it can be selected in a symmetrical manner. An impact hammer and accelerator were used, by hanging the wheel in the air to set the boundary condition free, using LMS for signal acquisition. In order to ensure the accuracy of the test results, the vibration data was collected multiple times for each test and the frequency response function of each test point was obtained using computer software calculations. The vibration test was carried out as shown in Fig.4.6 below.

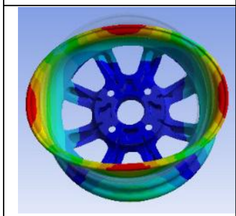
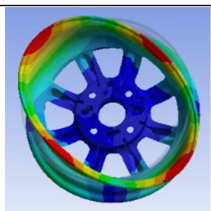
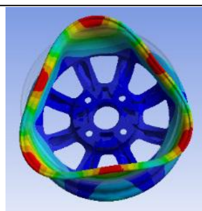
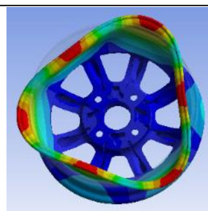
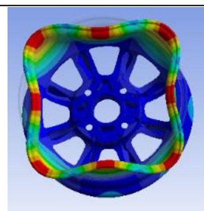
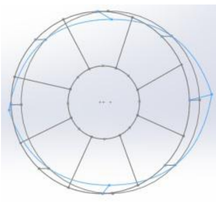
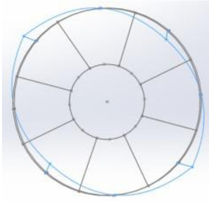
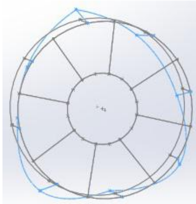
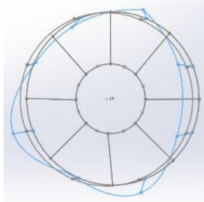
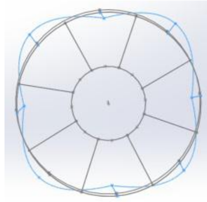


(a) (b)

Fig.4.6 Wheel modal test.

The comparison of the computational results and the experimental results is shown in table 4.2.

Table 4.2 Comparison of computational and experimental data.

Computational				
Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
				
Experimental				
Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
				

(a)

Mode 1	Experimental (Hz)	Computational(Hz)	Error
1	474.5	466.1	1.8%
2	480.4	494.3	2.7%
3	948.1	954.8	0.6%
4	948.5	959.1	1.1%
5	1582.8	1489.2	5.9%

(b)

It can be seen from the mode shape diagram that the mode shape of the wheel is primarily on the wheel rim, the low-order mode shapes were distributed on both sides of the rim, and the high-order mode shapes were distributed in the middle of the rim. As the natural frequency increases, the mode shape of the wheel structure becomes increasingly complex. The error between the computational and experimental result was within 10%, demonstrating the agreement between the model and test. The modal analysis evaluates the natural frequency, mode shape, and other related parameters of the object, which are the essential properties of any object with invariance and stability. Therefore, the finite element model was verified by modal experimental analysis and the dynamic impact performance comparison of different damping material wheels such as AZ91 magnesium alloy, 6061-T6 aluminum alloy, and SPFH540 steel could be carried out.

4.4 Results and Discussion

4.4.1 Wheel dynamic impact performance analysis results

The vibration response of the AZ91 magnesium alloy and 6061-T6 aluminum alloy were calculated by the frequency response analysis method. Vibration response results of the two materials under the same excitation load can be obtained. This research is primarily focused on the vertical road direction excitation and response. When applying vibration excitation to the center of the wheel with a vertical road surface, the response position is the other side of the vertical road surface where the wheel excitation point is symmetrical. An input load of 1 N with varying frequency was applied at the wheel application point. Constraints were established on the wheel rotary table. A magnesium alloy wheel and excitation load application in the finite element model of the wheel are shown in Fig.4.7 and 4.8 respectively.

Fig.4.7 Magnesium alloy wheel.

