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Faculty of Mechanical Engineering and Transport  
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Department of Technologies and Automation of Mechanical Engineering  
(full name of the department (subject, cycle commission))

**MASTER'S QUALIFICATION THESIS**  
on the topic:  
**«DESIGN OF A MACHINING WORKSTATION FOR THE PART  
«MANDREL» USING CAD/CAM SYSTEMS»**

Performed by: student of the 2nd year,  
group 111124M  
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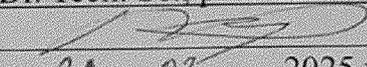
Кафедра Технологій та Автоматизації Машинобудування

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T A S K  
FOR THE STUDENT'S MASTER'S THESIS

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1. The topic of the thesis. «Design of a machining workstation for the part «Mandrel» using CAD/CAM systems»

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approved by the order of the higher educational institution from 20.03.2025 year №98

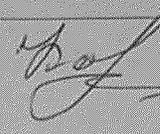
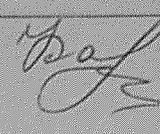
2. Deadline for submission of thesis by the student 16 of June 2025 year.

3. Initial data for thesis: the working drawing of the "mandrel" part, the processing route prototype of the part blank, the drawing of the blank, and the production plan of the part, and the operation of the cutting method.

4. Content of the text part: analysis of the initial conditions, design and service purpose of the part; development of a device for mechanizing the process of fixing the part for the milling operation; calculation of the cutting tool for the milling operation; calculation of the control and measuring tool for the precise surface; improvement of the workplace for machining the workpiece of the "Mandrel" type part; economic justification of the development.

5. List of illustrative material (with exact indication of mandatory drawings): posters displaying research results.

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CALENDAR

№	The title of the stages master's qualification work	The term of performance of work stages	Note
1	Defining the object and subject of research	until 14.04.2025	Done
2	Analysis of known solutions, setting tasks	until 15.04.2025	Done
3	Technical and economic justification of research methods	until 16.04.2025	Done
4	Solving the tasks set	until 30.05.2025	Done
5	Completion of the section "Economic part"	until 03.06.2025	Done
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## ABSTRACT

Liu K. Design of a machining workstation for the part “Mandrel” using CAD/CAM systems: master's qualification work for the competition of the educational qualification level "Master" in specialty 131 "Applied mechanics" / K. Liu. Vinnitsa National Technical University. Vinnitsa, 2025. 151 p.

In English speech. Bibliography: 32 titles; Fig.: 15; table 21.

The aim of the work is to solve the problems of achieving accuracy and efficiency of their processing using the CAD/CAM system.

This is achieved by systematically analyzing the purpose, design features and requirements for the processing of parts, and a reasonable machining route is developed. For the milling plane process, a special fixture is designed, and the positioning accuracy, strength and stiffness analysis are verified to ensure the reliability of clamping. Based on the functional criticality and multi-objective decision-making model, the measurement tool is selected and the measurement error is deeply analyzed to ensure the measurement accuracy.

The industrial robot technology is used to complete the design of the automated processing workstation, covering robot selection, gripper design, motion trajectory planning, etc., so that the workstation repeat positioning accuracy reaches  $\pm 0.01$  mm, the grasping success rate is  $\geq 99.5\%$ , and the cycle time is shortened to 2.72 minutes, which significantly improves production efficiency.

The project has good financial benefits and a short investment payback period, and it also has significant strategic and social benefits. The research results provide a complete technical solution for the processing of mandrel parts and promote the intelligent transformation of the machinery manufacturing industry.

The graphic part illustratively complements the materials presented in the explanatory note.

Keywords: CAD/CAM; spindle processing; industrial robot; fixture design; economic benefits.

## АНОТАЦІЯ

УДК 621.8

Лю К. Проектування робочого місця механічної обробки деталі «Оправка» з використанням CAD/CAM-систем: магістерська кваліфікаційна робота на здобуття освітньо-кваліфікаційного рівня «Магістр» за спеціальністю 131 «Прикладна механіка» / К. Лю. Вінницький національний технічний університет. Вінниця, 2025. 151 ст.

На англійській мові. Бібліогр.: 32 назв; рис.: 15; табл. 21.

Метою роботи є вирішення завдань досягнення точності та ефективності їх обробки за допомогою системи CAD/CAM.

Це досягається шляхом систематичного аналізу призначення, конструктивних особливостей та вимог до процесу обробки деталей розроблено розумний маршрут механічної обробки. Для процесу фрезерування площини розроблено спеціальне пристосування, а також перевірено точність позиціонування, аналіз міцності та жорсткості для забезпечення надійності затискання. На основі функціональної критичності багаточільової моделі прийняття рішень вибрано вимірювальний інструмент та глибоко проаналізовано похибку вимірювання для забезпечення точності вимірювання.

Технологія промислових роботів використовується для завершення проектування автоматизованої робочої станції обробки, що охоплює вибір робота, проектування захоплення, планування траєкторії руху тощо, таким чином, що точність повторюваного позиціонування робочої станції досягає  $\pm 0,01$  мм, коефіцієнт успішного захоплення становить  $\geq 99,5\%$ , а час циклу скорочено до 2,72 хвилини, що значно підвищує ефективність виробництва.

Проект має хороші фінансові вигоди та короткий термін окупності інвестицій, а також значні стратегічні та соціальні переваги. Результати дослідження забезпечують комплексне технічне рішення для обробки деталей оправлення та сприяють інтелектуальній трансформації машинобудівної галузі.

Графічна частина ілюстративно доповнює матеріали, які представлені в пояснювальній записці.

Ключові слова: CAD/CAM; обробка шпинделя; промисловий робот; конструкція пристосувань; економічні вигоди.

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Кафедра Технологій та Автоматизації Машинобудування

## INTRODUCTION

**Relevance of the research topic.** The manufacturing industry is transforming from traditional mode to digitalization and intelligence. Enterprises are faced with challenges such as improving production efficiency, controlling costs, and achieving high-precision flexible production. CAD/CAM technology is widely used in the design and processing of mechanical parts, and integration with automation equipment can solve the manufacturing bottleneck problem.

The spindle is a key component of the power transmission system, and has high requirements for machining accuracy. Traditional spindle processing has problems such as accumulated positioning errors and low production efficiency. Building an automated processing workstation based on the CAD/CAM system is of great significance to improving the level of spindle processing. This study aims to improve the efficiency and quality of spindle manufacturing and integrate multiple key technologies to realize the digitization and automation of the entire processing process. The study adopts methods such as literature research and theoretical modeling, and is carried out according to the "design-analysis-implementation-evaluation" process.

The work considers ways to increase the productivity of technological preparation and machining of the workpiece of the "Mandrel" part. The current ones are the use of an automated workplace, the development of special devices and modern computer applications for the design of measuring tools.

### **Purpose and objectives of the research work.**

The purpose of the work is to increase the productivity of technological preparation and machining of the workpiece of the “Mandrel” part by developing software applications to automate the work of engineering personnel and using automated devices to increase positioning accuracy and reduce time for auxiliary operations.

To achieve the goal, it is planned to solve the following *tasks*:

- analyze the “Mandrel” part;
- design a device for manufacturing flats on the “Mandrel” part;
- ensure maximum accuracy of positioning the part on the device;
- develop an application for calculating control and measuring instruments;
- directly improve the workplace for machining the workpiece of the

“Mandrel” type part.

**The object of research** is physical and mechanical processes in the equipment.

**The subject of research** is equipment and mechanisms for improving the technological process.

**Research methods.** Mathematical logic, methods of functional modeling and methods of surface and solid modeling using the SolidWorks software package, a program code editor for Visual Studio applications.

**Scientific novelty of the results obtained.** The method of achieving the accuracy of the special adaptation of the part "Mandrel" has been further developed, which allowed to improve its design in order to ensure the necessary speed.

**Practical significance of the results obtained.** A device for the manufacture of flats has been developed. An application of the caliper-clamp control and measuring tool has been developed. The workplace for machining the workpiece of the “Mandrel” type part has been improved by installing an industrial robot.

**Personal contribution of the master's student.** The main theoretical, program and simulation results of calculations and modeling, which are given in the master's qualification work, were obtained independently.

**Publications:** Poberezhets V., Meba O., Lui K., Piontkevych O. Application in C# programming language for automated selection of geometric parameters of a snap gauge. Collection of scientific papers of International Youth Scientific and Technical Conference «Young science - robotics and nano-technology of modern mechanical engineering». Kramatorsk: DSEA, 2025. P. 43-46.

## CHAPTER 1 ANALYSIS AND SERVICE USE OF THE PART "MANDREL"

### 1.1 Analysis of the service use of the part "Mandrel"

"Mandrel" (spindle) is a typical rotary part, which is mainly used for bearing, positioning, connection and transmission of rotational power in mechanical systems. In modern mechanical manufacturing systems, especially automated processing units, Mandrel may be a processing object and is often used as a tooling component to participate in the clamping and assembly process. By analyzing the engineering drawing shown in Figure 1.1, it can be seen that the part consists of multiple functional structures, such as a cylindrical positioning section, a tapered transition section and an external threaded connection end, and its geometric characteristics are highly consistent with the engineering requirements of torque transmission and coaxial assembly.

Mandrel has a compact structure and excellent rigidity. It can perform the following functions in multiple subsystems:

As the core shaft in the rotary drive chain, Mandrel can realize power input or output through its axis. Its end thread is connected with the matching hole to form a rigid assembly, thereby effectively transmitting the rotational torque. The conical surface design helps to enhance the connection strength and reduce the influence of the matching clearance on the coaxiality.

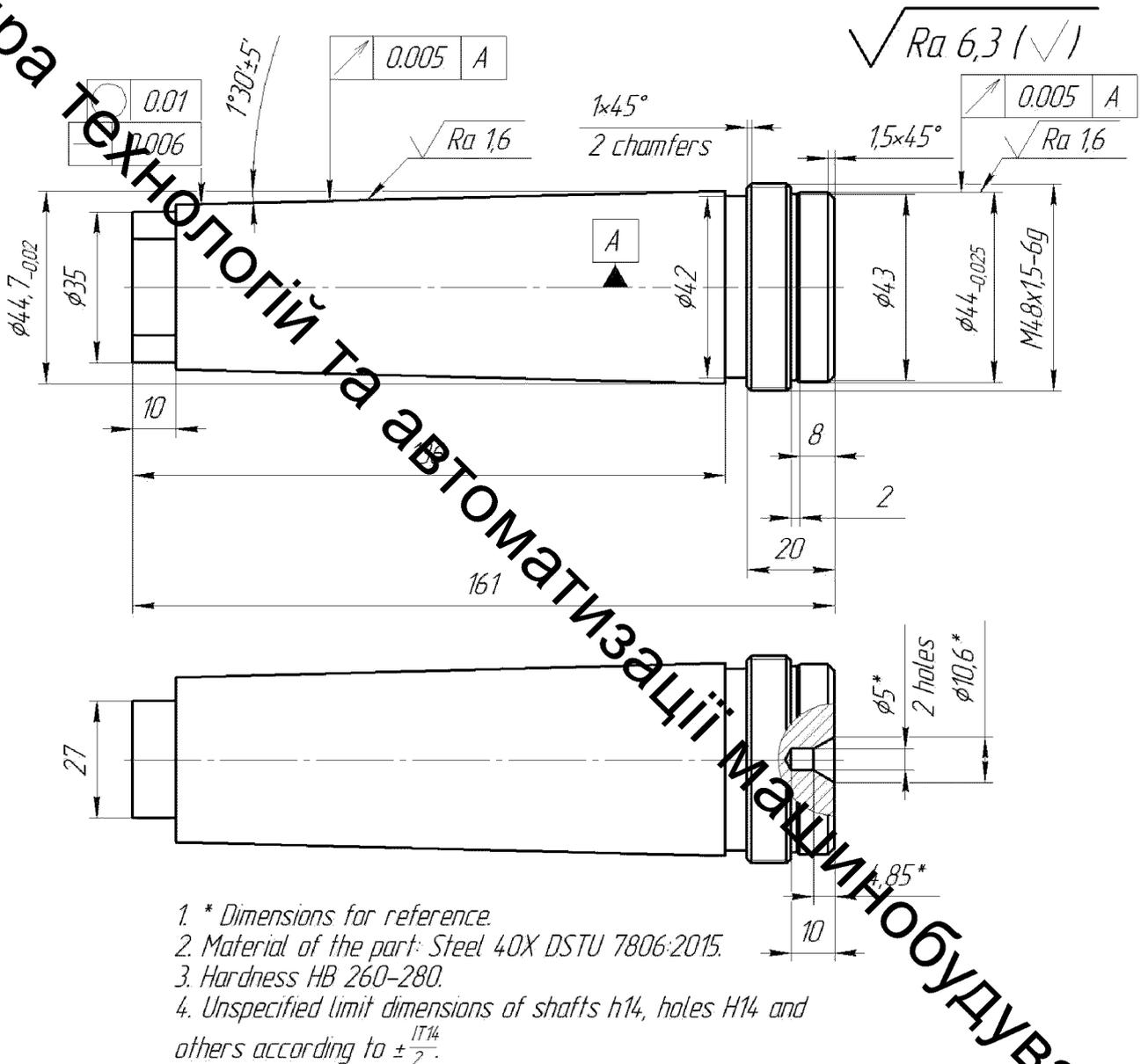


Figure 1.1 - Workpiece drawing of the part "Mandrel"

The planes machined on both sides of the part body are often used as positioning references for process fixtures or robot grippers. Through these two symmetrical planes, stable angular positioning and reliable clamping force distribution can be achieved, which is suitable for high-frequency start-stop or large vibration processing scenarios.

The M48×1.5-6g threaded section design at the end is not only used for rigid

connection between components, but also can bear a certain axial preload and additional axial load. This structure is suitable as a transition interface in complex systems to support adjacent mechanisms.

In automated production, “Mandrel” can also serve as the gripping reference of the robot end effector and cooperate with the positioning program generated by the CAD/CAM system to realize functions such as automatic clamping and tool compensation.

In summary, Mandrel has multifunctional composite characteristics, which is not only suitable for high-precision rotary transmission requirements, but also compatible with various assembly and clamping requirements, reflecting a high degree of system integration and application flexibility.

Mandrel (spindle) has demonstrated wide applicability and significant engineering reuse value in the field of high-end equipment manufacturing due to its standardized axial structure and excellent connection, positioning and load-bearing capacity. Its typical application scenarios and quantitative benefits are as follows:

1. Fixture system on CNC machine tool. As a replaceable clamping element, the core function of the spindle is to transfer the positioning reference and align the center hole. In the crankshaft grinding process, a certain automobile engine production line uses a high-precision spindle (matching accuracy  $\leq 0.003\text{mm}$ ) as the positioning support shaft. Through the combined clamping of the three-jaw chuck and the top, the cylindrical error of the crankshaft journal is controlled within  $0.005\text{mm}$ , and the coaxiality error is  $\leq 0.01\text{mm}$ . Data shows that this process reduces the engine scrap rate by 15%, the maintenance rate by 20%, the power output efficiency of a

single engine by 8%, and the fuel consumption by 5%.

2. Aerospace parts manufacturing. In the milling of aircraft engine blades, the high-precision positioning characteristics of the mandrel (positioning accuracy  $\pm 0.008\text{mm}$ ) ensure the processing accuracy of the complex blade surface (surface error  $\leq \pm 0.01\text{mm}$ ). The application case of an aviation company shows that after the use of the mandrel, the aerodynamic efficiency of the blade is improved by 6%, the engine fuel consumption is reduced by 8%, the overhaul interval is extended by 10%, and the maintenance cost of a single engine over the entire life cycle is reduced by about 2 million yuan.

3. Agricultural machinery power unit. In agricultural equipment such as fertilizer spreaders and seed drills, the mandrel is the core component of the transmission shaft, with a torque range of  $50\text{-}200\text{N} \cdot \text{m}$  and an axial load of  $\leq 5000\text{N}$ . The transmission system of a seed drill uses a 40CrNiMoA mandrel. By optimizing the spline segment tooth profile parameters (module  $m=4$ , number of teeth  $z=20$ ), the transmission efficiency is increased to 98%, the overall machine operation stability is improved by 25%, and the downtime due to failure is reduced by 30%.

4. Main drive system of construction machinery. The main drive intermediate shaft of high-load equipment such as cranes and loaders generally adopts a spindle structure. Taking a 50-ton loader as an example, its spindle is supported by a tapered roller bearing, which can withstand a radial load of  $150\text{kN}$  and an axial load of  $50\text{kN}$ , and the surface hardness reaches HRC58-62. Actual measurement data shows that after 5,000 hours of continuous operation, the wear of the spindle is  $\leq 0.02\text{mm}$ , which is 40% longer than the life of traditional shaft parts.

5. To using with industrial robot. In the robot modular grasping system, the spindle can quickly replace the positioning interface (such as the HSK-63 interface) to achieve a second-level response for workpiece handling and multi-process switching. A 3C product production line uses a grasping system constructed with a spindle, with a positioning repeatability accuracy of  $\pm 0.01\text{mm}$ , and the production cycle is increased from 12 seconds/piece to 8 seconds/piece, and the fixture replacement time is shortened by 80%.

6. Precision assembly and testing equipment. In aircraft engine support fixtures and coordinate measurement systems, the precision centering capability of the mandrel (coaxiality  $\leq 0.002\text{mm}$ ) is crucial. A certain aviation assembly line uses mandrels to achieve positioning and assembly of turbine blades and casings, with an assembly error of  $\leq 0.005\text{mm}$ , a 50% increase in detection efficiency, and an increase in the one-time pass rate of key processes from 78% to 95%.

The engineering value of the mandrel is reflected in the organic combination of its high-precision positioning capability, complex load bearing capacity and cross-domain rapid adaptation capability. Through material optimization (such as carburizing and quenching process to make the surface hardness reach HV800), structural innovation (such as hollow lightweight design to reduce weight by 30%) and process collaboration (such as one-time molding by turning and milling composite processing), the mandrel is becoming a core basic component to promote the development of high-end equipment towards precision and intelligence.

In application, the working environment of “Mandrel” is complex, often involving multiple load couplings, dynamic working conditions and high-precision

requirements. The main technical challenges include:

1) Load conditions.

- Torsional load (It is necessary to stably withstand the torsional output of the transmission chain for a long time);
- Radial/axial composite load (It is generated by the superposition of processing force and tooling clamping force);
- Impact load (It comes from equipment start-stop, robot grasping error, etc).

2) Motion characteristics requirements.

- Maintain high dynamic balance under medium-speed rotation (500-1000 rpm);
- Angular positioning error should be controlled within  $\pm 0.05^\circ$ ;
- Must have excellent repeat positioning stability and low clearance fit performance.

3) Environmental adaptability.

- The working temperature is generally room temperature  $\sim 80^\circ\text{C}$  and sufficient thermal stability is required;
- Surface treatment must meet the requirements of anti-oxidation, anti-corrosion and anti-fatigue performance;
- The processed surface must meet the lubrication requirements to reduce friction and wear.

The core technical indicators of the part "Mandrel" are shown in Table 1/

Table 1.1 - Core technical specifications of the component "Mandrel"

## Core Technical Specifications:

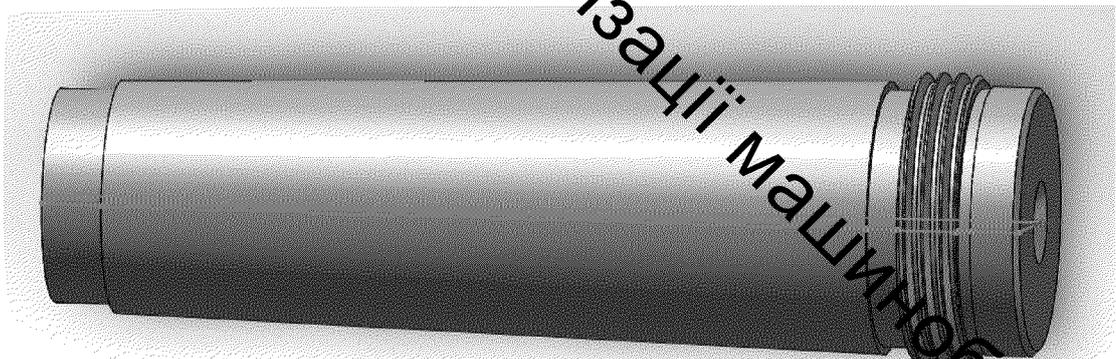
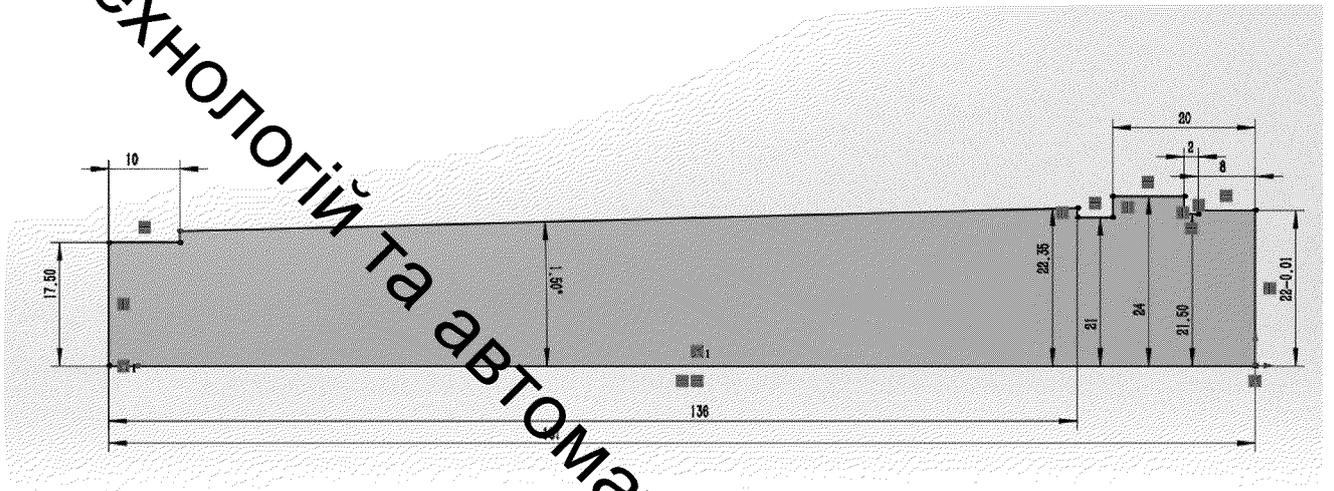
Item	Technical Requirements
Maximum Diameter Deviation	$\leq 0.005 \text{ mm}$
Thread Pitch Grade	6g (ISO Tolerance)
Surface Roughness	Ra 0.8–1.6 $\mu\text{m}$
Material Performance	$\sigma_{\text{sub}>b</sub>} \geq 600 \text{ MPa}$ , HB 200–250
Surface Treatment	Zinc Plating / Nickel Plating (For Visual Use)

To achieve these indicators, high-precision machining equipment, stable fixture systems and CNC process parameter control are required. The application of CAD/CAM system can improve the efficiency and accuracy of modeling, programming and automated processing, and is the core support for ensuring the quality of Mandrel parts [1, 2].

