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Research on the Application of Mirror Moulds for Masks

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Precision mirror mould CNC machining is a technology of great importance in industrial manufacturing. Precision mirror moulds are usually used to produce high-precision, high-quality parts and products, which are widely used in automotive manufacturing, aerospace, electronic equipment and other industries. However, the traditional mould polishing process often fails to meet the manufacturing needs of precision moulds, so the application of CNC machining technology has become an effective way to solve this problem. Through the use of CNC machine tools and computer control systems, etc., the detailed formulation of the process plan, so that precision mirror mould CNC machining can achieve high efficiency, accuracy and stability of the machining process, to improve the quality and productivity of the mirror mould. Therefore, the applied research on CNC machining of precision mirror mould is of great significance and economic value.

Keywords: Mirror mould, Process scheme, Validation comparison, Process parameters, Validation effect

1 Introduction

The research of ultra-precision machining technology has always been the hot and difficult point in the manufacturing field, and since the 1960s, relevant experts at home and abroad have invested a lot of manpower and material resources, and have already achieved preliminary research results. Aspherical optical products have incomparable optical performance and broad application prospects. In the field of national defence and aerospace, the development of large or ultra-large optical products is the key to national defence space technology, reflecting a country's technical strength and economic strength [1]. In the era of rapid progress of IT, in addition to the macro field of national defence and space technology, more civilian optical products such as digital cameras, computer cameras, fiber optic communications and laser products, are also developing in the micro direction of small, micro and other micro direction, and become the core technology closely related to people's lives [2].

Western developed countries, especially the United States, Japan and the United Kingdom, has a mature ultra-precision machine tool equipment and process research results, they represent today's world of ultra-precision manufacturing level, but its development cost is also quite high, some typical equipment market price of about 8 million yuan. In developing countries, there is still a considerable gap in this technology, especially the rapid economic development of China, on the one hand, faced with a strong market demand for ultra-precision machining is becoming more and more compelling. On the other hand, subject to the technology blockade and export restrictions of developed countries, the development of ultra-precision complete sets of equipment with independent property rights has become a hotspot and a difficult problem in the manufacturing industry [3]. Throughout the ultra-precision machining technology, its core focuses on the following aspects: (1) research and development of ultra-precision hardware technology; (2) development of ultra-precision software technology; (3) research on ultra-precision process technology, that is to say, the hardware technology is the foundation, the software technology is the key, and the process technology is the guarantee.

This paper focuses on the difficulties and challenges in the machining of precision mirror moulds as a case study. Precision mirror moulds are very demanding and need to be machined with very flat and smooth surfaces to ensure the quality and shape accuracy of the final product. However, the hardness of the material, thermal deformation during machining, surface roughness and other factors make the machining of precision mirror moulds difficult [4]. Traditional machining methods are often unable to meet the requirements.

In order to overcome the difficulties in precision mirror mould machining, it is necessary to develop the process plan in detail and adopt some key technologies. One of these technologies is high-speed cutting, which can reduce thermal deformation and surface roughness by increasing the cutting speed and reducing the cutting force, thus obtaining better machining results. In addition, it is also very important to choose suitable tools, such as using super hard alloy tools, which can enhance the cutting performance and wear resistance to improve the surface quality accuracy of moulds [5].

2 Background of the study

Guangzhou Optical Lens Manufacturing Co., Ltd. is a client of the Longgang branch. The company was established in the 1990s. After years of hard work, it has the capacity of mould design and manufacturing, optical lens production, safety helmet design and production, and plastic products. It is also an enterprise specialising in the research, development and production of safety helmets. The main production of goggles, mask windshield and other products, not only to meet the product precision, but also to meet the product surface roughness. Since the CNC machining process of ultra-precision mirror moulds requires very high requirements on equipment, materials and machining process, it is necessary to overcome the vibration and thermal deformation in the machining process, optimize the matching of tools and machine tools as well as the treatment of microscopic damage. Secondly, it is also necessary to solve the contradiction between machining efficiency and quality. Improving the processing efficiency while ensuring the quality and accuracy of the product is also a challenge. Therefore, higher machining requirements are imposed on the mask mould [6]. This mirror mould has the characteristics of free-form surface and gradient change, and its programming method and process control are representative. Through the integration of product programming ideas, cutting parameters and process control schemes, a mature mirror mould machining scheme was finally formed for reference [7].