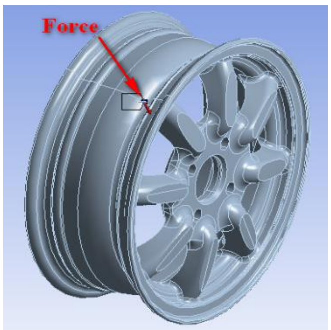
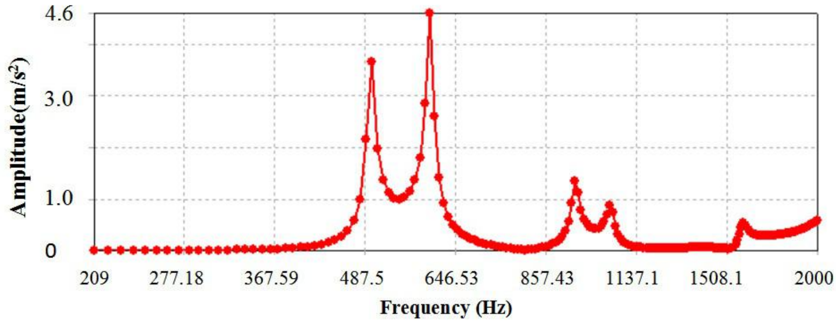
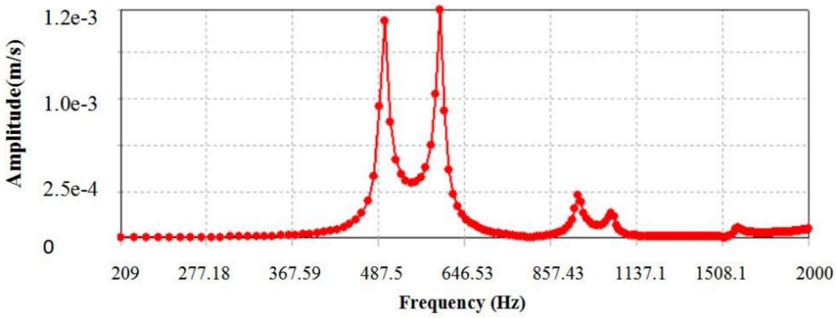


Fig.4.8 Wheel response model.

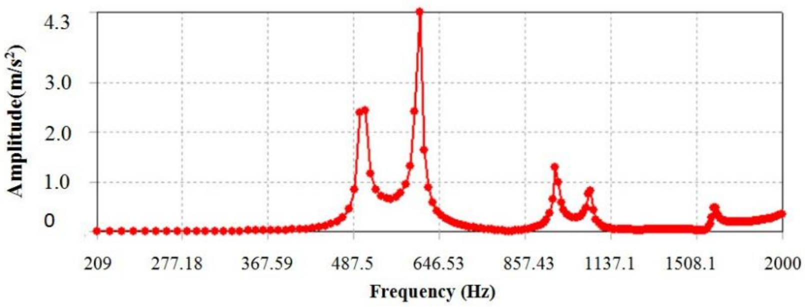
Through the comparative analysis of the vibration acceleration and the velocity of the identical position vibration response points at the center of the wheels made of the two materials, it was determined that the AZ91 magnesium alloy wheel damping and vibration damping performance was good. The wheel response characteristics are shown in Fig.4.9 and 4.10.



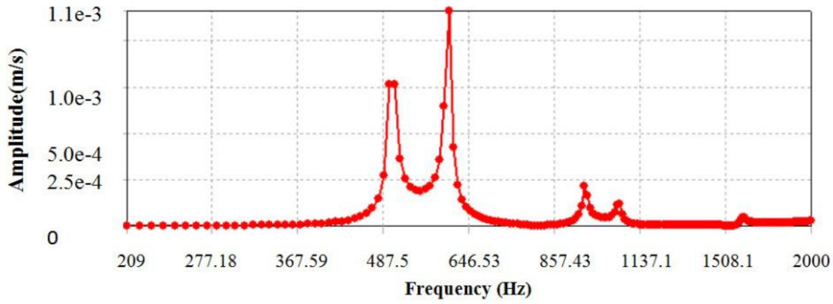
(a) Magnesium alloy a



(b) Magnesium alloy v

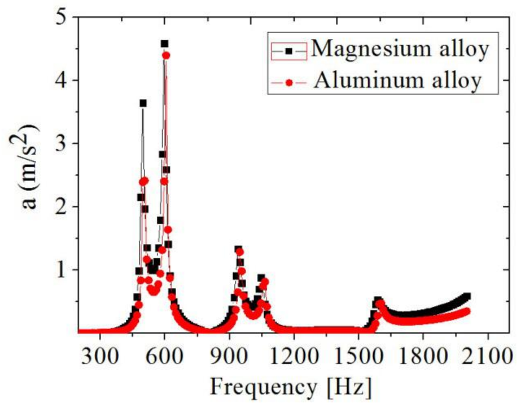


(c) Aluminum alloy a

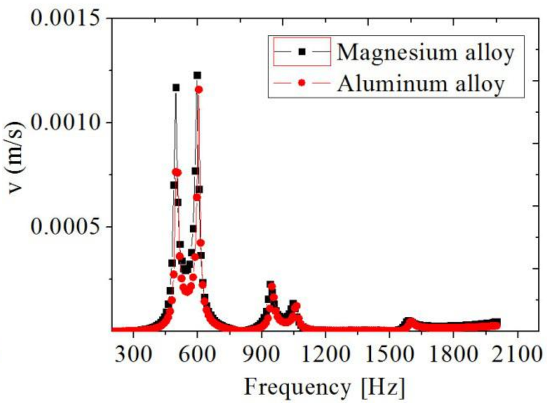


(d) Aluminum alloy v

Fig.4.9 The results of simulations.



