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Lightweight design of steering knuckle structure for vehicles based on topology optimization

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A B S T R A C T

The automotive industry has experienced rapid development in recent years, with a significant increase in the number of vehicles in China. To effectively reduce the energy consumption and carbon emissions of automobiles, implementing lightweight design for the steering knuckle structure is essential. In this paper, in order to prepare steering knuckle parts with less weight, the material of steering knuckle was changed from 40Cr to polyether ether ketone (PEEK), which has less density, while maintaining the performance of the part. Fused deposition molding (FDM) technology, as one of the main methods of thermoplastic material manufacturing, has the ability to machine any complex geometrical structure, which greatly enhances the degree of design freedom. However, in the case of FDM technology, the print parameters determine the performance of the printed sample. Based on this, this paper will explore the influence of process parameters on the mechanical properties of PEEK materials through orthogonal experiments to screen out the optimal parameter combinations for printing. For the printing layer height of 0.1mm, the temperature of the holding chamber is 90 ℃, the filling method for the spiral tetrahedron. The PEEK materials molded under the optimal parameters of FDM were insulated to investigate the effect of the heat treatment process on the mechanical properties of PEEK materials. The loaded condition of the steering knuckle in each working condition is calculated by the basic parameters of the car, the dangerous cross section of the part is determined by simulation, and the structural optimal design of the part is carried out by topology optimization. Under the premise of ensuring its mechanical properties, minimize the amount of material to achieve the goal of lightweight.

1. Introduction

The steering knuckle (also known as ram's horn) of a vehicle is a key component that connects the wheels to the suspension system, and is usually located at the front wheels to support the weight of the vehicle and transmit steering and braking forces. It connects the suspension control arms, steering tie rods, and braking system via ball joints or bearings. It drives the wheels around the main pin when the vehicle is steered. At the same time, it is subjected to longitudinal and lateral impacts and alternating loads generated during traveling, which requires high performance of the materials (Abdullah et al., 2018). Steering knuckles are mostly made of high-strength cast iron or alloy steel, and the structural design needs to take into account the strength, stiffness and lightweight. Its reliability directly affects vehicle handling stability and safety (Babu et al., 2014). If fracture or distortion occurs, it may lead to handling failure and threaten driving safety. The use of alloy steel or cast-iron manufacturing steering knuckle there will be some limitations, although the alloy steel strength is higher, but the weight is larger, not conducive to lightweight design, and the processing requirements of complex, high manufacturing costs. Although cast iron has low cost and good casting performance, the material is brittle and tends to increase the probability of brittle fracture under the action of severe impact and alternating loads. The significance of lightweight manufacturing is to reduce the overall mass of the vehicle through topology optimization, material innovation and process upgrading. This improves energy efficiency, reduces carbon emissions and enhances the dynamic performance of the vehicle, which can effectively reduce fuel consumption of fuel vehicles or extend the range of electric vehicles, helping to realize the goal of "double carbon" (Zhang & Xu, 2022). Reducing the vehicle's unsprung mass through lightweighting of the steering knuckle optimizes the

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vehicle's handling response and improves driving safety. In addition, lightweighting not only promotes the technological update of the industry chain, but also reduces material consumption and manufacturing costs, which has become a key pillar for the development of the automotive industry (Agarwa et al., 2020).

Topology optimization works by identifying and removing redundant materials to form efficient force transfer paths. It generates complex skeletonized structures that break through traditional design limitations and can significantly reduce component weight (Kadam et al., 2021). The combination of 3D printing and topology optimization allows for the production of lightweight models that would be difficult to achieve with traditional processes, while ensuring load-bearing capacity and dynamic response (Salonitis & Al Zarban, 2015). In addition, it is widely used in the body, chassis and other key components, helping automotive and aerospace fields to achieve lightweight purposes (Suavo Bulzis. 2020). In this paper, topology optimization will be used to reconfigure the steering knuckle to maximize the structural performance with minimum material usage under the constraints of strength and stiffness. As a semi-crystalline thermoplastic engineering material, PEEK demonstrates superior performance characteristics in comparison to traditional materials. It is distinguished by its excellent wear and corrosion resistance, high-temperature endurance, and extended service life. Its specific strength surpasses that of certain metal materials, while its density is merely one-third that of aluminum alloys, rendering it an ideal substitute for metal materials in various applications (Jones et al., 1985).

FDM technology is a widely used additive manufacturing technology for 3D printing, which works by heating thermoplastic materials to a molten state. The material is then extruded and stacked layer by layer on a build platform using a print head, which is cooled and cured to form a three-dimensional entity (Comb et al.,1994). The technology slices the digital model into horizontally thin layers through computer-controlled path planning and stacks them layer by layer to complete the print. Many researchers have focused on optimizing the printing parameters of this technology to achieve high quality products with desired mechanical properties (e.g. Jiang et al., 2022; Bazin et al., 2019; Kafshgar et al., 2021, 2025; Peng et al., 2021; Vates et al., 2021; Solouki et al., 2023, 2025; Borah et al., 2025; Rodríguez-Reyna et al., 2022). FDM technology has the advantages of low equipment cost, easy operation, and variety of materials. PEEK molding method is mainly 3D printing, which can break through the limitations of traditional casting and machining to realize the integrated molding of complex geometric structures, which can significantly reduce complex processes and material waste (Haleem and Javaid, 2019). In this paper, PEEK is used to replace the original metal material, and the loaded condition of the steering knuckle under each working condition is calculated from the basic parameters of the automobile, and the dangerous cross section of the part is determined through simulation. Through the topology optimization of the structural optimization design of the parts, under the premise of ensuring its mechanical properties, to minimize the amount of material to achieve the goal of lightweight.