2.1 Mirror processing performance of plastic moulds

The shape of the plastic mould is relatively complex, and each part has a different location in the use process, and the required material properties are also different. Therefore, the basic performance requirements of plastic moulds generally include [8]: sufficient surface hardness and wear resistance, sufficient strength and toughness, good cutting performance, good polishing performance, heat treatment deformation is small, good corrosion resistance and so on.

Mirror processing performance that is polished performance, it is not only on the mechanical properties and physicochemical properties of the material itself has high requirements, but also on the polishing process also has high requirements. The standard of mirror finish is divided into 4 levels : A0=RA0.008μm, A1=RA0.016μm, A3=RA0.032μm, A4=RA0.063μm. Plastic products with low surface quality have lower requirements for moulds[9]. The surface roughness of general injection moulds is about Ra0.1~0.25μm, and optics need to be below RA0.01μm. For example, the mould cavity roughness of optical discs is Ra0.01~0.02μm. this requires mould materials with good polishing properties and suitable polishing processes [10].

2.2 Product information

The material is NAK80 pre hardened steel, with a hardness range of 37-42HRC. The following is the basic information about NAK80 materials:

Chemical composition:

- Carbon (C): 0.1-0.2%
- Silicon (Si): 0.3-0.5%
- Manganese (Mn): 1.4-1.9%
- Phosphorus (P): ⩽ 0.03%
- Sulfur (S): ⩽ 0.03%
- Chromium (Cr): ⩽ 0.3%
- Nickel (Ni): ⩽ 0.1%
- Molybdenum (Mo): 0.1-0.3%
- Aluminum (Al): 1.0-1.5%

Heat treatment:

NAK80 materials generally undergo the following heat treatment processes to achieve the required hardness:

- Preheating:Maintain a temperature of 800-850℃ for a period of time to improve the thermal uniformity of the material.
- Tempering: Conduct tempering treatment at a temperature of 500-550 ℃ to eliminate internal stress and provide the required hardness.
- NAK80 material is widely used in industrial fields such as plastic molds and die-casting molds due to its excellent heat treatment performance and stable hardness. This material has excellent wear resistance, corrosion resistance, and dimensional stability, making it suitable for mold manufacturing with long service life and high quality requirements. [11].
- Dimensions: Convex mould: 325*220*68.974mm; Concave mould: 325*220*54.974 mm;
- Processing requirements:
- Machining is shown on the red side of the drawing file (Fig. 1);

- Good consistency of product surface effect, surface roughness Ra<0.1µm;
- Machining accuracy required ±0.01 mm.

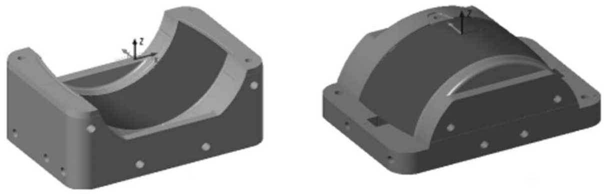


Fig. 1 *Mask mould model*

3 Materials and Methods

3.1 Process planning

3.1.1 Analysis of process difficulties

- 1) The product surface processing area is large, the finishing time is long, the margin accuracy requirement±0.01mm, the surface contour degree requirement is high, the product size accuracy is more difficult to ensure;
- 2) Three-axis clearing and loading tool L/D ratio >5.5:1, processing risk, need to use five-axis linkage clearing, R corner there are many times to connect the knife, the effect of connecting the knife is difficult to ensure;
- 3) Consistency of product surface effect, requiring Ra<0.1µm, finishing time up to 31~35 hours, the use of self-produced knife processing there may be a large tool wear and produce problems such as drawing;
- 4) The product datum is poor, the X datum needs to use the matching arc surface as the reference datum; the Z datum (Fig. 2) is very different from the customer's description of the flatness of 0.01mm, which is difficult to measure. [19-21]