(a)



(b)

Fig.4.10 Wheel response results comparison.

The spectrograms of the corresponding vibration and acceleration are shown in Fig.4.10. The frequency responses were analyzed and the velocity and acceleration results were obtained. The vibration response of the cover of the two materials is mainly determined by the stiffness, damping ratio, and excitation frequency. These results show that the vibration characteristics of the wheel are different under different damping ratios. Comparisons among the different results:

(1) While ensuring lightweight conditions, magnesium alloy wheels give acceleration and velocity changes similar to those for aluminum alloy wheels. The magnesium alloy wheel acceleration peak was 4.6 m/s^2 as shown in Fig.4.9 (a), the velocity peak was 1.2×10^{-3} m/s as shown in Fig.4.9 (b). The magnesium alloy frequency response was in an acceptable range compared with aluminum alloy. The influence of the damping ratio on the wheel was studied based on the damping characteristics.

(2) Using the AZ91 magnesium alloy material with high damping ratio is effective for vibration reduction. The 6061-T6 aluminum alloy acceleration peak was 4.3 m/s^2 and the velocity peak was 1.1×10^{-3} m/s. Aluminum alloy wheels showed better vibration performance than magnesium alloy wheels with the same structure. Therefore, the optimization of magnesium alloy wheel dynamic impact performance is important.

4.4.2 Wheel structure design optimization to improve structural damping

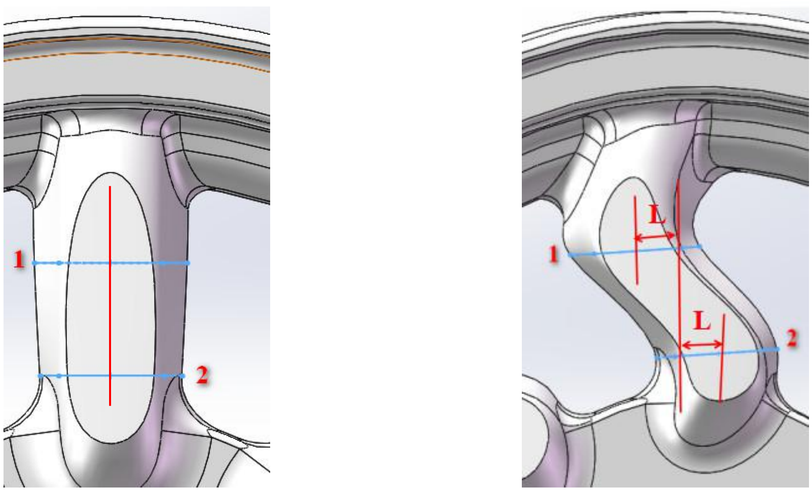
The objective function is the maximum damping coefficient, the design variable is the bending inertia coefficient and area in x and y directions, they can be obtained by changing the size in the S-shaped structure.

$$C = \alpha M + \beta K \tag{4-8}$$

In the equation, l is the amount of offset center in S type. α , β is damping coefficient. M,K is mass matrix and stiffness matrix.The constraint is the a points.In the formula above, by changing the structure size, the final maximum damping characteristics can be obtained.

$$\begin{cases} \text{Find that: variable}(x, y, l) \\ \text{Objective: Max } \beta \\ \text{Constraint: } \beta > 1 \text{ or } \beta \to 1 \end{cases} \tag{4-9}$$

The effect of altering the wheel structures was evaluated in combination with the different damping properties of the structures. Based on the relevant theoretical knowledge, the modal and frequency response performance of the bending structure model will change. The offset positions are indicated in Fig.4.11.



(a) (b)

Fig.4.11 Structural optimization.

Table 4.3 shows the size of the adjustments.

Table 4.3 Wheel optimization.

Name	Wheel a	Wheel b	Wheel c	Wheel d	Wheel e	Wheel f
Size L/mm	0	5	7.5	10	12.5	15

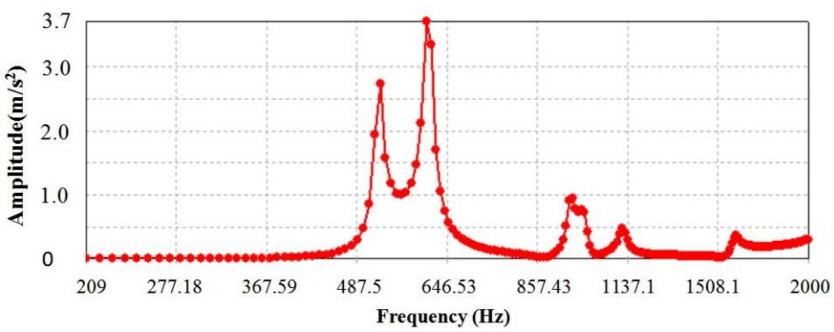
The models of the optimized wheel designs combined with structural design criteria and stress-strain related parameters are shown in Fig.4.12.