2. Influence of process parameters on mechanical properties of FDM molded PEEK

2.1 Experimental Preparation

2.1.1 Experimental material

The 3D printing material used in this paper is 1.75mm diameter PEEK filament produced by Dongguan Hongkai Composites Co. Its density is 1.3g/cm3, the temperature of glass transition is 143°C, and the melting temperature is 343°C.

2.1.2 *Laboratory Instruments and Equipment*

The 3D printer used to prepare the test pieces in the experiment was the Y2020 PEEK printer produced by Shenzhen Jumbo Shadow 3D Instrument Co; the equipment used to test the tensile properties of the PEEK samples was the WDW-100D microcomputer-controlled electronic universal testing machine produced by Jinan Chuanbai Instrument Co; the equipment used for the heat treatment experiments was a muffle furnace manufactured by Nabertherm Industrial Furnaces GmbH, Germany.

2.2 Preparation before printing

Before printing, in order to remove the moisture in the filament, it is necessary to put the PEEK filament into a drying oven and bake it at 150°C for more than 3 hours to avoid air bubbles during printing, which will affect the experimental results. Specimen size using the standard sample ISO527-1A experimental parameters, the size of the standard parts shown in **Fig. 1**, the specimens were modeled in 3D in the 3D modeling software SolidWorks and the STL format file was exported.

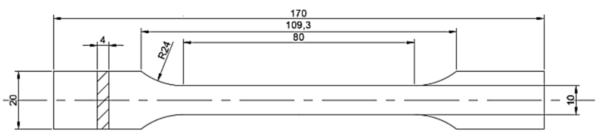
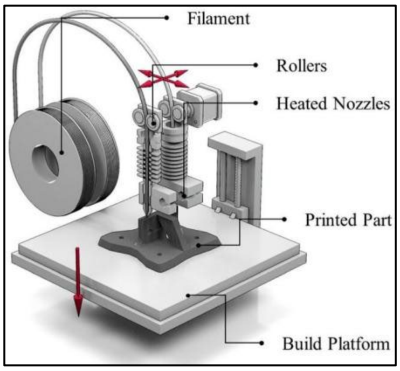
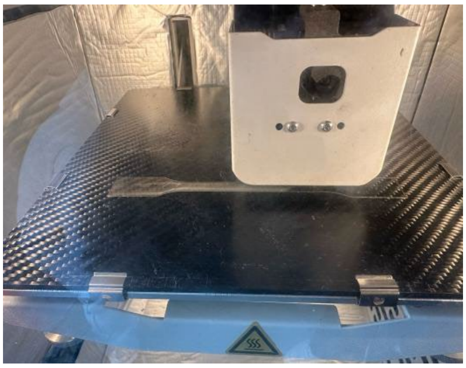


Fig. 1. Dimensional drawing of tensile test piece

The exported STL format file is imported into the slicing software for the setting of the relevant parameters: nozzle temperature of 430 ℃, molding platform temperature of 120 ℃, printing speed of 60 mm/s, fill rate of 100%, alignment width of 0.2 mm, and the printing parameters that have a greater impact on the results are changed according to the requirements. Determine the printing method and path, carry out slicing to generate the code, and use the 3D printer to print the specimen to complete, the printing principle and process is shown in **Fig. 2**.



(a)



(b)

Fig. 2. FDM molding process (a). Print schematic diagram;(b). Printing process diagram.

2.3 Orthogonal experiment

In order to optimize the performance of PEEK, this paper will use orthogonal experiments to investigate the effect on the material properties by varying the printing parameters such as the printing layer height, the temperature of the holding chamber and the filling method. Printing layer height is selected to select 0.1~0.3mm, with 0.1mm as the span of printing; when the temperature of the insulation chamber is not set, the temperature of the working chamber can reach about 50 degrees, so the temperature of the insulation chamber is selected from 50 to 90 degrees Celsius, and the effect of temperature on the mechanical properties of the test pieces is explored with a span of 20 degrees Celsius; the filling method is also one of the important factors affecting the mechanical properties of the test piece, and here three kinds of filling methods are selected and their impact on the experimental results are investigated. The specific parameter combinations for the orthogonal experiments are shown in **Table 1**.

Table. 1. Printing parameters of orthogonal experimental design

Specimen	Floor Height /mm	Temperature of the insulation chamber /℃	Fill style
1	0.1	50	Gridding
2	0.1	60	Octagon
3	0.1	70	Spiral icosahedron
4	0.2	50	Gridding
5	0.2	60	Octagon
6	0.2	70	Spiral icosahedron
7	0.3	50	Gridding
8	0.3	60	Octagon
9	0.3	70	Spiral icosahedron

2.4 Tensile testing

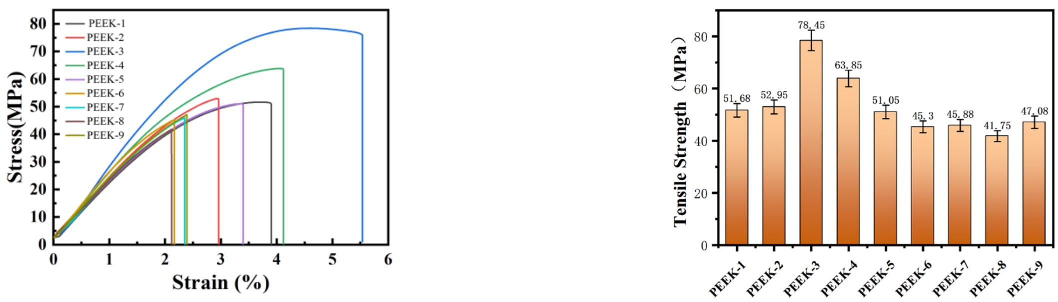
The tensile experiment was conducted with reference to the standard ISO 527, with an initial distance of 115 mm between clamps, a measured length of 50 mm, and a tensile speed of 0.5 mm/min. The tensile test process is shown in **Fig. 3**:

(a)

(b)

Fig.3. FDM molding process (a). Print schematic diagram;(b). Printing process diagram.