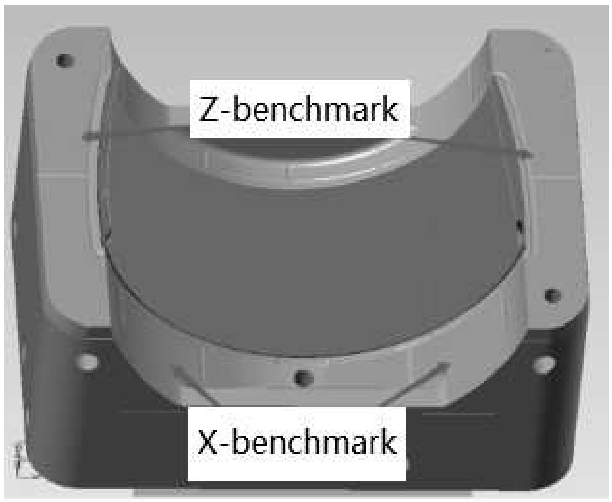


Fig. 2 *Z reference plane*

3.1.2 Machine tools and spindles

According to the machining accuracy requirements, we chose the JDGR400T_A15H machine (Fig. 3) shown in Fig. 3, which is equipped with a JD150S-20-HA50 spindle and the following peripheral conditions (Table 1).

Tab. 1 *Machine Configuration*

Form	Configuration
matrix	Processing is carried out in a temperature-controlled workshop with temperature fluctuations of less than 1.0 degree Celsius/24 hours and without large sources of vibration in the vicinity.
built-in air conditioner	The air direction of air circulating devices such as air conditioners and vents must not be directed to any part of the machine.
Machine Tool Basics	The required foundation for the machine needs to be at least 60 cm thick concrete foundation with vibration isolation grooves.

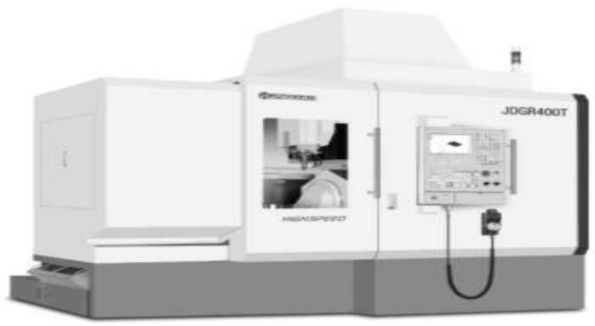


Fig. 3 *GR400T*

3.1.3 On-line product inspection module

The in-line measurement module enables product inspection on the machine tool. The on-machine measurement technology can measure the dimensional and form tolerances of the part directly after machining is completed, realising the integration of machining and inspection, and avoiding the effect of errors on the part caused by tool wear. The realisation consists of three main functions and a number of auxiliary functions, including: element detection, feature evaluation (dimensional and geometrical tolerance detection), and coordinate system detection (intelligent correction of the coordinate system); and auxiliary functions: 3D measurement, probe calibration, data processing, and path detection. Some of the functions of the CMM CMM are integrated in the software. Combined with the precision engraving CNC platform, the software can not only carry out high-precision intelligent correction of the coordinate system using online measurement, but also carry out on-machine inspection of the workpiece to evaluate the workpiece's margins, dimensions, position, shape, etc. [12].

A path adaptive compensation method for uneven machining dimensions due to deformation of the actual workpiece curve. This deformation is the deviation of the actual curve of the workpiece from the design curve. There are many reasons for the deformation, such as workpiece fixture deviation, clamping force deformation, deformation after treatment in the previous process (anodising, sandblasting, grinding, injection moulding, etc.) and deformation of the incoming material itself. Moreover, this deformation is generally irregular, and the deformation trend of each product is not the same. In order to achieve the uniformity and consistency of the machining dimensions of each product, it is necessary to measure the contour of each product, adjust the machining path according to the measurement results, and realise adaptive compensation machining, which greatly improves the product yield [13]. At the same time, it also reduces the inspection process and the time to review quality issues, solves the equipment standby problem, and effectively improves the yield.