Wheel a Wheel b Wheel c

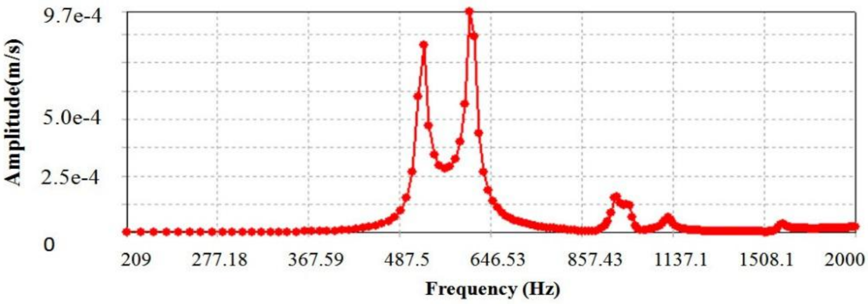
Wheel d Wheel e Wheel f

Fig.4.12 Different wheel structures.

Combining the wheel structure damping characteristics and material damping characteristics, the frequency response and vibration related performance of wheels with different structures are shown in Fig.4.13 and Fig.4.14.



(a)



(b)

Fig.4.13 The results of the optimized wheel simulation.

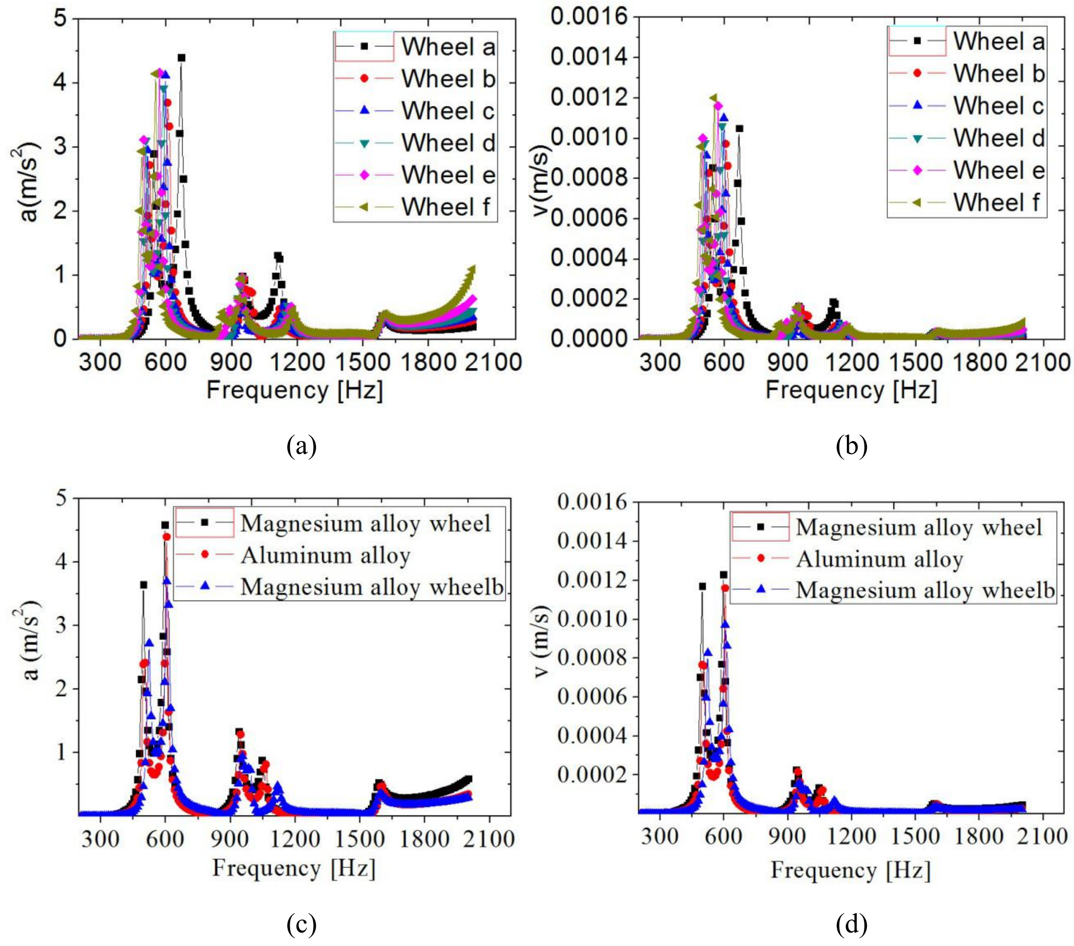


Fig.4.14 Different wheel analysis results.

