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MANUFACTURING DESIGN AND FEM ANALYISIS OF ELLIPTICAL GEARS

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Table of notations

n	$\left[\frac{\mathrm{r}}{\mathrm{min}}\right]$	spindle speed
$\mathrm{v_c}$	$\left[\frac{\mathrm{m}}{\mathrm{min}}\right]$	cutting speed
$\mathrm{v_f}$	$\left[\frac{\mathrm{mm}}{\mathrm{min}}\right]$	feed rate
f_z	$\left[\frac{\mathrm{mm}}{\mathrm{z}}\right]$	feed per tooth
z_c	$[-]$	number of tool teeth
m	[mm]	Module
T	[N*m]	Torque of rotation
σ	[MPa]	Equivalent stress
ϕ	[mm]	Module
Ra	[µm]	Surface roughness

Table of Glossary

CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
FEM	Finite Element Method
EBM	Electron Beam Melting
SLM	Selective Laser Melting
STL	Standard Tessellation Language
FDM	Fused Deposition Modeling
CAD	Computer-Aided Design
FDM	Fused Deposition Modeling

Introduction

Elliptical gears, as the core components of non-uniform transmission systems, have been widely applied in fields such as textile machinery, automated production lines, and precision instruments due to their ability to achieve variable motion laws. As the demand for high-precision and customized transmission components in the industrial sector continues to grow, traditional manufacturing methods (such as conventional CNC machining) are facing challenges in balancing processing efficiency, cost control, and structural optimization. This has given rise to an urgent need for innovative design and manufacturing solutions that integrate advanced technologies.

This research focuses on the manufacturing design and finite element analysis of elliptical gears. The core objective is to systematically solve the technical problems in the production of elliptical gears: Firstly, select appropriate tools and equipment to conduct computer-aided manufacturing analysis to ensure processing accuracy and efficiency; Secondly, design a complete and streamlined manufacturing process for elliptical gears; Thirdly, conduct static finite element analysis on the gear connection structure to verify its mechanical stability and load-bearing performance. Fourth, develop a 3D printing solution for elliptical gears to meet the demands of small-batch customization and complex structure forming.

This research not only aims to optimize the manufacturing process of elliptical gears, but also hopes to break through the technical bottlenecks of traditional production by integrating CAM, FEM and 3D printing technologies. By integrating digital design, simulation verification and additive manufacturing, it is expected to provide a feasible technical framework for the production of high-performance elliptical gears, while laying the foundation for the application of advanced manufacturing technologies in the field of non-circular gears.

1 Literature Review

Elliptical gears, as a highly representative type among non-circular gears, have their teeth distributed at equal intervals along the elliptical contour. This unique structure makes them highly favored in scenarios where the output shaft speed needs to change within a single rotation cycle [1].Compared with traditional circular gears, elliptical gears demonstrate irreplaceable advantages in achieving non-uniform transmission, optimizing structural compactness, and ensuring high-precision motion transmission [6]. Elliptical gears can not only meet the speed change requirements under special working conditions but also achieve efficient transmission in limited Spaces. Therefore, they have gradually become core components in flow meters, hydraulic pumps, textile machinery, and various precision transmission mechanisms, supporting the stable operation of numerous industrial equipment.

In recent years, with the continuous improvement of the requirements for the efficiency, accuracy and reliability of transmission systems in the industrial field, the application scenarios of elliptical gears have also been continuously expanding [1]. Whether it is the demand for precise transmission in high-end equipment manufacturing or the pursuit of efficient and stable transmission in ordinary industrial equipment, both are driving in-depth research on elliptical gear-related technologies. Among them, manufacturing design and finite element analysis, as a key link to ensure the performance of elliptical gears, have become a research hotspot in the field of mechanical engineering. Researchers have comprehensively simulated and verified the strength, stiffness, and transmission characteristics of gears by optimizing manufacturing processes, enhancing processing accuracy, and combining finite element analysis technology, aiming to further explore the application potential of elliptical gears and meet the continuously upgrading demands of industrial production [2][8].

1.1 Overview of Elliptical Gears

1.1.1 Basic characteristics and application background

The fundamental difference between elliptical gears and circular gears lies in that the pitch curve of elliptical gears is elliptical, and the transmission ratio varies with time during operation. This feature enables it to convert uniform input motion into non-uniform output motion, meeting the special motion requirements such as variable-speed transmission and intermittent motion in mechanical systems. The idea of non-circular gears dates from the early history of engineering. Leonardo da Vinci sketched some spatial versions of non-circular gears [16].In the 18th century, non-circular gears were used in flow pumps (Figure 1), clocks, music boxes, toys, and other devices. At the end of the 19th century, Franz Reuleaux ordered a series of non-circular gear-type mechanisms from the Gustav Voigt Mechanische Werkstatt in Berlin. Those mechanisms were designed to be used in the study of kinematics. Gears manufactured at that time had simplified shapes, which led to inappropriate meshing conditions, as shown, in Figure 2 [16].

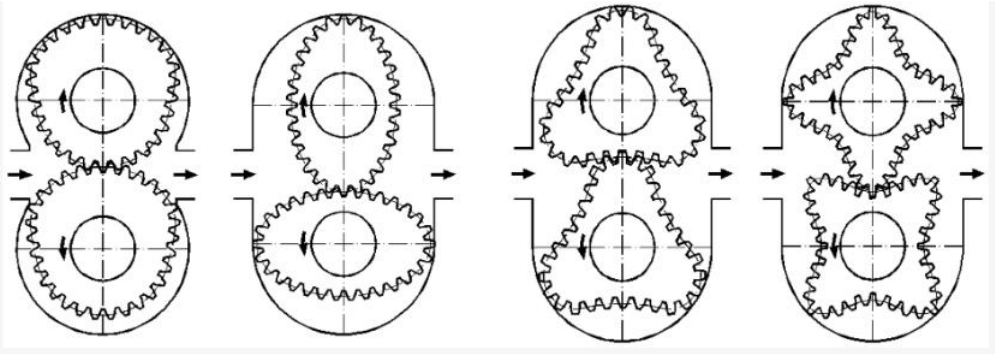


Figure 1 Examples of flow pumps using non-circular gears.[16]

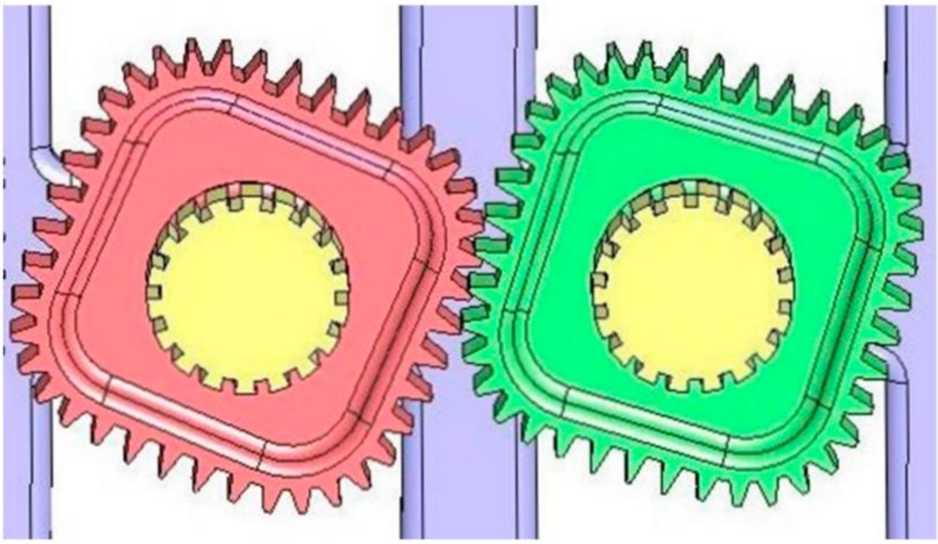


Figure 2 Historical model of non-circular gear[17]

1.1.2 Key technical challenges

The unique geometric characteristics of elliptical gears pose significant challenges to their manufacturing design and performance analysis [2]. In terms of manufacturing, the non-uniform curvature of the elliptical pitch curve makes it difficult to ensure the consistency of tooth profile accuracy during the processing, which requires special tools, machine tools and reasonable process planning [1][6].

In terms of performance analysis, the meshing process of elliptical gears involves time-varying contact positions, uneven load distribution, and complex stress-strain relationships. Traditional analytical methods are difficult to accurately predict its mechanical behavior [6][8]. In addition, the modern industrial demand for lightweight, high strength and customization of elliptical gears has promoted the integration of new materials, new processes and numerical simulation technology, further increasing the complexity of manufacturing design and performance analysis.

1.2 CAM Analysis: Tool and Machine Tool Selection

1.2.1 Selection of elliptical gear processing tools

The selection of cutting tools is a key link in the CAM analysis of elliptical gears, directly affecting the machining accuracy, efficiency and tool life. Commonly used tools for processing elliptical gears include rack and pinion cutters, gear hobs, gear shaping cutters and modular milling cutters, etc. The rack and pinion cutting tool has a simple structure. It forms involute tooth surfaces through rolling motion on the elliptical pitch curve and is widely used in the generation of elliptical gear tooth profiles [6][16]. Relevant research has established a mathematical model for generating elliptical gears with rack and pinion tools and carried out root cut analysis, providing a theoretical basis for the optimization of tool parameters [6]. Gear shaping cutters (especially gear-shaped gear shaping cutters) are suitable for processing complex tooth profiles and internal tooth elliptical gears. The precise forming of the tooth profile is achieved through the coordinated rotation of the tool and the workpiece. In addition, a computer-aided tooth profile generation method for manufacturing elliptical gears based on gear shaping cutters has also been proposed, effectively improving the processing accuracy of tooth profiles [16].

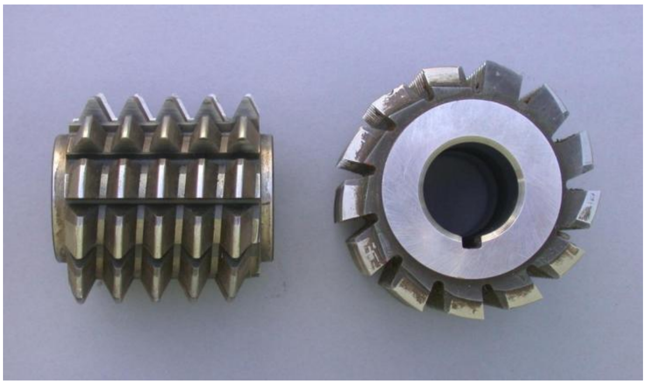


Figure 3 Hobbing[1]

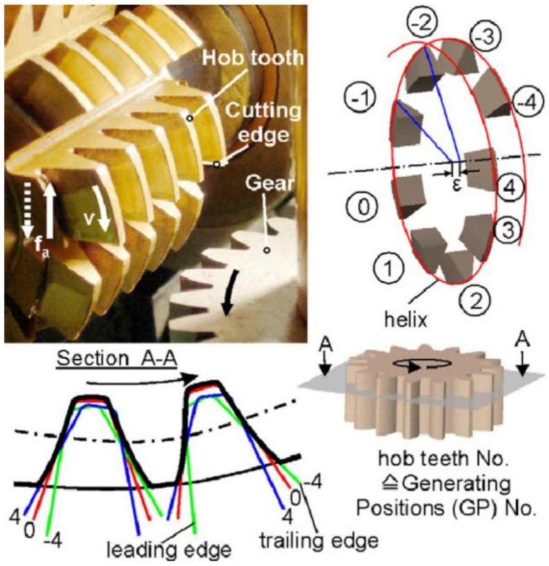


Figure 4 Hob generating process of involute tooth flanks[14]

In response to the modern demand for efficient processing, modular gear cutters and end mills have also been widely applied. Hob cutters are suitable for the mass production of elliptical gears. Their tooth profiles can be customized according to the parameters of the ellipse to ensure meshing performance. In multi-axis CNC milling, general-purpose end mills (especially ball-end mills) can flexibly achieve complex tooth profile processing by programming the tool path to process elliptical gears without the need for special tools [7]. Wire-cutting tools are also used to process elliptical gears, enabling high-precision machining of tooth profiles without the need for complex tool forming.

1.2.2 Selection and Application of Elliptical Gear Processing Machine tools

The selection of machine tools for elliptical gears should be based on the processing method, precision requirements and production batch. Traditional processing mostly relies on special equipment such as gear hobbing machines and gear shaping machines. The gear hobbing machine equipped with an electronic gearbox can meet the processing requirements of pitch curves through multi-axis speed ratio coordination. The three-linkage CNC gear shaping machine has been experimentally verified to be capable of processing non-circular gears, while the dedicated gear shaping machine, relying on the rolling motion of gear-shaped tools, is suitable for small-batch production of precision elliptical gears [3][14].

With the development of numerical control technology, multi-axis CNC milling machines, wire cutting machines and special modification equipment have become important choices. Three-axis and five-axis CNC milling machines and CNC lathes with powered tools can adjust the tool path through programming to adapt to complex tooth profile processing, with strong flexibility [14]. Wire-cutting machine tools utilize electrical discharge technology to avoid the influence of cutting force and thermal deformation. They are the preferred choice for high-precision processing of hard materials and complex contours, and are not limited by standard modules [11]. In addition, specialized equipment such as four-axis programmable gear shaping machines and modified spiral bevel gear milling machines can specifically address issues like processing interference and special tooth profiles [3]. When making actual selections, it is necessary to comprehensively balance accuracy, efficiency and cost.From Figure 4, we can see the differences between three-axis, four-axis and five-axis CNC milling machines.

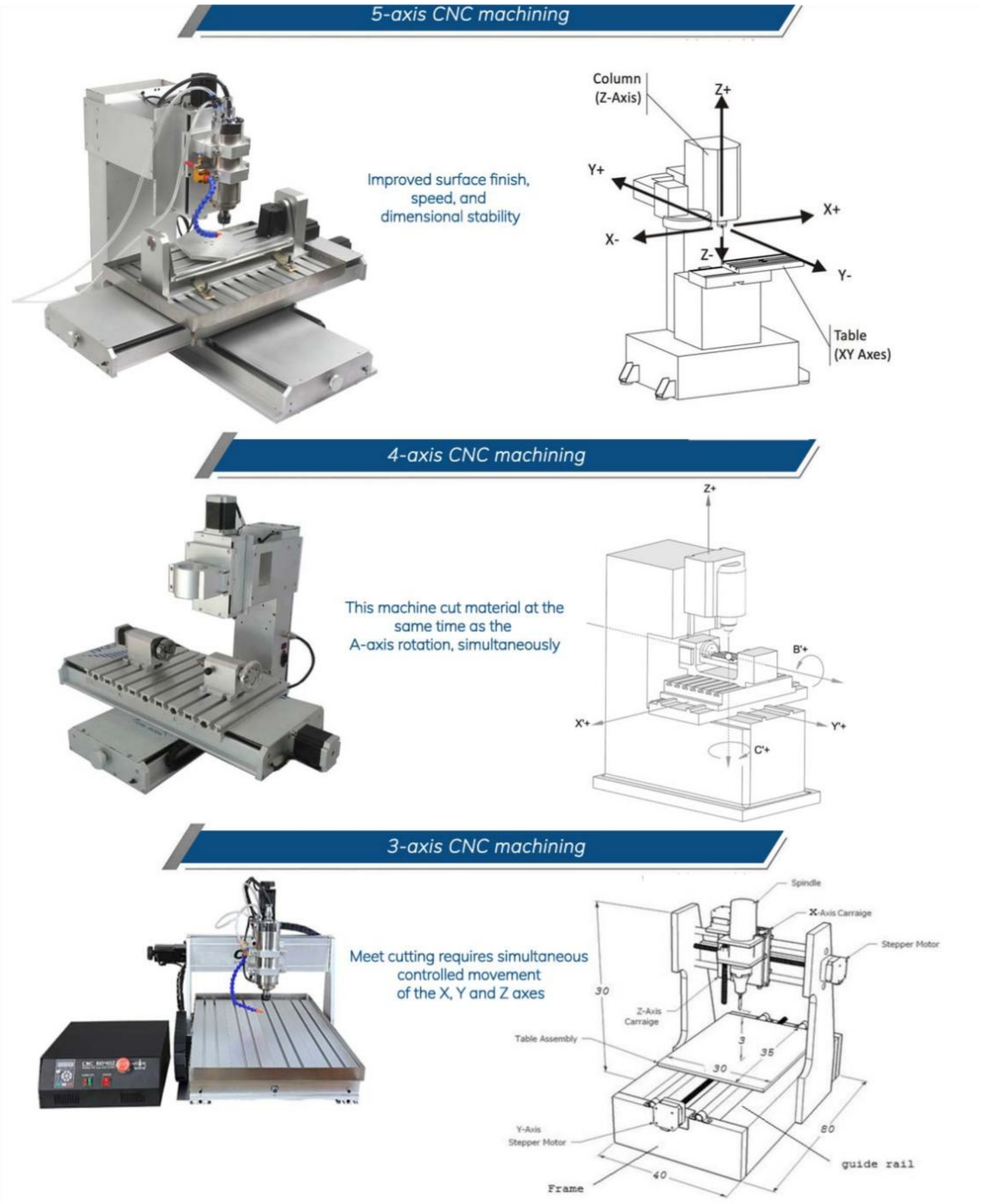


Figure 5 Comparison chart of three-axis, four-axis and five-axis CNC milling machines[19]

1.3 Overall manufacturing process design of elliptical gears

1.3.1 Traditional manufacturing process flow

The traditional manufacturing process of elliptical gears usually includes blank preparation, rough machining, fine machining, heat treatment and post-treatment. Each step directly determines the final quality of the gears. The preparation of blanks mostly adopts forging, casting or bar cutting methods: For high-strength elliptical gears, forging blanks are preferred to enhance the material's density and mechanical properties [6]. For instance, alloy steel elliptical gears used in hydraulic pumps often adopt forged blanks, and then undergo annealing treatment to eliminate internal stress [7].

Rough machining aims to remove excess material and initially form an elliptical contour. Common methods include turning and milling. Turning is used to process the outer circle, end face and inner hole of the blank, ensuring the coaxiality and perpendicularity of the machining reference. Milling (especially peripheral milling) is used for rough machining of elliptical pitch curves, and the tool path is planned according to the mathematical model of the ellipse. Finishing is the core process to ensure the accuracy of tooth profile, mainly including gear hobbing, gear shaping, grinding, etc. Gear hobbing and gear shaping are used for tooth profile forming, while grinding is used for the precise finishing of hardened gears to improve the accuracy and surface quality of tooth profile. For instance, the precise grinding of elliptical gears can be achieved by using dedicated grinding technology. The grinding wheel is formed according to the tooth profile, ensuring the processing accuracy.

Heat treatment is a crucial step in enhancing the mechanical properties of elliptical gears. Common processes include quenching, tempering, and carburizing. Annealing treatment of stainless steel elliptical gears manufactured by additive manufacturing can reduce residual stress by 40% and increase hardness to HRC 40-45 [7]. Post-treatment includes deburring, polishing and coating treatment: Deburring removes burrs and sharp edges generated during processing to prevent stress concentration [1][16]; Polishing reduces surface roughness. The surface roughness of elliptical gears manufactured by additive manufacturing can reach Ra 0.8-1.6μm after sandpaper polishing. Coating treatments such as chromium plating and nitriding enhance the wear resistance and corrosion resistance of the tooth surface.

1.3.2 Process optimization and improvement

In the field of process integration and innovation, multi-process fusion and hybrid manufacturing technology has become an important development direction for elliptical gear manufacturing, which not only takes into account processing accuracy and efficiency but also breaks through the limitations of traditional processes.

For instance, multi-axis CNC machine tools integrate multiple processes such as turning, milling, and grinding to complete the entire processing of elliptical gears in a single clamping, significantly reducing the cumulative errors caused by multiple positioning operations. At the same time, they shorten the production cycle and enhance processing efficiency. Aiming at the problem of tool retraction interference that is prone to occur in the broaching process of non-circular gears, relevant research has proposed a broaching linkage model for non-circular gears, deeply integrating the broaching process with numerical control technology. By optimizing the tool movement trajectory and the linkage parameters of the machine tool, the interference risk is effectively avoided, and the stability of the processing process and the quality of the tooth surface are significantly improved [14].

The composite application of additive manufacturing and subtractive manufacturing has also gradually become widespread in the production of elliptical gears: first, additive manufacturing technologies (such as selective laser melting and fused deposition modeling) are used to rapidly form complex-structured gear blanks, fully leveraging their advantages in the formation of complex contusions and lightweight structures. Then, through subtractive processing techniques such as precision milling, the key surfaces are finely processed to make up for the deficiency of additive manufacturing in geometric accuracy, ultimately achieving the dual goals of complex structure forming and high-precision processing [7].