Fig. 4 shows the stress-strain curves and tensile strengths of different PEEK samples. The tensile strengths of the PEEK samples were all above 40 MPa from the histograms, and the test pieces performed poorly when the height of the printed layer was 0.3 mm. The tensile strength of the test piece becomes higher when the temperature of the holding chamber is increased, which is mainly attributed to the fact that higher working chamber temperatures result in better fluidity of the PEEK during the melting process. It is better able to fill the pores during the printing process, minimizing defects that may occur during FDM printing. Complex filling can enhance tensile and flexural strength, among other things, by optimizing material distribution and stress transfer paths, which can disperse external loads more effectively.



(a) (b)

Fig. 4. Experimental results of mechanical properties of PEEK printed by FDM (a). Stress-strain curves;(b). PEEK Tensile Strength.

2.5 Extreme variance analysis

In orthogonal experiments, the analysis of extreme variance method can determine the degree of influence of each factor on the experimental results. For a certain factor X in an orthogonal experiment, assume that it has k levels (e.g. X1,X2,...,Xk), and that the test results corresponding to each level are $yX_1, yX_2, ..., yX_n$, respectively (each level is repeated for n trials) , then:

The mean value of factor X at level X_i, $\overline{X}_1 = \frac{1}{n}\sum_{j=1}^{n} yX_i$

The extreme variance reflects the extent to which a factor affects the results, the larger the extreme variance, the more important the factor is:

$$R_X = \max\left(\overline{X}_1, ..., \overline{X}_k\right) - \min\left(\overline{X}_1, ..., \overline{X}_k\right)$$

where R_X is the extreme variance of factor X and $\overline{X}_1$ is the mean value of the factor at each level. The effect of FDM parameters on the tensile properties of PEEK is analyzed and discussed through the level distribution of orthogonal factors in **Table 2**. The structure of the extreme variance analysis is shown in **Table 3**.

Table 2. Factor and level distribution.

Number	Floor Height /mm	Temperature of the Insulation Chamber /℃	Fill Style
1	0.1	50	Gridding
2	0.2	70	Octagon
3	0.3	90	Spiral Icosahedron

Table 3. Extreme variance analysis of tensile strength.

Sample Number	Factor			Experimental Result
	A	B	C	
	Floor Height/mm	Temperature Of The Insulation Chamber/℃	Fill Style	Tensile Strength/MPa
PEEK-1	1	1	1	51.68
PEEK-2	1	2	2	52.95
PEEK-3	1	3	3	78.45
PEEK-4	2	1	2	63.85
PEEK-5	2	2	3	51.05
PEEK-6	2	3	1	45.30
PEEK-7	3	1	3	45.88
PEEK-8	3	2	1	41.75
PEEK-9	3	3	2	47.08
K1	61.03	53.80	46.24	The Sequence Of Influence A>C>B
K2	53.40	48.58	54.63	
K3	44.90	56.94	58.46	
R	16.13	8.36	12.22	

From the final results, it can be seen that since R1 > R3 > R2, the primary and secondary relationships of the printed parameters are layer height, filling method, and insulation compartment temperature. That is, of the printing parameters chosen for this experiment, the one that had the greatest impact on the results was the layer height, followed by the filling method, and again by the temperature of the insulation compartment. For the optimal parameter combination of the experiment, the object of this experiment is tensile strength, tensile strength is directly proportional to the performance of the part, so the larger the value of Kj, it means that the tensile strength of the test piece at the jth level under the parameter is greater, so the optimal combination of parameters is 0.1mm layer height, insulation chamber temperature of 90°C, and filling method of spiral tetrahedron, as shown in **Table 4**.

Table 4. Extreme variance analysis of tensile strength

Floor Height/mm	Temperature of the Insulation Chamber/°C	Fill Style
0.1	90	Spiral Icosahedron

3. Influence of heat treatment process on the properties of PEEK

FDM technology is one of the most widely used technologies in 3D printing, mainly applied to the processing and manufacturing of thermoplastic materials. It can realize the customized molding of PEEK material, not only low manufacturing cost, easy to operate. More importantly, it does not pollute the environment and supports the free design of complex geometries (Dudek, 2013). However, due to the molding characteristics of FDM technology, molded parts may have defects such as residual stresses due to uneven temperature gradients, small gaps between the print filaments and insufficient adhesion between the print filaments. These inherent defects can seriously affect the crystallinity and properties of PEEK molded parts. And these inherent defects cannot be improved by changing the print parameters. As a thermoplastic material, the performance of PEEK is closely related to its crystallinity. Insulation treatment, as one of the common methods to improve the strength and surface quality of FDM molded parts, not only improves the crystallinity of PEEK molded parts, but also repairs the defects it produces during the printing process and further improves the performance of the material (Yang et al., 2017). In this paper, the effect of insulation heat treatment on the tensile strength of FDM-molded PEEK test pieces was investigated, and the changes in the mechanical properties of PEEK test pieces at different temperatures were explored.