From the overall analysis results in Fig.4.12–4.14, it was found that the Fig.4.12 wheel b structure reduced both acceleration and velocity effectively, which could result in enhanced ride comfort and a better vibration performance. Replacing 6061-T6 aluminum alloy with the lightweight material AZ91 magnesium alloy resulted in a 76.7% weight reduction. Based on the results above, considering both the material and structural characteristics:

(1) Based on the damping characteristics and the wheel structure, vibration performance analyses of different wheel structures were obtained. Magnesium alloy wheel *b* acceleration and velocity data are included in Fig.4.13 (a) and Fig.4.13 (b).

(2) The response characteristics of the wheel were obtained by changing the wheel structure. When the wheel structure was a, b, c, d, e, and f in Fig.4.12, the acceleration peak was 4.6, 3.7, 4.1, 3.9, 4.2, and 4.1 m/s^2, respectively, as shown in Fig.4.14 (a). The velocity of the different damping ratios was 1.2×10^{-3}, 9.7×10^{-4}, 1.1×10^{-3}, 1.1×10^{-3}, 1.2×10^{-3}, and 1.2×10^{-3} m/s, respectively, as shown in Fig.4.14 (b). This demonstrates that the acceleration and velocity performance can be altered by changing the magnesium alloy wheel structure. Magnesium alloy wheel *b* was the best structure tested in terms of vibration performance.

(3) Using a magnesium alloy structure with bent wheel spokes can effectively reduce vibration. Fig.4.14 (a) shows that, compared with the original magnesium alloy wheel design (*a*), magnesium alloy wheel *b* reduced the acceleration by 19.5% and the velocity by 19.1%. When bending of the wheel spokes was continued—wheel *c*, wheel *d*, wheel *e*, and wheel *f*—the acceleration and velocity rose. Magnesium alloy wheel *b*, which showed higher damping ratio, is expected to show better vibration performance. Table 4.4 shows the wheel performance comparison.

Table 4.4 Wheel performance comparison.

Wheel performance				Improvement /%
Weight/kg		Magnesium Alloy	4.0	_
		Aluminum Alloy	5.9	32.3
		Steel	17.2	76.7
Vibration	Acceleration/ m/s^2	Aluminum alloy	4.3	13.9
		Magnesium Alloy	4.6	19.5
		Magnesium Alloy (Optimized wheel b)	3.7	_
	Velocity/m/s	Aluminum alloy	1.1e-3	11.8
		Magnesium Alloy	1.2e-3	19.1
		Magnesium Alloy (Optimized wheel b)	9.7e-4	_

Based on material damping and structural damping, combined with stress and total deformation analysis, the most significant structure was found to be the Fig.4.12 wheel *b* structure. The wheel structure meet the static force test requirements when the structure of the magnesium alloy wheel *b* acceleration peak was 3.7 m/s^2 and the velocity peak was 9.7×10^{-4} m/s. Compared with the aluminum alloy wheel, the magnesium alloy wheel *b* reduced the acceleration by 13.9% and the velocity by 11.8%. Optimized magnesium alloy wheels were shown to have better vibration performance than aluminum alloy wheels while meeting lightweight design criteria. Therefore, in addition to studying the damping characteristics, it is critical to optimize the weight of magnesium alloy wheels and the vibration reduction performance.

4.5 Conclusions

In order to improve the ride comfort and reduce the weight of automotive vehicles, we designed a magnesium alloy wheel based on structural optimization and dynamic impact performance. In summary of the detailed researched, the results of the simulations and experiments led to the following conclusions:

(1) Study of the damping properties of the materials showed favorable damping properties for the magnesium alloy material. Based on the findings of structural optimization and dynamic impact theory, magnesium alloy wheels were designed and manufactured. Compared with the aluminum alloy wheel, the magnesium alloy wheel design can reduce the weight by 32.3%. The designed wheels meet the lightweight requirements in comparison with aluminum wheels, which is expected to increase ride comfort by reducing vibrations.

(2) Damping test methods for the magnesium alloy sample were designed to obtain the damping performance parameters of the magnesium alloy material. Finite element analysis models of the magnesium alloy wheels were established with certain boundary conditions and constraints. The applicability of the model was verified by the free modal experiments on the wheel. Dynamic impact simulation analysis of the designed wheels was carried out, and the dynamic speed response of magnesium alloy wheels under the impact of a dynamic load on the road surface was obtained.