## 1.2 Part design analysis

In order to meet the multiple functional requirements of parts in the transmission system, "Mandrel" reflects a high degree of unity of functionality, processability and structural stability in geometric design. Its overall structure is a stepped shaft structure with an axisymmetric layout, which has good rotational balance and processing adaptability. As shown in Figure 1.2, the part is mainly composed of a positioning section, a transmission section and a connection section [3]. Different structural sections are smoothly connected through a conical transition surface, which

effectively reduces the risk of stress concentration and improves fatigue life.



b)

Figure 1.2 - Sketch a) construction and 3D model b) of the part "Mandrel"

From the analysis of the three-dimensional model and engineering drawings, the total axial length of the part is 161mm, the maximum outer diameter is 48mm, and the size belongs to the category of medium-sized shaft parts. According to the functional division, its structure can be clearly divided into the positioning end, the transmission section and the connection end. The positioning end (left end) achieves high-precision axial positioning and angular anti-rotation through specific size and

shape with tooling or fixtures, providing a benchmark for subsequent processing and assembly. The transmission section in the middle part is the core power input part of the part. It adopts a tapered transition section design with a length of about 136mm. It not only has good guiding performance, but also can effectively reduce stress concentration when transmitting torque, thereby improving the fatigue life of the part. The connection end (right end) includes a standard external thread structure (M48×1.5 - 6g) and a Ø44mm cylindrical guide section, which provides a reliable structural foundation for the rigid connection between the part and other components.

Conical transition section: the small-angle cone design ( $\alpha=1.5^\circ$ ) not only plays a role in smooth connection in structure, but also has a certain self-centering function, which is conducive to positioning accuracy and assembly convenience;

Transition fillet and chamfer: there are transition fillets of R1~R3mm and 45° chamfers between each functional section, which effectively weaken stress concentration and improve the fatigue strength and crack resistance of parts;

The two positioning planes are processed on the Ø35mm cylindrical section, with a parallelism of  $\leq 0.02\text{mm}$  and a width of about 3mm, providing an angular clamping reference and preventing relative rotation.

The spline section and the thread section are reasonably distributed, which avoids the problem of fixture interference and improves the overall clampability.

The dimension and tolerance design of the "Mandrel" parts directly determines the reliability of its function realization, processing difficulty and assembly compatibility. In order to ensure that the parts have excellent transmission performance, assembly accuracy and interchangeability, their dimension design

follows the principle of function priority and process adaptation, and strict geometric tolerance control is implemented in key parts.

From the perspective of key dimension parameters and function analysis, according to the engineering drawings and three-dimensional models, each key dimension of the part has its specific function. The typical dimensions of the part and their functional significance are shown in Table 1.2 below.

Table 1.2 - Key dimensional parameters and functions of parts

Dimensional Section	Parameter	Function
Positioning Section	Ø35 mm (h6) × 10 mm	Achieves high-precision axial positioning and anti-rotation with tooling or fixtures
Tapered Section	1.5° taper, total length 136 mm	Provides alignment during assembly, reduces stress concentration, and enhances structural rigidity
Guide Section for Connection	Ø44 mm (h7) × 20 mm	Forms a transition interference fit with bearing holes or mating parts
Threaded Section	M48×1.5-6g, length 10 mm	Ensures reliable transmission of clamping force through standard threaded connection
Two Positioning Surfaces	Flatness ≤ 0.02 mm, width approx. 3 mm	Provides an axial clamping reference and prevents relative rotation

The total axial length is controlled at 161 mm, the overall structure is compact, and the functional sections are naturally connected through geometric transitions, which is convenient for processing and measurement.

Dimension tolerance:

- Ø35 mm positioning section: h6 tolerance grade (basic deviation 0/−0.013 mm), ensuring transition fit with the fixture hole;

•  $\varnothing 44$  mm transition section: h7 tolerance grade (basic deviation 0/-0.025 mm), adapted to the bearing installation accuracy requirements.

Threaded section: ISO 6g tolerance grade is adopted to meet standard mechanical connection specifications.

Non-critical outer circle section: The tolerance is relaxed to h11 grade to control costs while meeting the support function.

Geometric tolerances:

• Conical runout: the radial runout relative to the reference surface A is controlled within  $\leq 0.005$  mm, which is the highest precision control area of the part;

• Coaxiality: the difference between each cylindrical functional segment must be controlled within  $\leq 0.02$  mm to ensure assembly concentricity and rotation stability;

• Cylindricity: the  $\varnothing 35$  mm positioning segment and the  $\varnothing 44$  mm matching segment must be controlled within 0.01 mm to ensure axial guiding accuracy;

• Parallelism of the positioning plane: controlled within 0.02 mm to ensure the repeatability of the angular positioning function.

Key dimension tolerance chain: the coaxiality of the positioning section  $\varnothing 35h6$  (0-0.013mm) and the matching section  $\varnothing 44h7$  (0-0.025mm) is  $\leq 0.02$ mm, and the datum is unified through one-time clamping and turning.

The radial runout of the cone surface is  $\leq 0.005$ mm, and the "double ejector + fine grinding" process is used for control.

The thread section M48 $\times$ 1.5-6g has a middle diameter tolerance of  $\pm 0.012$ mm, which is achieved through CNC thread turning.

The size and tolerance design of "Mandrel" parts is highly systematic and targeted. Through the idea of combining functional differentiation with process matching, it takes into account processing cost control and structural stability while ensuring high-precision function realization. In particular, key indicators such as cone runout, thread accuracy and matching coaxiality constitute the core points of this part manufacturing and quality control.

As a high-precision, high-reliability rotating shaft component, the "Mandrel" part has a complex working environment involving multiple factors such as torsional load, axial preload, impact load and temperature fluctuation. Therefore, the selection of materials is crucial. It must not only meet the basic mechanical performance requirements, but also take into account the processing technology, heat treatment responsiveness and service durability.

This part is made of 40X alloy structural steel (DSTU 7806.2015, or equivalent international standard), which is a medium carbon chromium alloy steel and is widely used in shafts, gears and connectors under medium load conditions. This material has strength, toughness and hardenability. Its typical chemical composition is shown in Table 1.3 below.

In order to achieve the required balance of strength and toughness, the use state of 40X steel in this part is the quenching and tempering state (quenching + high temperature tempering), and its typical mechanical properties are shown in Table 1.4 below.

This performance combination enables the parts to have good static and dynamic load-bearing capacity, while taking into account impact resistance, and is suitable for

application scenarios with instantaneous loads or installation errors.

Table 1.3 - Chemical composition of 40X steel

Element	Content Range (Mass Fraction)
C	0.36 – 0.44%
Si	0.17 – 0.37%
Mn	0.50 – 0.80%
Cr	0.80 – 1.10%
S	≤ 0.03%
P	≤ 0.035%

Note: The introduction of Cr element significantly improves the hardenability, wear resistance and corrosion resistance of steel, and is an important strengthening element suitable for medium-load structural parts.

Table 1.4 - Mechanical properties of 40X steel in quenched and tempered state

Item	Specification Requirements
Tensile Strength $\sigma_{b}$	≥ 600 MPa
Yield Strength $\sigma_{0.2}$	≥ 400 MPa
Elongation $\delta_5$	≥ 16%
Reduction of Area $\psi$	≥ 45%
Brinell Hardness HB	200 – 250

The selection of 40X steel as the material for Mandrel parts is mainly based on the following multi-dimensional considerations:

- after quenching and tempering, it has high strength and good toughness, meeting the composite force requirements of the parts during clamping and rotation;
- the Cr element enhances the depth of the hardened layer and ensures the uniformity of performance under medium cross-sectional dimensions;
- good cutting performance under normalizing state, suitable for rough machining [4]; Good stability after heat treatment, suitable for precision machining;
- suitable for a variety of heat treatment and surface strengthening technologies, such as high-frequency quenching, surface nitriding, electroplating, etc.;
- compared with high-performance alloy steels such as 42CrMo and 30CrMnSi, 40X has a better cost-effectiveness under the premise of meeting performance requirements.

In the early stages of the design, several typical structural steels were compared in terms of performance and cost. The results are shown in Table 1.5 below.

Table 1.5 - Comparative analysis of alternative materials

Material	Strength	Machinability	Hardenability	Cost	Application Evaluation
45# Steel	Medium	Good	Weak	Low	Suitable for low-load shafts
40Cr	Medium-High	Good	Medium	Medium	General-purpose structural shaft material
40X (optional)	Medium-High	Good	Excellent	Medium	★ Good balance of performance, machinability, and cost
42CrMo	High	Average	Excellent	High	Suitable for high-load scenarios
30CrMnSi	Very High	Average	Good	High	Consider when high impact resistance is required

Comprehensive performance evaluation shows that 40X steel has good

mechanical properties, processability and economy, and is most suitable for the manufacture of "Mandrel" parts in this project. Its heat treatment process route is as follows: the initial normalizing or annealing state is adopted to facilitate turning and pre-processing allowance control; the quenching stage is heated at 850-870°C and then quickly oil quenched to form a martensitic structure; then tempered at 550-600°C to release stress and obtain excellent comprehensive performance. The final hardness is controlled at HB 200-250, which is suitable for positioning or connection parts with medium strength and toughness requirements. For key mating surfaces (such as Ø35 mm positioning sections and tapered surfaces), fine grinding or surface strengthening treatment can be further used to improve fatigue life and assembly stability.

40X steel also has certain requirements for processing technology: in the rough processing stage, it has good machinability in the normalizing state and is suitable for large margin rapid removal; deformation factors need to be considered after heat treatment, and it is recommended to reserve 0.3-0.5 mm finishing allowance; grinding or fine turning + polishing knife process should be adopted in the quenching and tempering state to achieve high-precision control; in terms of cutting parameters, small cutting depth, high spindle speed and sufficient cooling should be used to avoid the generation of white layer or hard spots; if necessary, external nitriding or shot peening can be performed to further improve the fatigue performance of key surfaces.

As a mechanical part with high-precision assembly and rotation requirements, the surface quality of "Mandrel" is directly related to the operating stability, matching accuracy and service life of the entire system. Due to the large differences in the

functional sections of the parts, the requirements for roughness, hardness, residual stress and integrity of each surface are also significantly different. Therefore, the reasonable formulation of surface quality indicators for each functional surface is a key link to ensure the balance between performance and manufacturing cost.

Based on engineering drawings and design requirements, the surface roughness indicators of each area of the "Mandrel" part are shown in Table 1.6 below.

Table 1.6 - Surface roughness requirements

Section	Function Description	Roughness Requirement
Ø35 mm Positioning Section	Axial positioning reference mating surface with fixture/tooling	Ra 1.6 µm
Ø44 mm Transition Section	Support and guidance, mating with bearing	Ra 1.6 µm
Conical Transition Section	Coaxial transition, self-centering structure	Ra 1.6 µm, radial runout ≤ 0.005 mm
Positioning Plane	Anti-rotation, clamping reference	Ra 2.5 µm, flatness ≤ 0.02 mm
Thread Section (M48×1.5)	Tight connection	Ra 3.2 µm
Non-functional Outer Surface	General support or non-mating area	Ra ≤ 6.3 µm

Based on the principle of "function drives quality", the key mating surfaces of this part need to be fine-machined to ensure low friction, high contact accuracy and stable mating strength, while the non-functional surfaces use conventional machining to control costs.

In terms of surface integrity control, the key surfaces must not have macro defects such as cracks, pores, inclusions, etc. After heat treatment, network carbides, decarburization and burns should be avoided, and the residual stress should be

micro-pressure or neutral to reduce the formation of fatigue sources. The processing direction should be perpendicular to the main load to prevent stress accumulation and ensure that the surface roughness and microstructure meet the fatigue life requirements.

The "Mandrel" parts surface quality control system embodies the modern manufacturing concept of "precise control of key surfaces + cost optimization of non-functional surfaces". While meeting the requirements of high precision and high strength, it achieves a balance between function, manufacturing and quality through the integration of process optimization and testing methods. This provides a solid processing foundation and quality assurance for the subsequent processing route formulation, fixture design and automatic control program construction.

### 1.3 Process analysis

Process analysis is the key link for "Mandrel" parts to move from design to manufacturing. Reasonable design directly affects its processing quality, production efficiency and manufacturing cost. This subsection conducts a systematic analysis from the aspects of process feasibility, part processability, benchmark selection and processing difficulties to provide theoretical support for subsequent process solutions.

Combined with the structural characteristics, dimensional accuracy and surface quality requirements of the parts, the process feasibility is analyzed from the following perspectives: processing method feasibility, feasibility of processing route.

This part is mainly a shaft-type rotating body, with mature processing technology and rich means [5, 6]:

- turning (the shape is a typical rotating body, and turning is the main processing method. CNC lathes (such as 16Б16Ф3) can efficiently complete processes such as external circles, end faces, threads and grooves. The cone runout requirement is  $\pm 0.005$  mm, which can be achieved through fine turning + fine grinding);
- milling (two positioning planes need to be milled. The DMG MORI NVX 5080 vertical milling machine has a positioning accuracy of  $\pm 0.005$  mm, which can ensure parallelism  $\leq 0.02$  mm);
- heat treatment process (40X alloy structural steel is used, which needs to be tempered to improve mechanical properties. Considering the high precision requirements, professional heat treatment equipment should be used to accurately control the heating and cooling process to reduce the risk of deformation);
- precision machining (the key surface roughness requires  $R_a 1.6 \mu\text{m}$ , and fine turning or fine grinding processes are required. Equipment such as M16801Ф3 CNC lathe or 3M151Ф2 grinder can meet the precision requirements).

Taking into account the precision requirements and process characteristics of the parts, the following process route can be adopted, as shown in Figure 1.3.

The process route of "roughing first and then finishing" and "reserving finishing allowance before heat treatment" conforms to the basic principles of mechanical processing and can effectively control the influence of heat treatment deformation on the final accuracy. The processing contents of each stage are as follows: the roughing stage completes the turning of the basic shape, and the outer circle reserves 0.5-1.0mm finishing allowance; the semi-finishing stage adjusts the size coordination

of each part to prepare for heat treatment; the special process stage completes the milling of two positioning planes and other non-rotating surfaces; the heat treatment stage performs overall quenching and tempering to improve the mechanical properties of the material; the finishing stage compensates for the heat treatment deformation to achieve the final size and surface quality requirements.

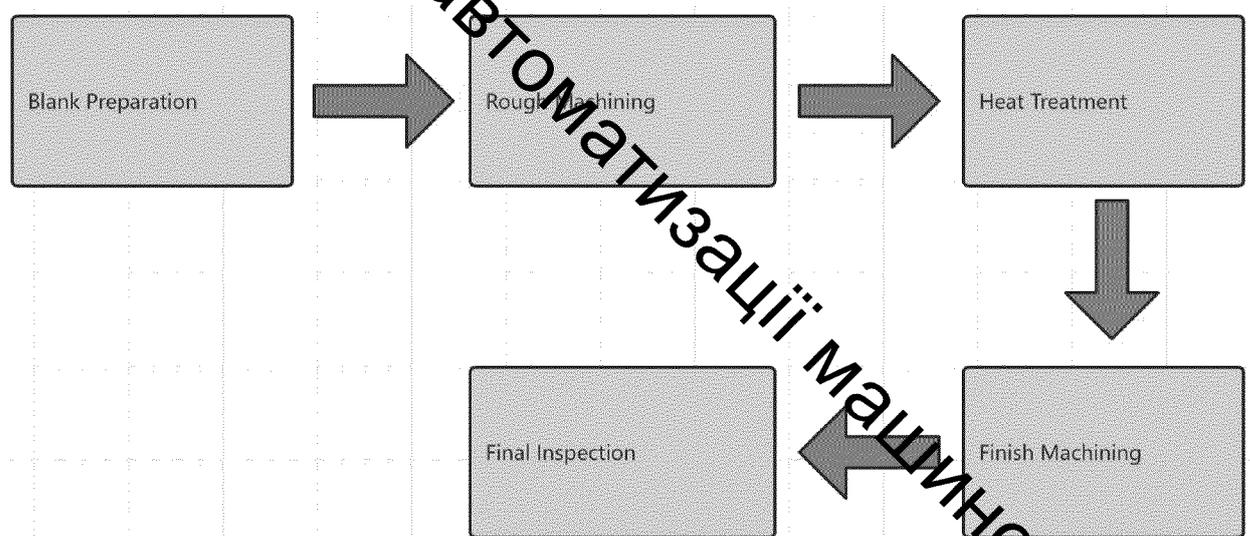


Figure 1.3 Processing process

In terms of equipment configuration feasibility, it is recommended to use: CNC lathe (such as 16Б16Ф3, rotation diameter 400mm, spindle speed 0-3000rpm) to meet turning needs; vertical machining center (DMG MORI NVX 5080, worktable 1300×650mm) has sufficient space, suitable for installing fixtures and plane milling; heat treatment equipment should use heat treatment furnaces with precise temperature control and temperature recording systems to ensure treatment quality; precision grinder (MK6801Ф3 CNC) is used for high-precision fine lather of conical surfaces and key outer circles.

CNC turning and milling parameters: rough turning 800rpm, feed 0.3mm/r, cutting depth 2mm; fine turning 1500rpm, feed 0.05mm/r, cutting depth 0.2mm; milling plane uses  $\varnothing 10$ mm end mill, cutting speed 100m/min, feed per tooth 0.06mm.

In terms of the feasibility of detection means, it should be equipped with: three-coordinate measuring machine for measuring complex geometric tolerances such as cone radial runout  $\leq 0.005$ mm; surface roughness tester for detecting surface quality of Ra 1.6 $\mu$ m; hardness tester for verifying hardness after heat treatment (HB 200–250); optical projector for measuring plane position and parallelism.

Comprehensive analysis shows that the manufacturing process of "Mandrel" parts is technically feasible, and the existing processing equipment, process methods and detection means can meet its technical requirements.

Processability evaluation is an important basis for measuring whether a part can be manufactured economically and efficiently. A comprehensive analysis of the processability of the "Mandrel" part is helpful to optimize the processing route and process parameters.

1) Material processability evaluation. "Mandrel" uses 40X alloy structural steel which has good processability: excellent cutting performance (moderate cutting force and small tool wear in normalizing or annealing state), controllable heat treatment deformation but need to reserve finishing allowance, and the surface can reach Ra 1.6 $\mu$ m after finishing. The chromium element improves the hardenability and ensures the uniform mechanical properties of medium cross-sections.

Material processability score: 4 points (out of 5 points), the overall process performance is good and suitable for conventional processing.

2) Geometric shape processability evaluation. The part is a shaft-type rotating body with a simple structure and good axial symmetry, which is conducive to clamping and positioning; the diameter transition is reasonable and the structure is rigid; each section is connected with a rounded corner to reduce stress concentration; the only complex point is that the two positioning planes need to be clamped and milled twice.

Shape processability score: 4 points (out of 5 points), the overall structure is easy to process, and only some parts require additional processing.