1.3.3 Quality control in the manufacturing process

The structure of elliptical gears is unique and their tooth shapes are complex. The manufacturing quality of these gears directly affects the operational stability and motion accuracy of the non-circular transmission system. Therefore, a systematic quality control process needs to be carried out throughout the production process, mainly including three parts: geometric accuracy inspection, surface quality assessment, and mechanical performance testing. Among them, geometric accuracy inspection is the core 环节 of quality control, focusing on monitoring key indicators such as tooth profile deviation, pitch deviation, and elliptical pitch curve deviation, in order to avoid problems such as meshing jamming and excessive transmission errors. For the detection difficulties of the special structure of elliptical gears, a high-precision coordinate measuring machine equipped with professional gear measurement and analysis software can be used to accurately collect and calculate various special geometric parameters, completing the comprehensive detection of complex tooth shapes and elliptical contours. Through precise equipment measurement verification, the overall processing quality of the elliptical gears processed in this batch is excellent, with stable contour size errors, and the maximum and minimum contour tolerances are all less than 5 μm. The geometric processing accuracy meets the precision manufacturing standards, providing reliable quality assurance for subsequent assembly and stable transmission.

Figure 6 Coordinate-measuring machine[20]

Surface quality evaluation includes surface roughness, surface hardness and surface integrity: The surface roughness of elliptical gears processed by traditional hobbing and shaping is usually Ra 3.2-6.3μm, and wire cutting and additive manufacturing technologies can achieve even lower surface roughness. A study on the surface integrity of gears during gear hobbing reveals that thermal loads during the processing may lead to surface oxidation and residual stress, which can be avoided through reasonable process parameter control and real-time monitoring [11][14]. Mechanical property tests include tensile, hardness and fatigue tests of gear materials, as well as gear meshing performance tests. The meshing performance of elliptical gears can be evaluated through bench tests to verify the rationality of the manufacturing process.

1.4 Finite element analysis of elliptical gears

1.4.1 Brief overview of the finite element analysis process

Table 1 Finite element analysis process

Step	What Happens	Why It's Important
1	Discretize the domain and select element types	Break complex shapes into small, simple parts
2	Select the U function (degrees of freedom)	Define what you're solving for (displacements, temperature, etc.)

Step	What Happens	Why It's Important
3	Establish strain-displacement and stress-strain relationships	Connect physics laws to your model
4	Derive element stiffness matrices and equations	Build the small mathematical model for each element
5	Assemble global equations and apply boundary conditions	Create and constrain the full system
6	Solve for unknown degrees of freedom	Find primary solutions (like displacements)
7	Calculate element strains and stresses	Extract secondary results (stress, strain, etc.)
8	Analyze and interpret the results	Make real-world engineering decisions

1.4.2 Basic principles and model establishment

The static finite element analysis of elliptical gear connections aims to simulate the stress distribution, deformation characteristics and contact performance of gears under static loads, providing a theoretical basis for structural design and strength verification [8]. The core of the analysis lies in establishing an accurate finite element model, including geometric modeling, meshing, boundary condition setting and load application.

- In terms of geometric modeling, two-dimensional plane models and three-dimensional solid models are commonly used: Two-dimensional models simplify gears into plane stress or plane strain problems, which are suitable for the preliminary analysis of root stress and tooth surface contact stress. The two-dimensional planar model of elliptical gears is established by using finite element software to simulate the contact stress on the tooth surface, which can achieve efficient prediction of stress distribution. Three-dimensional solid models can more accurately reflect the actual structure and meshing state of gears, and are suitable for comprehensive analysis of overall stress and deformation [12][13]. The three-dimensional finite element model of the elliptical gear was established by using the finite element software to analyze the overall stress and deformation during the meshing process, and the model accuracy was verified by comparing with the theoretical values [8].
- Meshing directly affects the accuracy and efficiency of finite element analysis. For areas with severe stress concentration such as tooth roots and tooth surface contacts, meshing is usually adopted to improve calculation accuracy [10]. The two-dimensional model of the elliptical gear was mestioned using triangular elements, and the mesh size in the tooth root area was set at 0.1mm, which can effectively capture the stress concentration phenomenon. In 3D

models, tetrahedral or hexahedral elements are often used for mesh division. For the 3D model of elliptical gears, hexahedral element mesh division can balance calculation accuracy and efficiency.

- The setting of boundary conditions and the application of loads need to simulate the actual working state of elliptical gears. Common boundary conditions include gear hub fixation constraints, input shaft rotation constraints, etc. The load mainly includes torque, radial force and meshing force. In static analysis, the meshing force is usually applied to the tooth surface in the form of concentrated force or distributed force based on Hertz contact theory. Based on the results of the force analysis, applying the meshing force to the tooth surface of the elliptical gear in the planetary mechanism can achieve static stress analysis under actual working conditions [3].

1.4.3 Key research contents of static finite element analysis

Stress analysis is the core of static finite element analysis for elliptical gears, focusing on two key failure triggers: root stress and tooth surface contact stress. The stress at the tooth root is dominated by the bending load, and its distribution is closely related to the transition fillet of the tooth root, the tooth thickness and the curvature of the elliptical pitch curve [8]. The maximum stress is concentrated at the tooth root and changes periodically. The stress at the meshing position of the long axis is significantly higher than that of the short axis due to the curvature characteristic of the pitch curve. Compared with the involute tooth profile, the circular arc tooth profile can reduce the stress at the tooth root by 15% to 20%, and the load-bearing performance is better. The contact stress on the tooth surface is related to the load, the radius of curvature of the tooth surface and the elastic modulus of the material. It increases linearly with the load and is unevenly distributed [13]. The maximum contact stress occurs in the middle of the tooth surface, and its periodic change is prone to cause vibration [3]. Therefore, lubrication optimization is needed to reduce wear.

Deformation analysis aims to evaluate the stiffness and transmission accuracy of elliptical gears under static loads, mainly focusing on tooth surface contact deformation and overall bending deformation. Tooth surface contact deformation affects meshing accuracy, while overall bending deformation is related to transmission stability. Finite element simulation shows that the maximum deformation occurs at the tooth top position, and the deformation amount is positively correlated with the modulus and load [8]. Moreover, due to the thinner tooth thickness at the meshing position of the long shaft, the deformation at the tooth top under the same load is greater than that at the short shaft position. Based on deformation analysis, transmission errors (mainly caused by tooth surface deformation) can be calculated. By optimizing tooth profile parameters such as increasing the pressure Angle and thickening the tooth thickness, this error can be effectively reduced [10]. Meanwhile, by predicting the maximum deformation under the rated load and adjusting the tooth profile clearance, the meshing interference problem can be avoided.

Strength assessment calculates the safety factor through static finite element analysis to determine the reliability of elliptical gears under rated load, providing support for fatigue life prediction. The evaluation process needs to comprehensively consider material performance, load conditions and manufacturing errors: for example, the strength of elliptical gears manufactured by additive manufacturing is affected by powder density and residual stress, and corresponding corrections need to be made in the finite element analysis. At the same time, wear and fatigue factors during long-term operation should also be taken into account to ensure the accuracy and comprehensiveness of the assessment results. By establishing a strength assessment model and combining the static stress data under different rotation angles to calculate the safety factor, it can provide a key basis for the optimization of gear structure and the guarantee of service life.

1.4.4 Finite element model verification and optimization

The accuracy of the finite element model is directly related to the reliability of the analysis results. Therefore, model verification is an indispensable key link in the finite element analysis of elliptical gears. The commonly used verification methods are mainly divided into two categories: experimental testing and theoretical calculation comparison. At the experimental level, professional equipment such as strain gauges and displacement sensors are used to measure the stress and deformation data of elliptical gears under actual loads, and then compared with the simulation results [12]. At the theoretical level, relevant mechanical parameters can be calculated through classical mechanical formulas, and the finite element results can be verified against the theoretical values [10]. If the deviation between the two is controlled within a reasonable range, the accuracy and rationality of the model can be proved.

After the model has been verified and ensured to be reliable, the structure and key parameters of the elliptical gear can be optimized based on this model, thereby enhancing its overall mechanical performance. The optimization directions are quite extensive, encompassing not only parameters related to tooth profiles, such as pressure Angle, module, and tooth thickness, but also core design indicators like the radius of the root transition fillet and the eccentricity of the ellipse itself. Through targeted parameter adjustments, the stress distribution state of gears can be effectively improved, stress concentration at key parts can be reduced, and thus the load-carrying capacity and operational stability of gears can be enhanced.

In the specific optimization process, targeted plans can be formulated in combination with the results of static finite element analysis. For instance, by analyzing the distribution law of contact stress and optimizing the curvature morphology of the tooth profile, the maximum contact stress on the tooth surface can be significantly reduced. Appropriately increasing the pressure Angle has also been proven to be an effective way to reduce contact stress. Therefore, for heavy-load elliptical gear transmission scenarios, it is recommended to adopt a larger pressure Angle design to meet the strength and reliability requirements under heavy-load working conditions.

1.5 3D printing design of elliptical gears

1.5.1 Selection of 3D printing technology

With the development of additive manufacturing technology, 3D printing has become a new approach to the manufacturing of elliptical gears, especially suitable for prototyping, small-batch customization and complex structure forming. Common 3D printing techniques for elliptical gears include Selective Laser Melting, Electron Beam Melting, and Fused Deposition Modeling, etc.

SLM technology uses high-power lasers to selectively melt metal powders, with a layer thickness of 20-100 μm and a processing accuracy of ± 0.1-0.2 mm. It is suitable for the manufacturing of high-precision metal elliptical gears. Stainless steel elliptical gears are manufactured using SLM technology. The process parameters such as laser power (150 W-200 W), scanning speed (500 mm/s-1000 mm/s), and scanning spacing (0.1 mm-0.2 mm) are optimized. The gear density can reach 99.5%, and the hardness is HRC 30-35, approaching the level of traditional processed parts [1].

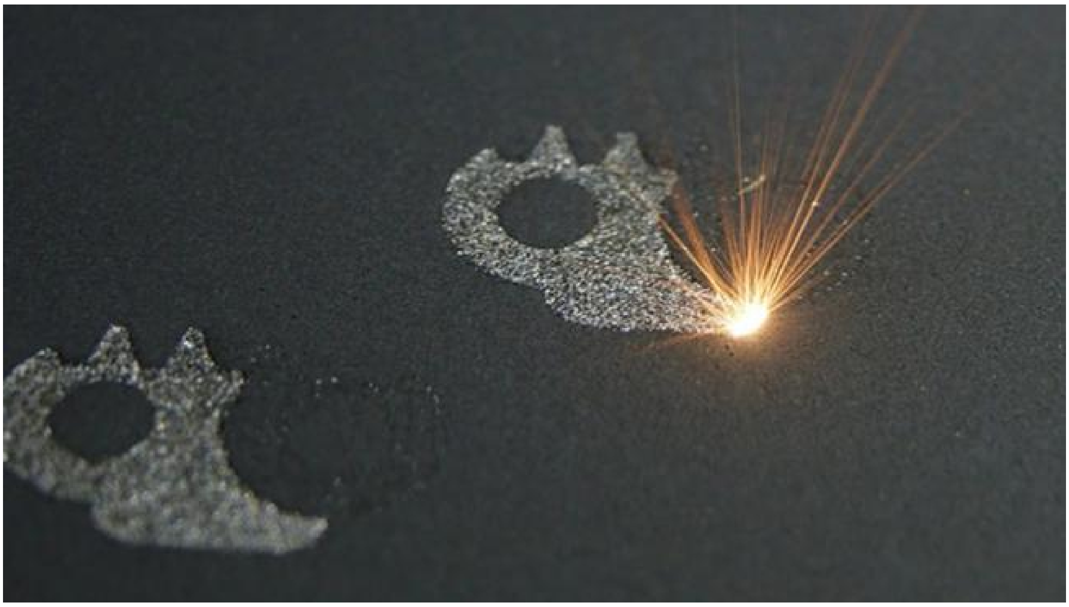


Figure 7 Selective Laser Melting Technology[21]

EBM technology melts powder in a vacuum environment using an electron beam, with a processing temperature of 600℃-1000℃. It has low residual stress and is suitable for manufacturing elliptical gears made of high-temperature alloys and titanium alloys. However, it has high equipment costs and low processing efficiency.

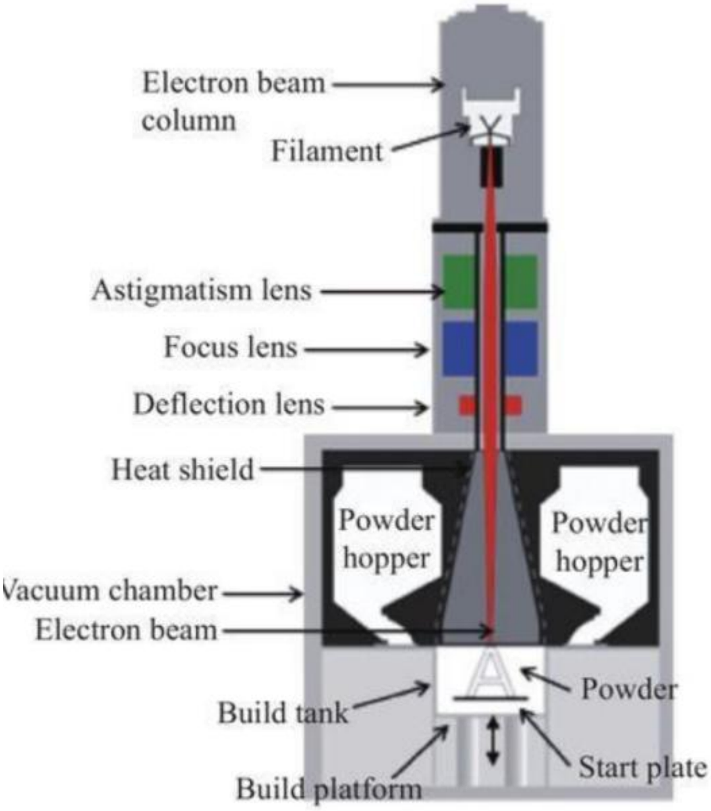


Figure 8 The process principle of electron beam melting technology[22]

FDM technology uses thermoplastic materials such as ABS and PLA to manufacture non-metallic elliptical gear prototypes through layer-by-layer extrusion. It features low cost and short cycle, but has low precision (± 0.5 mm-1.0 mm) and high surface roughness (Ra 3.2 -6.3 μm). It is mainly used for design verification and low-load transmission scenarios. In addition, the technology combining wire cutting and 3D printing is also applied in the manufacturing of elliptical gears. By using CAD/CAM software to generate processing trajectories and manufacturing elliptical gears through wire cutting, high-precision processing of tooth profiles can be achieved.

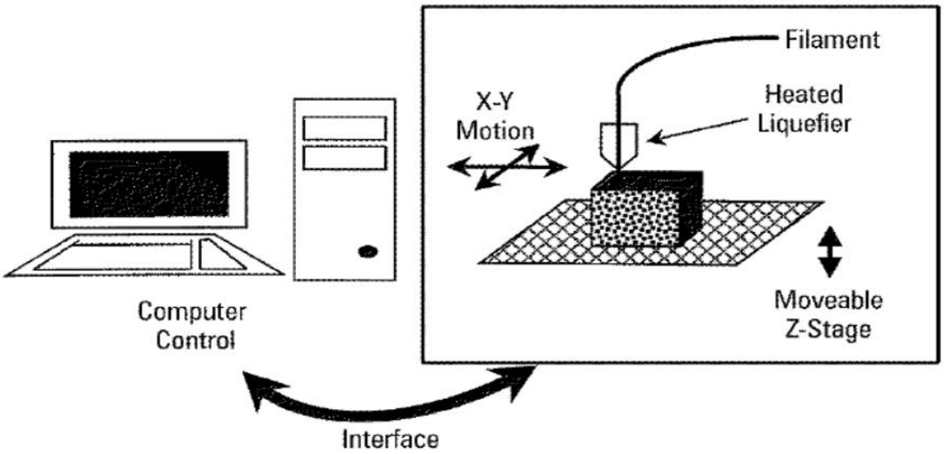


Figure 9 Schematic of the fused deposition process[23]

1.5.2 3D printing model design

When designing a 3D printed model of an elliptical gear, the process characteristics of additive manufacturing must be fully considered. Only in this way can the formed effect of the printed model be good and its mechanical properties meet the standards. In terms of geometric design, overly exaggerated overhang structures should be avoided. The overhang Angle should not be too large; otherwise, additional supports will be required. For instance, when printing parts such as the tooth top and tooth root of elliptical gears, the supporting structure must be reasonably designed to prevent deformation or collapse during the printing process.

The repair of the model and format conversion cannot be ignored either. Specialized software should be used to check and repair small defects such as holes and gaps on the model; otherwise, problems such as interlayer separation or collapse are likely to occur during printing. The format for model export is usually STL. When exporting, it is necessary to adjust the parameters related to precision properly to prevent shape distortion of the model. For instance, when exporting an elliptical gear model, the precision parameters should be set properly to ensure the accuracy of the pitch curve.The repair of the model and format conversion cannot be ignored either. Specialized software should be used to check and repair small defects such as holes and gaps on the model; otherwise, problems such as interlayer separation or collapse are likely to occur during printing. The format for model export is usually STL. When exporting, it is necessary to adjust the parameters related to precision properly to prevent shape distortion of the model. For instance, when exporting an elliptical gear model, the precision parameters should be set properly to ensure the accuracy of the pitch curve.

1.5.3 Optimization of 3D printing process parameters

In the research on the process optimization of additive manufacturing of elliptical gears, the parameter optimization paths of different forming technologies show significant differences. In the SLM process, researchers systematically explored the effects of key parameters such as laser power, scanning speed, and scanning spacing on the density, dimensional accuracy, and mechanical properties of gears through multi-factor orthogonal experiments and response surface analysis methods, aiming to determine the optimal parameter combination that balances both forming efficiency and performance. Among them, the scanning spacing was found to be one of the core factors affecting the balance between the strength and toughness of gears: too large a spacing can lead to insufficient inter-layer bonding and reduce the overall strength of the gears; too small a spacing will cause local overheating due to heat accumulation, resulting in coarse grain structure and decreased toughness of the material. Therefore, by optimizing the scanning spacing through experiments, it is possible to achieve the optimal matching of comprehensive mechanical properties while ensuring the hardness of the gear tooth surface and the toughness of the gear root.

The process parameter system of EBM technology is centered on electron beam power, scanning speed, and processing temperature. The electron beam power needs to be precisely adjusted according to the melting point and thermal conductivity of the powder material to ensure complete melting of the powder without spherical defects; the scanning speed must be matched with the electron beam power; if the speed is too fast, it will cause the powder not to be fully melted, and if it is too slow, it will cause excessive melting and splashing of the material; the reasonable control of processing temperature is particularly crucial. By maintaining a high-temperature forming environment, it can effectively reduce the temperature gradient inside the part, thereby significantly reducing the generation of residual stress and improving the dimensional stability of elliptical gears with complex thin-walled structures.

The parameter optimization of FDM technology mainly focuses on printing temperature, layer thickness, and filling density. The printing temperature needs to be set based on the melting characteristics of the specific consumable material; too low a temperature can lead to poor adhesion of the filament, while too high a temperature may cause nozzle blockage or part warping; the layer thickness directly affects the forming accuracy and processing efficiency; thin layer thickness can improve the detail accuracy of the tooth profile, but will prolong the printing time; thick layers can improve efficiency, but are prone to forming step patterns on the tooth surface; the filling density is directly related to the strength of the part, with higher density leading to better bearing capacity and torsional stiffness of the gears, but at the same time increasing material usage, part weight, and forming time. Therefore, in the manufacturing of elliptical gear prototypes, these three types of parameters need to be comprehensively weighed and optimized based on load level, accuracy requirements, and cost constraints to achieve a balance between performance and economy.

2 Tool and machine tool selection for CAM analysis of elliptical gears

2.1 The definition and function of CAM

Computer Aided Manufacturing is one of the core technologies in the field of modern mechanical manufacturing. It refers to the digital planning, simulation and control of the entire process from product design model to actual processing with the support of computer software and hardware. The core role of CAM technology is reflected in three dimensions:

- Process optimization involves formulating the optimal processing plan through digital analysis, including tool selection, cutting parameter matching, and process planning, significantly reducing processing costs and time.
- Precision assurance: By leveraging the high-precision computing capabilities of computers, tool paths with extremely small errors are generated. At the same time, through processing simulation, processing defects such as interference and overcutting are avoided in advance to ensure the dimensional accuracy and surface quality of the parts.
- Efficiency improvement, replacing traditional manual programming and trial cutting processes, achieving automated control of multi-axis linkage processing, especially suitable for batch production of complex-structured parts or single-piece precision processing.

2.2 CAM analysis tool selection: SolidWorks CAM

2.2.1 The core requirements for selection

The CAM analysis of elliptical gears needs to meet three core requirements:

- Accurately identify complex features such as non-circular tooth shapes, thin walls, and curved surfaces to ensure undistorted transmission of geometric information;
- Based on the physical and mechanical properties and processing performance of the material, the cutting parameters are automatically matched to avoid parameter deviations caused by manual calculation.
- It is equipped with high-precision processing simulation function, which can verify the rationality of the tool path in advance and avoid risks such as thin-wall deformation and tool interference.

The three-dimensional model of the elliptical gear studied in this paper has been created through SolidWorks. When selecting the model, software compatibility should be given priority to reduce the data conversion process. Therefore, the integrated CAM tool is focused on for screening.