(3) By defining the structural parameters of the magnesium alloy wheel and taking the acceleration and shock response of the wheel as the output, structural design optimization of the wheel was carried out to obtain the optimal magnesium alloy wheel structural parameters. The target of lightweight and high dynamic impact performance magnesium alloy wheels was achieved through optimization. Compared with the aluminum alloy wheel, the optimized magnesium alloy wheel *b* reduced the acceleration by 13.9% and the velocity by 11.8%, which is expected to increase ride comfort while satisfying the requirements for a lightweight wheel.

Our study opens avenues for the next generation of wheel design. This technique can be applied to a multitude of machine components to enhance various structure vibration performance values. We believe that our analysis can also be used to enhance the response of vibration reduction and lightweight wheel design. We hope that our results will instigate a resurgence of interest in the application of damping material for wheels and motivate future exploration of the effect of other types of structures on wheel vibration behavior.

References

[1] Cole G S. Magnesium vision 2020-a north american automotive strategic vision for magnesium[C]//IMA-PROCEEDINGS-.International Magnesium Association, 2007: 13.

[2] Upadhyayula, Venkata KK, et al. "Lightweighting and electrification strategies for improving environmental performance of passenger cars in India by 2030: A critical perspective based on life cycle assessment." Journal of Cleaner Production 209 (2019): 1604-1613.

[3] Xianhua C, Yuxiao G, Fusheng P. Research progress in magnesium alloys as functional materials[J]. Rare Metal Materials and Engineering, 2016, 45(9): 2269-2274.

[4] Jiang H J, Liu C Y, Zhang B, et al. Simultaneously improving mechanical properties and damping capacity of Al-Mg-Si alloy through friction stir processing[J]. Materials Characterization, 2017, 131: 425-430.

[5] Avedesian, Michael M., and Hugh Baker, eds. ASM specialty handbook: magnesium and magnesium alloys. ASM international, 1999.

[6] LI Y, CHENG H. Research status and Prospect of Damping Magnesium Alloys[J]. Electrical Engineering Materials, 2016 (5): 10.

[7] Ding Y, Ju D. Finite Element Analysis of Residual Stress in the Diffusion Zone of Mg/Al Alloys[J]. Advances in Materials Science and Engineering, 2018, 2018.

[8] Da Silva Botelho T, Bayraktar E, Inglebert G. Experimental and finite element analysis of spring back in sheet metal forming[J]. International Journal of Computational Materials Science and Surface Engineering, 2007, 1(2): 197-213.

[9] Lenik K, Wójcicka-Migasiuk D. FEM applications to the analysis of passive solar wall elements[J]. Journal of Achievements in Materials and Manufacturing Engineering, 2010, 43(1): 333-340.

[10] Srikanth N, Gupta M. Estimation of elasto-thermodynamic damping in the Al/SiC system using a finite element approach[J]. Acta materialia, 2006, 54(17): 4553-4563.

[11] Zhang S, El Kerdi O, Khurram R A, et al. FEM analysis of in-flight ice break-up[J]. Finite elements in analysis and design, 2012, 57: 55-66.
[12] Cook R D, Malkus D S, Plesha M E, et al. Concepts and applications of finite element analysis[M]. New York: Wiley, 1974.
[13] Xu Y L, Guo W H. Effects of bridge motion and crosswind on ride comfort of road vehicles[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2004, 92(7-8): 641-662.
[14] Lee D G, Kim J S. Computer simulation of the consolidation of fiber-reinforced resin matrix composites[J]. Journal of Materials Processing & Manufacturing Science(USA), 1994, 2(4): 357-372.
[15] Uys P E, Els P S, Thoresson M. Suspension settings for optimal ride comfort of off-road vehicles travelling on roads with different roughness and speeds[J]. Journal of Terramechanics, 2007, 44(2): 163-175.
[16] Trojanová Z, Mielczarek A, Riehemann W, et al. Cyclic bending and the damping behaviour of short fibre-reinforced magnesium alloy AZ91[J]. Composites science and technology, 2006, 66(3-4): 585-590.
[17] Wang J, Lu R, Qin D, et al. Effect of arc-bending deformation on amplitude-dependent damping in pure magnesium[J]. Materials Science and Engineering: A, 2014, 615: 296-301.
[18] Wang L M, Richert R. Dynamics of glass-forming liquids. IX. Structural versus dielectric relaxation in monohydroxy alcohols[J]. The Journal of chemical physics, 2004, 121(22): 11170-11176.
[19] Smits A L M, Wübbenhorst M, Kruiskamp P H, et al. Structure evolution in amylopectin/ethylene glycol mixtures by H-bond formation and phase separation studied with dielectric relaxation spectroscopy[J]. The Journal of Physical Chemistry B, 2001, 105(24): 5630-5636.
[20] YAO Y, CHEN L, WANG W. Damping Capacities of (B4C+ Ti) Hybrid Reinforced Mg and AZ91D Composites Processed by In Situ Reactive Infiltration Technique[J]. Acta Metall Sin, 2018, 55(1): 141-148.
[21] Bae J H, Jung K C, Yoo S H, et al. Design and fabrication of a metal-composite