3.1.4 DT Intelligent Programming

Traditional programming methods can affect the continuity of production and machining due to loading status, actual shape, matching problems, collision checking and travelling problems, which leads to low machine usage time, long auxiliary time, and the quality of machined products cannot be guaranteed [14].DT programming has also come into being. It is implemented by mapping the physical entities in actual machining into the digital space of the software, and modelling the machining process using virtual simulation technology. That is, the physical model information is reproduced to the maximum extent in the programming process, forming a virtual machining programming environment. Eliminate hidden problems in the machining process, reduce the time of trial cutting, improve the utilisation of machine tools, and improve the continuity of production [15].

3.1.5 Selection of laser tool setter (required)

In order to achieve thermal elongation control of the spindle and to detect the true state of the tool during machining, it is necessary to equip the Poron laser tool setter shown in (Fig. 4).

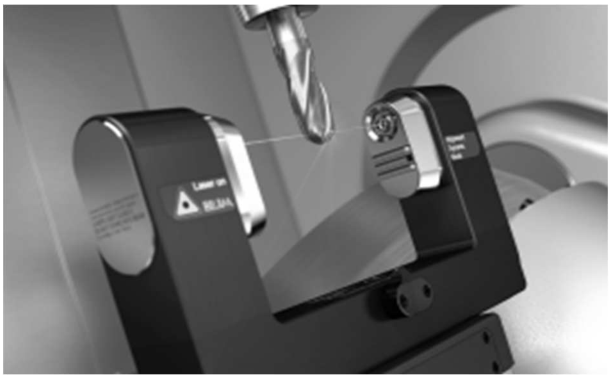


Fig. 4 *Laser Tool Setter*

3.1.6 Selection of contact probes (required)

For probe selection, the Renishaw OMP400 probe was chosen for its better anisotropy and sensitivity (Fig. 5).

Fig. 5 *Contact Probes*

3.1.7 Selection of calibration components (required)

To ensure the measurement accuracy of the probe, it is necessary to select both the standard ball and the standard ball base (Fig. 6) shown.

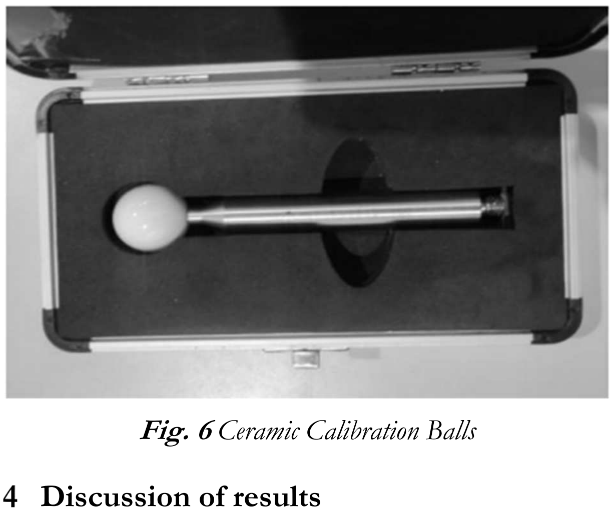


Fig. 6 *Ceramic Calibration Balls*

4 Discussion of results

4.1 Selection of accessories

4.1.1 Selection of micro-mist lubrication system (required)

In order to effectively maintain the machine condition and avoid unstable machining accuracy due to changes in the machine condition, a micro-mist lubrication and cooling method is used shown in (Fig. 7).

Fig. 7 *Micro-mist lubrication system*

4.1.2 Selection of oil mist collector (required)

In order to ensure the air quality in the workshop, to remove the oil mist in the machine in time, and to effectively control the fluctuation of the ambient temperature in the machine, the JDACM800 oil mist collector was selected (Fig. 8).

Fig. 8 *JDACM800 Oil Mist Collector*

4.1.3 Selection of shanks

A heat-shrinkable toolholder (Fig. 9) was selected to enhance tool clamping rigidity. A high degree of tool control awareness on the part of the operators always ensures that tool runout can be controlled to within 0.01mm. This ensures tool life and improves the dimensional accuracy of the workpiece and reduces production costs.