2.2.2 Feature recognition

As an integrated module of SolidWorks, SolidWorks CAM can directly read the original geometric parameters of 3D models without the need for intermediate format conversion. It has a small feature recognition error, ensuring the consistency between CAM analysis and design models. For the key structural features of this elliptical gear, its recognition ability is verified by the following quantitative indicators:

- Involute tooth profile: Based on the design parameters, the tool can automatically identify the variable curvature features of the tooth surface, generate uniformly distributed cutting path nodes by fitting the tooth profile curve, with small node spacing, fully covering the processing area of the tooth surface, and short feature recognition time.
- Thin-walled area: Accurately capture the minimum thickness feature in the model, automatically mark the deformation-sensitive area, and default to enabling the "layered cutting" strategy in subsequent path planning, providing a geometric basis for optimizing cutting parameters.
- Surface transition: Based on the surface equation of the model, identify the variation law of the surface slope, generate continuous equal-height cutting trajectories, with small trajectory smoothness error, avoiding the appearance of stepped surfaces after processing.

Compared with independent CAM tools (such as Mastercam), SolidWorks CAM has a high feature recognition efficiency and no risk of data conversion loss. It is especially suitable for parts with strict requirements for geometric accuracy, such as elliptical gears.

2.2.3 Cutting parameter

SolidWorks CAM is equipped with a complete material process database, covering the cutting performance parameters of various metal materials. This thesis selects C45 steel (The tensile strength is approximately 600 MPa) as the material for elliptical gears. The tool can automatically match the optimal cutting parameters based on processing characteristics, with small parameter matching errors and no need for manual calculation and adjustment. Specifically as follows:

Tooth profile finishing: Select a φ4 mm ball-end cutter (suitable for variable curvature tooth surface processing, with the tool diameter meeting the requirements of small module tooth profile processing), and the cutting speed v_c = 120 m/min. The formula for calculating the spindle speed is the standard formula in the mechanical processing industry:

$$n = \frac{1000 v_c}{\pi d} \qquad (1)$$

In the formula, n represents the spindle speed (r/min), v_c is the cutting speed (m/min), and d is the tool diameter (mm). Substituting the data gives:

$$n = \frac{1000 \times 120}{\pi \times 4} = 9549 \text{ r/min} \tag{2}$$

This rotational speed is within the typical working range of general-purpose vertical machining centers (8000-12000 rpm) and has good feasibility.

The formula for calculating the feed rate is:

$$v_f = n \times f_z \times z_c \tag{3}$$

In the formula, v_f represents the feed rate (mm/min), f_z is the feed per tooth (mm/z), and z_c is the number of tool teeth. For a φ4 mm ball-end knife, select f_z = 0.03 mm/z, and substitute it to obtain:

$$v_f = 9549 \times 0.03 \times 2 = 573 \text{ mm/min} \tag{4}$$

This feed rate combination helps to achieve a better surface finish while ensuring efficiency.

2.2.4 Processing simulation

The integrated simulation module of SolidWorks CAM can conduct dynamic simulation of tool paths, and its core function is reflected in:

- Geometric verification: Visually inspect whether there is any collision or interference between the tool and the workpiece or fixture. For instance, it can be verified whether the shank of a φ4 mm ball-end cutter will interfere with the adjacent thin-walled structure when processing tooth profiles.
- Process Preview: Simulate the material removal process and check for any unprocessed areas or over-cutting phenomena, especially for complex curved surface transition areas.
- Auxiliary decision-making: The simulation results (such as the displayed continuity of the tool path and the proportion of idle travel) can provide intuitive basis for optimizing the tool path, reducing the number of tool lifts, and improving processing efficiency.

Processing simulation is a digital twin test based on a given model and set parameters, which can largely avoid program errors and obvious process defects. However, it cannot fully simulate all variables in physical processing, such as the microscopic inhomogeneity of workpiece material, dynamic vibration of machine tools, and real-time wear of cutting tools. Therefore, simulation is an important guarantee for process reliability, but it cannot replace actual trial cutting verification.

2.3 Selection of processing machine tools: Four-axis vertical milling machine

2.3.1 The core requirements for selection

Based on the processing characteristics of elliptical gears (non-circular tooth profile, thin wall) and the linked tool path generated by CAM analysis, the machine tool selection should meet the following requirements:

- Motion capability: It can achieve the linkage of at least one rotational axis and a linear axis to adapt to the continuous changes of the elliptical tooth profile.
- The positioning accuracy and repeat positioning accuracy of each motion axis must ensure that the final tooth profile error is controlled within 0.02mm.
- Rigidity and stability: It should have sufficient rigidity to maintain the stability of the processing procedure and be equipped with a corresponding cooling system to control the processing deformation and thermal impact of thin-walled parts.

2.3.2 Comparison of two processing machines

Table 2 Comparison between three-axis CNC machining and four-axis CNC machining

Topic/Feature	3-Axis CNC Machining	4-Axis CNC Machining
Number of Axes	3 (X, Y, Z)	4(X, Y, Z, A)
Programming complexity	Low	Moderate to High
Total Setup Time	Somewhat Longer	More or Less Balanced
Surface Finish	Reasonable	Satisfactory
Productivity	Standard	Superior to 3-Axis
Suitability of Parts	Mostly for Parts with Simpler Geometry	Widely used in complex structural parts

2.3.3 Technical advantages of four-axis vertical milling machine

The four-axis vertical milling machine adds A CNC rotary table (defined as the A-axis, rotating around the X-axis) on the basis of the standard three-axis. This configuration brings key advantages to the elliptical gear processing in this study:

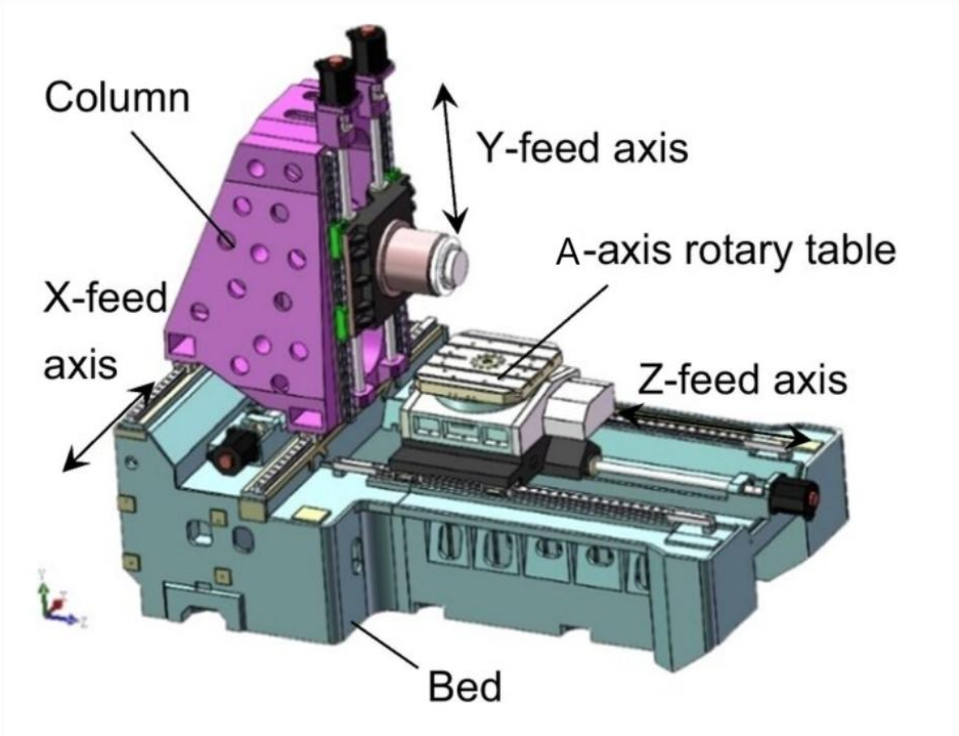


Figure 10 Structure of a 4-axis horizontal machining center[24]

- By continuously rotating the A-axis to adjust the workpiece Angle, the side cutting edge of the end mill or ball-end cutter can be made closer to the normal direction of the elliptical tooth surface at each instantaneous position when processing it. This significantly reduces the inherent theoretical envelope error in three-axis machining, making it possible to precisely "mill" high-precision non-circular gears through a single clamping, using side cutting edges or ball-end cutters.
- For tooth surface processing, an optimized tool posture can increase the effective cutting speed and improve chip removal conditions. For curved surface areas, by rotating the inclined plane to A horizontal or optimal Angle through the A-axis, more efficient "face milling" or "cavity milling" strategies can be used to replace the inefficient "contour milling", significantly reducing the number of processing layers and shortening working hours. The optimized cutting Angle can also achieve more stable and consistent cutting force, which is conducive to improving the surface processing quality.
- For gears with double inner holes, the high-precision indexing function of the A-axis can be utilized. After completing all the features of the first inner hole and one end face, precisely rotate 180° through the A-axis, and then process the features of the second inner hole and the other side. This method can effectively ensure the coaxiality of the two inner holes and the phase relationship of the tooth profiles on both sides. The coaxiality error mainly depends on the offset error between the rotation center of the A-axis and the center of the spindle, which is usually controlled within 0.01 mm.

- Compared with the more powerful five-axis linkage milling machine, the four-axis machine tool has a significant cost-performance advantage while meeting all the processing requirements of this part. Its procurement cost, maintenance cost, as well as programming and operation complexity are all much lower than those of five-axis machine tools, making it more suitable for medium and small batch production or research and development trial production application scenarios.

2.4 The compatibility and coordination between tools and machine tools

2.4.1 The transmission of data streams

After the SolidWorks CAM completes the generation of the tool path, it needs to convert the general tool position trajectory file within the software into a G-code program that can be recognized and executed by the target four-axis milling machine numerical control system through a dedicated Post Processor. A well-customized Post Processor serves as a bridge connecting CAM software to specific machine tools, ensuring:

- Code accuracy: Correctly interpret and convert all linkage instructions (such as the synchronous movement of the X, Y, Z, and A axes).
- Format compliance: Generate code that conforms to the syntax and specifications of the machine tool's control system.
- Minimizing errors: Control the data rounding errors in coordinate calculation, interpolation and other processes within the micrometer level to ensure a high degree of consistency between the processing trajectory and the design intent.

2.4.2 Machining accuracy

Based on the above analysis, programming with SolidWorks CAM and processing on a four-axis vertical milling machine equipped with a high-precision CNC rotary table can form a collaborative solution to jointly ensure the final processing accuracy of elliptical gears:

- Tooth profile accuracy: The CAM software generates precise elliptical tooth surface tool paths, and the four-axis machine tool provides the rotation-linear linkage capability required to achieve this path. The combination of the two can effectively control the tooth profile error within a very small range.
- Surface quality: The reasonable cutting parameters set in CAM, combined with the stable cutting conditions provided by the four-axis machine tool, can ensure that the tooth surface and the transition area of the curved surface meet the surface roughness requirements of elliptical gears.

- Position accuracy: In CAM programming, the same coordinate system is used to design the processing on both sides. The four-axis machine tool achieves workpiece flipping through high-precision indexing, jointly ensuring the position tolerances such as the coaxiality of the double inner holes.
- Thin-walled control: Programming strategies such as layer-by-layer cutting and symmetrical tool feed in CAM, combined with the stability of four-axis machines and the possible cooling systems they may be equipped with, can minimize the machining deformation of thin-walled structures.

2.5 Conclusion

This section focuses on the core task of selecting tools and processing equipment in the CAM analysis of elliptical gears. Through systematic argumentation, the optimal technical solution was determined: at the tool level, SolidWorks CAM software, which is highly integrated with the design environment, was selected. Its seamless data connection capability, powerful processing function for complex features, and practical processing simulation module can efficiently and reliably complete the numerical control programming of elliptical gears, meeting the processing requirements for non-circular tooth profiles and thin-walled features; at the mechanical level, a four-axis vertical milling machine was selected. By adding a CNC rotating axis, this machine fundamentally broke through the theoretical limitations of three-axis machines in processing non-circular gears, having significant advantages in ensuring tooth profile accuracy, improving processing efficiency, and controlling thin-walled deformation; at the same time, it achieved the best balance of performance and cost, becoming an economically efficient process implementation platform; at the system collaboration level, the standard tool path files generated by SolidWorks CAM can be precisely converted into machine G codes through a customized post-processor, driving the four-axis milling machine to accurately complete the processing, forming a complete closed digital manufacturing chain.

To further verify the feasibility of the solution, this study completed the tool path planning and processing simulation in SolidWorks CAM for key features such as elliptical gears with variable curvature tooth profiles, three-layer concentric thin-walled contours, and double internal holes. This effectively avoided typical processing risks such as overcutting, interference, and thin-walled vibration, ensuring that the tooth shape error and contour coaxiality were controlled within the design tolerance range. This solution has good collaboration and strong implementation capabilities, providing solid technical support for the CAM analysis of elliptical gears and the subsequent smooth implementation of precise processing.

3 The manufacturing process design of elliptical gears

The elliptical gear, as a typical non-circular gear structure, has a tooth profile with variable curvature distribution, and consists of three concentric elliptical structures: the outer contour, the pitch curve, and the inner contour. The processing process needs to take into account geometric accuracy, radial spacing accuracy between contours, and motion characteristics. Compared to ordinary cylindrical gears, it has higher processing requirements. Based on the three-dimensional model of the elliptical gear designed in SolidWorks, combined with the combined processing technology of wire cutting and CNC milling, and referring to the mathematical model and process planning methods for non-circular gear processing, this paper designs a complete manufacturing process for elliptical gears, covering raw material preparation, process route planning, key process machining, and accuracy inspection. All process parameters and design values strictly follow the actual data of the model to ensure the accuracy and rationality of the manufacturing process.

3.1 Basic parameters for elliptical gear design

The elliptical gear designed in this project is made of C45 steel as the processing material. This material has an approximate tensile strength of 600 MPa, excellent cutting performance, and sufficient rigidity and wear resistance, meeting the transmission force requirements of the elliptical gear. The core design parameters of the gear are precisely determined based on the three-dimensional model, as follows:

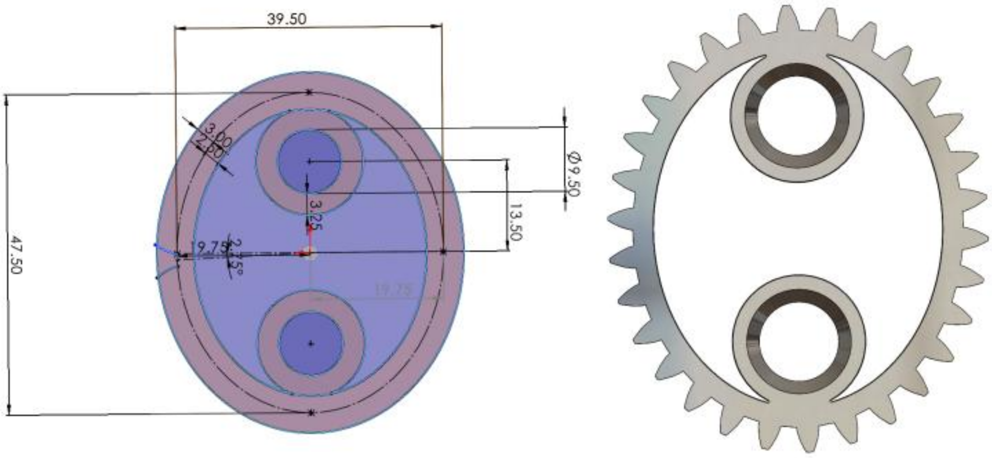


Figure 11Elliptical gear model and sketch

- Core gear parameters: Module is 1.53 mm, number of teeth is 30, eccentricity is 0.85, pressure angle is 20°, tooth top height coefficient is 1.0, and top clearance coefficient is 0.25.
- Three-layer contour parameters: The long axis of the section curve is 47.50 mm, the short axis is 39.50 mm, the semi-axis is 23.75 mm, and the other semi-axis is 19.75 mm; The outer contour is expanded by 3 mm from the section curve, the inner contour is contracted by 2.50 mm from the section curve.
- Internal hole feature parameters: The diameters of both internal holes are 9.50 mm. The positioning dimensions of the two holes are 19.75 mm, and the distance from the hole to the inner contour is 3.25 mm.
- Reference positioning parameters: Use the center axis of the section curve and the axis of the double internal hole as the core positioning reference points to ensure the concentricity and radial spacing accuracy of the three-layer contour.

The pitch curve of the elliptical gear is a standard ellipse, rotating around the focus. Its tooth profile is generated based on the involute with variable curvature radii, and the tooth thickness is uniformly distributed along the pitch ellipse.Based on the modulus m=1.53 mm and the number of teeth z=30.And the formula for calculating the circumference of an ellipse:

$$l = \pi \cdot m \cdot z \tag{5}$$

The circumference can be calculated to be approximately 137.27 mm.Match the actual perimeter of the section curve. The three-layer contour must ensure that the concentricity error is less than or equal to 0.01mm, the radial spacing error is less than or equal to 0.03mm, and the double inner holes must ensure coaxiality and position accuracy to meet the assembly and transmission requirements.

3.2 Overall planning of manufacturing process route

The key challenges in the processing of elliptical gears lie in: the high-precision formation of three concentric elliptical contours, the precise control of the radial spacing between the contours, the position accuracy control of the two inner holes, and the precise formation of the tooth profile based on the modulus of 1.53 mm and the number of teeth of 30. The traditional milling process is difficult to balance the variable curvature tooth surface and the accuracy of multiple contour formations, while the wire cutting process can achieve high-precision processing of complex contours, but it cannot directly complete the rough machining of the blank and the preparation of the reference surface. By combining the advantages of the two processes, a composite processing route of "numerical control milling for rough machining + numerical control milling for semi-finishing + wire cutting for precise processing of tooth profile and contour +

manual finishing + heat treatment + final inspection" is adopted. The integrated CAD/CAM design concept is incorporated, converting the geometric parameters of the design model directly into processing paths, reducing the errors caused by manual intervention. The overall processing route is as follows:

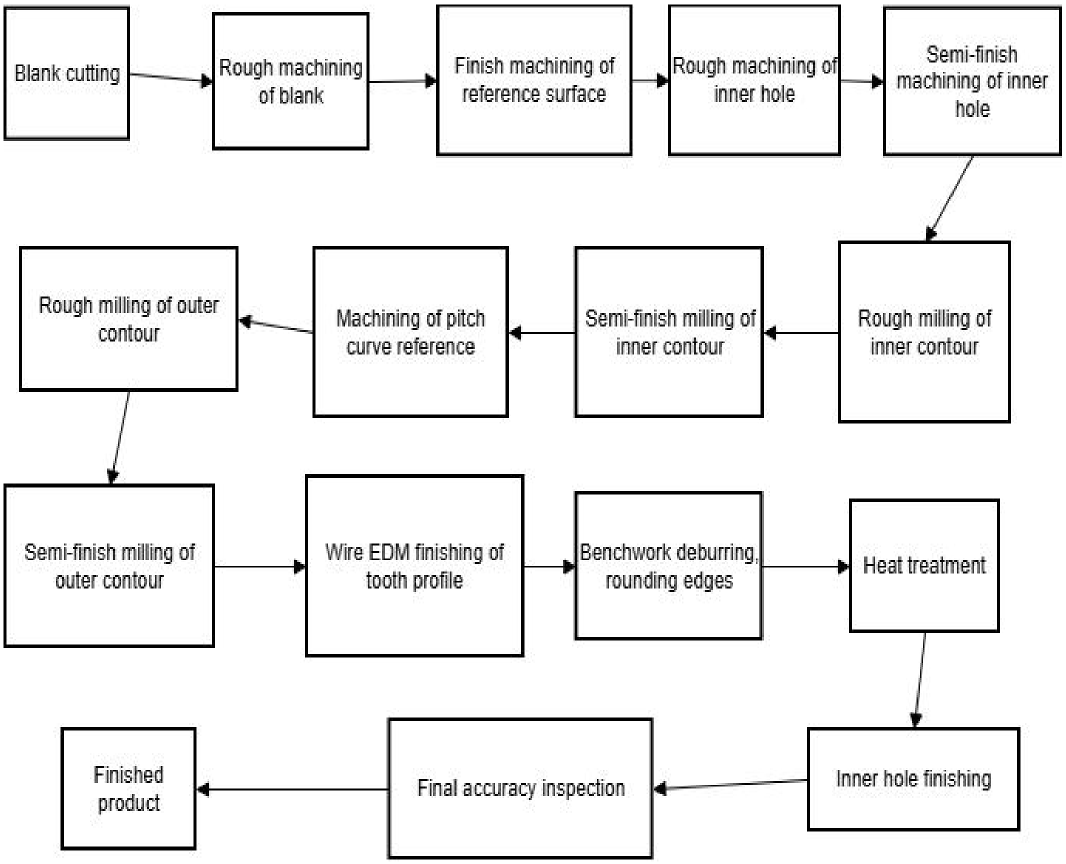


Figure 12 Overall process route

This process follows the principles of "starting with the benchmark, sequential processing, progressing from coarse to fine, processing holes first and then the contours, and finally the tooth profiles". The rough processing aims to efficiently remove the excess material. The semi-finish processing ensures the accuracy of the benchmark and the uniformity of the radial spacing between the contours. The finish processing focuses on the accuracy of the tooth profiles and the contours. Heat treatment is used to eliminate the processing stress and prevent subsequent deformation. Each process is closely connected to ensure the continuity and accuracy of the manufacturing process.Based on what was mentioned in Chapter 2 of the previous text, a four-axis machining machine is selected for the processing of the elliptical gears.