hybrid wheel with a friction damping layer for enhancement of ride comfort[J]. Composite Structures, 2015, 133: 576-584.
[22] Puga H, Carneiro V, Barbosa J, et al. Effect of ultrasonic treatment in the static and dynamic mechanical behavior of AZ91D Mg alloy[J]. Metals, 2015, 5(4): 2210-2221.
[23] Lindemann A, Schmidt J, Todte M, et al. Thermal analytical investigations of the magnesium alloys AM 60 and AZ 91 including the melting range[J]. Thermochimica acta, 2002, 382(1-2): 269-275.
[24] Mordike B L, Ebert T. Magnesium: properties—applications—potential[J]. Materials Science and Engineering: A, 2001, 302(1): 37-45.
[25] Mansourinejad M, Mirzakhani B. Influence of sequence of cold working and aging treatment on mechanical behaviour of 6061 aluminum alloy[J]. Transactions of Nonferrous Metals Society of China, 2012, 22(9): 2072-2079.
[26] Taban E, Gould J E, Lippold J C. Characterization of 6061-T6 aluminum alloy to AISI 1018 steel interfaces during joining and thermo-mechanical conditioning[J]. Materials Science and Engineering: A, 2010, 527(7-8): 1704-1708.
[27] Ma Y, Jin J E, Lee Y K. A repetitive thermomechanical process to produce nano-crystalline in a metastable austenitic steel[J]. Scripta Materialia, 2005, 52(12): 1311-1315.
[28] Granato A, Lücke K. Theory of mechanical damping due to dislocations[J]. Journal of applied physics, 1956, 27(6): 583-593.
[29] Granato A V, Lücke K. Application of dislocation theory to internal friction phenomena at high frequencies[J]. Journal of applied physics, 1956, 27(7): 789-805.
[30] Watanabe H, Sugioka M, Fukusumi M, et al. Mechanical and damping properties of fullerene-dispersed AZ91 magnesium alloy composites processed by a powder metallurgy route[J]. Materials transactions, 2006, 47(4): 999-1007.
[31] WANG N L，JI P G，et al.Research of M2052 high damping alloy applied in the vibration reduction of structural component[J].Journal of hebei university of technology,2017, 46(3).

[32] Tian T, Yuan Z, Tan W, et al. Effect of the dynamic evolution of dislocations under cyclic shear stress on damping capacity of AZ61 magnesium alloy[J]. Materials Science and Engineering: A, 2018, 710: 343-348.

[33] Kamesh D, Pandiyan R, Ghosal A. Passive vibration isolation of reaction wheel disturbances using a low frequency flexible space platform[J]. Journal of Sound and Vibration, 2012, 331(6): 1310-1330.

[34] Davis P, Cunningham D, Harrell J. Advanced 1.5 Hz passive viscous isolation system[C]//35th Structures, Structural Dynamics, and Materials Conference. 1994: 1651.

[35] Kamesh D, Pandiyan R, Ghosal A. Modeling, design and analysis of low frequency platform for attenuating micro-vibration in spacecraft[J]. Journal of sound and vibration, 2010, 329(17): 3431-3450.

[36] Sui Y K, Ye H L. Continuum topology optimization methods ICM [J]. 2013.

[37] Xiao D, Zhang H, Liu X, et al. Novel steel wheel design based on multi-objective topology optimization[J]. Journal of Mechanical Science and Technology, 2014, 28(3): 1007-1016.

[38] Liu J, Ma Y. A survey of manufacturing oriented topology optimization methods[J]. Advances in Engineering Software, 2016, 100: 161-175.

Chapter 5   Conclusions and recommendation

5.1 Conclusions

In this thesis, through the study of magnesium alloy materials, combined with the idea of lightweight design, a reasonable magnesium alloy wheel was designed and optimized. Research on casting analysis of magnesium alloy wheel and reasonable casting model were obtained. Dynamic performance analysis of magnesium alloy wheel were studied. We can get the following conclusions:

In Chapter 2, we design a new model of vehicle wheel and optimize the structure for lightweight. Through measuring and analyzing designed model under static force, clear and useful topology optimization result were obtained. Comparing wheel performance before and after optimization, the optimized wheel structure compliance with conditions such as strength can be obtained. Considering three different materials namely magnesium alloy, aluminum alloy and steel, the stress and strain performances of each materials can be obtained by finite element analysis. The reasonable and superior of magnesium alloy wheel for lightweight design were obtained. This research predicts the reliability of the optimization design, some valuable references are provided for the development of magnesium alloy wheel.