3.1 Experimental design

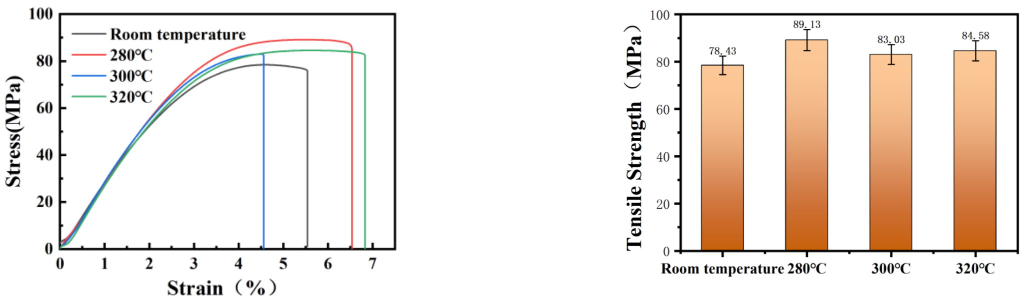
PEEK test pieces for heat treatment were prepared according to the optimal combination of parameters screened above, i.e. print layer height of 0.1mm, holding chamber temperature of 90°C and filling method of spiral icosahedron. The parameters of heat treatment conditions are shown in **Table 5.**

Table 5. Heat treatment parameters.

Heat treatment parameter	Temperature/°C	Time/h	Number
After preheating the muffle furnace to the specified temperature, the PEEK samples are placed in the furnace to keep warm, and then air-cooled after a predetermined period of time.	Room temperature	0	1
	280	2	2
	300	2	3
	320	2	4

3.2 Discussion of experimental results

The tensile test was conducted on the test pieces after heat treatment, and the test results are shown in the figure below. When the temperature is 280°C, the heat-treated test piece shows the optimal mechanical properties. The tensile strength reaches 89.13 MPa, which is 11 MPa higher than that of the non-heat-treated test piece, providing data support for the subsequent simulation.



(a) (b)

Fig. 5. Mechanical test results of PEEK after heat treatment (a). Stress-strain curves;(b). PEEK Tensile Strength.

4. Finite Element Modeling and Working Load Calculation

4.1 Finite element modeling

SolidWorks is a 3D mechanical design software based on parametric feature modeling, widely used in the field of mechanical engineering. Its core modeling logic through the geometric constraints and size-driven to achieve accurate design, the user can stretch, rotate, scan and other feature operations to build solid models. And the use of equations to establish parametric associations between features to ensure that the model automatically maintains the topological relationship when the design changes (Matsson, 2015). The software supports both Top-Down and Bottom-Up assembly design modes. Combined with interference checking, motion simulation and finite element analysis (Simulation module) to realize mechatronics verification. Generate GB/ISO compliant engineering drawings automatically for mechanical manufacturing needs, support dimension tolerance marking, shape and position tolerance annotation and BOM table output. Significantly improve the engineering efficiency from conceptual design to manufacturing, especially for complex mechanical systems, fixtures and precision parts development process.

The external dimensions of the steering knuckle are 206 mm × 222 mm × 135 mm. In order to improve the mesh quality and solution accuracy, the steering knuckle model is first simplified by removing small features such as rounded corners that do not affect the calculation results (Liu Yusheng, 2020). Because of the complex structure of the steering knuckle, a tetrahedral mesh with a size of 5mm is used (Tagade et al., 2015). The model is divided into 30523 cells and 49625 nodes, and the structural discrete model is shown in Fig.6.

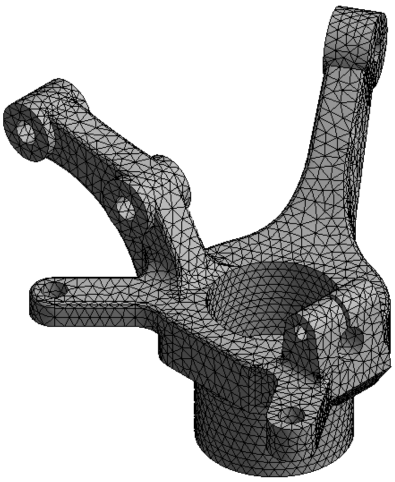


Fig. 6. Steering knuckle finite element meshing.

4.2 Typical working condition load calculation

The steering knuckle, as a key component of the automobile chassis, is connected to the suspension system, shock absorbers and brake calipers. The joints of this component are subject to variable loads and are designed for rigidity, strength and durability to meet the challenges of complex environments, where their performance is directly related to the safety of the vehicle (Tagade et al., 2016; Yadav et al., 2016). This study analyzes the steering knuckle loads under three typical conditions, namely, passing through uneven road surface, emergency braking and lateral slip, based on the vehicle driving conditions, which provides a theoretical basis for the subsequent static mechanical analysis and durability prediction. In this paper, a minicar is used as an object, and the specific parameters of the vehicle are detailed in **Table 6** (Wang Mengqian, 2021).

Table 6. Parameters of the whole vehicle.

Parameters	Symbol	Unit Dimension	Numerical Value
Vehicle mass (full load)	M	Kg	1265
Front axle static load (full load)	M1	Kg	699.5
Front wheel rolling radius	r	mm	278
Front wheel tread	B	mm	1305
Wheel base	L	mm	2360
Centroid height (full load)	h_g	mm	480
Dynamic factor	K_d	-	2.5
The distance from the center of mass to the posterior axis	b	mm	1305
Ground adhesion coefficient	ψ	-	0.8
Lateral sliding adhesion coefficient	Ψ	-	1.0
Front axle mass transfer coefficient during braking	m_1	-	0.62

In the design stage, due to the complexity of the vehicle driving environment, this paper carries out a simplified static analysis of the steering knuckle and selects three typical working conditions with large loads for detailed analysis (Yuan, 2010; Kang et al., 2015). The forces on the wheels under the three different working conditions are shown in **Fig. 7.**