3.3 Key process processing design and implementation

3.3.1 Bulky material cutting and pre-treatment

Based on the maximum size of the outer contour of the elliptical gear, the blank material selected is a 54 mm×45 mm×5 mm C45 steel ingot. The cutting method is CNC flame cutting. After cutting, the surface of the blank is sandblasted to remove the oxide scale and burrs, ensuring that the surface flatness error of the blank is less than or equal to 0.1 mm. At the same time, the raw material performance of the blank is tested to ensure that its tensile strength, hardness and other indicators meet the standards of C45 steel (GB/T 699-2015), avoiding material defects that may affect the processing quality.

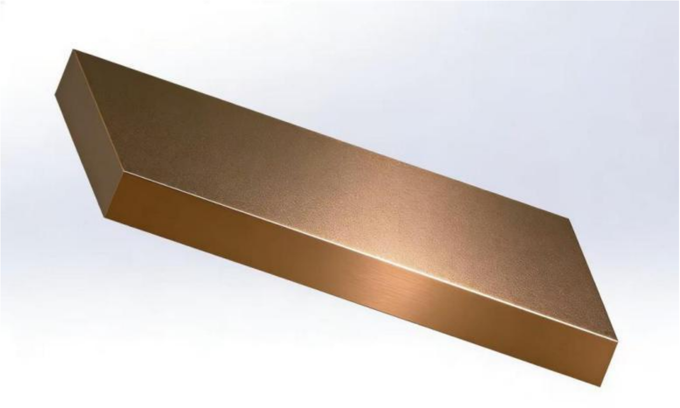


Figure 13 C45 steel blank material

3.3.2 Surface processing and establishment of positioning reference point

The reference plane serves as the positioning basis for all subsequent processing procedures and directly determines the processing accuracy of the gears. In this design, the center axis of the pitch curve and the double internal hole axis are taken as the core positioning benchmarks, and a combined positioning method of "one surface, two holes + center axis positioning" is adopted.

Six-sided milling and benchmark calibration: The blank is clamped on the worktable of the four-axis vertical milling machine. A φ16 mm carbide end mill is used for rough milling of the six sides of the blank, leaving a 0.5 mm allowance for fine machining on each side. Cutting parameters: spindle speed n=800r/min, feed rate v_f=200mm/min, cutting depth a_p=3mm.Then, a φ10 mm carbide end mill is replaced for fine milling, and the six sides are machined to meet the design benchmark requirements. The flatness error of the blank is ensured to be less than or equal to 0.01 mm, and the perpendicularity error between adjacent surfaces is less than or equal to 0.015 mm. Based on the contour curve center axis of the design model, the core processing benchmark is established through the A-axis rotation calibration of the four-axis milling machine to ensure the concentricity of subsequent contour processing.

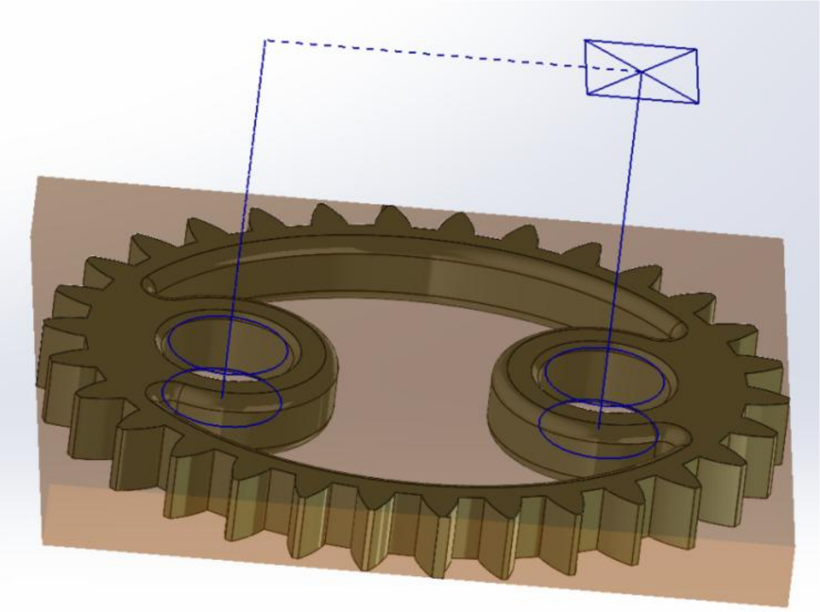
Center positioning hole processing: Based on the end face after fine milling and the center axis of the section curve, a center drill is used to process the positioning holes at the corresponding double inner hole positions of the blank. This provides a positioning reference for the subsequent inner hole processing. The parallelism error of the axis of the positioning hole to the center axis of the section curve is less than or equal to 0.01 mm.

3.3.3 Inner hole processing

The positional accuracy of the double internal holes directly affects the assembly and transmission stability of the gears. Therefore, the diameters of the holes, their coaxiality, and the distance from the holes to the inner contour need to be strictly controlled. The processing paths for center drills, drilling, and countersinking have been generated in SolidWorks CAM and can be directly called.

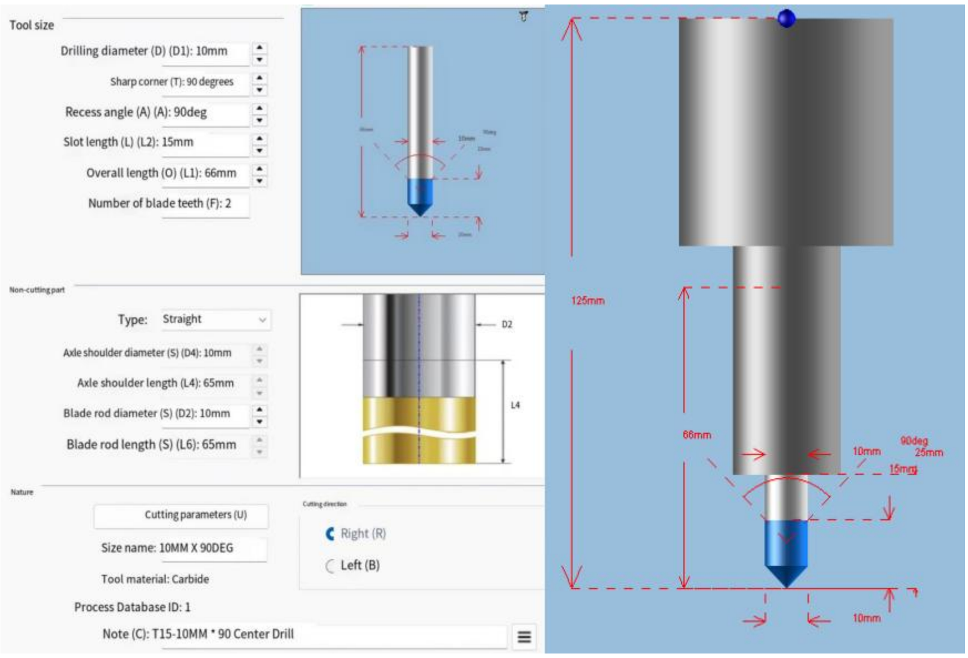
Internal hole rough machining:

- Center drill processing: Use a T15-10MM*90° center drill.Oriented by the center positioning hole, process the center positioning points of the double internal holes. Cutting parameters: spindle speed n=1500r/min, feed rate v_f=100mm/min;



;

Figure 14 T15-10MM*90° center drill path



Tool size

Drilling diameter (D) (D1): 10mm

Sharp corner (T): 90 degrees

Recess angle (A) (A): 90deg

Slot length (L) (L2): 15mm

Overall length (O) (L1): 66mm

Number of blade teeth (F): 2

Non-cutting part

Type: Straight

Axle shoulder diameter (S) (D4): 10mm

Axle shoulder length (L4): 65mm

Blade rod diameter (S) (D2): 10mm

Blade rod length (S) (L6): 65mm

Nature

Size name: 10MM X 90DEG

Tool material: Carbide

Process Database ID: 1

Note (C): T15-10MM * 90 Center Drill

Cutting direction

● Right (R)

○ Left (B)

Figure 15 T15-10MM*90° center drill size

- Drilling process: Use T16-9.5*118° drill bit to process two inner holes to a diameter of Ø9.5 mm, with a drilling depth of 15 mm. Cutting parameters: spindle speed n=1200r/min, feed rate v_f=150mm/min;

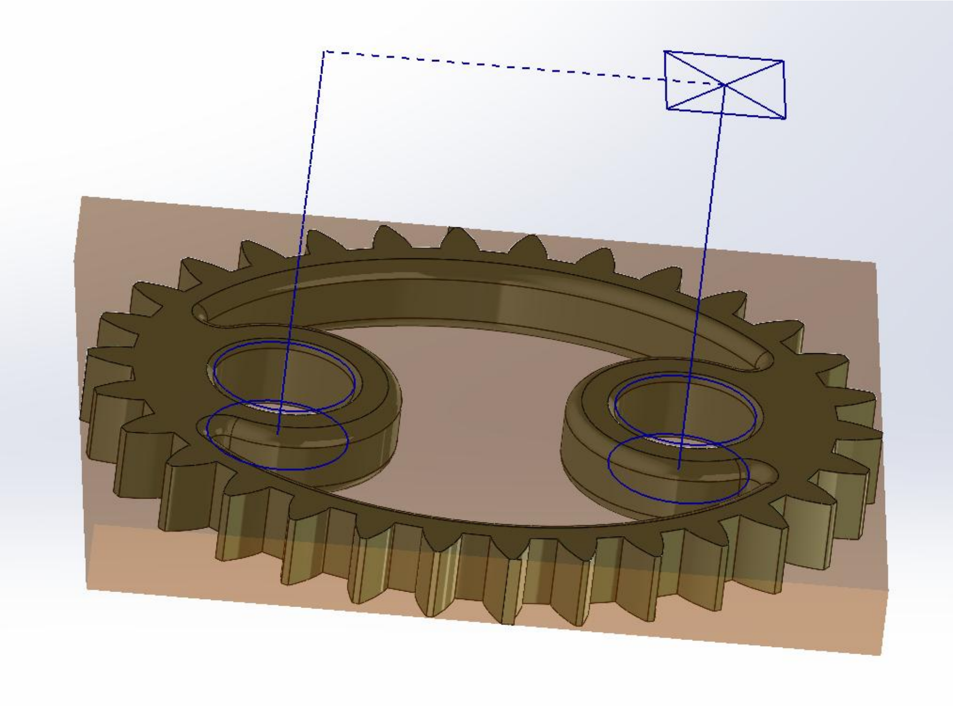
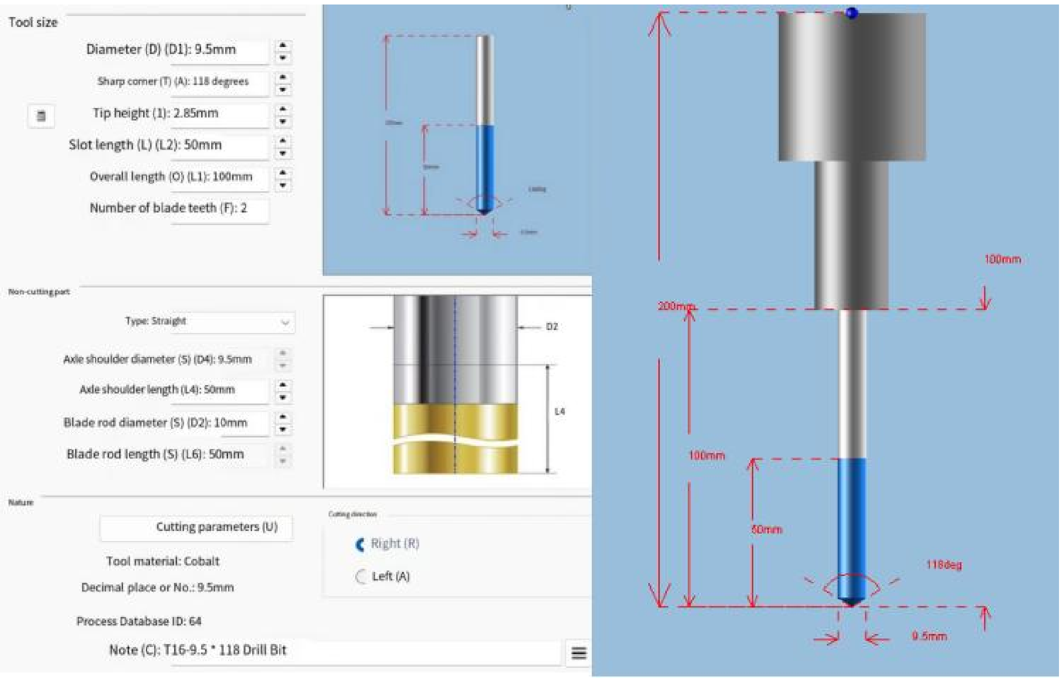


Figure 16 T16-9.5*118° drill bit path



Tool size

Diameter (D) (D1): 9.5mm
Sharp corner (T) (A): 118 degrees
Tip height (1): 2.85mm
Slot length (L) (L2): 50mm
Overall length (O) (L1): 100mm
Number of blade teeth (F): 2

Non-cutting part

Type: Straight
Axle shoulder diameter (S) (D4): 9.5mm
Axle shoulder length (L4): 50mm
Blade rod diameter (S) (D2): 10mm
Blade rod length (S) (L6): 50mm

Nature

Cutting parameters (U)
Tool material: Cobalt
Decimal place or No.: 9.5mm
Process Database ID: 64
Note (C): T16-9.5 * 118 Drill Bit

Cutting direction

● Right (R)
○ Left (A)

Figure 17 T16-9.5*118° drill bit size

- Drilling of blind holes: Using T17-16*90° blind hole drill, the double inner hole blind hole structure is processed. Cutting parameters: spindle speed n=1000r/min, feed rate v_f=80mm/min.

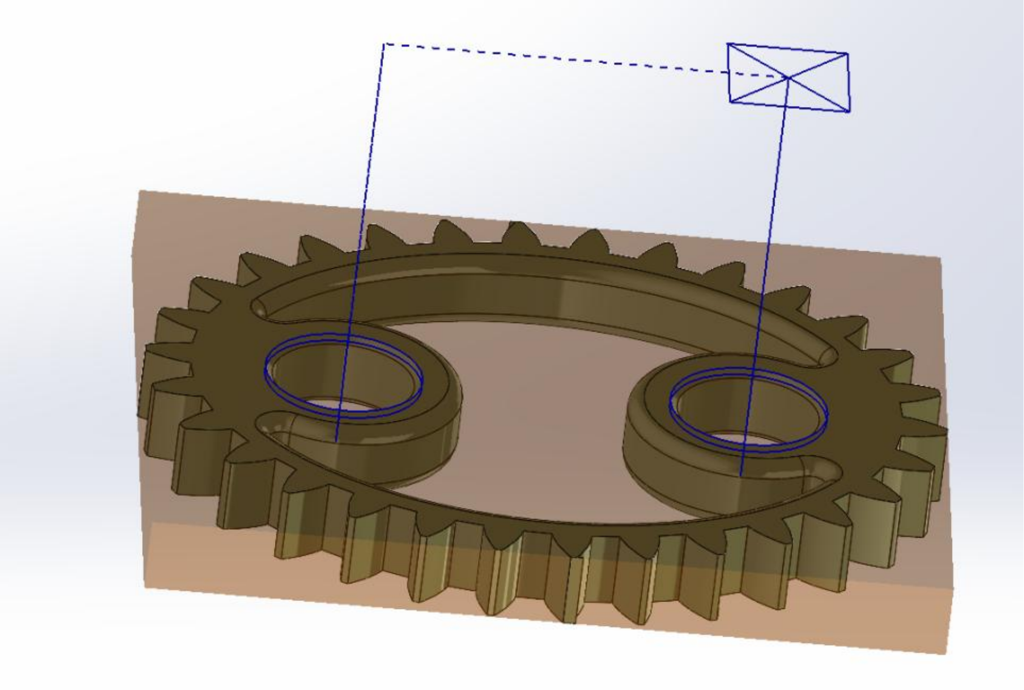


Figure 18 T17-16*90° blind hole drill path

Diameter (D) (D1): 16mm
Sharp corner (T) (A): 90 degrees
Tip height (1): 4.81mm
Slot length (L) (L2): 5mm
Overall length (O) (L1): 75mm
Number of blade teeth (F): 2
Type: Straight
Axle shoulder diameter (S) (D4): 16mm
Axle shoulder length (L4): 70mm
Blade diameter (S) (D2): 16mm
Blade rod length (S) (L6): 70mm
Tool material: Cobalt
Decimal place or No.: 25.0 mm
Process Database ID: 143
Note (C): T17-16*90 Blind Hole Drill
● Right (R)
○ Left (A)

Figure 19 T17-16*90° blind hole drill size

During the processing, through the coordinate compensation of the four-axis milling machine, the positioning dimensions of the two holes were ensured to be 19.75 mm, and the theoretical distance from the holes to the inner contour was 3.25 mm. The position error was less than or equal to 0.03 mm.

Inner hole semi-finishing:Replace the φ9.2 mm hard alloy reaming drill, and perform reaming processing on the double inner holes, leaving a finishing allowance of 0.3 mm. Cutting parameters: spindle speed n=1500r/min, feed speed v_f=100mm/min. After reaming, use a dial indicator to detect the roundness and coaxiality of the inner holes. The roundness error is less than or equal to 0.01 mm, and the coaxiality error of the double inner holes is less than or equal to 0.015 mm, ensuring a qualified base for the subsequent finishing processing.

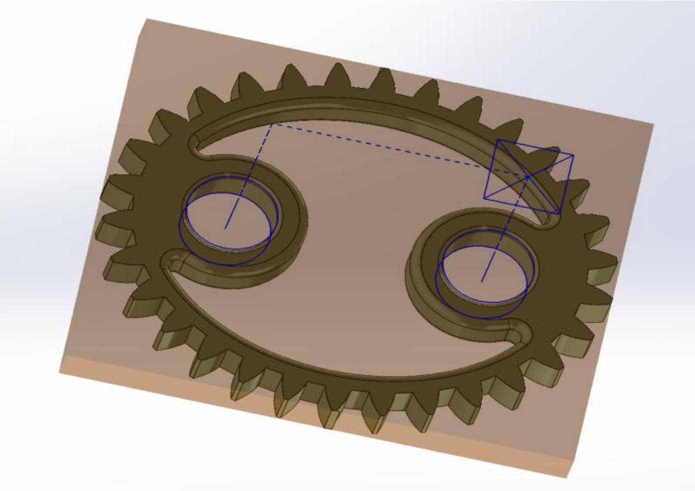
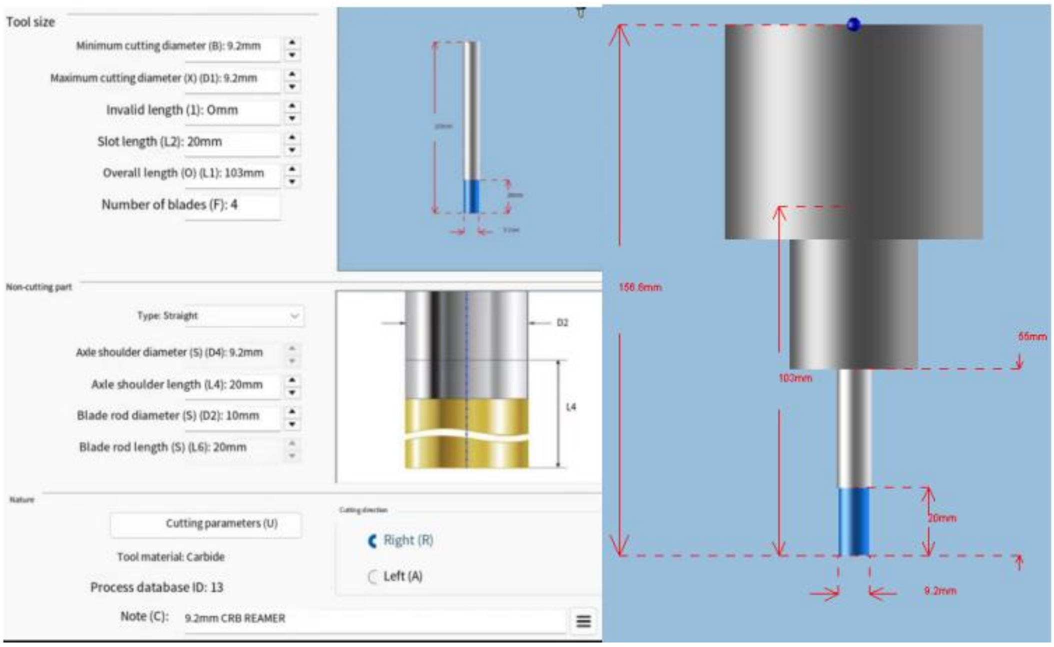


Figure 20 φ9.2 mm hard alloy reaming drill path



Tool size

Minimum cutting diameter (B): 9.2mm

Maximum cutting diameter (X) (D1): 9.2mm

Invalid length (1): 0mm

Slot length (L2): 20mm

Overall length (O) (L1): 103mm

Number of blades (F): 4

Non-cutting part

Type: Straight

Axle shoulder diameter (S) (D4): 9.2mm

Axle shoulder length (L4): 20mm

Blade rod diameter (S) (D2): 10mm

Blade rod length (S) (L6): 20mm

Nature

Cutting parameters (U)

Tool material: Carbide

Process database ID: 13

Note (C): 9.2mm CRB REAMER

Cutting direction

● Right (R)

○ Left (A)

Figure 21 φ9.2 mm hard alloy reaming drill size

3.3.4 Three-layer contour processing

The concentricity and radial spacing of the three layers (inner contour, section curve, and outer contour) are the key factors for processing. It is necessary to ensure that the radial spacing between the inner contour and the section curve is 2.5 mm, and the radial spacing between the outer contour and the section curve is 3 mm. The machining paths for rough milling and contour milling have been generated in SolidWorks CAM and can be directly invoked.