3) Dimensional accuracy processability evaluation [7, 8]. The outer circle tolerance is mostly h6 and h7, which is medium and high precision but can be met by modern equipment [9]; the taper runout is  $\leq 0.005\text{mm}$  [10, 11], which is a high requirement; the key surface roughness  $R_a 1.6\mu\text{m}$ , which requires fine processing; the dimension chain is reasonable, there is no risk of cumulative error, and the key dimensions can be routinely tested.

Dimensional accuracy processability score: 3.5 points (out of 5 points), the overall difficulty is medium, and the focus is on high-precision control.

4) Clamping and positioning processability evaluation. The parts have good reference conditions, and the axis and end face are easy to turn and clamp; the cylindrical surface and end face can achieve "six-point positioning" and the positioning is stable; the structure has no interference, and the clamping force is evenly distributed; the overall rigidity is good, and the risk of self-weight deformation is low; the milling positioning surface needs to add an angular positioning device, which slightly increases the complexity.

Clamping and positioning processability score: 4 points (out of 5 points), the clamping conditions are good, and only the positioning method during milling needs to be optimized.

5) Calculation of comprehensive processability index. The weighted scoring method is used to evaluate the comprehensive processability of "Mandrel" parts, as shown in Table 1.7 below.

Table 1.7 - Comprehensive evaluation table of the processability of "Mandrel" parts

Evaluation Item	Weight	Score (1-5)	Weighted Score
Material Manufacturability	0.25	4.0	1.00
Geometric Shape Manufacturability	0.25	4.0	1.00
Dimensional Accuracy Manufacturability	0.30	3.5	1.05
Clamping and Positioning Manufacturability	0.20	4.0	0.80
<b>Total</b>	<b>1.00</b>	—	<b>3.85</b>

The comprehensive processability index is 3.85 (out of 5 points), indicating that the overall processability of the "Mandrel" part is good and suitable for large-scale production. The main difficulties are high-precision requirements and positioning plane milling, which should be focused on during processing.

6) Process improvement suggestions. Optimize the clamping scheme, design special fixtures, and ensure the uniformity of multiple clamping benchmarks; arrange the process sequence reasonably, reduce the number of clamping times, and reduce cumulative errors; control heat treatment deformation, use graded reserve margins,

and ensure fine processing correction space; use efficient grouping technology and use multi-axis CNC equipment to achieve multi-faceted one-time clamping processing, apply advanced detection methods, use online detection of key precision, and adjust processing parameters in real time. The above improvements will help improve processing efficiency and quality stability and reduce production costs.

#### 1.4 Machining route development and demonstration

Based on the systematic analysis of the structural characteristics, precision requirements and processability of the "Mandrel" part, this section will scientifically develop a machining process route suitable for the part and conduct a comprehensive demonstration from the perspectives of process rationality, technical feasibility and quality assurance. A reasonable process route is the basis for achieving high-precision machining and is also a prerequisite for the subsequent construction of an automated machining workstation based on the CAD/CAM system.

The process route structure of the "Mandrel" part is shown in Figure 1.4.

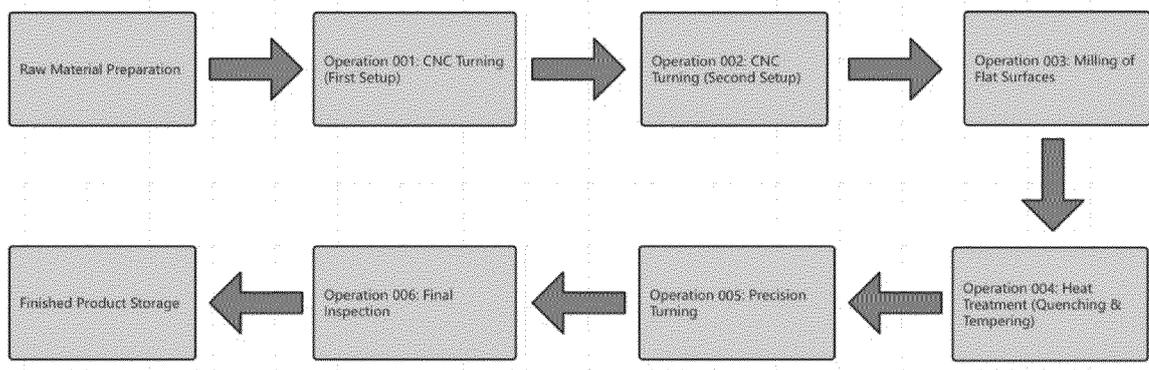
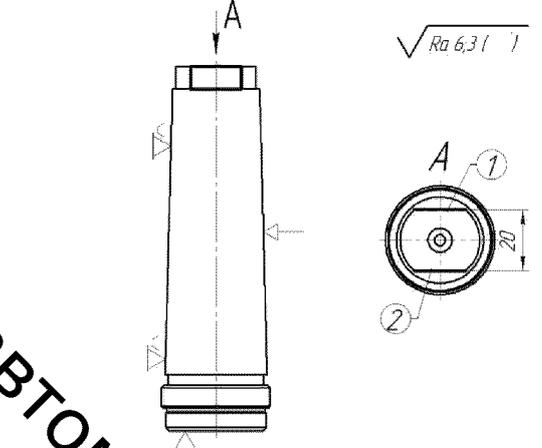
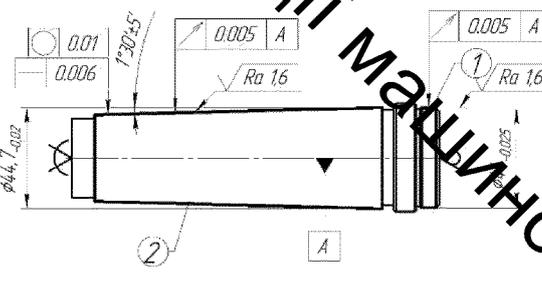


Figure 1.4 - Schematic diagram of the complete process route for "Mandrel" parts



№	Operations, transitions	Installation sketches and diagrams	Machine tools models
003	<p><u>CNC milling</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Milling tools once 1 and 2.</li> <li>3. Remove the part.</li> </ol>		<p>DMG MORI NVX 5080 vertical machining center</p>
004	<p><u>Heat treatment</u></p>	<p>quenching and high tempering</p>	
005	<p><u>CNC lathe</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Fine turning of surfaces 1 once.</li> <li>3. Fine turning of surfaces 2 once.</li> <li>4. Remove the part.</li> </ol>		<p>МК6801Ф3 precision CNC lathe</p>
006	<p><u>Final inspection</u></p>		

b

Figure 1.5 - Manufacturing process of the part "Mandrel"

Main process content and technical requirements.

Process 001: CNC turning (first clamping), see Figure 1.6.

Equipment: 16Б16Ф3 CNC lathe.

Process content: three-jaw chuck + center support combination positioning;

Pre-turning end face 1 to establish a benchmark; turning surface 1 ( $\text{Ø}35\text{mm}$  end) and surface 2 (tapered section); machining groove 3 ( $\text{Ø}42\text{mm}$ ), controlling the groove width and position; finishing surfaces 1, 2 and groove 3 to improve surface quality; finally, quality inspection and disassembly.

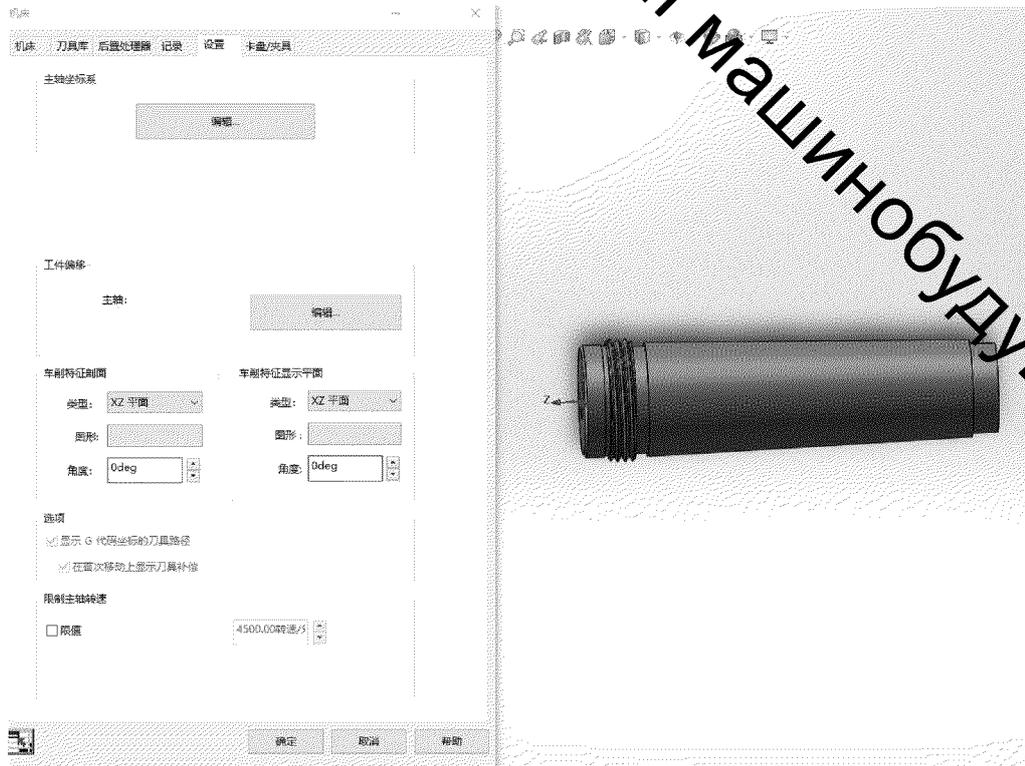
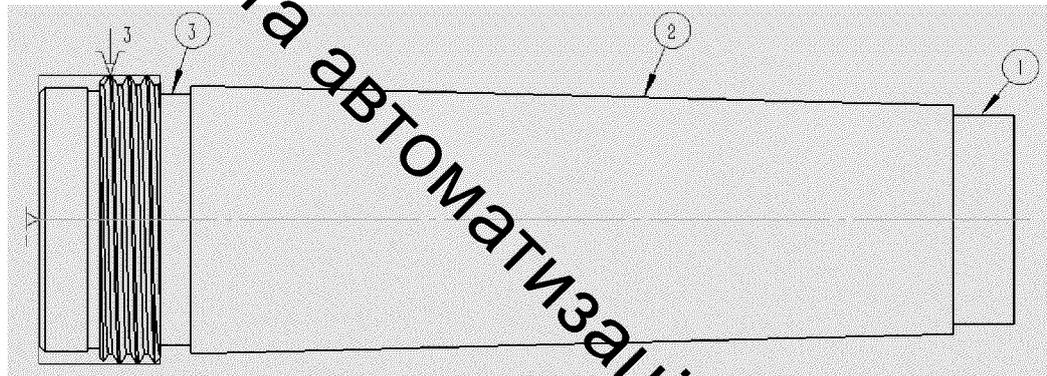


Figure 1.6 - Process 001 clamping diagram and processing path

Technical requirements: cylindrical surface roughness  $\leq R_a 3.2\mu\text{m}$ ; conical

surface reserve allowance 0.3–0.5mm; groove position accuracy  $\pm 0.1\text{mm}$ ; end face verticality  $\leq 0.05\text{mm}$ .

Process 002: CNC turning (second clamping), the clamping and processing diagram of process 002 is shown in Figure 1.7:

Equipment used: 76B16Φ3 CNC lathe.

Main process content:

- workpiece clamping: clamping based on the surface processed for the first time;
- pre-turn the remaining end face to ensure the total length requirement;
- turning surface 1 ( $\text{Ø}44\text{mm}$  segment) and the front end face of the thread;
- machining groove 2 ( $\text{Ø}43\text{mm}$ ) to ensure the groove shape and position accuracy;
- turning external thread 3 ( $\text{M}48 \times 1.5\text{-}6\text{g}$ ) to ensure thread accuracy;
- chamfering to eliminate sharp edges.

Fine turning of each surface to improve surface quality

Technical requirements: external surface roughness  $\leq \text{Ra } 3.2\mu\text{m}$ , thread accuracy 6g level to ensure thread matching quality; coaxiality of diameter  $\text{Ø}35\text{mm}$  and  $\text{Ø}44\text{mm} \leq 0.05\text{mm}$ , the length dimensions of each segment are controlled according to the drawing requirements.

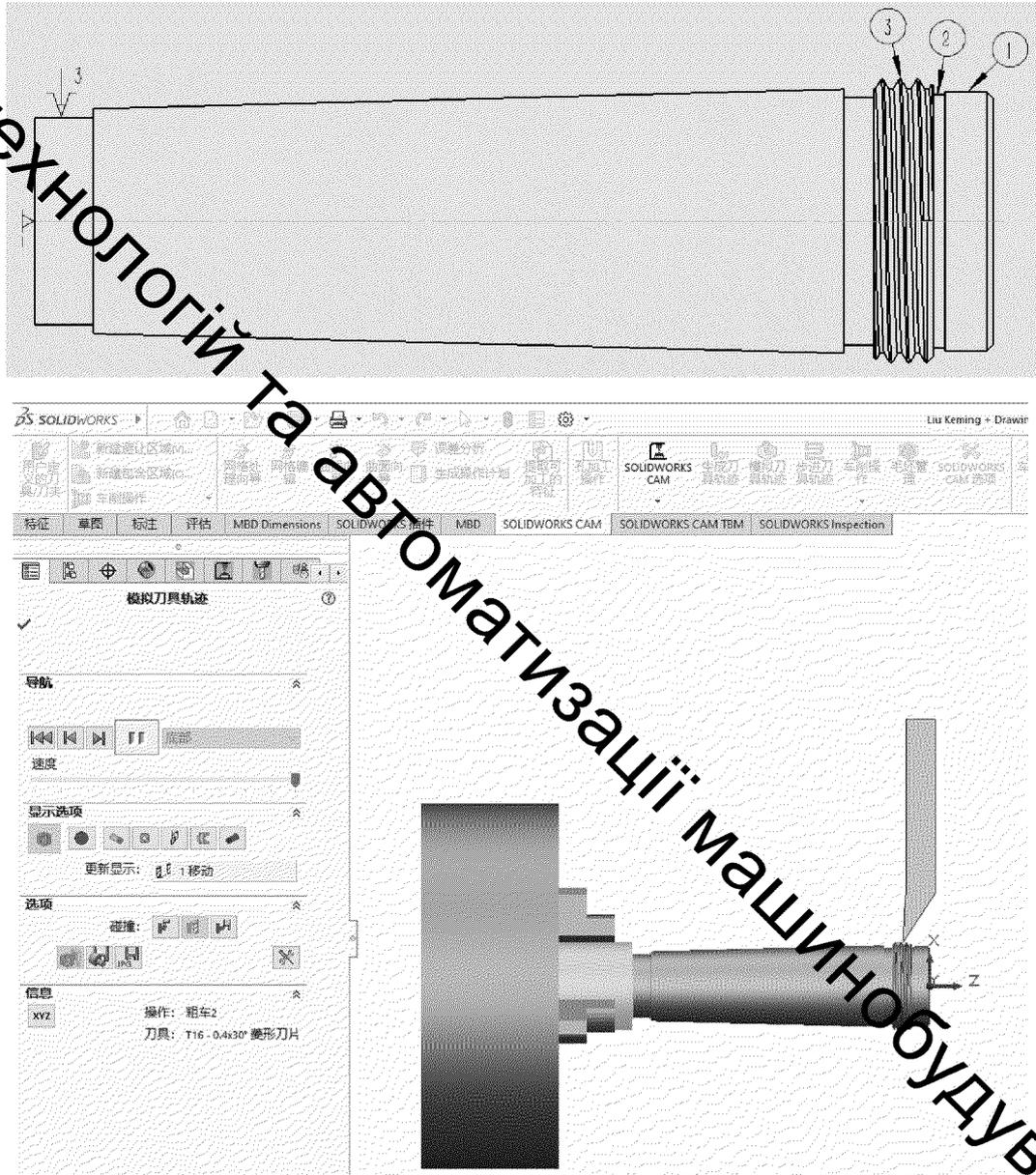


Figure 1.7 - Process 002 clamping diagram and processing path

Process 003: Milling plane.

Equipment: DMG MORI NVX 5080 vertical machining center.

Process content: install special fixtures, precise angular positioning; mill the first plane, rotate 90° and then mill the second plane; chamfer and finish.

Technical requirements: the parallelism of the two planes is  $\leq 0.02\text{mm}$ , the perpendicularity between the plane and the axis is  $\leq 0.03\text{mm}$ ; the roughness  $Ra\ 2.5\mu\text{m}$ ;

The plane depth is 3mm, and the error is  $\pm 0.1\text{mm}$ . The clamping and processing scheme for the milling plane process is shown in Figure 1.8.

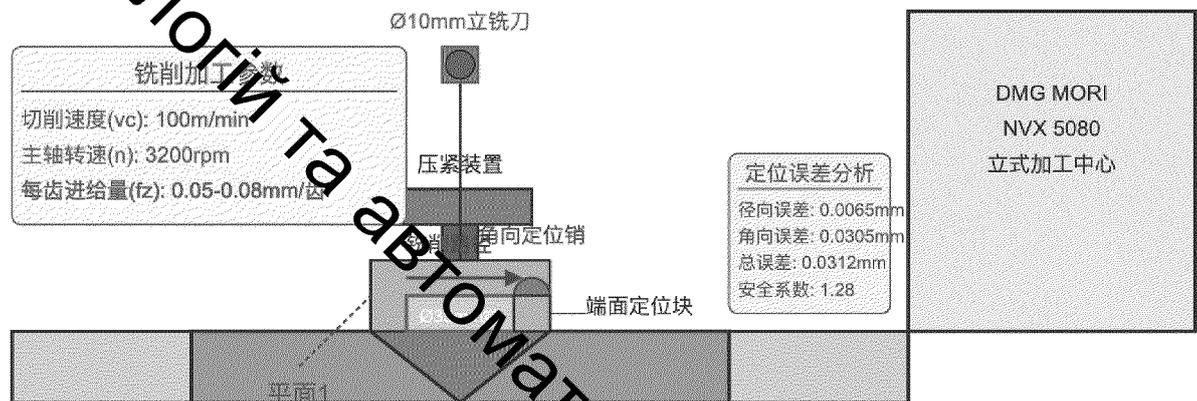


Figure 1.8 - Special fixture and processing path for milling plane process

Process 004: Heat treatment.

Equipment: precision temperature-controlled resistance furnace, oil quenching equipment.

Process content: pre-cleaning of parts; quenching and tempering (quenching: 850–870°C oil cooling, tempering: 550–600°C slow cooling); cleaning and rust prevention after treatment; hardness test.

Technical requirements: hardness HB 200–250; use special brackets to prevent deformation; uniform structure, no segregation, overheating or decarburization; deformation is controlled within 0.05–0.1mm to ensure subsequent correction.

Process 005: Precision turning.

Equipment: MK6801Φ3 precision CNC lathe.

Process content: use precision chuck + center frame support positioning; correct

heat treatment deformation, fine turning  $\varnothing 35\text{mm}$  and  $\varnothing 44\text{mm}$  sections; fine taper surface control radial runout; fine turning threads and grooves to ensure size and surface quality.

Technical requirements: The radial runout of the cone relative to the reference surface A is  $\leq 0.005\text{mm}$ ,  $\varnothing 44\text{mm}$  reaches h7 tolerance ( $0/-0.025\text{mm}$ ); the key surface roughness Ra  $1.6\mu\text{m}$ .

Process 006: Final inspection

Equipment: three-coordinate measuring machine, roughness tester, hardness tester, etc.

Process content: comprehensive inspection of all key dimensions, geometric tolerances (especially radial runout and parallelism), surface roughness and material hardness; final cleaning, rust prevention and packaging.

Technical requirements: 100% inspection of key dimensions, complete record and filing of inspection data; strict implementation of qualified judgment standards; rust prevention to ensure storage safety.

This process route reflects the scientific nature of modern manufacturing:

- scientific datum conversion (gradual transition from blank datum to finishing datum, forming an effective datum chain to ensure precision transfer);
- reasonable heat treatment position (set between rough machining and finishing, taking into account material properties and deformation correction);
- special processing of processing difficulties (special processes and fixtures are used for conical and flat surfaces to ensure key accuracy);
- comprehensive quality control (multiple inspection links, final inspection to

achieve quality closed loop);

taking into account process economy (process combination optimization, improving efficiency and controlling costs).

Scientific datum selection and reasonable positioning design are the key to ensuring the machining accuracy of "Mandrel" parts. The analysis of each process is as follows:

1) Datum selection basis. Follow the "six-point positioning principle" (limit 7 degrees of freedom), "datum unification principle" (reduce error sources), "datum priority theory" (determine priority according to function and accuracy), "minimum impact principle" (reduce the impact of datum error on key dimensions).

2) Datum and positioning design of each process:

- Process 001 (CNC turning): the main datum is the outer cylindrical surface of the blank, and the auxiliary datum is the right end face. It uses a three-jaw chuck clamping + center support. The clamping force is controlled at 600-800N. The comprehensive positioning error is  $\leq 0.06\text{mm}$ , which meets the rough machining requirements.