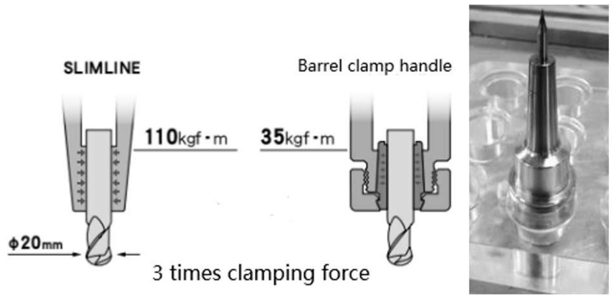


Fig. 9 *Heat Shrink Handle*

4.1.4 Selection of clamping programme

In terms of fixtures, since the product is a large steel part with a flat bottom, a300*300mm strong magnetic chuck is used for clamping (Fig 10) to ensure that the workpiece does not rotate or displace during the machining process.

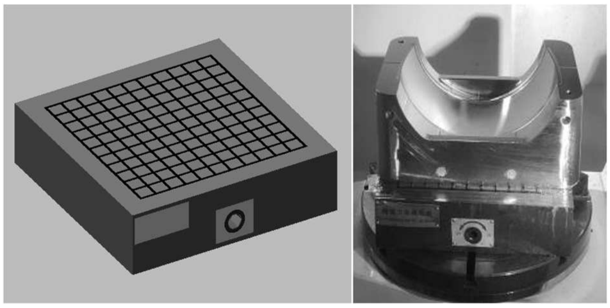


Fig. 10 *Schematic diagram of clamp*

4.1.5 Process programmes

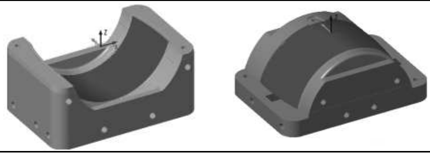
The product has formed a reusable and mature case through process validation and convergence of cutting parameters. By inserting step-by-step design management, process steps such as program warm-up, automatic centring, tool inspection and workpiece straightening are integrated into the program, reducing manual operation. On-site operators only need to follow the machine tool's prompts to carry out "cleaning reminder", "workpiece cleaning" and other operations to complete the mould processing, to achieve efficient and reasonable machine tool automation [16].

The mature in-flight automation programme is as follows:

Start → (11) Cleaning reminder → (12) T3 ball 2 warm-up → (13) Automatic centre-splitting → (14) T3 ball 2 short warm-up → (15) T3 ball 2 tool measurement → (16) T3 ball 2 finishing → (17) Tool wear detection → (18) 16 ball 1 clearing and rooting warm-up → (19) T6 ball 1 tool measurement → (20) T6 ball 1 clearing and rooting → (21) Tool wear detection → End.

4.1.6 Mask Mirror Mould Processing Equipment Configuration (Tab. 2)

Tab. 2 *Machine Configuration*

	Diethylammonium chloride	Mask Mirror Mould
1.Product Information	Product Pictures	
	Product Size	Front mould: 325*220*68.974 mm Rear mould: 325*220*54.974 mm
	Processing type	Precision Milling
	makings	NAK80
2. Mainframe	Models of machine tools	JDGR400T_A15SH
	principal axis (in mechanics, optics, botany etc)	JD150S-20-HA50
	Tools magazine	37-position self-retrieving chain tool changer
3. Annexes	Tool Measurement	Bolognese Laser Knife Detector
		Contact Tool Setter
	Workpiece measurement	Contact probe (Renishaw OMP400)
	standard component	Ceramic Standard Balls
		Standard tools for laser tool setting machines
	Oil Mist Collector	JDACM800 Oil Mist Collector
	Cooling nozzle 1	cyclone spray
	Cooling nozzles 2	Micro Mist Lubrication
4.CNC system	/	3D Tool Fillet Radius Compensation Command

4.1.7 Processes

Through the analysis of the difficulties of the mould process, in order to ensure the size of the product and meet the requirements of the effect, it is necessary to develop a stable, efficient and reasonable process plan flow [17].

The process is as follows. Roughing0.1mm→semi-finishing0.08mm→semi-finishing0.06mm→on-machine inspection margin analysis→semi-finishing0.035mm→finishing0.02mm →on-machine inspection margin analysis → finishing 0.01mm→clearing 1→clearing 2→on-machine inspection margin analysis→down-machine CMM product inspection.

4.2 Process validation and convergence of cutting parameters

In the early stages of the project, automatic axis searching and tool measurement at the machine end were achieved through software machining step control, and preliminary process validation was carried out to form an in-house automated process plan.