In Chapter 3, study on the properties of magnesium alloy materials, we designed reasonable casting model, instant filling and solidification data were obtained. Aiming at reducing casting defects, process optimization of casting riser structure were designed. Optimized casting process could reduce the probability of defects in castings, improve the quality of castings.Through the simulation and optimization in the casting process, provided a rational design for the casting process.On the basis of the foundation, it has important guiding significance for actual foundry production.

In Chapter 4, analysis of dynamic performance of magnesium alloy wheels. Damping test methods were designed to establish the damping performance parameters of the magnesium alloy material. A finite element analysis model of magnesium alloy wheels was established with certain boundary conditions and constraints. The applicability of the model was verified by free modal evaluation of the wheel. Dynamic impact simulation analysis of the designed wheels was carried out and the dynamic speed responses of magnesium alloy wheels under the impact of a dynamic load on the road surface were obtained. Comparing the dynamic impact performance of magnesium and aluminum alloy wheels with the same structure, showed that the magnesium alloy wheel achieved the target weight reduction of 32.3%, however the dynamic impact performance was reduced. In order to realize the lightweight design, the dynamic impact performance of the magnesium alloy wheel should not be inferior to that of the aluminum alloy wheel, therefore the design of the magnesium alloy wheel structure was optimized. The structural design optimization of the magnesium alloy wheel was carried out by defining the structural parameters of the wheel and using the acceleration and shock response of the wheel as the outputs. The optimization of weight reduction and dynamic impact performance of magnesium alloy wheels was achieved.

5.2 Recommendation

In this study, a reasonable magnesium alloy wheel was designed. In the future structural design, design the magnesium alloy wheel with diversify structure, make it more beautiful. Further consider the actual driving conditions. Considering the conditions of acceleration and braking of the car, the analysis of the simulation of the wheel can be more comprehensive. It can better reflect the situation of the wheel in actual use.

Research on casting analysis of magnesium alloy wheel and reasonable casting model were obtained. The numerical simulation of the micro structure of the material can be carried out to further understand the sand casting process. It can be more conducive to the study of magnesium alloy materials.

Dynamic and vibration performance advantages of magnesium alloy wheel were studied. The noise research related to magnesium alloy wheel can be simulated and tested, and the characteristics of magnesium alloy wheel in noise reduction and their possible advantages can be studied.

Related publications

[1] JIANG Xin, LIU Hai, Yoshio Fukushima, Minoru Otake, Naoki Kawada, ZHANG Zhenglai and JU Dongying. Multi-objective Optimization Design of Magnesium Alloy Wheel Based on Topology Optimization. Journal of Materials Science and Engineering:B.2019.1-2.003, 12:2019.

[2] Xin Jiang, Hai Liu, Rui Lyu,Yoshio Fukushima, Naoki Kawada, Zhenglai Zhang, Dongying Ju. Optimization of Magnesium Alloy Wheel Dynamic Impact Performance. Advances in Materials Science and Engineering.Vol.2019, Article ID 2632031. 2019

[3] Jiang X, Lyu R, Fukushima Y, M Otake and D Y Ju. Lightweight design and analysis of automobile wheel based on bending and radial loads. IOP Conference Series: Materials Science and Engineering. 2018, 372(1): 012048.

Acknowledgments

I would like to express my heartfelt thanks to Prof. Dongying Ju for for taking me as his student, providing me with the opportunity to pursue for my Ph.D. degree. Here, I would like to give my sincere thanks to Prof. Ju for his support, encouragement and guidance throughout my study. Without his support I could not have achieved so much.

I would like to thank Prof. Fukushima Yoshio and Prof. Otake Minoru, they give patient guidance to my thesis and experiment. I wish to sincerely thank Prof. Huruya seizo, Prof. Masataka Kosaka, Prof. Negishi Riichirou and staff at SIT for their help.

Thanks to Dr. Liu Hai who gave me guidance in the details of experiments and paper. I express my gratitude here. I would like to thank our visiting scholars Dr. Zhou Weimin, Dr. Zhao Huijun and Dr. Zhang Jian for give me precious suggestions. I would like to sincerely thank all the people who taught and gave hands to me.

My thanks also go to the members of Ju laboratory. I would like to express my sincere gratitude to all the people who have provided information to me for giving me the chance to study abroad.I would like to sincerely gratitude all the relatives who have encouraged and supported me to pursue the Ph.D.

I would like to dedicate this work to my parents, my deep appreciation is to my parents for their love, support and encouragement throughout my study and graduate work.