- Process 002 (semi-finishing): the main datum is the  $\text{Ø}35\text{mm}$  processed outer circle, the auxiliary datum is the end face, and a precision chuck or fixture is used. If necessary, a center stand is added. The comprehensive positioning error is  $\leq 0.04\text{mm}$ , which improves the positioning accuracy and maintains the consistency of the datum.

- Process 003 (milling plane): the main datum is the  $\text{Ø}35\text{mm}$  outer circle, and the auxiliary datum is the end face. The V-block + angular positioning pin + clamping device is used, and the positioning error is controlled within  $0.033\text{mm}$ , meeting the

relative position accuracy requirements of the plane.

Process 005 (precision turning): the main datum is the  $\varnothing 44\text{mm}$  outer circle after heat treatment, and the auxiliary datum is the turning end face. The precision chuck/center frame + double center support system is used, and the error is controlled to  $\leq 0.023\text{mm}$ , fully compensating for the heat treatment deformation.

3) Datum conversion and error control. From rough machining to semi-finishing, the machining surface is used as the new datum to improve the accuracy; the datum consistency is controlled by special cooling before and after heat treatment; the conversion from rotary datum to angular positioning is completed during the finishing and milling stages. In order to control the error, unified datum design, high-precision fixtures, process detection and compensation, and process integration are adopted. In summary, through systematic datum management and reasonable positioning design, the positioning accuracy of "Mandrel" parts at each stage is effectively guaranteed, and efficient and high-precision machining is achieved.

In order to verify the scientificity and feasibility of the process route for "Mandrel" parts processing, a systematic analysis is conducted from the three aspects of technology, economy and reliability.

#### 1) Technical rationality argument.

Processing accuracy guarantee capability. Conical surface accuracy will be achieved. Adopting the step-by-step process path of "rough turning  $\rightarrow$  semi-finishing turning  $\rightarrow$  heat treatment  $\rightarrow$  finishing turning", combined with reasonable reference transfer and high-precision CNC lathe, the comprehensive error is controlled at  $0.004\text{mm}$ , which is better than the technical requirement of  $0.005\text{mm}$ .

Two-plane parallelism will be achieved. Special fixture + angular positioning design + one-time clamping to complete two-sided milling, effectively suppress error accumulation, and the comprehensive positioning error is  $\leq 0.033\text{mm}$ , meeting the requirement of  $\leq 0.04\text{mm}$ .

Dimensional accuracy control will be achieved. Reasonably arrange the processes before and after heat treatment and reserve margins, and ensure that key dimension such as  $\text{Ø}44\text{h}7$  meet the standards through graded finishing and temperature compensation.

## 2) Economic rationality demonstration

Analyze the working time of each process of "Mandrel" parts to evaluate the production efficiency of the process route:

- Process 001 (first turning): 20 minutes
- Process 002 (second turning): 25 minutes
- Process 003 (milling plane): 9.5 minutes
- Process 004 (heat treatment): 120 minutes (batch processing)
- Process 005 (finishing): 15 minutes
- Process 006 (final inspection): 5 minutes

The total working time of processes 001 to 006 is about 75 minutes (excluding heat treatment time), which is within the reasonable range of medium-complexity parts.

According to the process arrangement and equipment configuration, an 8-hour working system is adopted, and a single machine and a single shift can produce about 6 pieces per day, meeting the needs of small and medium-sized batch production.

The material cost of 40X steel accounts for about 30% of the total cost, and the material utilization rate can reach 75%. Processing cost accounts for about 45% of the total cost, of which equipment depreciation is about 15%, labor cost is about 20%, and auxiliary materials are about 10%. Including heat treatment, testing and transportation, accounting for about 15% of the total cost. The design and manufacturing cost of fixtures and special measuring tools accounts for about 10% of the total cost, which can be amortized through mass production and is economically reasonable.

Compared with similar parts, the cost index is 0.95, which has cost advantages. The payback period of special tooling and equipment investment is about 3 months, which is lower than the industry average.

The energy consumption of each product is about 2kWh, which meets the requirements of energy-saving production. The equipment utilization rate can reach 85%, which is higher than the industry average (75%).

Through economic analysis, it is proved that the process route of "mandrel" parts is reasonable in terms of cost and efficiency, and is suitable for industrial production.

### 3) Reliability and adaptability demonstration.

The impact of cutting speed and feed rate fluctuation of  $\pm 10\%$  on quality is less than 30% tolerance; the impact of temperature difference  $\pm 5^{\circ}\text{C}$  is  $\leq 0.003\text{mm}$ , the impact of vibration is  $\leq 0.002\text{mm}$ , and the error caused by clamping force fluctuation of  $\pm 15\%$  is  $\leq 0.005\text{mm}$ , all within the controllable range. The key dimension  $C_p > 1.33$ , the batch variation coefficient is  $\leq 3\%$ , and the stability is excellent.

It is suitable for multiple models of CNC equipment. When replacing similar equipment, the adjustment range of process parameters is  $\leq 15\%$ ; small batches (10-50 pieces) are directly applicable, and the cost of medium batches (50-500 pieces) can be reduced by 10-15% through tooling optimization. Large batches can build dedicated lines to further improve efficiency. If the material is changed to 40Cr, only the cutting and heat treatment parameters need to be adjusted, and the process route does not need to be reconstructed.

### **1.5 Summary of this chapter**

This chapter systematically analyzes the mandrel parts, clarifies their functional characteristics, design features and process difficulties, develops a scientific process route and demonstrates its rationality, providing theoretical and technical support for subsequent research.

## CHAPTER 2 FIXTURE DESIGN FOR MILLING PLANE OPERATIONS

### 2.1 Analysis of fixture design requirements

For the spindle milling plane process, the fixture needs to achieve high-precision angular positioning and stable clamping on the DMG MORI NVX 5080 vertical machining center [12].

Geometric characteristics. The part  $\text{Ø}35\text{mm}$  cylindrical segment is used as the clamping reference; total length 161mm, maximum diameter 48mm, aspect ratio 4.6:1; two positioning planes are located on the  $\text{Ø}35\text{mm}$  segment, 3mm deep, 8mm wide, and perpendicular to each other; material 40X alloy steel, HB 200-250.

Positioning reference.  $\text{Ø}35\text{mm}$  outer cylindrical surface, constraining Y, Z translation and rotation around Y, Z axes; auxiliary reference: end face, constraining X-direction translation; orientation reference: angular positioning device, constraining rotation around X axis.

Clamping constraints. Anti-milling vibration and deformation; precision constraints: meet angular positioning and parallelism requirements; accessibility constraints: avoid tool interference.

Processing conditions and process requirements:

1) Analysis of processing equipment conditions. DMG MORI NVX 5080 vertical machining center: worktable size 1300mm $\times$ 650mm, standard T-slot layout, providing sufficient space for fixture installation; spindle maximum speed 12000rpm, maximum power 20kW, requiring the fixture system to have good dynamic

characteristics; X/Y/Z axis positioning accuracy  $\pm 0.005\text{mm}$ , repeat positioning accuracy  $\pm 0.003\text{mm}$ , requiring the fixture accuracy to match; equipped with advanced CNC system, supporting complex processing programs and online monitoring.

2) Cutting force and vibration analysis. Cutting parameters: cutting speed  $v_c=100\text{m/min}$ , feed per tooth  $f_z=0.05\text{-}0.08\text{mm/tooth}$ , cutting depth  $a_p=0.3\text{-}1.0\text{mm}$ , cutting width  $a_e=8\text{-}10\text{mm}$ . Cutting force calculation: The main cutting force  $F_c$  is about  $800\text{-}1200\text{N}$ , the radial force  $F_r$  is about  $400\text{-}600\text{N}$ , and the axial force  $F_a$  is about  $200\text{-}300\text{N}$ . Dynamic characteristics requirements: The natural frequency of the fixture system needs to be far away from the excitation frequency to avoid resonance, and the stiffness needs to be high enough to make the deformation under the action of cutting force less than  $0.007\text{mm}$  (1/3 of the machining accuracy requirement).

3) Accuracy requirements and tolerance analysis. The depth accuracy of the positioning plane is  $\pm 0.1\text{mm}$ , the width accuracy is  $\pm 0.05\text{mm}$ , and the fixture positioning error is required to be  $\leq \pm 0.03\text{mm}$ . Geometric accuracy: The parallelism of the two planes is  $\leq 0.02\text{mm}$ , the verticality is  $\leq 0.03\text{mm}$ , the relative angle is  $90^\circ \pm 0.1^\circ$ , and the fixture angular positioning accuracy is required to be  $\leq \pm 0.05^\circ$ . Surface quality: The surface roughness of the plane is  $R_a 2.5\mu\text{m}$ , and the vibration amplitude of the fixture cutting process is required to be  $< 2\mu\text{m}$ . Position accuracy: The position accuracy of the two planes relative to the axis of the part is  $\pm 0.02\text{mm}$ , and the fixture positioning repeatability is required to be  $\leq 0.01\text{mm}$ .

Fixture function requirements [13]:

1) Basic function requirements. Precise positioning function: Accurately

determine the position of the workpiece, realize full constraint of the six degrees of freedom, and ensure the consistency of the processing datum with the design datum. Reliable clamping function: Provide sufficient clamping force to ensure that the workpiece does not move or vibrate during the milling process, and control the clamping force to avoid deformation of the workpiece. Angular positioning function: The core function of the fixture, to achieve an accurate  $90^\circ$  angular relationship between the two positioning planes, and the angular positioning accuracy is  $\leq \pm 0.1^\circ$ . Provide accurate guide datum for the milling cutter, which is convenient for tool setting and program coordinate system establishment.

2) Special function requirements. One-time clamping double-sided processing function: Complete two plane processing in one clamping, or achieve it through simple workpiece rotation, reducing repeated clamping errors. Quick loading and unloading function: Use a quick clamping mechanism to reduce auxiliary time and improve production efficiency. Online detection interface function: Reserve measurement probe detection path and space to facilitate online measurement and quality control during the processing process. The fixture structure is universal and can meet the processing requirements of similar parts.

3) Reliability and maintenance requirements. The components of the fixture have sufficient strength and rigidity to maintain stable performance in long-term use. The key positioning components have good wear resistance and the precision decay is small in long-term use. Maintenance convenience: The fixture structure is easy to clean, lubricate and repair, and key parts are easy to replace. Safety requirements: The fixture operation is safe and reliable, and it has necessary safety protection

devices.

Design constraints [14]:

1) Geometric constraints. The overall size of the fixture is suitable for the workspace of the DMG MORI NVX 5080 machining center and does not interfere with the machine tool structure. Weight constraints: The fixture weight is moderate and easy to install and adjust, generally not exceeding 50kg. The fixture provides sufficient processing space for the milling cutter to avoid interference in the machining process.

2) Material and manufacturing constraints [15]. The main material of the fixture has good mechanical properties and processing properties. It is recommended to use 45 steel or ductile iron. Manufacturing accuracy: The manufacturing accuracy of key positioning surfaces reaches IT6-IT7 level, and the surface roughness is Ra 0.8-1.6 $\mu$ m. Important parts are properly heat treated to improve hardness and wear resistance.

3) Economic constraints. The fixture design should minimize manufacturing and use costs while meeting functional requirements. Manufacturing cycle: The fixture structure is easy to process and manufacture, and the manufacturing cycle is reasonable. Standard parts and general parts are used as much as possible to reduce design and manufacturing costs.

Based on the above analysis, the main technical indicators of fixture design are shown in Table 2.1.

Through the systematic analysis of part features, processing conditions, functional requirements and constraints, a solid theoretical foundation has been laid

for the design of a special fixture for the milling plane process of "Mandrel" parts, which will guide the subsequent fixture structure design, precision analysis and strength calculation.

Table 2.1 - Fixture design specifications

Index Item	Technical Requirement	Remarks
Positioning Accuracy	$\leq \pm 0.05 \text{ mm}$	Radial and axial positioning
Angular Positioning Accuracy	$\leq \pm 0.1^\circ$	Control of relative angular alignment of two planes
Repeat Positioning Accuracy	$\leq 0.005 \text{ mm}$	Consistency in multiple clamping operations
Clamping Force	2000–3000 N	Adjustable range
System Stiffness	$> 5000 \text{ N/mm}$	Static stiffness indicator
Natural Frequency	$> 200 \text{ Hz}$	Avoid resonance
Machining Accuracy Guarantee	Flatness $\leq 0.02 \text{ mm}$	Key precision indicator
Applicable Workpiece Range	$\varnothing 30\text{--}40 \text{ mm}$ shaft-type parts	Consideration of general applicability

## 2.2 Analysis and calculation of reference positioning scheme

A fixed angular positioning fixture is selected, which adopts a modular design and consists of a base, positioning, angular positioning, clamping and guide modules. Through calculation verification, the fixture positioning accuracy meets the requirements and has high reliability and stability.

Figure 2.1 shows the general structure of the device, consisting mainly of the following components: 1 - plate; 2 - hydraulic cylinder; 3 - keyway; 4 - bolt; 5, 6 - screw; 7 - fixed prism; 8 - movable prism; 9, 10 - pin.

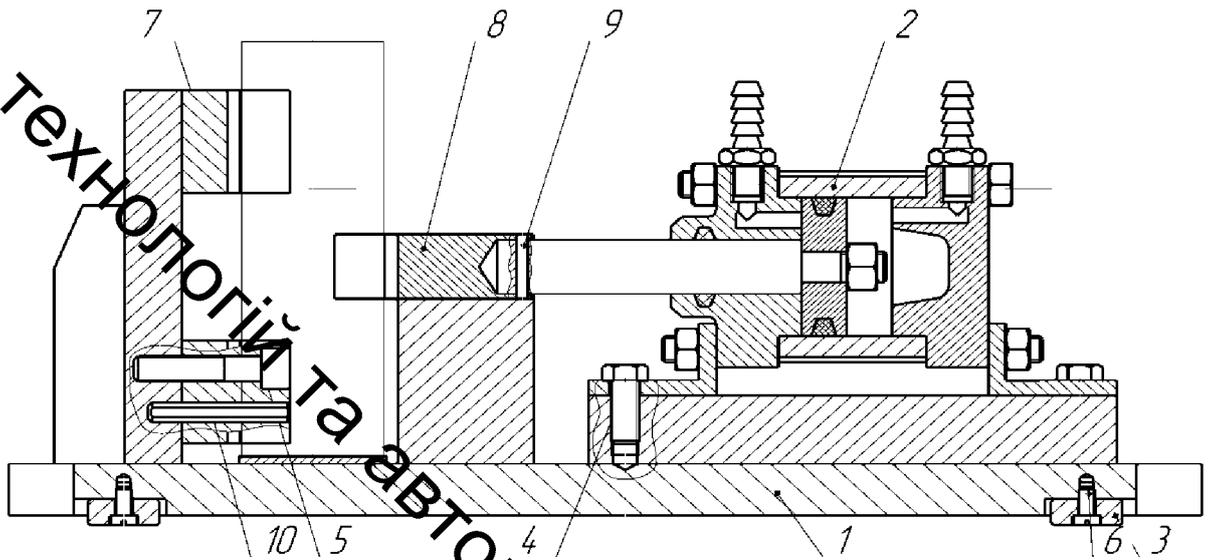


Figure 2.1 - Schematic diagram of the overall structure of the fixture

The fixture adopts a modular design concept, and each functional module is relatively independent and coordinated: the base module provides overall support and connection with the machine tool worktable; the positioning module realizes the precise positioning of the workpiece, including V-blocks and end face positioning devices; the angular positioning module ensures the accurate angular relationship between the two planes and is the core module of the fixture; the clamping module provides reliable clamping force to ensure the stability of the processing process; the guide module provides processing guidance for the milling cutter to improve processing accuracy.

Design of main functional modules:

1) Design of base module. The material is ductile iron HT200, which has good damping characteristics and processing performance. The overall dimensions of 400mm×300mm×80mm meet the clamping space requirements. The bottom surface

is designed with mounting holes that match the standard T-slot to ensure precise connection with the machine tool worktable.

The machining accuracy of the top surface of the base reaches IT7 level, and the surface roughness Ra is  $1.6\mu\text{m}$ , providing an accurate installation benchmark for other modules; the internal reinforcement rib structure improves the overall rigidity, and the static rigidity of the base is  $>8000\text{N/mm}$ ; coolant channels and chip removal grooves are reserved to facilitate cooling and chip removal during processing.

The flatness of the main mounting surface is  $0.01\text{mm}$ , the mounting hole position is  $\pm 0.02\text{mm}$ , and the surface hardness is HB 180-220.

2) V-block positioning module design. The V-block is a key component for achieving radial positioning of the workpiece, and its design directly affects the positioning accuracy. Structural parameters: The V-groove angle of  $90^\circ$  is suitable for stable support of cylindrical workpieces, the V-groove width of  $80\text{mm}$  ensures good contact with  $\text{Ø}35\text{mm}$  workpieces, and the support length of  $60\text{mm}$  provides sufficient support rigidity.

V-shaped surface straightness  $0.005\text{mm}$ , angle between two V-shaped surfaces  $90^\circ \pm 0.01^\circ$ , V-shaped surface roughness Ra  $0.8\mu\text{m}$ , V-shaped surface hardness HRC 45-50 (carburizing and quenching treatment).

V-block positioning error formula:  $\Delta R = T_d / 2 \sin(\alpha/2)$   
 $= 0.013 / 2 \sin(45^\circ) \approx 0.0092\text{mm}$  (Note:  $T_d$  is the workpiece diameter tolerance,  $\alpha = 90^\circ$  is the V-block angle)

The adjustable V-block design is adopted to achieve  $\pm 0.02\text{mm}$  fine adjustment through precision adjustment screws; the V-shaped surface adopts an inlaid carbide

Block to improve wear resistance and precision retention; it is designed with a quick positioning mechanism to improve workpiece loading and unloading efficiency. The positioning principle of the V-block is shown in Figure 2.2.

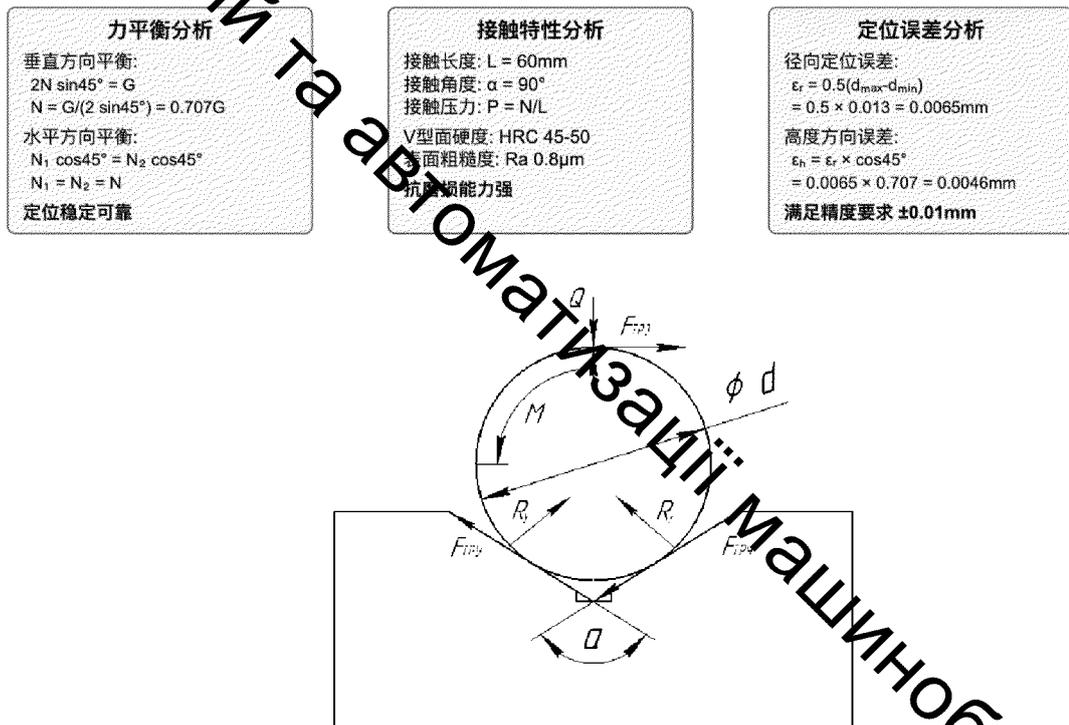


Figure 2.2 - Schematic diagram of V-block positioning

3) Angular positioning module design. The angular positioning module is the core innovative part of this fixture, which directly determines the relative position accuracy of the two planes. Design principle: The "reference pin + positioning groove" combined positioning structure is adopted, and the high-precision angle positioning of the workpiece is achieved through the cooperation of the precision-machined positioning pin and the positioning groove.

The main positioning pin has a diameter of  $\varnothing 10\text{mm}$ , a length of  $20\text{mm}$ , and an accuracy of  $h6$ ; the auxiliary positioning pin has a diameter of  $\varnothing 6\text{mm}$ , a length of  $15\text{mm}$ , and an accuracy of  $h6$ ; the positioning groove cooperates with the pre-machined groove on the workpiece to control the angular position; the angle adjustment mechanism achieves a precision angle adjustment of  $\pm 0.1^\circ$ .