4.2.1 Mould problems and countermeasures (Tab. 3)

Tab. 3 *Problems and responses*

Problems	Main reasons	Prescription
Uneven distribution of product edges after semi-finishing.	The semi-finishing time is up to 5 hours. Due to the large size of the product, the A-axis is used for fixed angle machining and the C-axis is used for oscillating angle machining. Insufficient warm-up time prevents the thermal stability of the machine from reaching the equilibrium point, so that the residual quantity after machining is not evenly distributed.	For the machining of such large products, it is not possible to set the preheating time with conventional thinking. The thermal stability of the machine is not balanced in the first few passes, and compensatory machining is carried out in conjunction with allowance allocation. Instead, the path spacing is adjusted to increase the warm-up time before semi-finishing. After finishing, the margins are relatively uniform and the range is controlled to within 8μm.

Analysis: The load of the rotary table in the machining process is relatively large, the C-axis generates more heat, the machining time is long, and the preheating time is insufficient, so that the thermal stability of the machine tool movement does not reach the equilibrium state, so that the machine tool does not reach the thermal stability during machining, and the residual quantity is not uniformly distributed in the end. In the machining process, attention should be paid to the details of the process, and the machine tool should be preheated sufficiently so that the machine movement reaches a thermally stable state [18].

4.2.2 Surface Effect Verification

Since the final product requires a surface roughness Ra<0.1μm; to ensure the surface effect of the product, finishing trial machining was carried out to verify the correctness of the process parameters after controlling the uniform distribution of the product allowance. Two different parameters (Figs. 11 and 12) were used for the post mould finishing trial tooling as shown in the following comparisons (Tabs. 4 and 5).

Tab. 4. *First processing effect*

Finishing parameters and results			
AP/mm (axial)	AE/mm (road distance)	Speed (rpm)	Feed mm.min^{-1}
0.01	0.035	13,000	2000

Tab. 5 *Second processing effect*

Finishing parameters and results			
AP/mm (axial)	AE/mm (road distance)	Speed (rpm)	Feed mm.min^{-1}
0.01	0.018	13,000	2000

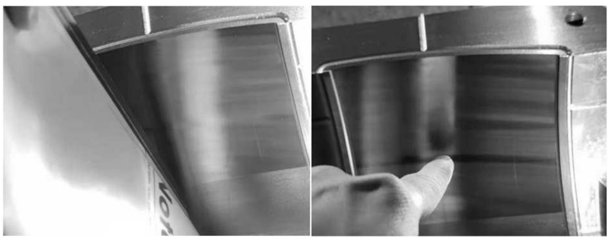


Fig. 11 *Poor surface effect, Ra>0.1μm, does not meet the customer's requirements*

Fig. 12 *Good surface finish, Ra<0.1μm, meets requirements*

The former uses a path pitch of 0.035mm and refers to the process parameters for CBN tool machining. As the product material HRC42 does not meet the material hardness conditions for CBN tool machining. Therefore, a customised R3 coated tool is used to reduce the path spacing and the surface effect meets the requirement.

4.2.3 Validation of the root removal process

The edge of this type of product is R0.6 R-angle transition, high clearing requirements, long clearing time, large workpieces, and clearing the root origin drift and the product surface machining origin drift is inconsistent with the phenomenon of overcutting, undercutting and other phenomena are prone to occur. This requires retaining sufficient margin, increasing the root clearing process, and gradually clearing the root (Fig. 13) shown.

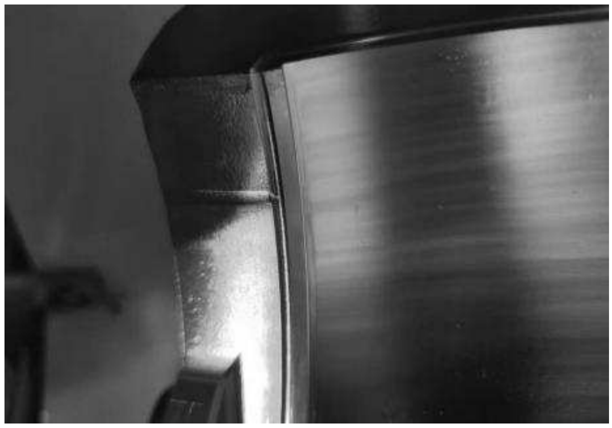


Fig. 13 *Root removal effect*

4.2.4 Programming methodology

The product surface is machined by the surface projection method, and the R angle is machined by the hybrid root cleaning method (Fig. 14) shown. In order to ensure the surface effect of the product surface, the tool axis control method is adopted, which is tilted along the cutting direction, and the positive and lateral inclination angles of the tool axis are adjusted to avoid tip cutting and improve the surface effect.