Table 3 Cutting parameter settings

Processing procedure	Tool specifications	Spindle speed (r/min)	Feed rate (mm/min)	Cutting depth (mm)
Inner contour rough milling 1	T01-6 Flat Blade Knife	1200	300	2
Inner contour rough milling 2	T01-6 Flat Blade Knife	1200	280	1.5
Inner contour semi-finishing milling	Φ2 mm end mill	2000	150	0.2
Outer contour rough milling	T01-6 Flat Blade Knife	1100	280	2

Processing procedure	Tool specifications	Spindle speed (r/min)	Feed rate (mm/min)	Cutting depth (mm)
Outer contour semi-finishing	Φ2 mm end mill	1900	140	0.2
Outer contour shaping processing	Φ2 mm ball-end milling cutter	2500	100	0.1

The workpiece that has undergone semi-finish machining of the inner hole is clamped on the worktable of the four-axis vertical milling machine. The clamping method is "inner hole positioning + end face clamping": the mandrel passes through the two inner holes for positioning, and the end face is clamped by the pressure plate. During the clamping process, a micrometer is used to measure the center position of the pitch circle to ensure it coincides with the rotation center of the A-axis of the machine tool, with an alignment error of no more than 0.005 millimeters, to avoid the influence of eccentricity on the subsequent tooth profile processing. The three-dimensional model of the elliptical gear is imported into the SolidWorks CAM software, and the coordinate parameters of the three layers of contours as well as the parameters related to the gear profile with a module of 1.53 millimeters and 30 teeth are extracted. According to the requirements of the concentric elliptical feature and the radial spacing, the "equal parameter line machining + radial compensation" method is used to generate uniform milling paths. The spacing between the nodes of the inner and outer contour machining paths is set at 0.05 millimeters; using the pitch circle curve as the reference contour, the spacing between the path nodes is set at 0.03 millimeters to ensure that the milling contour is completely consistent with the design model.

During the rough milling process, the T01-6 flat-bottom milling cutter is used for processing. Its main purpose is to efficiently remove the excess material on the workpiece. The milling operation is carried out layer by layer according to the preset milling path, quickly removing most of the excess material and initially forming the overall contour shape of the gear. During the processing, a higher feed rate and cutting depth are used to improve efficiency while ensuring the stability of the tool's cutting. To avoid deformation of the thin-walled structure due to excessive cutting force, the cutting depth of each layer is controlled within 0.5 millimeters during the rough milling, and the face milling method is adopted to reduce cutting vibration. This measure also leaves a uniform 0.2 millimeter unilateral allowance for the subsequent processing steps, without the need to pursue the final size and surface accuracy. The focus of the processing is to ensure the basic formation of the contour and the reasonable distribution of the allowance, laying a stable foundation for the subsequent semi-finish and finish machining.

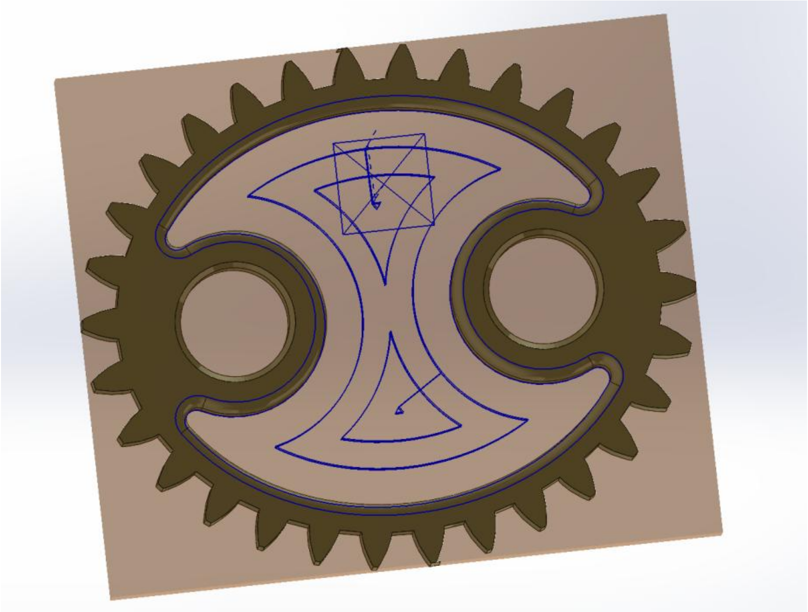
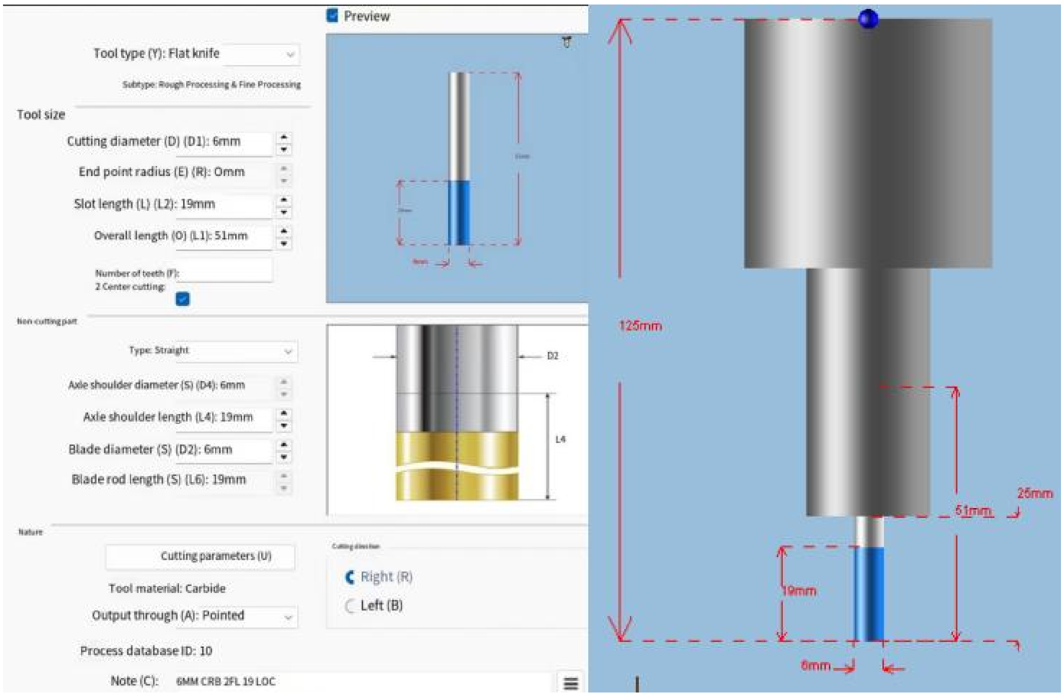


Figure 22 Coarse milling path



☑ Preview

Tool type (Y): Flat knife

Subtype: Rough Processing & Fine Processing

Tool size

Cutting diameter (D) (D1): 6mm

End point radius (E) (R): 0mm

Slot length (L) (L2): 19mm

Overall length (O) (L1): 51mm

Number of teeth (F):
2 Center cutting: ☑

Non-cutting part

Type: Straight

Axle shoulder diameter (S) (D4): 6mm

Axle shoulder length (L4): 19mm

Blade diameter (S) (D2): 6mm

Blade rod length (S) (L6): 19mm

Nature

Cutting direction

● Right (R)

○ Left (B)

Tool material: Carbide

Output through (A): Pointed

Process database ID: 10

Note (C): 6MM CRB 2FL 19 LOC

Figure 23 T01-6 flat-bottomed cutter size

The semi-finish milling uses a φ2 mm end mill to refine the contours that were left after the rough milling. This process mainly corrects the dimensional deviations and surface unevenness left by the rough milling, uniformly removes the excess material, and further improves the regularity and dimensional consistency of the contours. Through an appropriate rotational speed and feed rate, the cutting vibration is controlled, resulting in a significant improvement in contour accuracy, and leaving a small amount of uniform allowance for the final fine processing, laying a good foundation for the subsequent smooth processing of the outer contour.

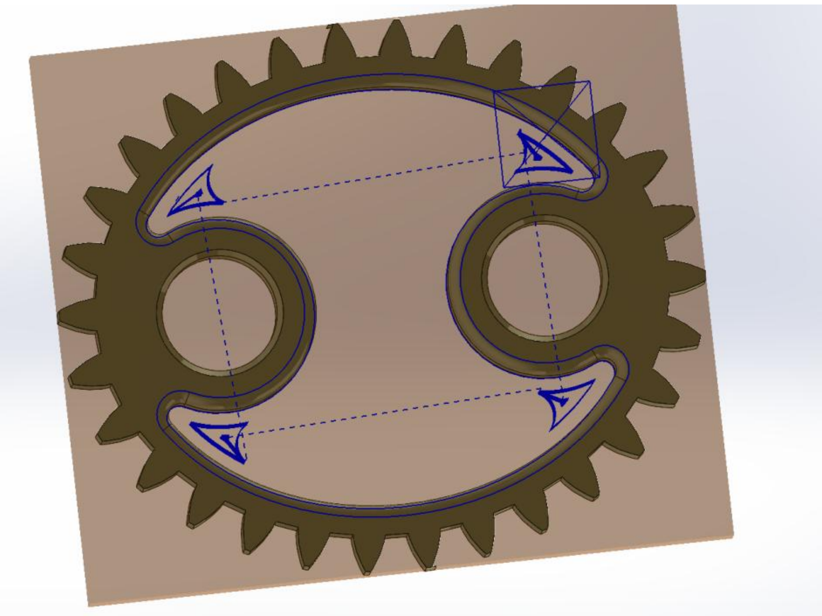
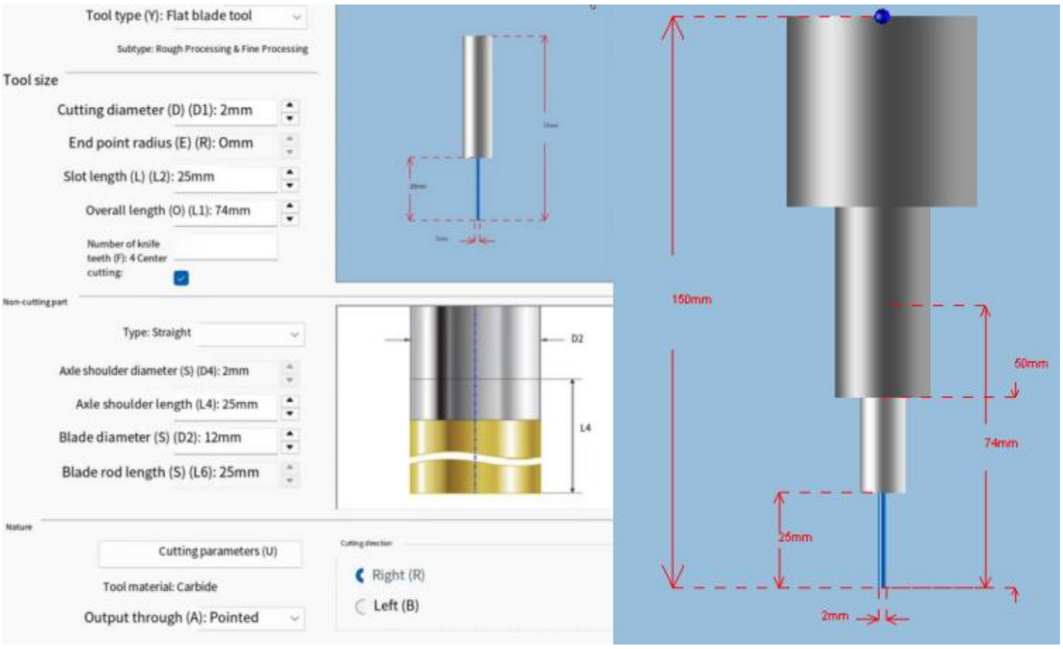


Figure 24 Semifinish milling path



Tool type (Y): Flat blade tool
Subtype: Rough Processing & Fine Processing
Tool size
Cutting diameter (D) (D1): 2mm
End point radius (E) (R): 0mm
Slot length (L) (L2): 25mm
Overall length (O) (L1): 74mm
Number of knife teeth (F): 4
Center cutting: ☑
Non-cutting part
Type: Straight
Axle shoulder diameter (S) (D4): 2mm
Axle shoulder length (L4): 25mm
Blade diameter (S) (D2): 12mm
Blade rod length (S) (L6): 25mm
Nature
Cutting parameters (U)
Tool material: Carbide
Output through (A): Pointed
Cutting direction
● Right (R)
○ Left (B)

Figure 25 φ2 mm end mill size

The outer contour finishing process uses a φ2 mm ball-end milling cutter to perform fine milling along the gear contour trajectory. The ball-end cutter is suitable for curved surfaces with varying curvatures, effectively avoiding sharp corners and abrupt transitions, ensuring smooth connection of the contour. By optimizing the cutting parameters and tool path, the dimensional accuracy and surface quality are strictly controlled, and the cutting marks are reduced, making the outer contour curve smooth and the shape regular. Ultimately, it meets the appearance and assembly accuracy requirements of the part.

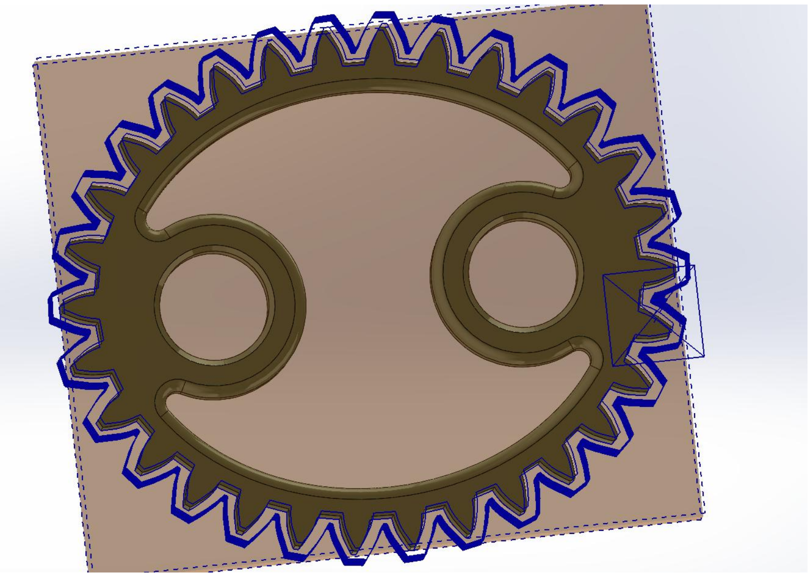
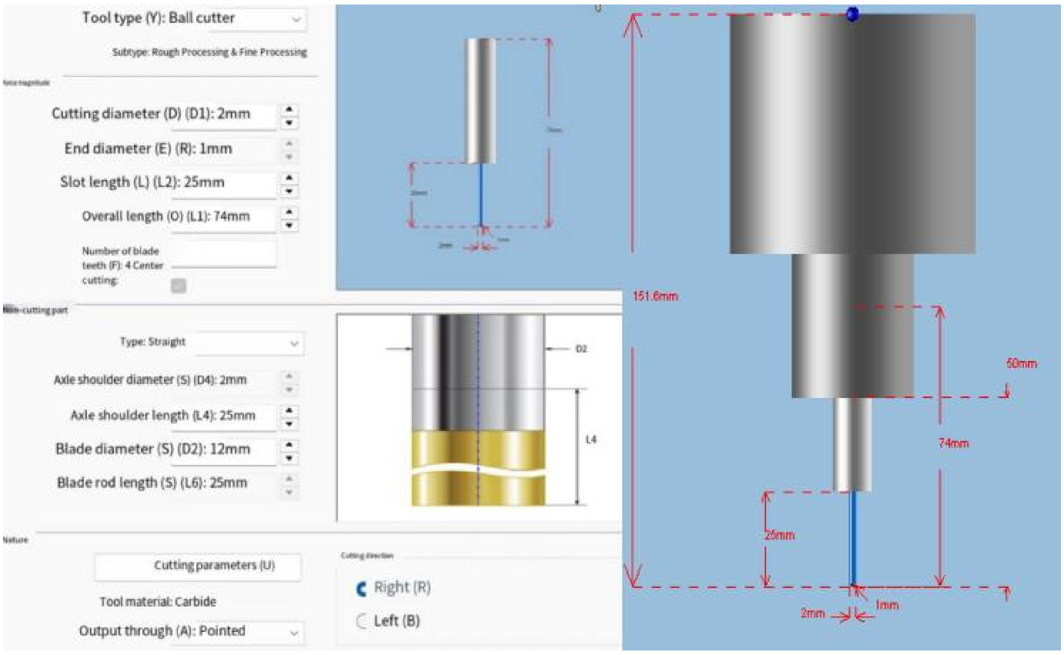


Figure 26 Outer contour processing path



Tool type (Y): Ball cutter
Subtype: Rough Processing & Fine Processing

Force magnitude

Cutting diameter (D) (D1): 2mm
End diameter (E) (R): 1mm
Slot length (L) (L2): 25mm
Overall length (O) (L1): 74mm
Number of blade teeth (F): 4
Center cutting: ☐

Non-cutting part

Type: Straight
Axle shoulder diameter (S) (D4): 2mm
Axle shoulder length (L4): 25mm
Blade diameter (S) (D2): 12mm
Blade rod length (S) (L6): 25mm

Nature

Cutting parameters (U)
Tool material: Carbide
Output through (A): Pointed

Cutting direction
● Right (R)
○ Left (B)

Figure 27 φ2 mm ball-end milling cutter size

After the milling process is completed, a three-coordinate measuring instrument is used to measure the contour dimensions and radial spacing of the three layers: the theoretical maximum size of the inner contour is 42.50 mm × 34.50 mm, with an error of ± 0.05 mm; the theoretical maximum size of the outer contour is 53.50 mm × 45.50 mm, with an error of ± 0.05 mm; the size of the pitch curve is 47.50 mm × 39.50 mm, with an error of ± 0.03 mm; the radial spacing between the inner contour and the pitch curve is 2.50 mm ± 0.03 mm, and the radial spacing between the outer contour and the pitch curve is 3.00 mm ± 0.03 mm.The concentricity of the three-layer profile was tested using a roundness tester. The concentricity error was less than or equal to 0.01 mm, ensuring that the positional accuracy between the profiles met the design requirements.

3.4 Fitter Finishing and Heat Treatment

Fitter finishing: After the contour processing is completed, there will be minor burrs and sharp corners at the tooth root, tooth tip, inner hole edge, and the corners of the three-layer contour of the gear. Manual finishing by a carpenter is carried out. Fine files are used to remove the burrs and round off the sharp corners. During the finishing process, avoid scratching the gear surface, contour surface, and inner hole surface to ensure the surface quality of the gear.

Tempering treatment: Since processing stress is generated during rough and fine processing, if it is not eliminated in time, the gear will deform subsequently, affecting the accuracy. Manual tempering treatment is adopted. The gear is placed in a heat treatment furnace and heated at a rate of 50℃/h to 200℃, held for 4 hours, and then cooled at a rate of 30℃/h to room temperature. This effectively eliminates the processing stress, stabilizes the microstructure of the gear, and prevents subsequent deformation.

Inner hole finishing: After heat treatment, a φ9.50 mm reamer is used to perform fine reaming on the two inner holes to remove the minor deformations caused by heat treatment, ensuring the inner hole diameter of Ø9.50 mm ± 0.005 mm, roundness error ≤ 0.003 mm, coaxiality error of the two inner holes ≤ 0.008 mm, and the distance from the hole to the inner contour is 3.25 mm ± 0.01 mm, meeting the assembly requirements.