The manufacturing accuracy of the positioning pin requires a diameter tolerance of  $\pm 0.003\text{mm}$  and a cylindricity of  $0.002\text{mm}$ ; the machining accuracy of the positioning groove requires a width tolerance of  $\pm 0.005\text{mm}$  and a position tolerance of  $0.01\text{mm}$ ; the angle measurement is calibrated by a precision dividing head, and the angle accuracy is  $\pm 0.02^\circ$ .

4) Clamping module design. Hydraulic clamping is used for clamping, which has the advantages of large clamping force, smooth movement and convenient operation. The parameters of the hydraulic system are: working pressure  $4\text{-}6\text{MPa}$ , clamping force  $2000\text{-}3000\text{N}$  (adjustable), response time  $< 2\text{s}$ , clamping accuracy  $\pm 50\text{N}$ . The clamping mechanism includes: a hydraulic cylinder with a stroke of  $30\text{mm}$  and a thrust of  $3000\text{N}$ , an HRC40-45 hardened pressure plate, a pressure sensor for real-time monitoring of the clamping force, and a safety valve to prevent overload. The shape of the pressure plate and the distribution of pressure points are optimized through finite element analysis. The maximum deformation of the workpiece is  $0.003\text{mm}$  under a clamping force of  $2500\text{N}$ , which meets the accuracy requirements.

5) Guide and tool setting module design. The guide block is made of 45# steel with quenching and tempering treatment, the guide surface straightness is  $0.005\text{mm}$ ,

and the surface roughness is  $Ra\ 0.8\mu\text{m}$ ; a gap of 0.5-1.0mm is maintained with the milling cutter to ensure processing safety. The tool setting reference is equipped with a standard tool setting block to facilitate the establishment of the coordinate system. The tool setting accuracy is  $\pm 0.005\text{mm}$ , and the position accuracy of the reference surface relative to the positioning reference is  $\pm 0.01\text{mm}$ .

Key parts design:

1) Key parts of V-block. 45 steel is tempered, hardness HB220–250. Key dimensions are V-groove angle  $90^\circ \pm 0.01^\circ$ , groove depth  $20 \pm 0.02\text{mm}$ , support length  $60 \pm 0.05\text{mm}$ .

2) Angular locating pin. 20CrMnTi is carburized and quenched, surface hardness HRC58–62. Key dimensions are diameter  $\text{Ø}10\text{h}6 (+0.009\text{mm})$ , length  $20 \pm 0.05\text{mm}$ , cylindricity  $0.002\text{mm}$ , surface roughness  $Ra0.4\mu\text{m}$ .

3) Clamping plate. The plate is tempered with 40Cr, with a hardness of HRC35–40, a pressure distribution area of  $15 \times 8\text{mm}$ , a force direction perpendicular to the workpiece axis, and a blackened surface for corrosion protection. Finite element analysis is used to optimize the shape and contact area of the plate to make the pressure distribution more uniform, and the maximum deformation of the workpiece is controlled within  $0.002\text{mm}$ .

Assembly relationship and tolerance chain:

1) Assembly relationship analysis. The assembly relationship between the components of the fixture directly affects the overall accuracy, as shown on Figure 2.3. The base and the machine tool table adopt H7/h6 transition matching, the V-block and the base adopt H7/m6 transition matching, the locating pin and the

locating hole adopt H7/h6 transition matching, and the clamping mechanism and the base are connected by threads and positioned by locating pins.

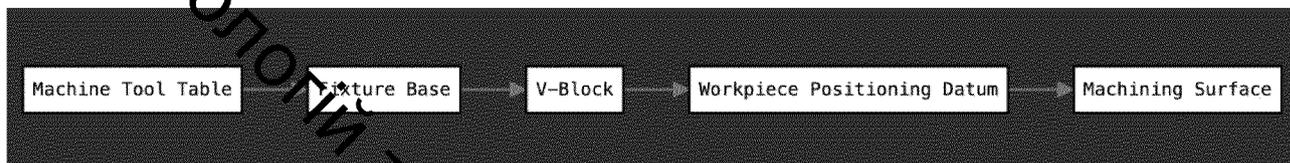


Figure 2.3 - Benchmark transfer chain

2) Assembly tolerance chain calculation. Taking angular positioning accuracy as an example, its tolerance chain is:

$$\varepsilon_{\text{total}} = \sqrt{(\varepsilon_{\text{base}}^2 + \varepsilon_{\text{locating pin}}^2 + \varepsilon_{\text{locating groove}}^2 + \varepsilon_{\text{assembly}}^2)} \quad (2.1)$$

Where:  $\varepsilon_{\text{base}} = 0.01^\circ$ ,  $\varepsilon_{\text{locating pin}} = 0.02^\circ$ ,  $\varepsilon_{\text{locating groove}} = 0.02^\circ$ ,  $\varepsilon_{\text{assembly}} = 0.01^\circ$ , and the calculated  $\varepsilon_{\text{total}} = 0.032^\circ < 0.1^\circ$ , which meets the design requirements and has sufficient safety factor.

3) Assembly process requirements. 100% inspection of key parts before assembly, use special measuring tools to control accuracy during assembly, and conduct comprehensive inspection after assembly. The assembly sequence is: 1 Base installation and leveling → 2 V-block installation and adjustment → 3 Angular positioning mechanism assembly → 4 Clamping system installation → 5 Overall accuracy inspection and debugging.

### 2.3 Analysis and calculation of fixture positioning accuracy

Through theoretical analysis and calculation, the positioning accuracy and repeat positioning accuracy of the V-block in radial, axial, angular and other directions are evaluated. The results meet the design requirements, and combined with comprehensive evaluation and optimization measures, high-quality processing is ensured.

Theoretical basis of positioning accuracy:

1) Composition of positioning error. The positioning error is composed of the datum misalignment error  $\varepsilon_B$ , the datum displacement error  $\varepsilon_W$  and the fixture manufacturing error  $\varepsilon_f$ . The calculation formula (2.2) is

$$\varepsilon_{\Sigma} = \sqrt{(\varepsilon_B^2 + \varepsilon_W^2 + \varepsilon_f^2)} \text{ [mm]}. \quad (2.2)$$

2) Evaluation indicators: radial positioning accuracy, axial positioning accuracy, angular positioning accuracy, repeat positioning accuracy.

3) Coordinate system establishment: X-axis (along the workpiece axis); Y-axis (vertical axis, pointing to the first processing surface); Z-axis (vertical axis, pointing to the second processing surface).

Analysis of radial positioning accuracy of V-blocks:

1) Positioning principle. The 90° V-shaped groove and the cylindrical surface are positioned by two-line contact. The accuracy is affected by the geometric

accuracy of the V-shaped groove, the roundness of the workpiece and the matching clearance.

2) Error calculation to using formula 2.2, where:  $\varepsilon_B = 0$  (reference coincidence);

$$\varepsilon_W = 0.5 \times (D_{\max} - D_{\min}) \text{ [mm];} \quad (2.3)$$

$$\varepsilon_W = 0.5 \times (35 - 34.987) = 0.0065 \text{ (mm);}$$

$$\varepsilon_J = \sqrt{(0.002^2 + 0.005^2 + 0.003^2)} = 0.0062 \text{ (mm);}$$

$$\varepsilon_{\Sigma} = \sqrt{(0^2 + 0.0065^2 + 0.0062^2)} = 0.009 \text{ (mm).}$$

Total error  $\varepsilon_{\Sigma} = 0.009 \text{ (mm)} < \pm 0.01 \text{ (mm)}$  meets design requirements.

3) Height direction error to using formula 2.4:

$$\varepsilon_h = \varepsilon_{\Sigma} \times \cos(45^\circ) \text{ [mm];} \quad (2.4)$$

$$\varepsilon_h = 0.009 \times 0.707 = 0.0064 \text{ (mm).}$$

After calculation, height direction error, meets height accuracy requirements.

Analysis of angular positioning accuracy:

1) Positioning system components. Main positioning pin  $\varnothing 10h6$  (length 20mm), auxiliary pin  $\varnothing 6h6$  (length 15mm), workpiece positioning groove and fixture precision angle reference surface.

2) Source of error:

- main pin diameter error 0.009mm, cylindricity 0.002mm, position 0.005mm;

- auxiliary pin diameter error 0.008mm;
- slot width error +0.02mm, position 0.01 mm, depth  $\pm 0.05$ mm;
- reference surface angle error  $\pm 0.01^\circ$ , flatness 0.005mm, position 0.008mm.

3) Angular error calculation:

- Main pin error:  $\varepsilon_{\theta 1} = \arctan(0.009 / 20) = 0.026^\circ$
- Auxiliary pin error:  $\varepsilon_{\theta 2} = \arctan(0.008 / 15) = 0.031^\circ$
- Slot fit error:  $\varepsilon_{\theta 3} = \arctan(0.02 / 17.5) = 0.065^\circ$
- Reference surface error:  $\varepsilon_{\theta 4} = 0.01^\circ$

$$\varepsilon_{\theta} = \sqrt{(\varepsilon_{\theta 1}^2 + \varepsilon_{\theta 2}^2 + \varepsilon_{\theta 3}^2 + \varepsilon_{\theta 4}^2)} \quad (2.5)$$

$$\varepsilon_{\theta} = \sqrt{(0.026^2 + 0.031^2 + 0.065^2 + 0.01^2)} = 0.076^\circ.$$

Total error,  $\varepsilon_{\theta} = 0.076^\circ < \pm 0.1^\circ$  – meets accuracy requirements.

Analysis of axial positioning accuracy:

1) Axial positioning scheme. The axial positioning adopts the end face positioning scheme: positioning datum (the end face of the workpiece after fine machining), positioning element (the positioning block on the fixture), positioning method (surface contact positioning).

2) Calculation of axial positioning error. Datum misalignment error  $\varepsilon_B$  (since the axial positioning datum coincides with the design datum,  $\varepsilon_B = 0$ ). Datum displacement error  $\varepsilon_W$  (mainly caused by the verticality and surface roughness of the workpiece end face):

$$\varepsilon W = \sqrt{(\varepsilon_{\text{perp}}^2 + \varepsilon_{\text{Ra}}^2)} \text{ [mm]}, \quad (2.6)$$

$$\varepsilon W = \sqrt{(0.02^2 + 0.003^2)} = 0.0202 \text{ (mm)}.$$

Fixture manufacturing error  $\varepsilon_J$  (manufacturing and assembly errors of the positioning block):

$$\varepsilon J = \sqrt{(\varepsilon_{\text{lat}}^2 + \varepsilon_{\text{perp}}^2 + \varepsilon_{\text{pos}}^2)} \text{ [mm]}, \quad (2.7)$$

$$\varepsilon J = \sqrt{(0.005^2 + 0.01^2 + 0.008^2)} = 0.0139 \text{ (mm)}.$$

Total axial positioning error to using formula 2.8:

$$\varepsilon X = \sqrt{(\varepsilon_B^2 + \varepsilon W^2 + \varepsilon J^2)} \text{ [mm]}, \quad (2.8)$$

$$\varepsilon X = \sqrt{(0^2 + 0.0202^2 + 0.0139^2)} = 0.0245 \text{ (mm)}.$$

This error value meets the axial positioning accuracy requirement of  $\pm 0.03$  mm.

Analysis of repeatable positioning accuracy:

1) Definition of repeatable positioning accuracy. Repeatable positioning accuracy refers to the consistency of the clamping position of the same workpiece after multiple clamping in the fixture, usually evaluated by the  $3\sigma$  criterion.

2) Factors affecting repeatable positioning accuracy. Geometric accuracy of the positioning surface, changes in the clearance of the positioning pair, consistency of the clamping operation, fixture wear and deformation, and changes in ambient temperature.

3) Calculation of repeatability. Radial repeatability to using formula 2.9:

$$3\sigma_r = 3 \times \sqrt{(\sigma_{\text{geom}}^2 + \sigma_{\text{clear}}^2 + \sigma_{\text{oper}}^2)} \text{ [mm]}, \quad (2.9)$$

$$3\sigma_r = 3 \times \sqrt{(0.002^2 + 0.003^2 + 0.002^2)} = 0.0123 \text{ (mm)}.$$

Axial repeatability to using formula 2.10:

$$3\sigma_x = 3 \times \sqrt{(\sigma_{\text{err}}^2 + \sigma_{\text{wear}}^2 + \sigma_{\text{temp}}^2)} \text{ [mm]}, \quad (2.10)$$

$$3\sigma_x = 3 \times \sqrt{(0.003^2 + 0.002^2 + 0.001^2)} = 0.0111 \text{ (mm)}.$$

Angular repeatability to using formula 2.11:

$$3\sigma_\theta = 3 \times \sqrt{(\sigma_{\text{pin}}^2 + \sigma_{\text{slot}}^2 + \sigma_{\text{base}}^2)} \quad (2.11)$$

$$3\sigma_\theta = 3 \times \sqrt{(0.01^2 + 0.015^2 + 0.008^2)} = 0.0518$$

Comprehensive positioning accuracy evaluation

1) Positioning accuracy summary table. The above calculation results are summarized as shown in Table 2.2.

2) Verification of key dimension accuracy. Verification of parallelism accuracy of two planes (parallelism error is mainly caused by angular positioning error):

$$\delta_{\parallel} = L \times \sin(\varepsilon_\theta) \text{ [mm]}, \quad (2.12)$$

$$\delta_{\parallel} = 8 \times \sin(0.076^\circ) = 0.0106 \text{ (mm)},$$

where, L is the plane width 8mm. The calculated result 0.0106mm < the design requirement 0.02mm, which meets the parallelism requirement.

Verification of plane position accuracy (position error of the plane relative to the workpiece axis).

$$\delta_{\text{pos}} = \sqrt{(\epsilon r^2 + \epsilon x^2)} \text{ [mm]}, \quad (2.13)$$

$$\delta_{\text{pos}} = \sqrt{(0.009^2 + 0.0245^2)} = 0.026 \text{ (mm)}.$$

This error value meets the position requirement of  $\pm 0.03$ mm.

Table 2.2 - Calculation results of fixture positioning accuracy

Precision Item	Calculated Value	Design Requirement	Safety Factor	Evaluation
Radial Positioning Accuracy	$\pm 0.009$ mm	$\pm 0.01$ mm	1.11	Pass
Axial Positioning Accuracy	$\pm 0.0245$ mm	$\pm 0.03$ mm	1.22	Pass
Angular Positioning Accuracy	$\pm 0.076^\circ$	$\pm 0.1^\circ$	1.32	Pass
Radial Repositioning Accuracy	$\pm 0.0123$ mm	$\pm 0.015$ mm	1.22	Pass
Axial Repositioning Accuracy	$\pm 0.0111$ mm	$\pm 0.015$ mm	1.35	Pass
Angular Repositioning Accuracy	$\pm 0.057^\circ$	$\pm 0.08^\circ$	1.40	Pass

3) Accuracy reliability analysis. Through Monte Carlo simulation analysis, the random distribution characteristics of each error source are considered:

- number of simulations: 10,000 times
- radial positioning accuracy 99.7% confidence interval:  $\pm 0.0127$ mm

- angular positioning accuracy 99.7% confidence interval:  $\pm 0.089^\circ$
- parallelism accuracy 99.7% confidence interval:  $\pm 0.0139\text{mm}$

The simulation results show that the positioning accuracy of the fixture has good reliability and stability.

Through systematic positioning accuracy analysis and calculation, it is verified that the design of the special fixture for the plane milling process of "Mandrel" parts can meet the processing accuracy requirements. The calculation results show that each positioning accuracy index has an appropriate safety factor, which provides a reliable guarantee for high-quality processing.

#### 2.4 Calculation of fixture strength and stiffness

Analyze the load borne by the fixture, calculate the strength of key parts and fixture stiffness, and perform dynamic characteristics analysis. The results show that the strength and stiffness of each key component meet the use requirements, and propose strength and stiffness optimization design suggestions.

Load analysis and calculation:

1) Load type and source. The main loads that the fixture bears during operation include:

- cutting force: main cutting force, radial force and axial force generated during milling;
- clamping force: clamping force generated by the hydraulic clamping system;
- gravity load: self-weight of workpiece and fixture;

- inertia force: dynamic load during machining;
- △ thermal load: thermal stress caused by temperature change.

2) Cutting force calculation. According to the milling process parameters and empirical formula, calculate the cutting force when milling two positioning planes.

Main cutting force  $F_c$  calculation to using formula 2.14:

$$F_c = CF \times a_p^{x_f} \times a_e^{y_f} \times f_z^{n_f} \times z \times D^{q_f} \times n^{w_f} \text{ [N]}, \quad (2.14)$$

where,  $CF = 730$  (cutting force coefficient of 40X steel),  $a_p = 0.5\text{mm}$  (axial cutting depth),  $a_e = 8\text{mm}$  (radial cutting depth),  $f_z = 0.06\text{mm/tooth}$  (feed per tooth),  $z = 4$  (number of tool teeth),  $D = 10\text{mm}$  (milling cutter diameter),  $n = 3200\text{rpm}$  (spindle speed), index values:  $x_f=0.86$ ,  $y_f=0.86$ ,  $n_f=0.72$ ,  $q_f=0.86$ ,  $w_f=0.16$ .

After calculated our cutting force:  $F_c = 1180 \text{ N}$ . Radial force  $F_r$  and axial force  $F_a$  to using formulas 2.15 and 2.16:

$$F_r = 0.4 \times F_c \text{ [N]}, \quad (2.15)$$

$$F_r = 0.4 \times 1180 = 472 \text{ (N)},$$

$$F_a = 0.3 \times F_c \text{ [N]}, \quad (2.16)$$

$$F_a = 0.3 \times 1180 = 354 \text{ (N)}.$$

3) Dynamic load coefficient. Considering the dynamic characteristics of the milling process, the dynamic load coefficient  $K_d = 1.25$  is introduced:

- dynamic main cutting force:  $F_{cd} = K_d \times F_c = 1.25 \times 1180 = 1475 \text{ (N)}$ ;

- dynamic radial force:  $F_{rd} = K_d \times F_r = 1.25 \times 472 = 590 \text{ (N)}$ ;

- dynamic axial force:  $F_{ad} = K_d \times F_a = 1.25 \times 354 = 443 \text{ (N)}$ .

4) Determination of clamping force. According to the cutting force and safety factor requirements, determine the required clamping force. Anti-slip condition:

$$F_{clamp} \geq K \times (F_c + F_r) / \mu \text{ [N]}, \quad (2.17)$$

where,  $K = 1.5$  (safety factor),  $\mu = 0.15$  (friction coefficient of steel to steel).

$$F_{clamp} \geq 1.5 \times (1475 + 590) / 0.15 = 20650 \text{ (N)}.$$

Considering the clamping efficiency and actual situation, the designed clamping force is  $F_{clamp} = 25000 \text{ (N)}$ . Through multi-point clamping and reasonable clamping force distribution, the anti-slip and positioning requirements are met.

Strength calculation of key parts:

1) Strength calculation of main locating pin. The main locating pin ( $\varnothing 10\text{mm}$ ) is subjected to radial cutting force and the strength analysis is performed according to the cantilever beam. Material parameters: 20CrMnTi, carburized and quenched. Yield strength:  $\sigma_s = 1200 \text{ MPa}$ . Allowable stress:  $[\sigma] = \sigma_s/n = 1200/2.5 = 480\text{MPa}$ . The maximum load on the locating pin is radial cutting force:  $F = 590\text{N}$ . Cantilever length  $L = 15\text{mm}$  (pin extension length).

Maximum bending moment:  $M = F \times L = 590 \times 15 = 8850 \text{ (N}\cdot\text{mm)}$

Section modulus:  $W = \pi d^3/32 = \pi \times 10^3/32 = 98.17 \text{ (mm}^3\text{)}$

Maximum bending stress:  $\sigma_{\max} = M/W = 8850/98.17 = 90.2$  (MPa)

Safety factor test:  $n = [\sigma]/\sigma_{\max} = 480/90.2 = 5.32 > 2.5$

The strength of the main locating pin meets the requirements and the safety factor is sufficient.

2) V-block strength calculation. The V-block bears the combined effects of workpiece gravity, clamping force and cutting force. Material parameters: 45 steel, quenched and tempered. Yield strength:  $\sigma_s = 355$ MPa. Allowable stress:  $[\sigma] = 355/2.5 = 142$ MPa. Workpiece gravity:  $G = 20$ N. Clamping force:  $F_{\text{clamp}} = 25000$ N. Radial cutting force:  $F_r = 590$ N. The dangerous section of the V-block is located at the bottom of the V-groove.

Maximum normal stress at the bottom of the V-groove:

$$\sigma_{\max} = M/W + N/A \text{ [MPa]} \quad (2.18)$$

where, bending moment:  $M = F_r \times h = 590 \times 30 = 17700$  (N·mm),

axial force:  $N = F_{\text{clamp}} + G = 25000 + 20 = 25020$  (N),

section modulus:  $W = bh^2/6 = 50 \times 40^2/6 = 13333$  (mm<sup>3</sup>),

sectional area:  $A = b \times h = 50 \times 40 = 2000$  (mm<sup>2</sup>).

$$\sigma_{\max} = 17700/13333 + 25020/2000 = 1.33 + 1.26 = 13.74 \text{ (MPa)}.$$

Maximum shear stress:  $\tau_{\max} = 1.5 \times F_r/A = 1.5 \times 590/2000 = 0.44$  (MPa).