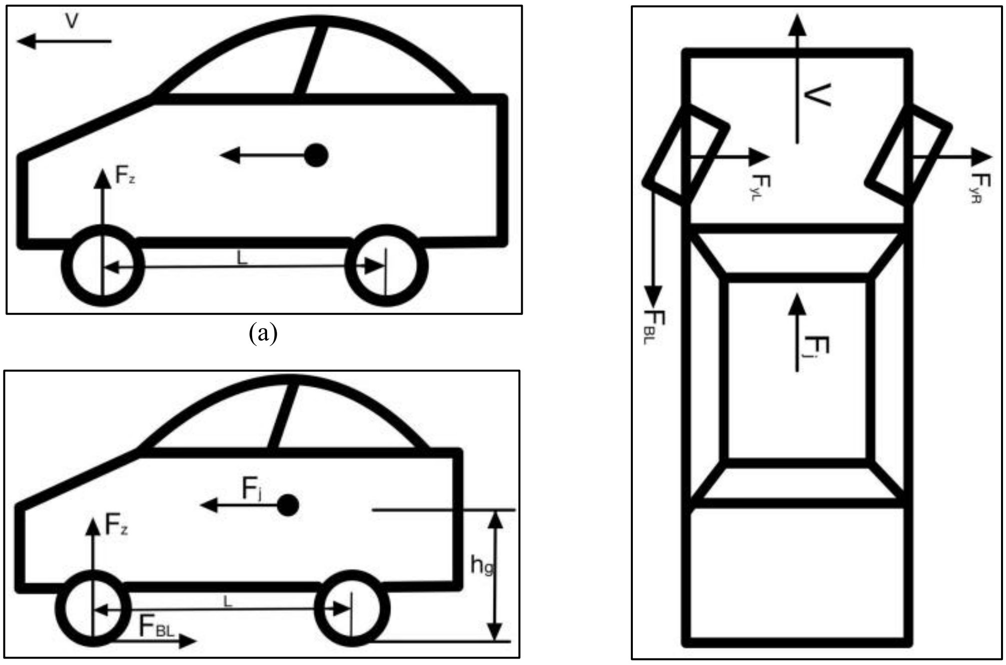


Fig. 7. The force conditions of tires under three typical working conditions (a). Force analysis when crossing an uneven road surface;(b). Analysis of forces under emergency braking conditions;(c). Force analysis during lateral slip.

4.2.1 Over uneven road condition

When the vehicle is driven through a pothole, the steering knuckle is subjected to a vertical impact and the load is transferred to the steering knuckle through the tires and other parts. Neglecting the effect of suspension stiffness, the force on the tires when the vehicle passes over an uneven road is:

The longitudinal force on the wheels at this point is:

$$F_z = \frac{K_d M_1 g}{2} \tag{1}$$

where K_d is the dynamic load factor, in this paper K_d is taken as 2. i.e.:

$$F_x = \frac{K_d M_1 g}{2} = \frac{2 \times 699.5 \times 9.8}{2} = 6855\text{N} \tag{2}$$

4.2.2 Emergency braking condition

In the emergency braking state, the vehicle decelerates at the maximum speed reduction, at this time the steering knuckle mainly bears the longitudinal load generated by braking and the vertical load caused by inertia. The force on the tire is calculated as follows:

In the process of emergency braking, the inertia force generated by the vehicle due to the sudden reduction of speed is:

$$F_j = Mg = 1265 \times 9.8 = 12397\text{N} \tag{3}$$

Based on the moment equilibrium it can be obtained that the amount of load ΔG change when the car is decelerating is:

$$\Delta G = \frac{F_j h_g}{L} = \frac{12397 \times 480}{2360} = 2521\text{N} \tag{4}$$

During braking, the mass transfer coefficient m1 of the front axle is 0.62, so the braking force for a single front wheel can be calculated as:

$$F_x = F_{BL} = \frac{F_j m_1}{2} = \frac{12397 \times 0.62}{2} = 3843N \quad (5)$$

From the force analysis of the front wheels, the support reaction force on each front wheel is:

$$F_z = \frac{M_1 g + \Delta G}{2} = \frac{699.5 \times 9.8 + 2521}{2} 4688N \quad (6)$$

After calculation,$F_z/F_x = 4688/3843 = 1.2$, is greater than the attachment coefficient, so it meets the requirements.

4.2.3 Lateral slip condition

When a vehicle encounters an emergency situation, the vehicle needs to perform emergency braking and needs to adjust its direction for safe avoidance. The front tires are subjected to complex loads under commutative braking conditions, as well as forces from the ground and brake calipers. When the vehicle is deflected, the steering knuckle is subjected to a moment around the forward direction due to the transfer of loads from the left and right sides. In this study, the vehicle is turned to the right direction as an example, and the forces on the front wheels are analyzed as follows:

$$F_{yL} = \frac{1}{2} M_1 g \Psi \left(\frac{2h_g \Psi}{B} + 1 \right) \quad (7)$$

$$F_{yR} = \frac{1}{2} M_1 g \Psi \left(\frac{2h_g \Psi}{B} - 1 \right) \quad (8)$$

When the vehicle is braked to the right, the centrifugal force causes the load on the wheels to increase as the centrifugal force increases. The left wheel is on the outer side of the centrifugal force circle, and its load is larger than that of the right wheel. In order to study the loaded condition of the steering knuckle in the limit state, the steering knuckle on the left wheel is analyzed in detail.

$$F_{yL} = \frac{1}{2} M_1 g \Psi \left(\frac{2h_g \Psi}{B} + 1 \right) = 5948.97N \quad (9)$$

The vertical load on the left front wheel is:

$$F_{zL} = \frac{F_{yL}}{\Psi} = 5948.97N \quad (10)$$

The braking force applied to a single wheel of a vehicle under emergency braking conditions is:

$$F_x = F_{BL} = 3843N \quad (11)$$

The moment applied to the steering knuckle is:

$$M_x = F_{yL} r = 1653.81N \cdot m \quad (12)$$

Through the calculation of the above three typical working conditions, the wheel steering knuckle loaded situation can be obtained as shown in **Table 7** for each working condition.