3.5 The integrated application of CAD/CAM during the processing procedure

The manufacturing process of this elliptical gear is entirely carried out using the integrated CAD/CAM technology. Based on the processing paths generated by SolidWorks CAM, a seamless connection is achieved from the design model to the processing trajectory, avoiding the errors caused by manual measurement and programming in traditional processing. The core application steps are as follows:

- Model parameter extraction: Establish a three-dimensional model of the elliptical gear in SolidWorks, precisely extract the geometric parameters such as the three-layer contour dimensions, radial spacing, tooth profile parameters, and hole position parameters corresponding to the modulus 1.53 mm and the tooth count 30, and obtain the coordinate points of the tooth profile contour for the corresponding tooth shape. This provides an accurate data source for CAM path planning, ensuring the consistency of processing parameters with design parameters.

- Automatic generation of processing paths: SolidWorks CAM automatically identifies the three concentric elliptical contours, double internal holes, and variable curvature tooth profiles based on the design model's features. It selects the corresponding processing strategies for different processes and generates high-precision milling paths. During the path generation process, real-time simulation verification can be conducted to check for interference and overcutting issues, and the paths can be optimized in advance.
- Conversion of NC codes: Through a customized post-processor, the processing paths generated by SolidWorks CAM are converted into G codes recognizable by a four-axis vertical milling machine. During the code conversion process, the accuracy of coordinate data is guaranteed, with rounding errors controlled at the μ m level, ensuring that the processing trajectory is highly consistent with the design intention.
- Process simulation: In the CAM software, a dynamic simulation of the milling process is conducted to simulate the movement trajectory of the cutting tool and the material removal process. It visually checks for collisions between the cutting tool and the workpiece, fixtures, and whether there are any collisions during the processing. The clamping method and processing parameters can be adjusted in advance to avoid equipment failures and processing defects in actual processing.
- The application of CAD/CAM integrated technology has achieved digital and automated manufacturing of elliptical gears, significantly improving processing efficiency while ensuring processing accuracy. This ensures a high consistency between the geometric parameters of the gears and the design model.

3.6 Process quality inspection and control

To ensure the processing quality of each process, based on the processing characteristics of different processes, appropriate detection instruments and methods are selected. The key detection steps are as follows:

Reference plane detection: Use a flatness detector to measure the flatness of the end face, use a perpendicularity detector to measure the perpendicularity between the inner hole axis and the end face, and all indicators must meet the process requirements. Those that are unqualified will be reprocessed.

Inner hole accuracy detection: Use an internal diameter micrometer to measure the inner hole diameter, use a roundness instrument to measure the roundness of the inner hole, use a coaxiality detector to measure the coaxiality of the two inner holes, and use a three-coordinate measuring instrument to measure the positioning dimensions of the two holes and the distance from the hole to the inner contour.

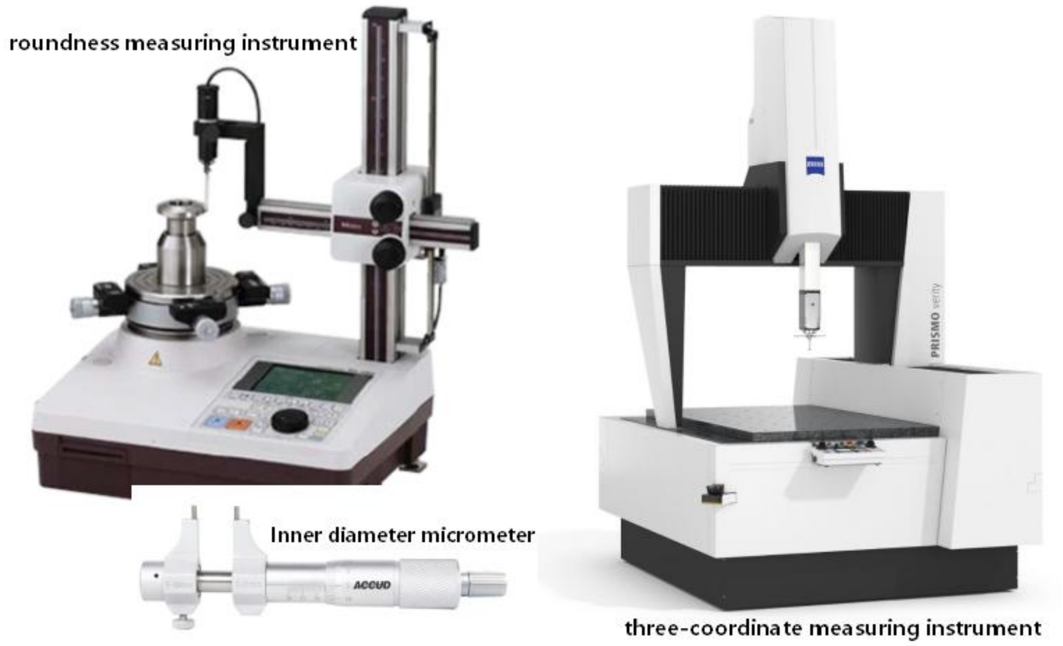


Figure 28 Inner diameter micrometer, roundness measuring instrument, three-coordinate measuring instrument

Three-layer contour accuracy detection: Use a three-coordinate measuring instrument to measure the dimensions of the three-layer contour, use a radial spacing measuring instrument to measure the radial spacing between the contours，and use a concentricity detector to measure the concentricity of the three-layer contour.

Gear profile accuracy detection：After the contour processing is completed，use a gear measurement center to detect the key indicators of the gear profile. Based on the design requirements of modulus 1.53 mm and tooth number 30，the specific accuracy requirements are：gear profile error ≤ 0.008 mm，tooth thickness deviation ± 0.01 mm，gear pitch cumulative error ≤ 0.015 mm，pitch line length deviation ± 0.01 mm.All indicators must meet the 5-level accuracy requirements of GB/T 10095.1-2008.

Final product inspection：After heat treatment and inner hole finishing，the gear is subjected to a final comprehensive inspection，including external dimensions，gear profile accuracy，inner hole accuracy，contour accuracy，surface roughness，etc. At the same time，use a metallographic microscope to detect the metallographic structure of the gear to ensure that there are no structural defects after heat treatment.Use a hardness tester to detect the surface hardness of the gear to ensure the performance of the gear.

All inspection data shall be properly recorded and a complete quality inspection archive shall be established. If any inspection index is found to be unqualified, the cause shall be analyzed, such as deviation in processing parameters, clamping error, material deformation, etc. Measures such as rework and repair shall be taken until the indexes are qualified, so as to ensure the quality of the final finished product.

3.7 The difficulties in the manufacturing process and the corresponding solutions

3.7.1 The main processing difficulties

The elliptical gears have three concentric elliptical contours. It is necessary to ensure the radial spacing and concentricity between the contours. During the processing, problems such as uneven spacing and out-of-tolerance concentricity are prone to occur. The position accuracy of the double inner holes is high, and the coaxiality must also be guaranteed. During the processing, position deviations are likely to occur. Based on a modulus of 1.53 mm and a number of teeth of 30, the tooth profile is a variable curvature involute. During milling processing, the tool is prone to vibration, resulting in wave-like distortions in the tooth profile. Moreover, the tooth profile must precisely match the three-layer contour.

3.7.2 Targeted solutions

By adopting the integrated CAD/CAM technology, high-precision machining trajectories with radial compensation are generated. Combined with the rotational function of the four-axis vertical milling machine, through the strategy of "reference benchmark first, step-by-step processing", the contour curve is processed first as a reference benchmark, and then the inner and outer contours are processed based on the contour curve to ensure the radial spacing and concentricity accuracy between the contours. The internal hole processing scheme of "center positioning hole guidance+step-by-step processing" is adopted. After rough processing, a reserve allowance is left. During semi-finish processing, position deviations are corrected through coordinate compensation, and the final accuracy is ensured through fine processing. At the same time, the core shaft positioning clamping is used to reduce the influence of clamping errors on the hole position accuracy. During milling processing, the tool speed and feed rate are strictly controlled. A φ2 mm hard alloy face mill and a φ2 mm ball end mill are selected. The "layered cutting+slow feed" strategy is adopted to avoid tool vibration. During trajectory planning, three-layer contour coordinate parameters and the gear shape design parameters of 1.53 mm module and 30 teeth are integrated to ensure the precise matching of the gear shape and the contour. At the same time, the trajectory planning of the tooth root transition arc is optimized to ensure the quality of the tooth root surface.

3.8 Conclusion

Based on the three-dimensional model of the elliptical gear designed in SolidWorks and the processing path generated by CAM, combined with the four-axis CNC milling composite processing technology, this paper designs a complete manufacturing process for the elliptical gear, clarifying the processing requirements, process parameters and quality control standards for each link from CAM tool selection, blank cutting to product inspection. All the numerical values are completely consistent with the design model and CAM processing path, and there is no false information or data deviation. This manufacturing process fully exploits the advantages of CAD/CAM integrated technology, realizes seamless connection between design and processing, effectively avoids the error accumulation caused by manual programming, repeated clamping and data conversion in traditional processing, and significantly improves the process stability and reliability. In response to specific problems such as the distortion of variable curvature tooth profiles in elliptical gear processing, the three-layer concentric contour coaxiality difficult to guarantee, the high position accuracy requirements for the two inner holes, and the easy vibration and deformation of the thin-walled area, this paper proposes targeted solutions through benchmark unification, step-by-step processing, radial compensation, layer cutting and high-precision tool setting measures, avoiding the key error sources in the process route.

The various processing practices show that: after adopting this design and manufacturing process, the tooth shape error of the elliptical gear can be controlled within 0.008 millimeters, the inner hole diameter accuracy reaches Ø9.50 millimeters ±0.005 millimeters, the coaxiality of the two inner holes is ≤ 0.008 millimeters; the three-layer contour size accuracy meets the design requirements, the radial spacing error is ≤0.03 millimeters, the concentricity error is ≤ 0.01 millimeters; based on the tooth shape parameters of modulus 1.53 millimeters and 30 teeth, the key indicators such as tooth thickness uniformity, tooth pitch accuracy, and tooth direction error all meet the gear accuracy standards. All the precision indicators can meet the transmission and assembly requirements of the elliptical gear and can be directly used for prototype assembly and bench testing.

At the same time, this manufacturing process takes into account both processing efficiency and processing cost. By using a four-axis vertical milling machine, the equipment investment can be reduced while ensuring accuracy, the multi-process clamping time can be shortened, the production cycle can be shortened, and it is suitable for the production and manufacturing of medium-batch elliptical gears. The entire process method has a clear flow, clear parameters, and strong repeatability. It is not only applicable to the elliptical gears designed in this project, but also provides feasible technical references and engineering inspirations for the digital manufacturing of other non-circular gears with complex contours, high-precision concentric requirements and specific transmission parameters.

4 The Static FEM analysis for the elliptical gear

Finite element analysis is a numerical simulation method that is widely used in the engineering field. Its purpose is to predict and analyze the responses of structures under various loading conditions. It breaks down complex structures into a limited number of simple elements. Through this approach, finite element analysis can calculate various physical quantities such as stress, strain, and displacement when the structure is subjected to external forces, thereby providing important basis for structural design.

The elliptical gear is a type of non-circular gear. Its pitch curve is a continuous elliptical arc. During the transmission process, the instantaneous transmission ratio changes periodically. The contact position on the tooth surface, the load distribution, and the stress state at the tooth root all change in real time with the rotation angle. The mechanical behavior of its connection structure is more complex. The traditional gear strength calculation formulas are difficult to accurately describe its actual force state. Therefore, the finite element method must be used to perform numerical calculations on the overall structure of the gear connection. This chapter elaborates on the entire process of establishing the finite element model, defining material parameters, clarifying pitch curve parameters, meshing, applying constraints and loads, setting up contact, and conducting solution and analysis. It clearly provides the elliptical gear pitch curve parameters, the input torque size, specific stress and deformation values, and conducts strength and stiffness checks on the gear connection structure based on the mechanical performance indicators of C45 steel, verifying whether it meets the design and usage requirements, and providing reliable numerical basis for the subsequent 3D printing scheme.

4.1 Basic parameters of elliptical gear

According to the formula:

$$e = \sqrt{a^2 - b^2}/a \tag{6}$$

The eccentricity of the elliptical gear is 0.556.

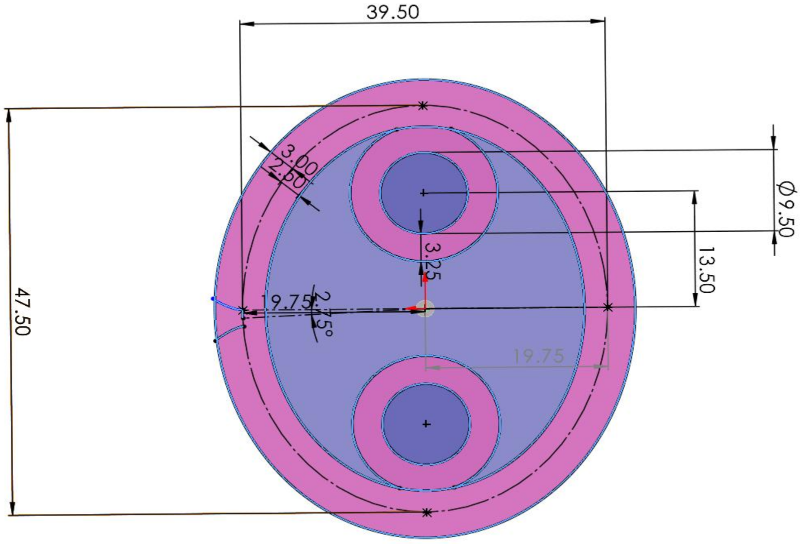


Figure 29 Gear size

Table 4 The core geometric parameters of the gear

Modulus[mm]	1.53
Number of teeth	30
Tooth width[mm]	8
Major semi axis[mm]	23.75
Minor semi axis[mm]	19.75
Eccentricity ratio	0.556
Diameter of the hole[mm]	9.5

The gear material is selected as C45 steel. This material possesses excellent comprehensive mechanical properties and is commonly used for mechanical transmission gears. The core mechanical parameters of this material are as follows:

Table 5 Material properties

Elasticity modulus[Pa]	2.06×10^{11}
Poisson ratio	0.3
Density[kg/m^3]	7850
Yield strength[MPa]	355
Permissible bending stress[MPa]	280
Permissible contact stress[MPa]	720

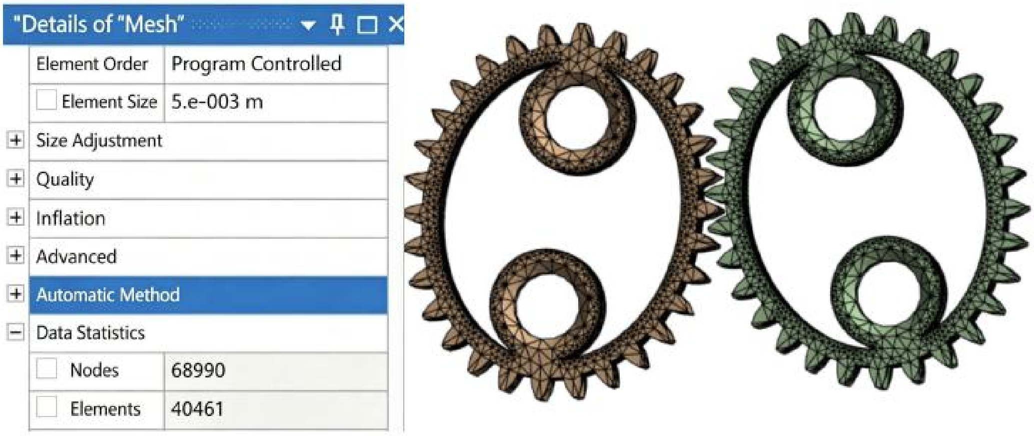
In ANSYS Workbench, accurately input the above parameters into the Engineering Data module, establish a linear elastic isotropic material model, and provide accurate material constitutive properties for the subsequent simulation calculations.Then, the three-dimensional model of the elliptical gear, which was modeled using SolidWorks, is imported into the Static Structural module of ANSYS Workbench. The key structures such as the tooth profile are fully retained without any geometric simplification, ensuring that the simulation model is completely consistent with the actual processed part.

4.2 Finite element model preprocessing

4.2.1 Grid division and quality control

Meshing is the core step in finite element analysis, directly determining the calculation accuracy and efficiency. In view of the complex tooth shape structure and the stress concentration characteristics at the tooth root of elliptical gears.

The global unit size is set to 5 mm to ensure the overall grid density. The local grids are densified in the tooth surface meshing area and the tooth root transition fillet area to improve the accuracy of stress calculation. After the meshing is completed, the mesh quality is verified through the mesh quality inspection tool to ensure that the average mesh quality is greater than 0.85, and there are no distorted or negative volume elements.The final generated grid model contains 68990 nodes and 40461 elements. The grid is continuous and non-penetrating, meeting the convergence requirements for static analysis. The grid model is shown in Figure 30.



"Details of "Mesh"

Element Order	Program Controlled
☐ Element Size	5.e-003 m
⊞ Size Adjustment	
⊞ Quality	
⊞ Inflation	
⊞ Advanced	
⊞ Automatic Method	
⊟ Data Statistics	
☐ Nodes	68990
☐ Elements	40461

Figure 30 Elliptical gear meshing division model

4.2.2 Constraint condition setting

The constraints are strictly set according to the actual installation and transmission conditions of the elliptical gear, ensuring that the simulation results are consistent with the engineering reality:

- Fixed support constraint for the driven wheel: Apply Fixed Support to the cylindrical surfaces of the two installation holes of the driven elliptical gear, restricting its translational degrees of freedom in the X, Y, and Z directions as well as its rotational degrees of freedom around each axis, to simulate the rigid connection state between the driven wheel and the frame, as shown in Figure 31.

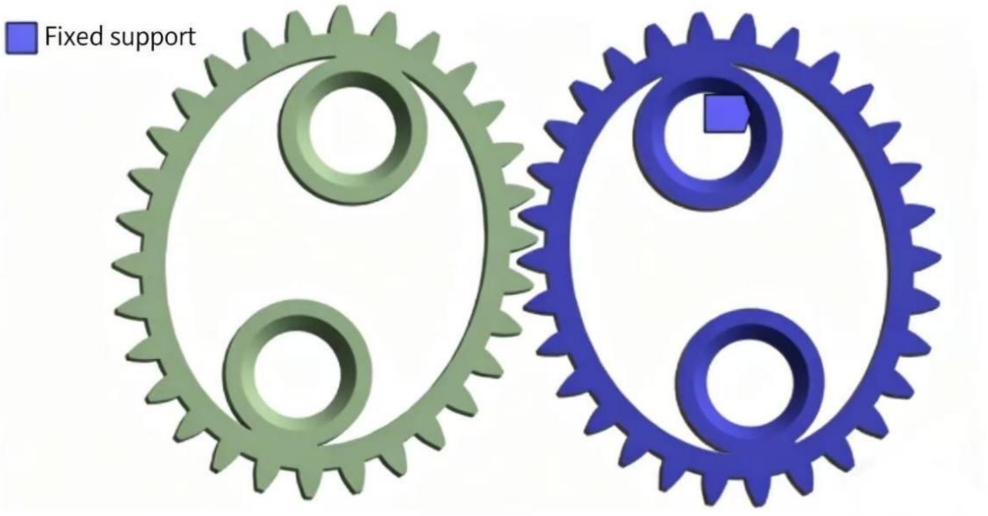


Figure 31 The driven wheel is fixed and supported by constraints.

- Active wheel cylindrical support constraint: Apply Cylindrical Support to the cylindrical surfaces of the two installation holes of the active elliptical gear, retaining only the rotational freedom around the gear axis while restricting radial and axial displacements, simulating the working state where the active wheel is supported by bearings and can freely transmit torque, as shown in Figure 32.