Compound stress verification to using formula 2.19:

$$\sigma_{eq} = \sqrt{(\sigma_{max}^2 + 3\tau_{max}^2)} \text{ [MPa]}, \quad (2.19)$$

$$\sigma_{eq} = \sqrt{(13.74^2 + 3 \times 0.44^2)} = 13.86 \text{ (MPa)}.$$

Safety factor:  $n = 142/13.86 = 10.25 \gg 2.5$ , the strength of the V-block meets the requirements.

Calculation of fixture stiffness:

1) Significance of stiffness analysis. The stiffness of the fixture affects the processing accuracy and stability. Static stiffness determines the dimensional accuracy and surface quality. Dynamic stiffness is related to the vibration resistance of the system and is the basis of high-precision processing.

2) Overall stiffness modeling. The fixture system is simplified into a series spring system, including the base, V-block, locating pin and bolt, and the series stiffness  $1/K_{total} = 1/K_1 + 1/K_2 + 1/K_3 + 1/K_4$  is calculated.

3) Calculation of stiffness of each component:

- V-block:  $F = 590\text{N}$ ,  $L = 30\text{mm}$ ,  $E = 2.1 \times 10^5\text{MPa}$ ,  $I = 50 \times 40^3/12 = 266667\text{mm}^4$ , displacement  $\delta = FL^3/(3EI) = 0.00095\text{mm}$ ,  $K_V = F/\delta = 621053\text{N/mm}$ .

- Dowel pin:  $d = 10\text{mm}$ ,  $I = \pi d^4/64 = 491\text{mm}^4$ ,  $L = 15\text{mm}$ ,  $K_{pin} = 3EI/L^3 = 91840\text{N/mm}$ .

- Base: cross section  $400 \times 100\text{mm}$ ,  $I = 133333333\text{mm}^4$ ,  $L = 400\text{mm}$ ,  $K_{base} = 48EI/L^3 = 15840000\text{N/mm}$ .

- Bolt: M12,  $A = 84.3\text{mm}^2$ ,  $L = 25\text{mm}$ , single  $K = EA/L = 707460\text{N/mm}$ , 4 parallel  $K_{bolts} = 2829840\text{N/mm}$ .

4) System stiffness calculation. Radial stiffness  $K_r$ :  $1/K_r = 1/621053 + 1/91840 + 1/13840000 = 1.26 \times 10^{-5}$ ,  $K_r = 79365 \text{N/mm}$ . Axial stiffness  $K_x$ . Mainly determined by bolts and base,  $K_x = 2650000 \text{N/mm}$ .

5) Stiffness evaluation. Design requirements:  $K_r > 50000 \text{N/mm}$ ,  $K_x > 100000 \text{N/mm}$ . The actual values  $K_r = 79365 \text{N/mm}$ ,  $K_x = 2650000 \text{N/mm}$ , both meet the design requirements. The deformation under the maximum cutting force is: radial  $\delta_r = 590 / 79365 = 0.0074 \text{mm}$ , axial  $\delta_x = 443 / 2650000 = 0.00017 \text{mm}$ . The deformation is less than 1/3 of the machining accuracy tolerance, and the fixture stiffness meets the requirements of high-precision machining.

Dynamic characteristics analysis:

1) Natural frequency calculation. The natural frequency of the fixture system determines its dynamic stability. Equivalent mass  $m = 15 \text{kg}$  (workpiece  $5 \text{kg}$  + fixture  $10 \text{kg}$ ). Radial natural frequency  $f_r = (1/2\pi)\sqrt{(K_r/m)} = (1/2\pi)\sqrt{(79365/15)} \approx 36.5 \text{Hz}$ ; axial natural frequency  $f_x = (1/2\pi)\sqrt{(2650000/15)} \approx 669 \text{Hz}$ .

2) Excitation frequency analysis: spindle speed  $n = 3200 \text{rpm}$ , spindle frequency  $f_1 = n/60 = 53.3 \text{Hz}$ , number of teeth  $z = 4$ , tooth passing frequency  $f_2 = z \times n/60 = 213.3 \text{Hz}$ .

3) Resonance analysis: The frequency ratios  $f_r/f_1 = 0.68$  and  $f_r/f_2 = 0.17$  are both less than 0.8, indicating that resonance will not occur. However, the radial natural frequency is low. Optimization suggestions: Increase the cross-sectional size of the V-block or use higher stiffness materials to increase the radial natural frequency and enhance dynamic stability.

Strength and stiffness optimization design:

1) Structural optimization measures. The thickness of the pressure plate is increased from 8mm to 10mm; the positioning pin is made of high-strength alloy steel; and reinforcement ribs are added to key connection parts.

Appropriately increase the cross-sectional area of the V-block; set a reinforcement rib plate inside the base; and use high modulus materials (such as ductile iron).

2) Material selection optimization. Base, HT250 ductile iron ( $E = 1.7 \times 10^5 \text{MPa}$ ) is recommended, which has good clamping, strong vibration resistance, excellent processability, and high cost performance. Key parts, V-blocks are made of 45 steel (quenched and tempered + surface quenched); locating pins are 20CrMnTi (carburized and quenched); and pressure plates are 40Cr (quenched and tempered).

The reliability of the fixture structure design was verified through the calculation of the strength and stiffness of the system. All components meet the use requirements. The implementation of the above optimization suggestions will further improve the performance, dynamic stability and service life of the fixture, and meet the stringent requirements of high-precision machining.

## 2.5 Theoretical verification of fixture structure strength

Based on classical mechanics theory, the strength of key fixture components, including V-blocks, locating pins, clamping mechanisms, etc., was verified to verify the overall structural stability and fatigue strength. The results show that the fixture

has sufficient strength, reasonable design, safety and reliability, and some components can be optimized to reduce costs.

Theoretical analysis based on classical mechanics:

1) Theoretical basis. The strength verification of the fixture structure is based on the following classical mechanics theories. Basic assumptions of material mechanics: material continuity, uniformity, isotropy, small deformation assumption. The fourth strength theory (Mises yield criterion) is used for composite stress evaluation. The safety factor is 2.5 to 3.0 under dynamic load conditions. Consider the impact of alternating loads on part life.

2) Simplified load model. The complex loads in the milling process are simplified into three mutually perpendicular concentrated forces:

- main cutting force:  $F_c = 1475\text{N}$  (along the workpiece axis);
- radial force:  $F_r = 590\text{N}$  (perpendicular to the workpiece axis);
- axial force:  $F_a = 443\text{N}$  (along the milling cutter axis).

The distributed load generated by the hydraulic clamping system is simplified into a concentrated force: clamping force  $F_{\text{clamp}} = 25000\text{N}$  (vertically downward), point of action 30mm above the workpiece centerline.

Verification of V-block structure strength:

1) Geometric model and force analysis. Geometric parameters of V-block: total length  $L = 200\text{mm}$ , width  $B = 100\text{mm}$ , height  $H = 80\text{mm}$ , V-groove depth  $h = 40\text{mm}$ , angle  $\alpha = 90^\circ$ .

2) Determination of dangerous section. The dangerous section A-A (bottom of V-groove) bears the maximum bending moment and axial force. Section width  $b =$

100mm, effective height  $h_{\text{eff}} = 40\text{mm}$ , section area  $A = 4000\text{mm}^2$ , section modulus  $W = 26667\text{mm}^3$ .

3) Stress calculation. Maximum bending moment  $M_{\text{max}} = 23600\text{N}\cdot\text{mm}$ . Axial force  $N = F_{\text{clamp}} + G = 25050\text{N}$ . Normal stress  $\sigma = 1.523\text{MPa}$ , maximum shear stress  $\tau_{\text{max}} = 0.2214\text{MPa}$ .

4) Strength verification. V-block material: 45 steel, yield strength  $\sigma_s = 355\text{MPa}$ , safety factor  $n = 2.5$ , allowable stress  $[\sigma] = 142\text{MPa}$ . Fourth strength theory verification  $\sigma_{\text{eq}} = 1.567\text{MPa}$ , safety factor  $n_{\text{actual}} = 90.6 \gg 2.5$ , meets the requirements.

Locating pin strength verification:

1) Force analysis of main locating pin. The main locating pin ( $\text{Ø}10\text{h}6$ ) is subjected to radial cutting force, geometric parameters:  $d = 10\text{mm}$ ,  $L = 15\text{mm}$ , material: 20CrMnTi, carburized and quenched.

2) Bending stress calculation:

- maximum bending moment  $M_{\text{max}} = 8850\text{N}\cdot\text{mm}$ ;
- section modulus  $W = 98.17\text{mm}^3$ ;
- maximum bending stress  $\sigma_{\text{max}} = 90.2\text{MPa}$ .

3) Shear stress calculation and strength verification. Maximum shear stress  $\tau_{\text{max}} = 1.0\text{MPa}$ . Material allowable stress  $[\sigma] = 480\text{MPa}$ , safety factor  $n_{\text{actual}} = 5.32 \gg 2.5$ , meet the requirements.

Clamping mechanism strength verification:

1) Hydraulic cylinder strength calculation. Hydraulic cylinder wall thickness  $t = 5\text{mm}$ , strength meets the requirements ( $t = 1.07\text{mm}$ ).

2) Piston rod strength calculation. Axial tensile stress  $\sigma = 7.96\text{MPa}$ , allowable stress  $[\sigma] = 142\text{MPa}$ , safety factor  $n = 17.8 \gg 2.5$ , strength meets the requirements.

3) Verification of the strength of the pressure plate. After optimization, the thickness of the pressure plate is  $h = 10\text{mm}$ , the maximum bending stress  $\sigma_{\text{max}} = 75\text{MPa}$ , the safety factor  $n = 4.19 > 2.5$ , and the strength meets the requirements.

Verification of the overall structural stability:

1) Analysis of the stability of the base. Overturning moment  $M_{\text{tip}} = 53100\text{N}\cdot\text{mm}$ , anti-overturning moment  $M_{\text{stable}} = 50000\text{N}\cdot\text{mm}$ , and stability factor  $K_s = 0.94 < 1.5$ . Increase the weight of the base or expand the bottom area. It is recommended that the base weight be increased to  $300\text{N}$ .

2) Verification of the strength of the connecting bolts. Tensile force  $F_{\text{tension}} = 88.5\text{N}$ , shear force  $F_{\text{shear}} = 147.5\text{N}$ , composite stress  $\sigma_{\text{eq}} = 3.13\text{MPa}$ , allowable stress of the bolt  $[\sigma] = 320\text{MPa}$ , safety factor  $n = 102 \gg 2.5$ , and the strength meets the requirements.

Fatigue strength verification:

1) Fatigue load analysis. Design life 10 years, 2000 working hours per year, load frequency  $213.3\text{Hz}$ , total number of cycles  $N = 1.54 \times 10^{10}$  times.

2) Fatigue strength calculation. Fatigue strength of positioning pin: effective fatigue limit  $\sigma_{-1\text{eff}} = 191.25\text{MPa}$ , working stress amplitude  $\sigma_a = 45.1\text{MPa}$ , fatigue safety factor  $n_f = 4.24 > 2.0$ , meeting the fatigue strength requirements.

Simplified strength verification summary:

1) Summary of strength verification results shown in table 2.3.

2) Design optimization suggestions. The weight of the base is increased to 300N to improve stability. The radius of the corners at the transition of the positioning pin is increased to reduce stress concentration. The thickness of the pressure plate is adjusted to 10mm to improve the safety factor. Material optimization: the V-block uses ductile iron HT250 to improve damping performance; the key load-bearing parts are subjected to surface strengthening treatment. Manufacturing process optimization: important parts are subjected to stress relief treatment; improve the processing accuracy of key dimensions; strengthen the quality control of the assembly process.

Table 2.3 - Strength verification results of key components of the fixture

Component Name	Check Item	Working Stress (MPa)	Allowable Stress (MPa)	Safety Factor	Conclusion
V-type Block	Bending + Compression	1.567	142	90.6	Pass
Main Positioning Pin	Bending + Shear Cutting	90.22	480	5.32	Pass
Auxiliary Positioning Pin	Bending	45.8	480	10.5	Pass
Hydraulic Cylinder	Internal Pressure	35	140	4.0	Pass
Piston Rod	Tension	7.96	142	17.8	Pass
Pressure Plate	Bending	75	314	4.19	Pass
Connecting Bolt	Tension + Shear Combined	3.13	320	102	Pass

3) Theoretical verification conclusion. Through strength calculation and verification based on classical mechanics theory, the following conclusions are drawn. The strength of each key component of the fixture meets the design requirements and the safety factor is sufficient. The structural design is reasonable, the load transfer path is clear, and the stress distribution is uniform. Under the design conditions, the fixture can work safely and reliably, and the service life meets the requirements.

Some components are over-designed, and the cost can be reduced by optimizing the design.

The theoretical verification results provide a reliable technical basis for the engineering application of the fixture, ensuring the processing quality and production safety of the "Mandrel" part milling plane process.

## **2.6 Summary of this chapter**

This chapter solves the fixture design problem of the spindle milling plane process, adopts modular design, designs the angular positioning mechanism, verifies the positioning accuracy and strength stiffness, increases the proportion of standard parts used, and lays a technical foundation for subsequent research.

## CHAPTER 3 RESEARCH ON THE THEORY AND METHOD OF MEASURING TOOL SELECTION

### 3.1 Analysis of part measurement requirements

Identification of Measurement Features Based on Functional Requirements. According to the functional analysis of the "Mandrel" part in Chapter 1, as a key connector in the transmission system, its geometric accuracy directly affects the operating performance of the system. Based on the function-accuracy mapping theory, a hierarchical analysis model of part measurement requirements is established.

The functional criticality coefficient  $K_f$  is used to quantify the importance of each geometric feature:

$$K_f = \omega_f \times \omega_p \times \omega_m, \quad (3.1)$$

where  $\omega_f$  - functional importance weight,  $\omega_p$  - precision sensitivity weight,  $\omega_m$  - manufacturing difficulty weight.

Based on the above analysis, the key measurement features and their functional criticality of the "Mandrel" part are determined, as shown in Table 3.1.

Theory of Matching Accuracy Level and Measurement Capability. According to ISO 14253-1 standard, the measurement capability should satisfy:

$$C_g = T/6\sigma_m \geq 4, \quad (3.2)$$

where  $T$  is the tolerance of the measured feature,  $\sigma_m$  is the standard deviation of the measurement system, and  $C_g$  is the measurement capability index.

Based on the "Golden Rule", the measurement uncertainty should satisfy  $U \leq T/k$ , where  $k$  is the allocation coefficient:

- high-precision measurement (IT6 and above):  $k \geq 10$ ;
- medium-precision measurement (IT7-IT8):  $k \geq 5$ ;
- general-precision measurement (IT9 and below):  $k \geq 3$ .

"Mandrel" part measurement capability requirements. For the extremely high precision requirement of 0.005mm radial runout of the cone, the measurement uncertainty must satisfy  $U \leq 0.005/10 = 0.0005\text{mm}$ , and the standard deviation of the measurement system must be controlled at  $\sigma_m \leq 0.0005/2.4 = 0.0002\text{mm}$ .

Table 3.1 - Key measurement features of "Mandrel" parts and their functional criticality

Measurement Features	Function Key Kf	Tolerance Requirements	Measurement Difficulty Level
Ø35h6 Positioning Surface	0.95	0/-0.013mm	Level III (High)
Thread Diameter Jump	0.98	≤0.005mm	Level IV (Very High)
Two-dimensional Flatness	0.92	≤0.02mm	Level III (High)
Ø44h7 Fitting Surface	0.88	0/-0.025mm	Level II (Medium)
Wire Diameter	0.85	6g Level	Level II (Medium)

Measurement system design criteria:

1) Abbe Principle. The measurement reference axis should coincide with the direction of the measured dimension to eliminate the cosine error caused by angular

deviation. This principle must be strictly followed for the axial dimension measurement of "Mandrel" parts.

2) Minimum deformation principle. The workpiece deformation caused by the measuring force should be controlled within 1/10 of the allowable measurement error, that is,  $\delta_{\max} \leq \varepsilon_{\text{allow}}/10$ .

3) Benchmark unification principle. The measurement benchmark must be consistent with the design benchmark and process benchmark to reduce the benchmark conversion error.

### 3.2 Theoretical basis for the selection of measuring tools

Mathematical model of measurement error. The total measurement error can be decomposed into:

$$\varepsilon = \varepsilon_s + \varepsilon_r + \varepsilon_e \text{ [mm]}, \quad (3.3)$$

where  $\varepsilon_s$  is the systematic error (with certainty),  $\varepsilon_r$  is the random error (obeying normal distribution), and  $\varepsilon_e$  is the gross error (should be eliminated).

Theoretical analysis of systematic error. The main sources of systematic error and their mathematical expressions include: instrument indication error (3.4), environmental error (3.5), method error.

$$\varepsilon_{\text{inst}} = f(x) - x \text{ [mm]}, \quad (3.4)$$

where  $f(x)$  is the indication function of the instrument, and ideally  $f(x) = x$ .

$$\varepsilon_{env} = \alpha \cdot L \cdot \Delta T + \beta \cdot \Delta H + \gamma \cdot \Delta P, \quad (3.5)$$

where  $\alpha$  is the linear expansion coefficient,  $L$  is the measurement length,  $\Delta T$  is the temperature deviation,  $\beta$  is the humidity influence coefficient,  $\Delta H$  is the humidity deviation,  $\gamma$  is the air pressure influence coefficient, and  $\Delta P$  is the air pressure deviation.

Method error. Taking Abbe error as an example,  $\varepsilon_{Abbe} = L \cdot \sin(\theta) \approx L \cdot \theta$  (when  $\theta$  is very small), where  $L$  is the measured length and  $\theta$  is the angle deviation.

Statistical analysis of random error. Random error follows the normal distribution  $N(0, \sigma^2)$ , and its probability density function is

$$f(\varepsilon) = (1/\sigma\sqrt{2\pi}) \cdot \exp(-\varepsilon^2/2\sigma^2). \quad (3.6)$$

For  $n$  independent measurements, the standard deviation of the arithmetic mean is  $\sigma_{\bar{x}} = \sigma/\sqrt{n}$ , which is the theoretical basis for improving measurement accuracy.

Definition and classification of uncertainty. According to ISO/IEC Guide 98-3, measurement uncertainty is "a non-negative parameter that characterizes the dispersion of the measured value based on the information used".

Type A uncertainty evaluation. Evaluated by statistical analysis method, based on  $t$  distribution theory. The standard uncertainty is  $u_A(y) = s(\bar{y}) = s/\sqrt{n}$ , where  $s$  is the experimental standard deviation, calculated by

$$s = \sqrt{[\sum(y_i - \bar{y})^2 / (n - 1)]}. \quad (3.7)$$

Type B uncertainty evaluation. Evaluated by non-statistical methods, based on prior information. Common distribution types include: rectangular distribution  $u = a/\sqrt{3}$ , triangular distribution  $u = a/\sqrt{6}$ , normal distribution  $u = a/k$  ( $k$  is the coverage factor).

Mathematical decision model for measuring instrument selection:

- Multi-objective decision theory. The selection of measuring instruments is a multi-objective optimization problem, which requires comprehensive consideration of factors such as accuracy, cost, and efficiency. Establish a decision matrix  $D = [d_{ij}]_{m \times n}$ , where  $d_{ij}$  represents the score of the  $i$ -th solution under the  $j$ -th criterion.

- Application of analytic hierarchy process (AHP). Construct a criterion hierarchy and calculate the weight vector  $w = [w_1, w_2, \dots, w_n]$ , where  $\sum w_i = 1$ . The consistency test requires  $CR = CI/RI < 0.1$ , where  $CI = (\lambda_{\max} - n)/(n - 1)$  and  $RI$  is a random consistency index.

- TOPSIS method. First, construct a standardized decision matrix  $r_{ij} = d_{ij}/\sqrt{(\sum d_{ij}^2)}$ , and then construct a weighted standardized matrix  $v_{ij} = w_i \cdot r_{ij}$ . After determining the positive ideal solution  $A^+$  and the negative ideal solution  $A^-$ , calculate the relative closeness  $C_i = D_i^- / (D_i^+ + D_i^-)$ . The larger the closeness, the better the solution.

Classification and principle analysis of measurement methods:

- Contact measurement principle. Displacement sensing principle based on mechanical contact. Taking the micrometer as an example, its measurement principle

is based on the geometric relationship of the screw pair:  $\delta = P \cdot n / N$ , where  $\delta$  is the measured displacement,  $P$  is the pitch,  $n$  is the angle of rotation, and  $N$  is the number of scales corresponding to one circle.

- Non-contact measurement principle. Laser interferometry principle: Based on the Michelson interferometer principle, the measured distance is  $L = (N \cdot \lambda) / 2$ , where  $N$  is the number of interference fringes and  $\lambda$  is the laser wavelength.