Table 7. Wheel loads under various operating conditions

Name of working condition	Load type	Load symbol	Calculate the numerical value
Crossing uneven road conditions	Normal load	F_z	6855.00N
Emergency braking condition	Normal load	F_z	4688.00N
	Longitudinal load	F_x	3843.00N
Lateral sliding condition	Normal load	F_z	5949.00N
	Longitudinal load	F_x	3843.00N
	Lateral load	F_y	5949.00N
	Additional torque	M_x	1653.81N·m

5. Steering knuckle typical working condition simulation

In the design and development process of steering knuckle, in order to shorten the development cycle and cost savings, usually before the actual production of its mechanical analysis, timely adjustment of components, cost savings and shorten the development cycle (O'Kane et al., 2000). Through the above calculation, the force data of the steering knuckle under three typical working conditions are obtained, and these data are utilized to carry out the static simulation of the steering knuckle. The hydrostatic analysis is mainly to analyze the ability to withstand the maximum load under the extreme working conditions to ensure the safety of the vehicle in the actual driving. This chapter will determine the dangerous cross section of the steering knuckle under each working condition through simulation to provide theoretical support for the subsequent structural design.

5.1 Material setup

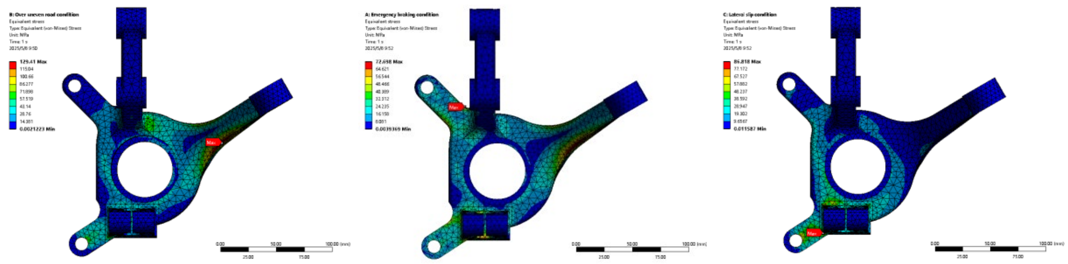
The conventional material used for this steering knuckle is 40Cr. In this paper, the raw material is firstly used for simulation to determine the hazardous cross section of the steering knuckle. Some of the parameters of the material are shown in **Table 8**.

Table 8. Selected Properties of 40Cr Material.

Additional Torque/GPa	Poisson Ratio	Density/kg/m^3	Yield Strength/MPa	Tensile Strength/MPa
211	0.29	7850	785	810

5.2 Strength analysis

The constructed model is imported into the static analysis module of Ansys Workbench to perform the static simulation. After completing the mesh delineation and material property setting, the calculated load data under different working conditions are inputted into the simulation program. The stress distribution of the steering knuckle under each working condition is generated (Li et al., 2018), as shown in **Fig. 8**.



(a) (b) (c)

Fig. 8. Stress cloud diagram of steering knuckle under typical working conditions (a). Over uneven road condition;(b). Emergency braking condition;(c). Lateral slip condition.

5.2.1 Crossing uneven road condition

From the stress map, it can be seen that when the vehicle passes through the uneven road surface, the bottom of the right connecting arm is subjected to the maximum stress, the peak value of which reaches 129.41MPa. Since the steering knuckle is made of 40Cr, its ultimate strength is far more than this pressure value, and therefore complies with the strength safety standard.

5.2.2 Crossing uneven road condition

Under emergency braking condition, due to the longitudinal load and vertical load, the stress concentration of the steering knuckle occurs at the left upper lug, the maximum value is 72.698MPa, which is far less than the ultimate strength of 40Cr. Therefore, it is also safe and meets the requirements under this working condition.

5.2.3 Crossing uneven road condition

Compared with the emergency braking condition, the lateral slip condition is not only subjected to vertical and longitudinal loads, but also subjected to a lateral load from the ground and a moment generated by this force. From the cloud diagram, it can be seen that due to the influence of lateral force and additional moment. The stress concentration occurs at the junction of the left lower lug and the support table, and the maximum value is 86.818MPa. This value is much less than the ultimate strength of the material, so it meets the use requirements.

6. Structural design of steering knuckle

In the traditional process, the raw material for manufacturing the steering knuckle is 40Cr, which has the disadvantages of large mass, compact structure, high requirements for processing technology and brittleness. With the progressive development of the times, by the end of 2024, the number of automobiles in China reached 353 million. Studies have pointed out that if the weight of the vehicle is reduced by 100 kg, the fuel consumption per 100 km can be reduced by 0.3 to 0.5 liters (Fan et al. 2014). It can be seen that reducing the weight of automobiles can effectively reduce fuel consumption, thus alleviating environmental and energy problems.