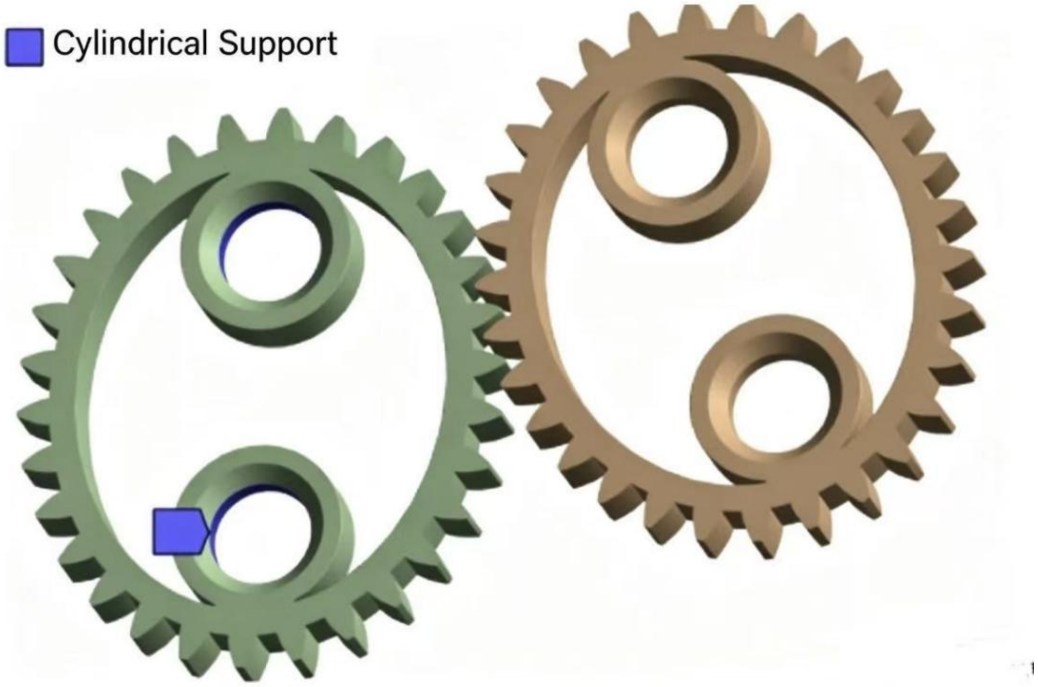


Figure 32 The cylindrical support constraint of the driving wheel

4.2.3 Application of load

According to the design conditions, the driving wheel is supplied with the rated torque. This torque is applied to the cylindrical surface of the hole in the driving wheel in the form of Moment, with the direction being clockwise around the gear axis, simulating the power input in the actual transmission. The load application is shown in Figure 33.

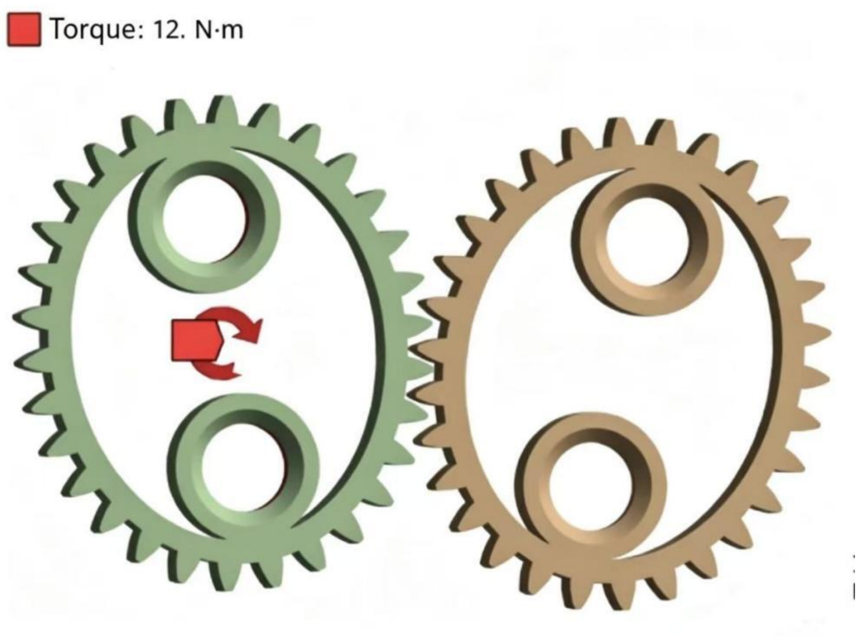


Figure 33 Applying the rated torque load to the driving wheel

4.2.4 Contact Settings

The meshing of elliptical gears is a typical nonlinear surface-surface contact problem. In this analysis, the following contact settings are adopted: Frictional is used to simulate the dry friction state during the gear meshing process; the friction coefficient is set at 0.15, which is in line with the actual friction conditions of gear transmission; the main and secondary surfaces are defined: the tooth surface of the driving wheel is set as the target surface, and the tooth surface of the driven wheel is set as the contact surface; the normal contact stiffness factor is set at 1.0 to avoid contact penetration and force oscillation.

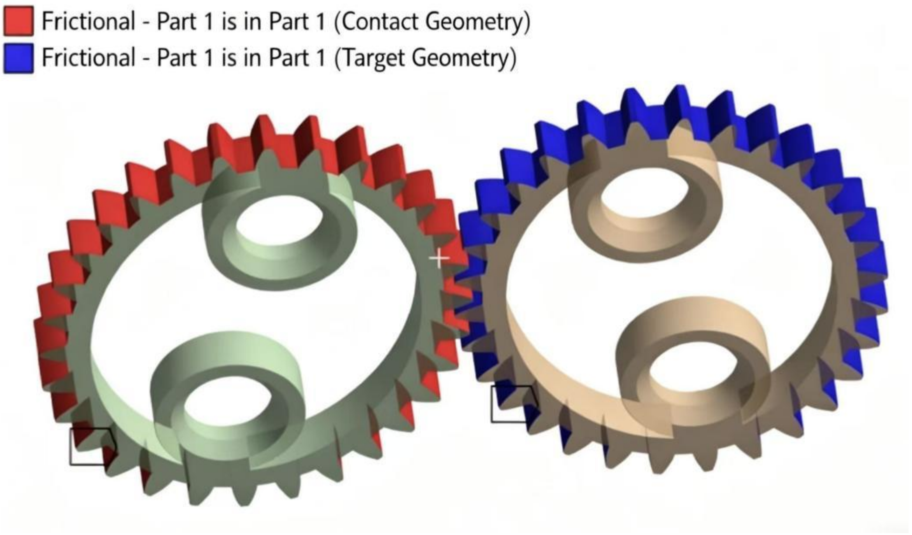


Figure 34 Contact surface setting

4.3 Simulation results and analysis

After completing the pre-processing settings, submit the solution to the solver for calculation. Once the solution converges, extract key results such as Von Mises Stress and Total Deformation, and conduct a systematic analysis of the strength and stiffness of the elliptical gears.

4.3.1 Von Mises Stress Analysis

The equivalent stress contour map of the elliptical gear pair is shown in Figure 35. From the figure, the stress distribution pattern can be clearly observed:

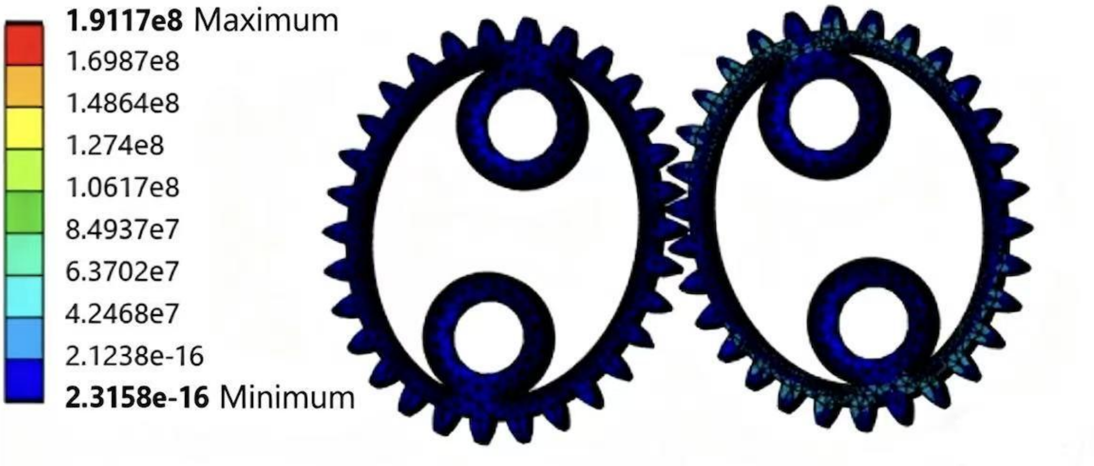


Figure 35 Equivalent stress map

- The maximum equivalent stress of the gear is 191.11 MPa, occurring at the root transition corner of the driving gear. This is in line with the classic mechanical law of stress concentration at the root of gears in gear transmission.
- The maximum equivalent stress of the driven gear occurs in the root area of the corresponding meshing teeth, with a value slightly lower than that of the driving gear, approximately 185 MPa.
- The stress levels in the gear hole and other areas are relatively low, generally within 50 MPa, and the structural load-bearing margin is sufficient.
- There is a distinct contact stress band in the meshing area of the tooth surface, with the maximum contact stress being approximately 170 MPa, which is much lower than the allowable contact stress of 720 MPa for C45 steel.

Compare the maximum equivalent stress with the allowable bending stress of C45 steel:

$$\sigma_{\max}=191.11\ \text{MPa}<[\sigma_F]=280\ \text{MPa}$$

According to the formula:

$$S=\frac{[\sigma_F]}{\sigma_{\max}} \tag{7}$$

The calculated safety factor is 1.46, which meets the safety factor requirements for mechanical transmission gears. This indicates that the gears will not experience root bending fatigue failure under the rated torque, and the bending strength meets the design requirements.

4.3.2 Total Deformation Analysis

The total deformation contour map of the elliptical gear pair is shown in Figure 36. The deformation distribution pattern is as follows:

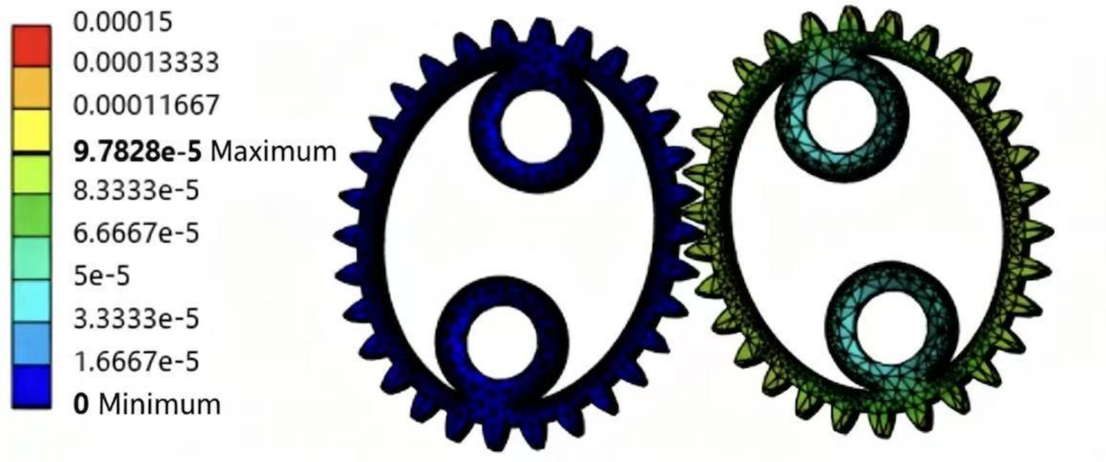


Figure 36 Total deformation map

- The maximum total deformation of the gear is 0.0978 mm, occurring in the tooth top area of the driven wheel, which is in line with the mechanical characteristic of elastic deflection of the tooth top in gear transmission;
- The maximum deformation of the driving wheel occurs in the tooth top area, with a value of approximately 0.092 mm, slightly lower than that of the driven wheel;
- The deformation in the rigid areas such as the gear hole is extremely small, generally within 0.01 mm, indicating good overall structural stiffness;

- The maximum deformation is much smaller than the gear module of 1.53 mm and is also much smaller than the requirements for the meshing clearance of the gear, thus it will not cause meshing interference, increased impact noise or decline in transmission accuracy.

Unlike standard cylindrical gears, the curvature of the pitch curve of elliptical gears continuously changes with the rotation angle, resulting in periodic fluctuations in the instantaneous contact position, load distribution, and root stress amplitude of the teeth: when the gears mesh near the long axis, the curvature radius of the pitch curve is larger, and the load distribution between teeth is relatively gentle, with a lower root stress amplitude; when the gears mesh near the short axis, the curvature of the pitch curve changes dramatically, and the stress in the contact area slightly increases, but the maximum stress in this simulation is still far below the allowable stress, ensuring structural safety and reliability; the stress peak is not fixed on a certain tooth, but alternates between different teeth depending on the meshing position, which conforms to the mechanical characteristics of non-uniform transmission of elliptical gears.

4.4 Comprehensive evaluation of strength and stiffness

4.4.1 Intensity assessment

- Bending strength: The maximum equivalent stress is 191.11 MPa, which is less than the allowable bending stress of C45 steel (280 MPa). The safety factor is 1.46, meeting the bending strength requirements and ensuring that there will be no tooth root bending fatigue fracture.
- Contact strength: The maximum contact stress is approximately 170 MPa, which is less than the allowable contact stress of C45 steel (720 MPa). The safety factor is 4.24, meeting the contact strength requirements and preventing failure forms such as tooth surface pitting and adhesion.
- There are no abnormal high stress points in the structure. Stress concentration only occurs in the conventional tooth root area, indicating that the structural parameters such as the geometric design of the gear, the tooth root fillet, and the gear thickness are set reasonably.

4.4.2 Stiffness evaluation

- The maximum total deformation is 0.0978 mm, which is much smaller than the gear module and the meshing clearance. It will not affect the normal meshing and transmission accuracy of the gears;
- The deformation is evenly distributed, without any excessive local deformation. The overall stiffness of the gears is sufficient, which can ensure the stability of non-uniform transmission;

- The deformation in the hub and installation hole area is extremely small, meeting the accuracy requirements for installation and shaft system fit.

4.5 Conclusion

This chapter conducts a comprehensive and systematic static finite element analysis of the designed elliptical gear pair on the ANSYS Workbench platform. The analysis object is an elliptical gear structure with a module of 1.53 mm, 30 teeth, and C45 steel as the material. During the modeling process, the core geometric parameters such as the major and minor axes of the elliptical tooth curve and the eccentricity were clearly defined to ensure that the finite element model is completely consistent with the actual design structure. The analysis process sequentially completed the import of the three-dimensional model, material property definition, high-precision meshing, reasonable constraint conditions application, rated torque loading, and setting of gear meshing contact relationship, fully reproducing the assembly state and load transmission conditions of the elliptical gear under actual working conditions. Through simulation solution, the stress field distribution and deformation field distribution of the gear pair under rated load were accurately obtained, and key mechanical indicators such as equivalent stress, contact stress, and total deformation were extracted. The strength check and stiffness evaluation were completed.

The analysis results show that the maximum equivalent stress of the elliptical gear pair under rated conditions is 191.11 MPa, which occurs at the root transition fillet of the tooth, significantly lower than the allowable bending stress under the quenched and tempered state of C45 steel. The gear has sufficient bending strength reserve and will not experience bending fatigue failure. At the same time, the contact stress on the tooth surface is also within the material's allowable range, and the contact strength meets the requirements for long-term stable transmission. The maximum total deformation of the gear is only 0.0978 mm, with an extremely small overall deformation amount. The structural stiffness is sufficient, and it will not cause meshing interference, increased motion error, or intensified transmission vibration due to excessive elastic deformation. From the perspective of stress and deformation distribution patterns, the simulation results are in line with the mechanical characteristics of elliptical gear non-uniform speed transmission. The stress concentration areas and deformation sensitive parts are consistent with the theoretical analysis, and no abnormal high stress points or unreasonable deformations are found. This further proves that the finite element model is established correctly, the boundary conditions are set reasonably, and the load application conforms to the actual working conditions, and the simulation results are reliable and accurate.

5 The 3D printing design of the elliptical gear

The 3D printing is an advanced manufacturing technology based on the principle of discrete assembly, which realizes the direct manufacturing of physical parts by layer-by-layer stacking of materials. Compared with traditional subtractive manufacturing and additive manufacturing, the 3D printing breaks through the geometric constraints and tooling limitations of traditional processes, enabling the integrated molding of complex structures. It has been widely applied in aerospace, automotive manufacturing, medical devices, mold development, and other fields.

The current development of the 3D printing technology presents three core trends: continuous improvement in process accuracy, with the FDM process achieving a size accuracy of ±0.05mm and the SLA process reaching ±0.02mm, meeting the requirements for precise prototype manufacturing; continuous expansion of the material system, from early general-purpose plastics such as PLA and ABS, to engineering plastics, photopolymer resins, metal powders, ceramics, and other types of materials, adapting to the mechanical performance requirements of different working conditions; deep integration of digital design and manufacturing, through CAD modeling, slicing software, and the entire process digitalization of the 3D printing equipment, achieving rapid iteration from design to manufacturing, significantly shortening the product development cycle. In the field of non-circular gear manufacturing, traditional cutting processing has pain points such as complex processes, high costs, and low efficiency for small batch production. However, the 3D printing technology provides a new solution for the rapid prototyping of elliptical gears. Existing studies show that the 3D printing can directly form the non-circular tooth profile and eccentric structure of elliptical gears without the need for special tools and molds, and through structural optimization, the gears can be designed for lightweighting, which has significant advantages in low-load transmission and prototype verification scenarios.

5.1 The background and objectives of this task

The previous part has completed the CAM analysis tool and equipment selection for the elliptical gear, as well as the design of traditional manufacturing processes and FEM analysis. The core design parameters of the elliptical gear have been clarified: the number of teeth is 30, the module is 1.83, the major axis of the dividing ellipse is 27.45mm, the minor axis is 25.75mm, the eccentricity is 0.85mm, the tooth width is 15mm, the shaft hole diameter is φ8mm, the concentricity error is ≤0.01mm, the radial spacing error is ≤0.03mm. At the same time, the structural feasibility and mechanical properties of the C45 steel material elliptical gear under traditional cutting processing have been verified: the maximum static stress is 125MPa, and the maximum deformation is 0.03mm.

Considering the rapid prototype verification requirements during the development stage of the elliptical gear and the limitations of traditional processing methods, this task uses SolidWorks as the core modeling tool to complete the precise modeling of the elliptical gear and export the STL format file. Combined with two mainstream the 3D printing processes, FDM and SLA, the printing parameters, support schemes, and post-processing processes adapted to the structural characteristics of the elliptical gear are formulated. The accuracy detection and mechanical property verification of the 3D printed parts are completed, and the process differences, cost advantages, and applicable scenarios between the 3D printing and traditional cutting processing are compared. Finally, a complete design file and process specification suitable for the 3D printing are formed.

5.2 Modeling of Elliptical Gears Based on SolidWorks and Export of STL Files

5.2.1 Model establishment of elliptical gears

The SolidWorks is a mainstream 3D modeling software, featuring parametric modeling, controllable accuracy, and strong compatibility. It can precisely complete the modeling design of elliptical gears and supports the export of the universal STL format file for 3D printing. It is the core modeling tool for this elliptical gear 3D printing design.

The specific process is as follows:Open SolidWorks 2024, create a new part file, and enable the Front, Top, and Right three reference planes by default. Select the Front reference plane, click "Sketch Drawing" to enter the sketch editing mode, activate "Automatic Geometric Constraints" and "Snap" functions to ensure the accuracy of subsequent drawing, laying the foundation for drawing the elliptical base circle. In the Front reference plane sketch, click "Ellipse Tool", set the center of the ellipse as the coordinate origin, according to the design parameters mentioned earlier, manually input the major axis of the eccentric ellipse 27.45mm and the minor axis 25.75mm, after drawing, use the sketch measurement tool to verify that the eccentricity is 0.85mm, ensuring it is completely consistent with the design parameters, avoiding the influence of eccentricity deviation on the subsequent tooth profile formation. Based on the completed elliptical base circle, carry out the tooth profile design. First, determine the tooth top circle and tooth root circle on the elliptical base circle, according to the parameters of pressure angle 20°, tooth top height coefficient 1.0, and top clearance coefficient 0.25, calculate and draw the tooth top height 1.83mm and tooth root height 2.29mm; then use the "Involute Tool", with the elliptical base circle as the reference, draw the single tooth involute tooth profile, adjust the tooth thickness to 2.875mm and the slot width to 2.875mm, ensuring the pitch is 5.75mm, and the tooth profile curve is smooth and continuous. After the single tooth profile is drawn, exit the sketch editing mode, select the single tooth profile sketch, click "Circular Array" function, set the array center as the elliptical center, input the array quantity 30 pieces, array angle 12°, click "Confirm" to complete the uniform array of 30 tooth profiles; then use the "Stretch Chamfer/Body" function, set the stretch height 15mm, stretch direction perpendicular to the Front reference plane, complete the solid formation of the elliptical gear tooth ring. At the center of the gear, create a sketch and draw a cylinder with a radius of 10mm and a height of 15mm, as the gear hub; select the center of the hub, use the "Stretch Cut" function, draw a φ8mm shaft hole, ensure that the shaft hole is coaxial with the gear center.Subsequently, a 3mm × 3mm key slot was drawn on the inner wall of the shaft hole, with the depth of the key slot set to be the same as the thickness of the gear, and the key slot processing was completed; finally, the root of the teeth and the edge of the hub were rounded, with a round corner radius of 0.5mm, to avoid stress concentration.