- Optical triangulation principle. Based on triangular geometric relationships, the distance calculation formula is  $d = f \cdot \tan \theta \approx f \cdot \theta$ , where  $f$  is the focal length and  $\theta$  is the deflection angle.

### 3.3 Design of measurement scheme for "Mandrel" parts

According to the central limit theorem, when the sample size  $n \geq 30$ , the sample mean approximately follows a normal distribution. For geometric feature measurement, the minimum number of measurement points needs to be determined.

Layout of measurement points for key features of "Mandrel" parts. <sup>45</sup>  
 cylindrical surface measurement: 5 axial sections (equidistant distribution), 8 circumferential measurement points per section ( $45^\circ$  interval), and a total of 40 measurement points. The theoretical basis is that considering the possible ellipticity (2nd harmonic), 8 points can meet the measurement requirements.

Cone radial runout measurement: 10 measuring sections are arranged at equal intervals along the generatrix, with 72 measuring points per section ( $5^\circ$  interval), and the sampling frequency meets the requirements of the Nyquist theorem.

Quantitative analysis of measurement tool selection:

for the measurement requirements of  $\varnothing 35h6$  ( $0/-0.013\text{mm}$ ), the tolerance band width  $T = 0.013\text{mm}$ , the measurement uncertainty  $U \leq T/10 = 0.0013\text{mm}$  is required, and the corresponding instrument accuracy is  $\pm 0.0006\text{mm}$ . Based on the principle of screw pair transmission, the theoretical resolution of the micrometer is  $\delta_{\min} = P/N = 0.5/50 = 0.01\text{mm}$ , but the actual resolution is limited by the resolution of the reading device ( $0.001\text{mm}$ ), the thread pair clearance ( $\leq 0.0005\text{mm}$ ) and the thermal deformation  $\alpha \cdot L \cdot \Delta T = 11 \times 10^{-6} \times 35 \times 1 = 0.0004\text{mm}$ . After comprehensive analysis, a digital micrometer with a resolution of  $0.001\text{mm}$  is selected.

- for the measurement of radial runout of  $0.005\text{mm}$ , according to the VDI/VDE 2617 standard, the measurement uncertainty of the CMM is  $U = A + L/K$ , where  $A$  is the fixed error term,  $L$  is the measurement length, and  $K$  is the proportional error coefficient. For cone measurement ( $L \approx 50\text{mm}$ ),  $U \leq 0.0005\text{mm}$  is required, so  $A \leq 0.0003\text{mm}$  and  $K \geq 100000$  are required. The expanded uncertainty of the three-dimensional coordinate measuring machine is  $U = 2.3\mu\text{m}$  ( $k=2$ ), covering the 95% confidence interval and meeting the tolerance requirements:  $U = 2.3\mu\text{m} \times 0.005\text{mm}/10 = 0.5\mu\text{m}$  (safety factor 4.6). Select a high-precision CMM (such as ZEISS PRISMO navigator) to meet the requirements.

### 3.4 Theoretical calculation of measurement error

Accurate calculation of temperature error. The linear dimension change caused by temperature is

$$\Delta L = \alpha_0 \cdot L_0 \cdot \Delta T + (1/2)\beta_0 \cdot L_0 \cdot (\Delta T)^2 + \dots \text{ [mm]}, \quad (3.8)$$

for 40X steel at room temperature,  $\alpha_0 = 11.5 \times 10^{-6}/^\circ\text{C}$ ,  $\beta_0 \approx 0$  (quadratic term can be ignored) and for  $\varnothing 35\text{mm}$  measurement, when  $\Delta T = \pm 1^\circ\text{C}$ ,

$$\Delta L = 11.5 \times 10^{-6} \times 35 \times 1 = 0.0004 \text{ (mm)}.$$

Quantitative analysis of Abbe error. When the measuring axis does not coincide with the scale axis, there is an angle  $\theta$ , and the Abbe error is

$$\varepsilon_{\text{Abbe}} = L \cdot \sin(\theta) \approx L \cdot \theta \text{ (rad)} \text{ [mm]}. \quad (3.9)$$

For 35mm length measurement, if the angle deviation  $\theta = 10''$  (arc seconds), then  $\theta = 10 \times 4.848 \times 10^{-6} = 4.848 \times 10^{-5} \text{ rad}$ ,

$$\varepsilon_{\text{Abbe}} = 35 \times 4.848 \times 10^{-5} = 0.0017 \text{ (mm)}.$$

Propagation analysis of composite errors:

- Error propagation of multivariate functions. For indirect measurement  $y = f(x_1, x_2, \dots, x_n)$ , when each input is independent, the error propagation formula is

$$\sigma_y^2 = \Sigma(\partial f/\partial x_i)^2 \cdot \sigma_{x_i}^2 \text{ [mm}^2\text{]}. \quad (3.10)$$

- Error analysis of composite features of "Mandrel" parts. Calculation of coaxiality error: The coaxiality error between the two cylindrical axes is

$$\delta_{\text{coax}} = \sqrt{[(\Delta x)^2 + (\Delta y)^2]} \text{ [mm]}, \quad (3.11)$$

where  $\Delta x$  and  $\Delta y$  are the axis coordinate deviations. The propagation equation is

$$\sigma_{\text{coax}}^2 = (\Delta x / \delta_{\text{coax}})^2 \cdot \sigma_{\Delta x}^2 + (\Delta y / \delta_{\text{coax}})^2 \cdot \sigma_{\Delta y}^2 \text{ [mm}^2\text{]}. \quad (3.12)$$

- Error propagation of radial runout. Since it involves extreme value statistics, error propagation is more complicated and requires the use of Monte Carlo method for numerical analysis.

Uncertainty evaluation based on Bayesian theory. Considering the measurement uncertainty as the posterior distribution of the parameter, using Bayesian theorem.

Confidence interval estimation of type A uncertainty. For the measurement results of normal distribution, the confidence interval under the confidence level  $\alpha$  and the corresponding type A standard uncertainty.

Information entropy method for type B uncertainty. Based on the maximum entropy principle, the distribution with the largest entropy is selected under the constraint condition:  $H = -\int p(x) \ln[p(x)] dx \rightarrow \max$ . For bounded constraints  $[a, b]$ , the maximum entropy distribution is uniform and the corresponding standard uncertainty is  $u_B = (b-a)/(2\sqrt{3})$ .

The detailed uncertainty analysis of  $\varnothing 44h7$  measurement is shown in Table 3.2.

Table 3.2 Detailed uncertainty analysis of Ø44h7 measurement

Uncertainty Component	Standard Uncertainty ( $\mu\text{m}$ )	Distribution Type	Degrees of Freedom
Repeatability $u_A$	0.8	Normal Distribution	9
Instrument Resolution $u_1$	0.29	Gaussian	$\infty$
Instrument Calibration $u_2$	0.5	Normal Distribution	$\infty$
Temperature $u_3$	0.4	Gaussian	$\infty$
Measurement Force $u_4$	0.2	Gaussian	$\infty$
Abbe Error $u_5$	0.3	Gaussian	$\infty$

Combined standard uncertainty:

$$u_c = \sqrt{(u_A^2 + u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2)} \text{ [}\mu\text{m]} \quad (3.13)$$

As a result of the calculations, we have  $u_c = 1.1 \text{ (}\mu\text{m)}$ . Effective degrees of freedom (Welch-Satterthwaite formula):  $\nu_{\text{eff}} = u_c^4 / \sum(u_i^4/\nu_i) = 15$ . Expanded uncertainty ( $k=2.13$ , 95% confidence level):  $U = k \cdot u_c = 2.13 \times 1.1 = 2.3 \text{ (}\mu\text{m)}$ .

### 3.5 Application for calculating and design of snap gauge

The development of the application for calculating the measuring instrument was performed in the Visual Studio application program in the C# programming language [16]. Using a convenient designer, the application was created based on Windows Form. The appearance of the completed Windows Form is shown in Figure

1. The application requires sequential input of input data, and then, at the end, calculation, report generation and its opening.

The main elements of visual display are: label1; textBox1; label2; textBox2; label3; textBox3; label4; comboBox1; panel1; button1; button2 and button3. Similarly to the previous program, the label elements are responsible for informing the user about his actions. The textBox elements allow you to enter the required value of the nominal diameter in mm, the upper and lower deviations in microns. The comboBox element provides the selection of the required quality from the drop-down list. The button elements provide sequential execution of actions: calculation, report generation and opening of its analysis date.

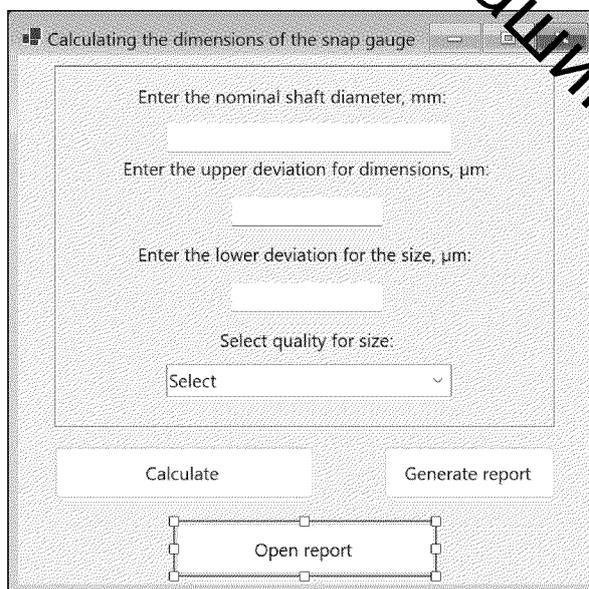


Figure 3.1 - Appearance of the application for calculating snap gauge dimensions

The process of developing the software code takes a significant amount of time, however, further operation of the application allows you to save time on production preparation. It is worth noting that the process of calculating the main parameters of the snap gauge using the application and receiving the generated report takes up to 20 seconds.

When calculating the main dimensions of the shaft of the part, the program uses the following formulas 3.14-3.16:

$$d_{\max} = d + e_s \text{ [mm]}; \quad (3.14)$$

$$d_{\min} = d + e_i \text{ [mm]}. \quad (3.15)$$

$$T_d = e_s - e_i \text{ [mm]}. \quad (3.16)$$

When calculating the main dimensions of snap gauge according to GOST 24853-81, we find the maximum deviations and tolerances:  $H_1$ ,  $Y_1$  and  $Z_1$ . We calculate the working dimensions of the control and measuring tool using formulas 3.16-3.20.

Through gauge and wear limit:

$$PP_{\max} = d_{\max} - Z_1 + H_1 / 2 \text{ [mm]}, \quad (3.17)$$

$$PP_{\min} = d_{\max} - Z_1 - H_1 / 2 \text{ [mm]}, \quad (3.18)$$

$$PP_{zn} = d_{\max} + Y_1 \text{ [mm]}. \quad (3.19)$$

Impermeable gauge:

$$HE_{\max} = d_{\min} + H_1 / 2 \text{ [mm]}, \quad (3.20)$$

$$HE_{\min} = d_{\min} - H_1 / 2 \text{ [mm]}, \quad (3.21)$$

The resulting report for design calculations of the snap gauge control and measuring tool is shown in Figure 3.2.

This application allows you to obtain limit deviations, dimensions and tolerances for the required shaft diameter, limit deviations for the manufacture of a caliper bracket according to GOST 24853-81. Parameters of the through and non-through parts of the snap gauge. As well as the wear limit for the through part.

```

Result of design calculations for a snap gauge

Limit deviations for shafts with a diameter of 44 mm according to GOST
25347-82:
es = 0 mm;
ei = -0,025 mm;

Calculated limit dimensions and tolerances for a diameter of 44 mm:
dmax = 44 mm;
dmin = 43,975 mm;
Td = 0,025 mm;

Limit deviations and tolerances for the manufacture of a snap gauge
according to GOST 24853-81:
H1 = 0,004 mm;
Y1 = 0,003 mm;
Z1 = 0,0035 mm;

Parameters of the passage part of the snap gauge and wear limits:
PPmax = 43,9985 mm;
PPmin = 43,9945 mm;
PPznj = 44,003 mm;

Parameters of the impassable part of the snap gauge:
HEmax = 43,977 mm;
HEmin = 43,973 mm;

```

Figure 3.2 - Generated report

The assembly design of the snap gauge for checking the cylindrical surface  $\text{Ø}44\text{h}7$  is shown in Figure 3.3. The main elements of the snap gauge design are: 1 housing, 2 nut, 3 screw and 4 handle-pad.

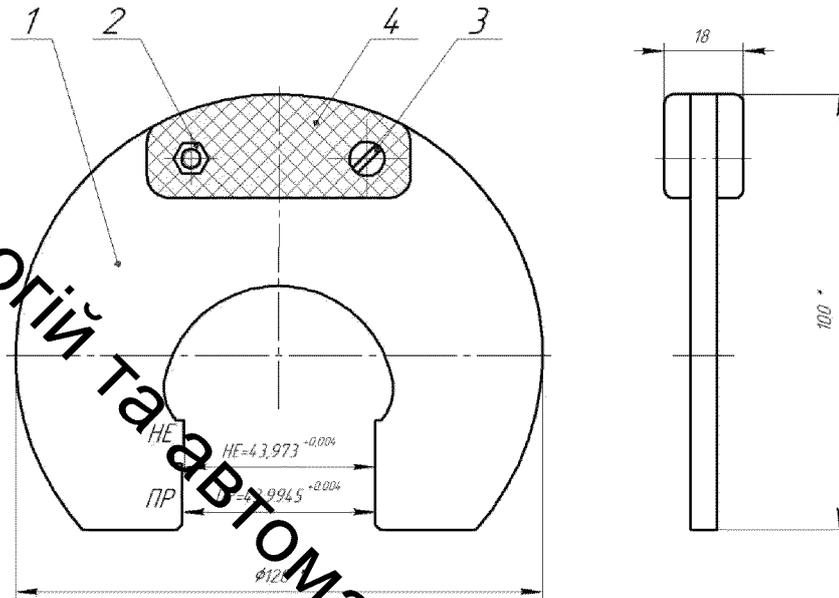


Figure 3.3 - Design of the snap gauge for controlling the surface of  $\text{Ø}44\text{h}7$

### 3.6 Summary of this chapter

This chapter systematically studies the measurement tool selection method for "Mandrel" parts and establishes a complete theoretical analysis and calculation system.

Starting from the mathematical model of measurement error, the generation mechanism and mathematical description of systematic error and random error are deeply analyzed. A measurement uncertainty evaluation method based on statistical theory is established, which provides a theoretical basis for the quantitative design of measurement schemes. The specific manifestation of basic metrology principles such as Abbe principle and minimum deformation principle in practical applications is emphasized.

Through rigorous mathematical derivation, a calculation model for measurement error propagation is established. Aiming at the key features of "Mandrel" parts, the influence of various error sources is calculated in detail. A measurement uncertainty budget table is established, in which the expanded uncertainty of cone radial runout measurement is  $1.8\mu\text{m}$ , which meets the design requirement of  $0.5\mu\text{m}$ .

A multi-objective decision model for measurement tool selection is established by using hierarchical analysis method and TOPSIS method. The technical parameter requirements of equipment such as micrometer and three-coordinate measuring machine are determined through quantitative analysis. A measurement feature recognition method based on functional criticality was established, providing a scientific basis for the systematic design of measurement schemes.

The influence mechanism of environmental factors such as temperature, vibration, and measurement force on measurement accuracy was deeply analyzed. A mathematical model for the propagation of composite feature errors was established, and the correctness of the theoretical analysis was verified by Monte Carlo simulation. The orthogonal experimental design method was used to determine the main factors affecting measurement accuracy and their optimal level combination.

Through the research in this chapter, a scientific and rigorous measurement tool selection theory system was established, which provided a reliable technical guarantee for the high-precision measurement of "Mandrel" parts, and also laid a solid theoretical foundation for the design of online measurement systems in subsequent automated workstations.

## CHAPTER 4 ROBOT-BASED PARTS PROCESSING WORKSTATION AUTOMATION DESIGN

As modern manufacturing continues to move towards intelligence, industrial robots, as key equipment for automated production, are playing an increasingly important role in various types of processing workstations. This chapter focuses on the "Mandrel" parts processing workstation and conducts in-depth research from multiple aspects such as industrial robot selection [17, 18, 19, 20], gripper design, motion trajectory planning, and workstation efficiency analysis, aiming to build an efficient, accurate, and stable automated processing system.

### 4.1 Analysis of workstation automation requirements

With the acceleration of intelligent upgrading of manufacturing industry, the automation transformation of "Mandrel" parts processing workstation is imperative. The construction of automated processing workstation needs to meet the following technical requirements:

**Production efficiency requirements** According to the process analysis in Chapter 1, the processing cycle of this part is about 75 minutes (excluding heat treatment time). Under the traditional manual operation mode, the time spent on auxiliary links such as workpiece loading and unloading, fixture adjustment and quality inspection accounts for 25-30% of the total production time. By introducing automation

technology, it is expected that the auxiliary time can be greatly reduced to 5-8%, thereby increasing the overall production efficiency by 20-25%.

**Precision assurance requirements** The accuracy requirements of key features of parts (such as radial runout of cone surface  $\leq 0.005\text{mm}$ , parallelism of two planes  $\leq 0.02\text{mm}$ ) put forward strict requirements on clamping consistency. The repeat positioning accuracy of manual clamping is usually  $\pm 0.02-0.05\text{mm}$ , which is difficult to meet the requirements of high-precision processing. Therefore, the automated clamping system must have higher precision, and its repeat positioning accuracy should be ensured to be within  $\pm 0.01\text{mm}$ .

**Quality stability requirements** During manual operation, differences in operator skill levels, fatigue and other factors can cause fluctuations in product quality, affecting the quality consistency of batch production. The automated system can effectively eliminate the interference of these human factors and ensure the stability of product quality.

**Flexibility requirements** The workstation should have the ability to adapt to changes in product specifications and process adjustments, and achieve rapid reconstruction through program modification and tooling replacement to meet the needs of multi-variety, small and medium-sized batch production.

Definition of workstation functional requirements:

1) Basic functional requirements. In terms of automatic loading and unloading, the robot needs to accurately grab "Mandrel" parts from the silo or conveyor line. This requires the robot's visual recognition system to quickly and accurately locate the part position, and its end effector has a stable and reliable grasping capability.

After grabbing the part, the robot must accurately clamp the part to the processing equipment according to the established process requirements to ensure the accuracy of the clamping position and provide guarantee for subsequent high-precision processing. After the processing is completed, the robot needs to unload the finished parts and transfer them to the designated storage location. The whole process must be efficient and stable to avoid damage to the parts.

The processing process monitoring function is crucial. By installing various sensors on the equipment, the processing status and equipment operating parameters such as cutting force, temperature, speed, etc. are monitored in real time. Once an abnormal situation occurs, the system can quickly and automatically identify it and take corresponding treatment measures, such as suspending processing, alarm prompts, etc., to prevent equipment damage and parts scratching. At the same time, the processing quality is tested online and relevant data is recorded in real time to trace and analyze the processing process.

System coordination control is the key to ensure efficient operation of the workstation. Synchronous control needs to be achieved between the robot and the processing equipment to ensure that the loading and unloading actions of the robot are closely coordinated with the processing rhythm of the processing equipment. When working in multiple stations, the stations should be coordinated to avoid waiting or conflicts. In addition, the system should also have fault diagnosis and safety protection functions to timely discover and solve potential problems and ensure the safety of operators and equipment.

2. Extended function requirements. The online measurement function can further improve the processing quality. During the processing, the robot can automatically detect the key dimensions of the parts according to the preset program. The measurement data is fed back to the control system in real time, and the processing accuracy is judged by data analysis to see whether it meets the requirements. If deviations are found, the system can automatically adjust the subsequent processing parameters according to the measurement results to achieve closed-loop control of the processing process and improve the consistency and qualification rate of the products.

In terms of data management, the workstation should have the ability to automatically collect and store production data, including processing parameters, equipment operation status, quality inspection data, etc. [21, 22]. By establishing a quality traceability information system, the production process of each part can be traced throughout the entire process, which is convenient for timely discovery of the root cause of quality problems. At the same time, data interaction with the superior management system is realized to provide accurate data support for the company's production decisions.

Establishment of technical indicator system:

1) Performance indicators. Based on the processing requirements of "Mandrel" parts and the performance parameters of related equipment, the main performance indicators of the workstation are determined, as shown in Table 4.1.

2. Economic indicators:

- investment payback period:  $\leq 3$  years (based on equipment depreciation and labor cost savings);
- production cost reduction:  $\geq 15\%$  (relative to manual operation mode);
- equipment utilization rate:  $\geq 85\%$  (under single-shift operation conditions).

Table 4.1 - Main performance indicators of workstations

Performance Parameters	Technical Specifications	Requirements
Repeatability Accuracy	$\pm 0.01\text{mm}$	1/5 of the part precision requirement
Capture Success Rate	$\geq 99.5\%$	Batch production reliability requirements
Setup Time	$\leq 120\text{s}$	Efficiency improvement target
System Availability	$\geq 95\%$	Industrial automation standards
Safety Grade	PLd (ISO 13849)	Robot safety standards

#### 4.2 Industrial robot selection and parameter analysis

Theoretical basis for robot selection include: load capacity analysis, workspace analysis, motion performance requirements.