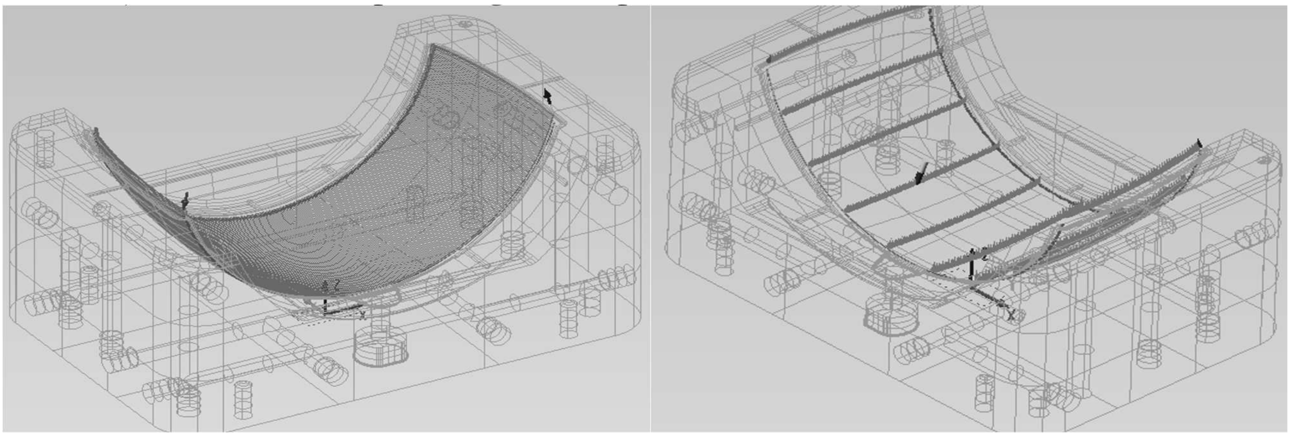


Fig. 14 *Schematic diagram of the cutter shaft*

4.2.5 Convergence of cutting parameters of the back mould tool (Tab. 6)

Tab. 6 *Tool cutting parameters*

Mask Mirror Mould Post Mould Process Parameters								
marching order	arts and crafts	brand name	cutters	AP/mm (axial)	AE/mm (road distance)	number of revolutions per minute (rpm)	feed mm.min^{-1}	times
open and rough	curved projection	carved	R2*TW	0.04	0.15	12000	2500	02:30:57
Semi-finishing 1	curved projection	carved	R3*TW	0.01	0.1	13,000	2000	03:15:32
Semi-finishing 2	curved projection	carved	R3*TW	0.01	0.1	13,000	2000	03:15:32
Finishing test tool machining 1	curved projection	carved	R3*TW	0.01	0.035	13,000	1500	02:33:19
Finishing test tool machining 2	curved projection	carved	R3*TW	0.01	0.018	13,000	1500	02:10:15
Semi-finishing 3	curved projection	carved	R3*TW	0.04	0.1	13,000	2500	02:30:57
Semi-finishing 4	curved projection	carved	R3*TW	0.01	0.05	13,000	2000	05:30:54
Semi-finishing 5	curved projection	carved	R3*TW	0.01	0.03	13,000	2000	08:40:54
finishing	curved projection	carved	R3*TW	0.01	0.018	13,000	1500	30:50:35
Clear Roots 1	Mixed Clear Roots	carved	R1*TW	0.05	0.1	13,000	1500	01:15:25
Clear Roots 2	circumcision and root removal	carved	R0.5*TW	0.01	0.05	13,000	1500	03:30:25

Convergence of cutting parameters of the front mould tool (Tab. 7)