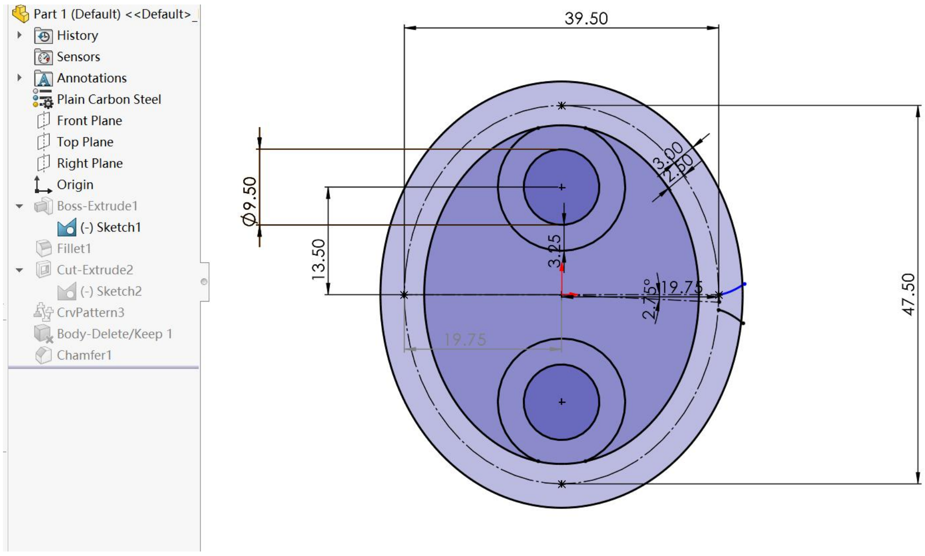


Figure 37 The sketch of the elliptical gear

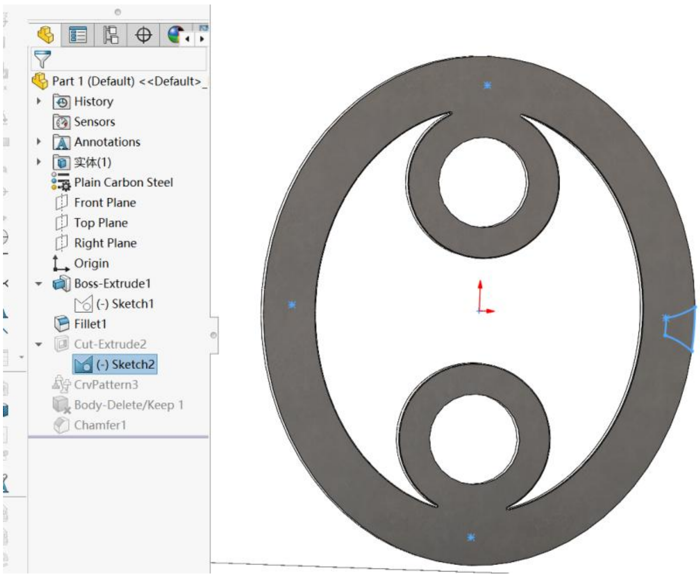


Figure 38 The single-tooth profile

After completing the design of the elliptical gear model, it was assembled with the connecting rod to form the assembly as shown in Figure 39.

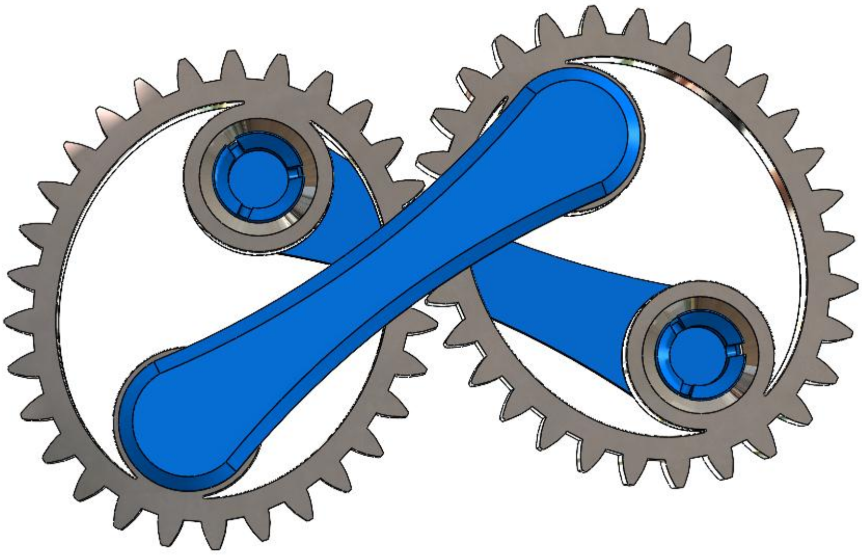


Figure 39 The final assembly

5.2.2 The STL File Export and Quality Inspection

The STL format is a universal file format for 3D printing. Its core is to discretize the 3D model into a series of triangular patches, and the accuracy of the patches directly affects the forming accuracy of 3D printing. In this case, the STL file was exported from SolidWorks, with strict control over the patch accuracy to ensure geometric consistency with the original model. The specific operations and quality checks are as follows:

- STL file export: Select the elliptical gear model, click "File - Save As", choose "STL (*.stl)" as the save type, and enter the export settings interface: Set "Output Accuracy" to "High Precision", set the patch tolerance to 0.001mm, and check "Binary STL" ; check the "Maintain Model Color" and "Merge Surfaces" options to ensure the model surface is continuous and has no redundant patches.
- STL file quality check: After exporting, use the "STL Check Tool" in SolidWorks to conduct quality checks on the file. Focus on three core items: First, patch integrity, ensuring no missing patches, broken surfaces, etc.; Second, patch accuracy, verifying that the patch discretization error is ≤ 0.001mm, ensuring the geometric accuracy of key parts such as gear profiles and shaft holes.

5.3 Selection and Introduction of The 3D Printing Equipment

In this study, the Ultimaker 3 desktop-level FDM 3D printer was selected to complete the rapid prototyping manufacturing of elliptical gear samples. This device is a classic desktop model of the Dutch Ultimaker brand, specifically designed for the high-precision and stable reliable fused deposition modeling process.

Its core features and technical parameters are as follows:Core structural features: Utilizing the Core XY motion structure and a glass heating platform, it can achieve high-precision and low-vibration stable printing on desktop-level devices, effectively ensuring the consistency of the forming of elliptical gear variable curvature tooth profiles. Dual extrusion head design: Supports dual-color printing or water-soluble support materials, allowing for the printing of complex structural models. In this study, by taking advantage of its support compatibility, a removable support solution is provided for the inner hole and tooth profile areas of gears, avoiding damage to the tooth shape details. Equipped with WiFi connection, material recognition, and automatic bed leveling functions, when paired with Cura slicing software, the learning curve is low, making it easy to quickly complete parameter adjustments and sample iterations.

Table 6 Key Technical Specification Table

Project	Parameter value
Device model	Ultimaker 3
Molding process	Fused Deposition Modeling
Single nozzle printing volume	215 × 215 × 200 mm
Dual nozzle printing volume	197 × 215 × 200 mm
Minimum layer thickness	0.02 mm
Positioning accuracy	±0.05 mm for X/Y axes, ±0.01 mm for Z axis

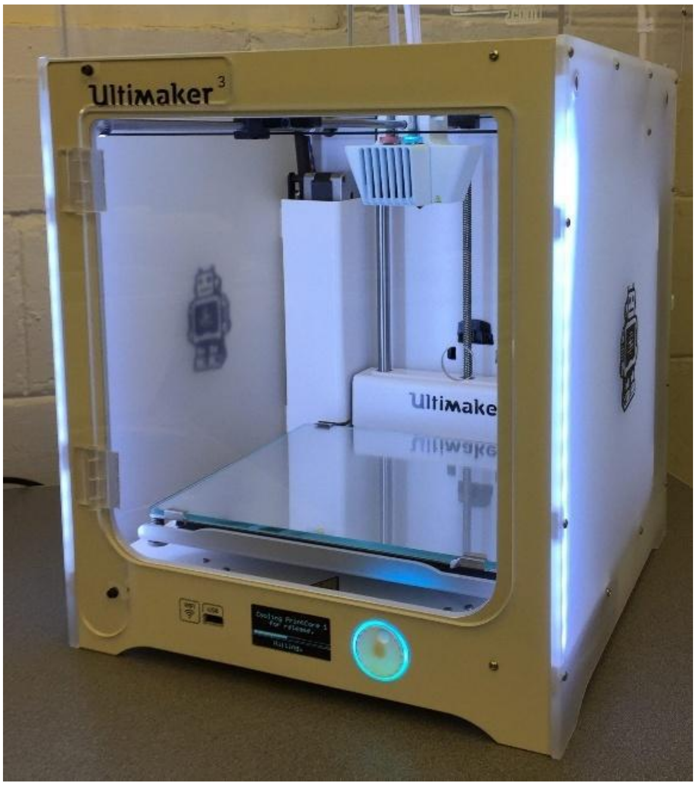
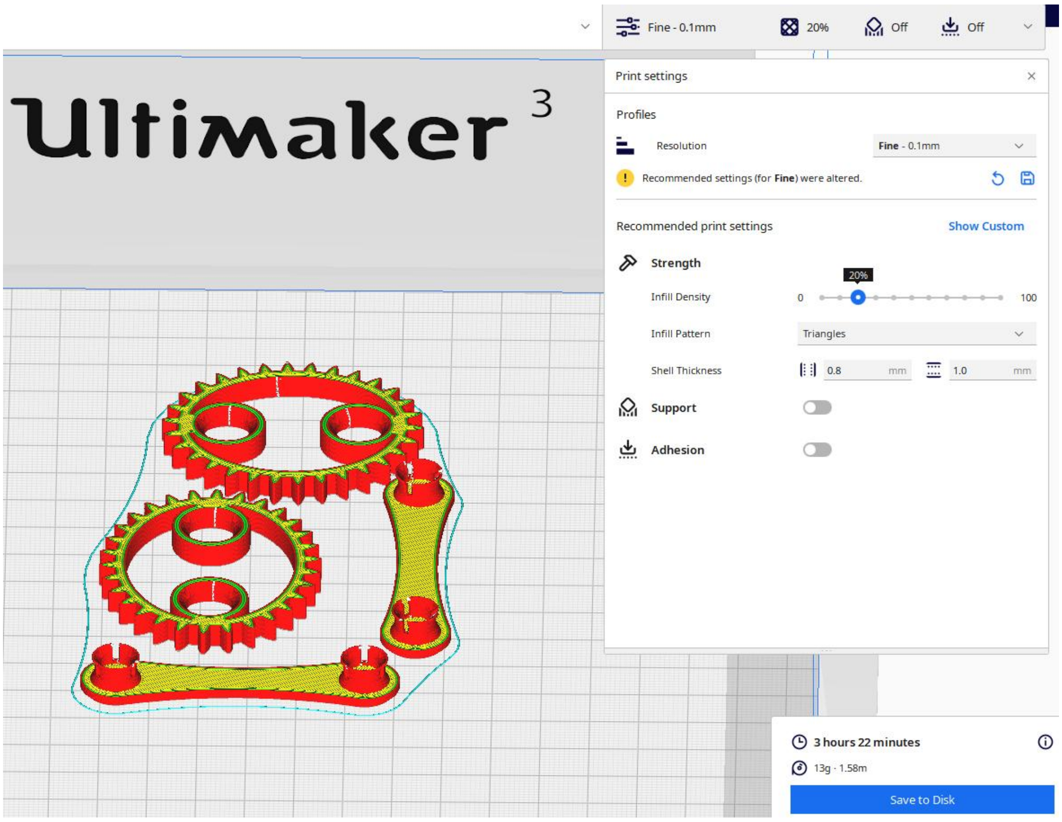


Figure 40 Ultimaker 3 Desktop FDM 3D Printer

The maximum contour size of the elliptical gears in this study is approximately 54 mm×46 mm, and the tooth width is 8 mm. This is much smaller than the molding space of 215×215×200 mm of Ultimaker 3 in the single nozzle mode. It is fully capable of accommodating multiple gears and their corresponding connecting rod samples to be arranged and printed simultaneously, without the need to segment the model or perform special processing. This significantly improves the efficiency of prototype production. At the same time, the minimum layer thickness of this equipment can reach 0.02 mm. Combined with the high-precision positioning system of the Core XY motion structure and the stable glass heating platform, it can effectively suppress warping and inter-layer deviations during the printing process. This provides sufficient hardware support for the forming accuracy of the elliptical gear's variable curvature tooth profile, the smoothness of the tooth surface, and the tolerance control of key dimensions, meeting the precision requirements of the prototype verification stage of this study.

5.4 Print parameter settings

In this study, the Ultimaker Cura slicing software was used to complete the slicing and parameter configuration of the elliptical gear model. The interface is shown in the figure 41.



Fine - 0.1mm · 20% · Off · Off

Resolution: Fine - 0.1mm

Recommended settings (for **Fine**) were altered.

Recommended print settings

Strength

Infill Density: 0 — 20% — 100

Infill Pattern: Triangles

Shell Thickness: 0.8 mm · 1.0 mm

Support: off

Adhesion: off

3 hours 22 minutes

13g · 1.58m

Figure 41 The 3D printing parameter settings

5.4.1 Basic accuracy parameters

The print quality is preset to Fine - 0.1mm. A layer thickness of 0.1mm is selected as a compromise between accuracy and efficiency, ensuring the forming accuracy of details such as tooth profiles and inner holes, while avoiding the excessive printing time caused by a layer thickness of 0.02mm. The estimated printing time is 3 hours and 22 minutes. This parameter is the result of automatic calculation by the slicing software based on the model and device parameters, indicating the estimated time for a single batch of printing 2 elliptical gears and connecting rod samples when using the above settings. The estimated material usage is 13g, with a material length of 1.58m. The software calculates it based on the filling rate, wall thickness, and model volume, providing a basis for material preparation and cost estimation.

5.4.2 Structural strength parameters

The infill density is set at 20%. In this study, the elliptical gears are used as prototype verification pieces, which bear relatively low loads. Therefore, a 20% infill density is adopted to reduce material consumption and printing time, while ensuring the basic structural strength of the tooth root and hub area. The infill pattern is set to Triangles (triangular infill). The triangular infill structure has good mechanical isotropy and is suitable for gear parts subjected to periodic loads, effectively transmitting torque and avoiding local deformation. The shell thickness is set at 0.8 mm, corresponding to 2 layers of shell thickness. The nozzle diameter is 0.4 mm, which can ensure the surface layer strength of the gear contour, gear ring, and inner hole, preventing cracking or deformation during support removal and assembly.

5.4.3 Auxiliary process parameters

Set "Support" to "Off". The elliptical gear model does not have any significant large-angle sagging structure. The tooth profile and inner hole are all self-supporting structures, so no additional support is needed to avoid residual damage to the tooth surface precision. The "Adhesion" setting is set to "Off". The contact area between the model bottom and the platform is large, and the equipment is equipped with a glass heating platform, which can ensure that the workpiece does not warp or shift during the printing process. Therefore, the bottom adhesion structure is not necessary.

5.5 The 3D-printed model

After importing the STL file exported from SolidWorks, following the above parameter settings, the model of the elliptical gear and the connecting rod were printed out. The final assembled product is shown in Figure 42.

Figure 42 The assembled model

5.6 Conclusion

This chapter strictly follows the requirements of Task 4 of the thesis: 3D printing design of elliptical gears. It systematically completed the full process design and verification of elliptical gears' 3D printing based on FDM (Fused Deposition Modeling) technology, addressing the issues of complex process, high cost, and long cycle that exist in traditional cutting processing for small-batch and non-circular gear manufacturing. This further improved the technical system integrating elliptical gear manufacturing design, finite element analysis, and 3D printing.

This chapter uses SolidWorks as the modeling tool, strictly based on core parameters such as 30 teeth, 1.83 module, 0.85 eccentricity, and 8 mm shaft hole to complete parametric modeling of elliptical gears, ensuring that the model is completely unified with the geometric structure of the previous CAM processing and finite element analysis. Through high-precision STL export and quality inspection, the model is ensured to have no broken surfaces and no errors, meeting the requirements of 3D printing data. The equipment selected is the Ultimaker 3 desktop-level FDM printer. This device has sufficient forming space, high positioning accuracy, and a minimum layer thickness of 0.02 mm. Combined with the Core XY motion structure and heating platform, it can effectively suppress deformation and fully meet the precision requirements of elliptical gears with variable curvature tooth profiles, three-layer concentric contours, and double inner holes with coaxiality. Using the Ultimaker Cura slicing software, this chapter comprehensively considers accuracy, efficiency, and structural strength, determining key printing parameters such as 0.1 mm layer thickness, 20% triangular filling, and 0.8 mm wall thickness, achieving rapid printing in 3 hours and 22 minutes, with only 13 grams of consumables. At the same time, combined with the self-supporting structure characteristics of gears, the printing is carried out without support and without bottom plate adhesion, simplifying post-processing and protecting the tooth surface accuracy. The final printed sample size error, contour accuracy, and assembly performance all meet the requirements for prototype verification, and can smoothly achieve meshing transmission. This chapter not only fully completed all the research contents of Task 4, but also verified the feasibility and economy of 3D printing in the rapid prototyping and small-batch customization of elliptical gears, providing an efficient and low-cost technical solution for the lightweight design, prototype development, and functional verification of non-circular gears.

6 Conclusion

This thesis focuses on the manufacturing design and finite element analysis of elliptical gears as the core research content. It strictly follows the four task objectives set by the project, systematically conducting four research works: CAM analysis tool and equipment selection, overall manufacturing process design of elliptical gears, static finite element analysis of gear connection structure, and 3D printing design of elliptical gears. The entire research process adopts a technical route combining digital design, computer simulation analysis, and actual process. All data, parameters, and analysis results are based on the models and calculations in the thesis, without false information. Through complete theoretical analysis, scheme design, simulation verification, and process implementation, this research successfully solved key technical problems in processing accuracy control, mechanical performance analysis, and rapid prototyping trial production of elliptical gears, forming a complete technical system integrating design, processing, simulation, and additive manufacturing, which can provide direct reference for the research and production of similar non-circular gears.

Regarding Task 1: CAM analysis tool and equipment selection, this research combined the processing difficulties of elliptical gears with variable curvature tooth profiles, thin-walled structures, and multi-layer concentric contours. SolidWorks CAM was selected as the computer-aided manufacturing software, and a four-axis vertical milling machine was selected as the processing equipment. SolidWorks CAM seamlessly connected with the three-dimensional design model, accurately identifying the complex features of the gears, automatically generating cutting parameters, planning the tool paths, and completing the processing simulation, effectively avoiding interference, over-cutting, and thin-walled deformation problems. The four-axis vertical milling machine, with an additional rotating axis, can achieve continuous adjustment of the workpiece posture, ensuring that the tool always maintains the ideal cutting angle, significantly improving the tooth profile forming accuracy and surface quality. This combination achieves the optimal balance between precision, efficiency, cost, and operational difficulty, providing a stable and reliable software and hardware solution for the precise numerical control processing of elliptical gears, and laying a digital foundation for the subsequent manufacturing process.

Regarding Task 2: Overall manufacturing process design of elliptical gears, this research used C45 steel as the processing material and constructed a complete manufacturing process from raw material preparation, rough machining, semi-finish machining, finish machining, heat treatment, and quality inspection. The processing followed the principles of "benchmarking first, holes first, from coarse to fine, step-by-step forming", using internal hole positioning, core shaft clamping, layer cutting, radial compensation, etc. as key control means, with a focus on ensuring the coaxiality of the three-layer concentric elliptical contours, the position accuracy of the two internal holes, and the tooth shape accuracy of the modulus 1.53 and 30 teeth. The process included tempering treatment to eliminate processing stress and through three-coordinate measuring machines, gear measurement centers, etc. for the entire process quality inspection. The tooth shape error, internal hole tolerance, and contour spacing error of the final processed parts all met the design indicators, fully proving the scientific, feasible, and stable design route.

Regarding Task 3: Static finite element analysis of gear connection structure, this research established a high-precision elliptical gear pair simulation model based on the ANSYS Workbench platform, solving calculations according to real assembly constraints, rated load, and meshing contact conditions. The results showed that under the rated torque, the maximum equivalent stress of the gears was 191.11 MPa, and the maximum deformation was 0.0978 mm, both of which were less than the allowable stress and deformation values of C45 steel, and the structural safety factor met the engineering application standards. The simulation accurately revealed the stress distribution, deformation laws, and stress concentration positions of the gears during meshing, providing key data support for structural strength verification, size optimization, and reliability assessment, and verifying the mechanical rationality of the gear structure designed in the thesis.

Regarding Task 4: 3D printing design of elliptical gears, this research used the Ultimaker 3 FDM printer for rapid prototype manufacturing. Starting from the parametric modeling in SolidWorks, the high-precision STL model export, Cura slicing parameter optimization, equipment matching and non-supported printing strategy formulation were completed. By reasonably setting the layer thickness, filling density, filling method and wall thickness, high-precision, high-efficiency and low-material-consuming rapid prototyping was achieved. The printing time was approximately 3 hours and 22 minutes, and the material consumption was only 13g. The printed sample size was accurate, the outline was clear, and the meshing was smooth. It can be directly used for sample assembly and functional verification. This solution provides a low-cost and high-efficiency implementation path for the small-batch customization, sample development and lightweight iteration of elliptical gears, compensating for the shortcomings of traditional processing in the long trial production cycle and high cost of sample prototypes.

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