6.1 Steering Knuckle Structural Enhancements

After the above simulation results, it is known that the stress concentration of the steering knuckle mainly occurs in the upper and lower lugs, the connection between the fixing platform and the center hole, and the weak spot of the right connecting arm. For this reason, the key parts are rounded and strengthened with reinforcement based on experience. It should be noted that the redesigned structure cannot change the size and position of the mounting holes to ensure the reliability of the design. This structure is used as the initial model of the steering knuckle after replacing the material, as shown in **Fig. 9**:

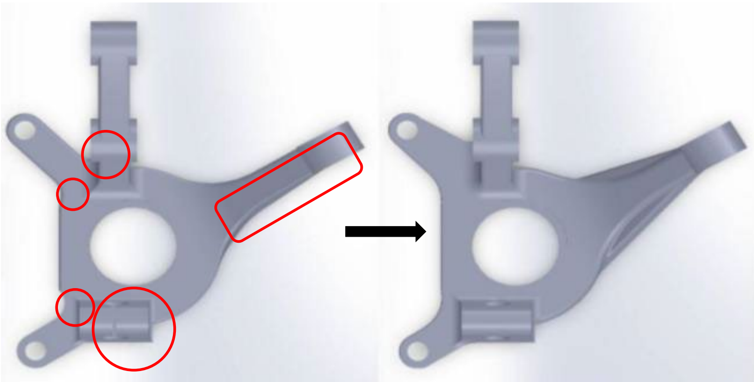


Fig. 9. Schematic diagram of structural enhancements.

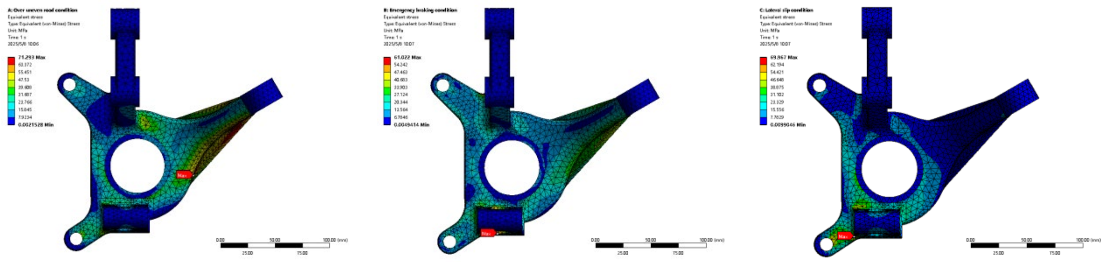
6.2 Strength analysis of steering knuckle after structural reinforcement

The structurally enhanced steering knuckle model is imported into Ansys Workbench for simulation again. In order to achieve the purpose of lightweight design, the material is replaced with PEEK in this simulation, and the stress cloud is obtained as shown in **Fig. 10**.

The tensile ultimate strength of the material is obtained through the experiments in Section 2, and its specific parameters are shown in **Table 9**. PEEK material has many superior properties, including high temperature resistance, corrosion resistance, self-lubrication, easy processing and high mechanical strength. These properties allow PEEK to be used as a replacement for metals, especially steel, in many applications. PEEK materials have a lower density and are lighter than steel, about one-third the density of aluminum alloys, but are stronger. This provides significant advantages in terms of weight reduction and improved performance.

Table 9. PEEK Material Properties

Additional torque/GPa	Poisson ratio	Density/kg/m^3	yield strength/MPa	Tensile strength/MPa
3.6	0.2	1300	88	89



(a) (b) (c)

Fig. 10. Stress cloud diagram of the steering knuckle after structural reinforcement under typical working conditions (a). Over uneven road condition;(b). Emergency braking condition;(c). Lateral slip condition.

6.2.1 Crossing uneven road surface condition

From the stress cloud diagram (a), it can be seen that when the structurally enhanced steering knuckle crosses the uneven road surface, the stress concentration occurs at the connection between the reinforcement and the steering knuckle, and the maximum value is 71.293.MPa. It is less than the ultimate strength of PEEK, so it meets the requirements. And compared with the original structure, the maximum value of stress in the reinforced steering knuckle is reduced by 58MPa.

6.2.2 Emergency braking condition

From the stress map (b), it can be seen that under the emergency braking condition, the stress concentration of the enhanced steering knuckle mainly occurs at the bolt holes connecting the tray and the suspension, and the maximum stress is 61.022MPa. It is smaller than the ultimate strength of the PEEK material, so it meets the requirements. Compared with the original structure, the maximum value of stress is reduced by 11MPa.

6.2.3 Lateral slip condition

From the stress map (c), it can be seen that the stress concentration of the steering knuckle occurs at the rounded corner of the tray in the lateral slip condition, and the maximum value of the stress is 69.967MPa, which is smaller than the ultimate strength of the PEEK material, so it meets the requirements. And the stress is reduced by 17MPa compared with the original steering knuckle structure. The simulation results point out that the optimized steering knuckle structure has been significantly improved in terms of load carrying performance.

7. Steering knuckle topology optimization

In this paper, we will use Altair Inspire to optimize the topology of steering knuckles, which is an integrated software platform for engineering design and optimization. With topology optimization as the core, it combines structural simulation, motion analysis, and additive manufacturing to help users quickly generate innovative design concepts for lightweight and high-performance. It adopts an intuitive interactive interface and automated processes to support the whole process of optimization from initial concepts to manufacturable solutions. Through intelligent algorithms (e.g. SIMP), it automatically allocates material layouts and significantly reduces the weight under the constraints of strength and stiffness (Zeng. 2018). At the same time, seamlessly connects with 3D printing technology to realize the production of complex structures. The software is widely used in automotive, aerospace, industrial equipment and other fields. It empowers engineers to break through traditional design thinking, shorten development cycles and reduce costs (Bendsoe and Sigmund, 2013; Lan et al., 2014).

7.1 Optimization of design space

When using Altair Inspire for structural optimization, the first step is to determine the design space, which consists of three parts: the starting geometry, the retained geometry and the excluded geometry (Krish, 2011). The starting geometry defines the limits of the optimization model. Retention geometry refers to the parts that remain unchanged throughout the optimization process and whose structure is maintained as is. Excluded geometry refers to the parts that are removed during the optimization process and are not allowed to appear in the optimization results. The main focus of this study is on the determination of the starting geometry and the retained geometry, and the excluded geometry is not addressed.