Tab. 7 *Tool cutting parameters*

Mask mirror mould front mould process parameters								
marching order	arts and crafts	brand name	cutters	AP/mm (axial)	AE/mm (road distance)	number of revolutions per minute (rpm)	feed mm.min-1	times
open and rough	curved projection	carved	R3*TW	0.04	0.15	14000	2500	03:10:57
Semi-finishing 1	curved projection	carved	R3*TW	0.01	0.1	14000	2000	04:15:32
Finishing test tool machining 1	curved projection	carved	R3*TW	0.01	0.019	14,000	2000	03:15:32
Semi-finishing 2	curved projection	carved	R3*TW	0.04	0.15	14000	2500	03:10:57
Semi-finishing 3	curved projection	carved	R3*TW	0.01	0.1	14000	2000	06:40:15
Semi-finishing 4	curved projection	carved	R3*TW	0.04	0.05	14000	1500	11:30:57
Semi-finishing 4	curved projection	carved	R3*TW	0.01	0.019	14000	1500	35:50:35
Clear Root Processing 1	circumcision and root removal	carved	R1*TW	0.04	0.1	14000	1000	01:40:54
Clear Root Processing 2	circumcision and root removal	carved	R0.5*TW	0.01	0.05	14000	1000	04:50:35

4.2.6 Processing results

Machining path planning and accuracy control is one of the key technologies to achieve ultra-precision mirror mould CNC machining. By reasonably planning the machining path, it can effectively reduce the number of cutting times and tool trajectory, and improve the machining efficiency. At the same time, precise control of various parameters in machining, such as cutting speed, feed rate, depth of cut, etc., can ensure that the shape and dimensional accuracy of the mould meet the requirements.

Lubrication and cooling technology is also an indispensable key technology for CNC machining of ultra-precision mirror moulds. In the processing process, the selection and use of appropriate lubricants and coolants can effectively reduce frictional wear and thermal deformation, and improve the surface quality of the mould and processing accuracy. To ensure the stability and consistency of the processing effect.

Selection of appropriate machine tools and tooling is critical to achieving CNC machining of ultra-precision mirror moulds. The selection of machine tools should take into account factors such as rigidity, stability and accuracy, and have a high-speed and high-precision motion control system. The design and selection of tooling needs to take into account the fixing and positioning of the mould, as well as vibration control and cutting force balance during machining, in order to ensure the quality and efficiency of machining. Finally, the product has achieved the desired results for both surface and curved surface margin accuracy as shown in (Fig. 15). The mirror mould parameters are as follows (Tab. 8).

Tab. 8 *Sample cutting parameters*

name (of a thing)	rear mould	pre-mould
makings	NAK80 Pre-hardened steel (37-42 HRC)	
Mould Size	325*220*54.974 mm	325*220*68.974 mm
processing result	In-machine detection margin 3µm ~ 11µm, extreme difference 8µm	In-machine detection margin -4.8µm ~ 1.2µm, extreme difference 6µm
Completion time	66 hours 15 minutes	74 hours 10 minutes

Fig. 15 *Machining effect of the rear mould and the front mould*

5 Conclusions

- 1) The key technologies for CNC machining of ultra-precision mirror moulds include material selection and pretreatment, machining path planning and precision control, lubrication and cooling technology, and selection and optimisation of machine tools and tooling. The reasonable application and optimisation of these technologies can improve the precision and surface quality of the mould.

- 2) The influence of CNC machining process parameters on the quality of ultra-precision mirror moulds is also an important research direction. Better machining results can be achieved by optimising the machining speed, feed rate and cutting parameters, reasonably controlling vibration and tool wear, as well as evaluating and testing surface quality and accuracy.
- 3) Practice has proved that this process solution, combined with the online inspection module in the actual processing, can effectively produce ultra-precision mirror moulds to meet the market demand. At the same time, it can also reduce the manufacturing cost of mirror mould, shorten the mould manufacturing cycle, improve the mirror processing performance, and form a set of mature mirror mould manufacturing scheme.
- 4) The CNC machining of ultra-precision mirror mould is a complex and critical field, and the machining efficiency and mould quality can be continuously improved through continuous research and practice. It is expected that this study can provide certain reference and reference for scholars and engineers in related fields.

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