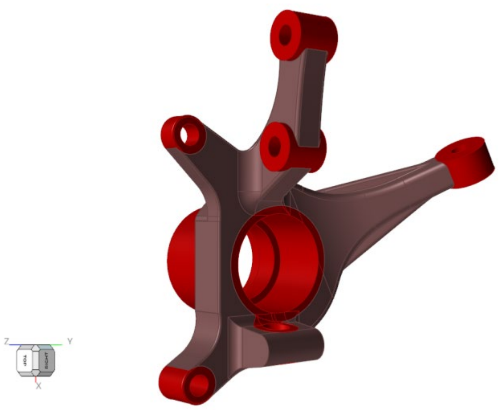


Fig. 11. Design Space.

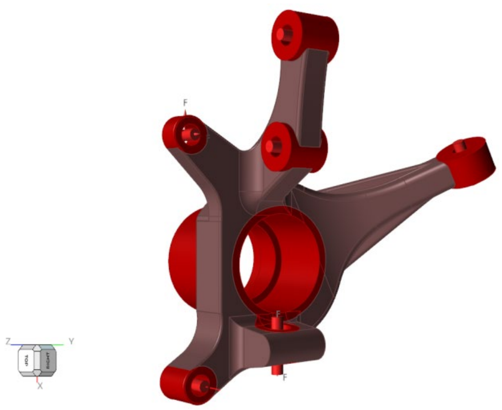


Fig. 12. Schematic diagram of adding load.

The starting geometry is the limiting boundary set during the topology optimization process, beyond which the material reduction during the design process is not allowed. In this study, the entire steering knuckle structure is used as the starting geometry. The retained geometry is the portion of the steering knuckle structure that remains unchanged during the optimization process, so it is necessary to determine which portions of the steering knuckle structure are retained based on the assembly. The upper end of the steering knuckle is connected to the shock absorber sleeve, the left lug is bolted to the caliper, the steering tie-arm is connected to the steering tie-rod, and the lower support table is connected to the suspension via a ball hinge. During the structural optimization process, these mounting holes can neither be changed in size nor position, for this reason the retained geometry needs to be determined prior to the optimized design. As shown in **Fig. 11**, the red area is the retained geometry and the rest of the brown part is the starting geometry.

7.2 Optimization of design space

The loading conditions have been detailed during the simulation and analysis of the steering knuckle. For structural optimization, it is sufficient to add the loads and constraints of the three conditions discussed above to the model in turn, as shown in **Fig. 12**.

7.3 Optimization process analysis

The volume limit has a large impact on the design results, and the volume limit affects the results through the ratio of the optimized model volume to the original model volume. When the volume limit is too large, the optimization effect is not obvious, and when the volume limit is too small, it may lead to too much stress on the model, or even molding failure, and this paper chooses a volume limit of 30%. As shown in **Fig. 13**, the maximum force of the optimized steering knuckle model under each working condition reaches 75.27 MPa. Compared with the pre-optimization, the increase is 4MPa, but it is less than the ultimate strength of PEEK material, which meets the requirements. The weight of the original steering knuckle is 2807.94g, while the weight of the topology-optimized steering knuckle structure is 843.06g and the mass of the parts is reduced by 69%.

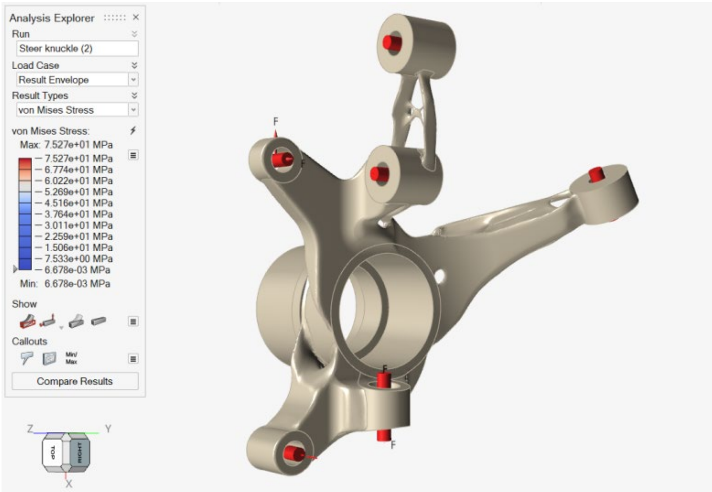


Fig. 13. Steering knuckle forces after topology optimization.

8. Conclusion

This study is an attempt to prepare PEEK material steering knuckle to realize its light weight by using FDM technology. Firstly, the loaded condition of the steering knuckle under each working condition is calculated by the automobile parameters, and the original structure is statically analyzed by using Ansys Workbench finite element analysis software to determine the hazardous cross section. Then the steering knuckle was redesigned to reduce the stress concentration phenomenon, and the original 40Cr alloy steel was replaced with lighter weight PEEK material. Finally, topology optimization of the redesigned steering knuckle is carried out by Altair inspire software. By analyzing the above results, the following conclusions are drawn:

(1) The optimal parameter combinations for FDM molding are explored through orthogonal experiments as follows: the printing layer height is 0.1mm, the temperature of the holding chamber is 90°C and the filling method is spiral icosahedron.

(2) From the experiments, it can be seen that the heat treatment can optimize the defects generated during the fused deposition molding process and holding the test piece at 280°C for two hours improves its tensile strength by about 14%.

(3) In the structural redesign, the stress concentration can be effectively reduced and the maximum stress on the steering knuckle can be greatly reduced by adding rib and increasing rounded corners.

(4) By replacing the raw material with PEEK material and optimizing its topology, the mass of the steering knuckle is reduced by 69%, which achieves the purpose of lightweighting.

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