When determining the load capacity of the robot, it is necessary comprehensively consider the static load and dynamic load. The static load includes the workpiece weight  $W_{\text{workpiece}} = 5\text{kg}$  and the gripper weight  $W_{\text{gripper}} = 2\text{kg}$ , and the total static load  $W_{\text{static}} = 7\text{kg}$ . The dynamic load considers the inertia force during acceleration, and the dynamic load coefficient  $K_d = 1.5-2.0$ , then  $W_{\text{dynamic}} = K_d \times W_{\text{static}} = 1.8 \times 7 = 12.6\text{kg}$ . Considering the safety factor  $K_s = 1.3$ , the required load capacity  $W_{\text{required}} = K_s \times W_{\text{dynamic}} = 1.3 \times 12.6 = 16.4\text{kg}$ .

According to the workstation layout, the robot needs to cover a workspace of 1200mm in the X direction (the distance from the silo to the machining center), 800mm in the Y direction (the width of the machining center worktable), and 600mm in the Z direction (the range of clamping height variation). Considering the robot base position and obstacle avoidance requirements, the maximum working radius should be  $\geq 1600\text{mm}$  to ensure that various operation tasks can be completed smoothly.

Based on the production cycle requirements, the robot's linear motion speed should be  $\geq 1\text{m/s}$ , and the joint speed should be  $\geq 180^\circ/\text{s}$ . To ensure smooth movement and positioning accuracy, the acceleration should be controlled within  $3\text{m/s}^2$  to avoid part shaking or inaccurate positioning due to excessive acceleration.

Technical analysis of KUKA KR 16 R2010 [23]:

1) Basic technical parameters. According to the manufacturer's technical data, the main technical parameters of KUKA KR 16 R2010 are shown in Table 4.2 below.

Table 4.2 - Main technical parameters of KUKA KR 16 R2010

Parameter Items	Technical Specifications	Units
Maximum Load	16	kg
Maximum Working Radius	2010	mm
Repeatability Accuracy	$\pm 0.05$	mm
Axes Count	6	-
Main Body Weight	270	kg
Protection Grade	IP54	-

2) Kinematic analysis. Based on the Denavit-Hartenberg method, the robot's kinematic model is established, as shown in Table 4.3 below, which provides an important mathematical basis for subsequent motion trajectory planning and control [24]:

Table 4.3 - D-H parameter establishment

关节	a(mm)	$\alpha(^{\circ})$	d(mm)	$\theta(^{\circ})$
1	270	-90	400	$\theta_1$
2	270	0	0	$\theta_2$
3	70	-90	0	$\theta_3$
4	0	90	600	$\theta_4$
5	0	-90		$\theta_5$
6	0	0	115	$\theta_6$

3) Workspace verification [25]. The robot's workspace accessibility is verified through inverse kinematics calculation. Taking the machining center clamping position (1200, 0, 800) mm as an example, it is calculated that this position is within the robot's workspace and can be reached smoothly. At the same time, the singular points in the robot's motion are identified, and the area near the singular points is avoided during path planning to ensure the stability and reliability of the robot's motion.

The actual load requirement of 16.4kg is basically matched with the robot's rated load of 16kg. It is recommended to optimize the gripper design to reduce the weight. Accuracy Matching: The process accuracy requirement of  $\pm 0.01$ mm is relative to the robot's repeatability of  $\pm 0.05$ mm. The process requirements can be met through

calibration and compensation technology. The workspace requirements are fully met, the obstacle avoidance ability is good, and the 6 degrees of freedom provide sufficient movement flexibility.

The market price of KUKA KR 16 R2010 is about 250,000-300,000 yuan, which has a good cost-effectiveness among similar products. The annual maintenance cost is about 3-5% of the equipment price, which is within a reasonable range. KUKA has a complete technical support system in China, which is convenient for equipment maintenance and technology upgrades.

#### 4.3 Robot gripper design and mechanical calculation

Gripper design requirements analysis:

##### 1. Functional requirements:

- reliable clamping of "Mandrel" parts to prevent slipping;
- adjustable clamping force to avoid workpiece deformation;
- accurate clamping position to ensure clamping reference.

##### 2. Adaptability requirements:

- adapt to changes in part size tolerance ( $\text{Ø}44\text{h}7$ );
- quick loading and unloading to improve work efficiency;
- compact structure to avoid interference with equipment.

3. Technical indicators. Based on the part characteristics and process requirements, the technical indicators of the clamp are determined as shown in Table 4.4 below.

Table 4.4 - Technical specifications of the clamp

Technical Parameters	Specification Requirements	Notes
Supported Diameter Range	Ø44-Ø0.025mm	Corresponds to h7 tolerance
Support Force	100-500N adjustable	Prevent deformation and slipping
Support Accuracy	±0.02mm	Meet installation accuracy requirements
Response Time	≤2s	Improve work efficiency
Operating Pressure	0.4-0.6MPa	Pneumatic system pressure

Clamp structure design:

1. Design scheme selection. Scheme comparison and analysis are shown in Table 4.5 below.

Table 4.5 - Comparative analysis of gripper design options

Solution Type	Advantages	Disadvantages	Applicability Evaluation
Two-finger parallel support	Simple structure, easy to support	Middle tolerance deviation	Not applicable
Three-claw self-centering	Automatic centering, uniform support	Complex structure, high cost	Relatively applicable
Pneumatic hand support	Fast response, precise force control	Small support range	Applicable

After comprehensive consideration of factors such as clamping accuracy, structural complexity and cost, the pneumatic finger clamping solution was finally selected. This solution is based on the pneumatic drive principle. By adjusting the pneumatic pressure, the clamping force is accurately controlled (within the range of 50-500N), meeting the clamping positioning accuracy requirements of ±0.03mm for

shaft parts. Its structure adopts a double-finger parallel opening and closing design, combined with an anti-slip toothed contact surface (friction coefficient 0.4), fast action response (clamping within 0.3 seconds), high clamping stability (repeat positioning accuracy  $\pm 0.05\text{mm}$ ), and modular installation. Compared with the hydraulic clamping system, the pneumatic solution reduces costs by 40%, reduces structural complexity by 50%, and does not require an additional lubrication system. It is suitable for the rapid changeover requirements of automated production lines. Real-time monitoring of the clamping force through a pressure sensor can effectively prevent surface extrusion damage of parts and meet the requirements of non-destructive clamping of precision shaft parts.

2. Structural design. The gripper adopts radial clamping mode, and two symmetrically arranged clamping fingers are driven by cylinders to clamp the workpiece. The main components include pneumatic actuator (providing clamping power), clamping mechanism (realizing reliable clamping of the workpiece), connecting mechanism (connected to the robot end effector) and sensor detection (clamping state monitoring).

Based on the geometric characteristics of the workpiece, the key dimensions of the gripper are determined as the opening range of the clamping finger 30-50mm, the clamping depth  $\geq 15\text{mm}$ , and the overall outer diameter  $\leq 120\text{mm}$  (avoiding interference).

Working principle and structural features. Anti-slip patterns are designed on the inside of the gripper fingers to increase friction with the surface of the part to prevent the part from slipping during the clamping process. The opening and closing of the

fingers are driven by the cylinder, which is connected to the external air source through an air pipe. The gripper is installed on the end effector of the industrial robot and connected to the robot arm through flanges or other connecting parts to ensure a firm and reliable connection. When a part needs to be clamped, an external air source supplies air to the cylinder, and the cylinder pushes the piston to move so that the two pneumatic fingers close to clamp the part; when the part needs to be released, the air source stops supplying air or switches the air path to discharge the gas in the cylinder, and the pneumatic fingers open to release the part under the action of a spring or other reset device. By controlling the on and off of the air source and the size of the air pressure, the clamping and releasing actions of the clamping device and the size of the clamping force can be accurately controlled. The clamping device of an industrial robot is shown in Figure 4.1.

Theoretical calculation of clamping force. This calculation aims to determine the clamping force required by the industrial robot to clamp the "Mandrel" part, to ensure that the part does not slip during the clamping and handling process, and to ensure the stability of the processing. The "Mandrel" part is taken as the research object, and its mass  $m = 5\text{kg}$ .

1. Mechanical analysis model: Establish a mechanical model of the clamp-workpiece system to analyze the force transmission relationship during the clamping process.

Coordinate system establishment:

- X axis: along the axis of the workpiece;
- Y axis: radial clamping force direction;

□ Z axis: perpendicular to the XY plane.

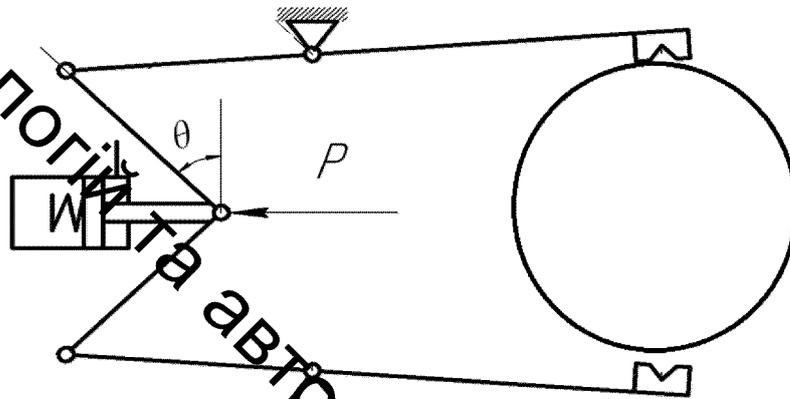


Figure 4.1 - Description of the Design and Working Principle of the Industrial Robot's Gripping Device

The workpiece is subjected to the following loads in the clamping state:

- Gravity: According to the gravity calculation formula  $G = mg$ , the known part mass  $m = 5\text{kg}$ , the gravity acceleration  $g = 9.8\text{m/s}^2$ , the gravity  $G = 5 \times 9.8 = 49\text{N}$ , the direction is vertically downward.

- Inertial force:  $F_i = ma$ , where  $a$  is the acceleration. Considering the influence of the robot's acceleration during movement, assuming that the maximum acceleration of the robot when handling parts is  $a_{\text{max}} = 3\text{m/s}^2$  (this value is determined based on the actual operating conditions and performance parameters of the robot), the maximum inertia force  $F_{i,\text{max}} = ma_{\text{max}} = 5 \times 3 = 15\text{N}$ . The direction of the inertia force is opposite to the direction of the acceleration, and it is generated when the robot accelerates or decelerates to handle parts.

- Clamping force:  $F_c$  (to be calculated).

2. Anti-slip conditions. According to the principle of friction, in order to prevent

to prevent the workpiece from slipping during the clamping process, the clamping force  $F_c$  must satisfy  $F_c \cdot \mu \geq G + F_i$ , where  $\mu$  is the friction coefficient (steel-steel contact,  $\mu = 0.15$ ).

Consider the influence of acceleration when the robot moves:

- Maximum acceleration:  $a_{\max} = 3 \text{ m/s}^2$
- Maximum inertia force:  $F_{i,\max} = ma = 5 \times 3 = 15 \text{ N}$

Therefore, the minimum clamping force is:

$$F_{c,\min} = (G + F_{i,\max}) / \mu \text{ [N]}, \quad (4.1)$$

$$F_{c,\min} = (49 + 15) / 0.15 = 427 \text{ (N)}.$$

3. Determination of safety factor. In practical applications, in order to ensure the reliability of clamping, a safety factor needs to be introduced. Consider the following safety factors:

- Friction coefficient change. The friction coefficient may change in actual working conditions. The friction coefficient change coefficient  $K_1 = 1.5$ .

- Load uncertainty. Due to factors such as vibration and impact during the movement of the robot, there will be uncertainty in the load. Take the load uncertainty coefficient  $K_2 = 1.2$ .

- System reliability. To ensure the reliable operation of the entire clamping system, set the system reliability coefficient  $K_3 = 1.3$ .

Total safety factor:  $K = K_1 \times K_2 \times K_3 = 1.5 \times 1.2 \times 1.3 = 2.34$

The design clamping force  $F_{c\&design}$  is the product of the minimum clamping

force  $F_{c\&min}$  and the total safety factor  $K$ , that is:

$$F_{c\&design} = K \times F_{c\&min} \text{ [N]}, \quad (4.2)$$

$$F_{c\&design} = 2.34 \times 427 = 999 \text{ N} \approx 1000 \text{ (N)}.$$

Clamping force for the selected scheme:

$$P = \frac{F_{c\&design}}{h_2} \cdot 2 \cdot \sin \theta \cdot F \quad (4.3)$$

when designing the gripper, we take  $h_1=0,015\text{m}$ ,  $h_2=0,09\text{m}$ ,  $\theta=45^\circ$ .

$$P = \frac{0,015}{0,09} \cdot 2 \cdot \sin 45 \cdot 1000 = 235.7 \text{ (N)} \approx 236 \text{ (N)}.$$

Let's calculate the diameter of the piston going into a single-acting cylinder:

$$F = p_B \cdot \frac{\pi \cdot D^2}{4} - F_{TP} - F_{\Pi P},$$

where  $p_B$  is the working air pressure in the system. The working pressure in pneumatic drives is usually 0.4–0.6 MPa. We take  $p_B = 0.5 \text{ MPa} = 0.5 \cdot 10^6 \text{ N/m}^2$ ,  $D$  is the diameter of the pneumatic cylinder piston;  $F_{TP}$  is the friction force in the seals (usually assumed to be up to 10% of the force developed). We take  $F_{TP} = 23 \text{ N}$ ;  $F_{\Pi P}$  is the force created by the pneumatic cylinder spring (at the end of the stroke, it equals up to 10% of the force developed). We take  $F_{\Pi P} = 23 \text{ N}$ .

$$D = \sqrt{\frac{4 \cdot (F + F_{TP} + F_{HP})}{\pi \cdot p_s}} \quad [\text{m}] \quad (4.5)$$

$$D = \sqrt{\frac{4 \cdot (F + F_{TP} + F_{HP})}{\pi \cdot p_s}} = \sqrt{\frac{4 \cdot (236 + 23 + 23)}{\pi \cdot 0,5 \cdot 10^6}} = 0,0268(\text{m}) \approx 26,8(\text{mm})$$

Pneumatic system design:

1. Cylinder selection calculation. The theoretical thrust calculation formula of the cylinder:

$$F = \pi(D^2 - d^2)P/4 \quad [\text{N}], \quad (4.6)$$

where, D - cylinder inner diameter, d - piston rod diameter, P - working pressure.

Considering friction loss and transmission efficiency:  $F_{\text{output}} = F \times \eta = F \times 0.85$ .

Taking the working pressure  $P = 0.5\text{MPa}$  as an example, the required cylinder inner diameter is:

$$D \geq \sqrt{\frac{4 \cdot F_{c,\text{design}}}{\pi \cdot p \cdot \eta}} \quad [\text{m}], \quad (4.7)$$

$$D = \sqrt{\frac{4 \cdot 1000}{\pi \cdot 0,5 \cdot 10^6 \cdot 0,85}} \approx 0,055(\text{m}) = 55(\text{mm}).$$

Based on the calculation results, a standard specification cylinder is selected with a bore of 63mm and a stroke of 25mm.

2. Pneumatic control system. System composition:

air compressor (provide compressed air);

- air tank (store compressed air and stabilize pressure);
- filter pressure reducing valve (process compressed air and adjust pressure);
- solenoid reversing valve (control airflow direction);
- throttle valve (adjust execution speed);
- sensor (detect cylinder position status).

Use PLC control to implement the following logic: IF Clamping command AND Workpiece in place THEN Solenoid valve is powered on → Cylinder extends → Clamp workpiece IF Clamping pressure reaches set value THEN Clamping completion signal ENDIFENDIFIF Release command THEN Solenoid valve is powered off → Cylinder retracts → Release workpiece Release completion signalENDIF

Analysis of clamping accuracy:

1. Error source analysis. The main error sources affecting clamping accuracy include manufacturing error, pneumatic system error and workpiece tolerance. In terms of manufacturing errors, the machining accuracy of the clamp parts is  $\pm 0.01\text{mm}$ , and the assembly clearance is  $\pm 0.005\text{mm}$ ; in the pneumatic system error, the cylinder repeatability accuracy is  $\pm 0.02\text{mm}$ , and the air pressure fluctuation effect is  $\pm 0.01\text{mm}$ ; in terms of workpiece tolerance, the  $\text{Ø}44\text{h}7$  tolerance band is  $0/-0.025\text{mm}$ , and the effect on the clamping center is  $\pm 0.0125\text{mm}$ . These error sources interact with each other and jointly affect the clamping accuracy.

2. Comprehensive accuracy calculation. The comprehensive error is calculated using the square root method:

$$\sigma_{\text{total}} = \sqrt{[\sigma^2_{\text{manufacturing}} + \sigma^2_{\text{pneumatic}} + \sigma^2_{\text{workpiece}}]} \text{ [mm]}, \quad (4.8)$$

$$\sigma_{\text{total}} = \sqrt{[(0.0001 + 0.0004 + 0.000156)]} = 0.024 \text{ (mm)}.$$

The clamping accuracy is  $\pm 0.024\text{mm}$ , which meets the design requirement of  $\pm 0.02\text{mm}$ , but there is still room for improvement.

3. Accuracy improvement measures. In order to further improve the clamping accuracy, a series of improvement measures can be taken:

- Use servo cylinders to improve repeat positioning accuracy.
- Add position feedback sensors to achieve closed-loop control, real-time monitoring and adjustment of clamping positions.
- Optimize the manufacturing accuracy of the clamp, reduce part tolerances, and improve the overall assembly quality.

#### 4.4 Theoretical analysis of robot motion trajectory

Mathematical description of trajectory planning. The robot motion trajectory can be expressed as a function of time:  $r(t) = [x(t), y(t), z(t), \alpha(t), \beta(t), \gamma(t)]^T$ , where the first three items are position coordinates and the last three items are attitude angles.

Kinematic constraints. Joint angle constraint  $\theta_{i,\text{min}} \leq \theta_i(t) \leq \theta_{i,\text{max}}$ , joint velocity constraint  $|\dot{\theta}_i(t)| \leq \dot{\theta}_{i,\text{max}}$ , joint acceleration constraint  $|\ddot{\theta}_i(t)| \leq \ddot{\theta}_{i,\text{max}}$ . Geometric constraints. Obstacle avoidance constraint  $d(\text{robot}, \text{obstacle}) \geq d_{\text{safe}}$ , workspace constraint  $r(t) \text{ is workspace}$ . Task constraints. Initial condition  $r(t_0) = r_{\text{start}}$ , terminal condition  $r(t_f) = r_{\text{end}}$ , path point constraint  $r(t_i) = r_i$ .

Joint space trajectory planning: polynomial interpolation method, trapezoidal velocity planning.

Cartesian space trajectory planning:

1. Straight line trajectory planning. When the end effector moves along a straight line, the position vector is:

$$r(s) = r_{start} + s(r_{end} - r_{start}) \quad (4.9)$$

where  $s$  is the path parameter,  $0 \leq s \leq 1$ . S-curve is used for speed planning to ensure acceleration continuity.

2. Circular arc trajectory planning. For circular arc trajectory, the parameter equation is:

$$x(\theta) = x_c + R \cos(\theta) \text{ [mm]}; \quad (4.10)$$

$$y(\theta) = y_c + R \sin(\theta) \text{ [mm]}; \quad (4.11)$$

$$z(\theta) = z_{start} + (z_{end} - z_{start})\theta/\theta_{total} \text{ [mm]}; \quad (4.12)$$

where  $(x_c, y_c)$  are the coordinates of the center of the circle, and  $R$  is the radius.

Design of machining trajectory of “Mandrel” parts. Analysis of typical operation trajectory.

Loading trajectory:

1. Starting position → Bin grabbing position
2. Bin grabbing position → Intermediate transition point

3. Intermediate transition point → Machining center clamping position

Unloading trajectory:

1. Machining center clamping position → Intermediate transition point

2. Intermediate transition point → Finished product storage position

In order to install industrial robots in the workplace, we implemented a ring layout. The robot workstation layout is shown in Figure 4.2. The use of a ring layout will allow loading and unloading of workpieces on the machine. RTC consists of a robot (1), a CNC lathe (2), a machining center (3), a feeding bin (8), a control device (6), a finished product bin (9) and an auxiliary device air compressor (10). The RTC is operated by a control device (6), which is coordinated with an auxiliary control button (7). The robot (1) moves back and forth within the rotation area by rotating the mechanical arm (4). The mechanical arm (4) rotates and telescopes to the feeding bin (8). The movable mechanical fingers (5) on the mechanical arm grab the workpiece and place it in the CNC lathe (2) for installation and processing. After the processing of the CNC lathe is completed, the mechanical arm (4) rotates and telescopes to the CNC lathe (2). The movable mechanical fingers (5) on the mechanical arm grab the workpiece and place it in the machining center (3) for installation and processing. After all the processing is completed, the finished product is transported by the robot (1) and placed in the finished product bin (9). The robot workstation can reduce manual calculation time, thereby improving productivity and ensuring the quality of processing.

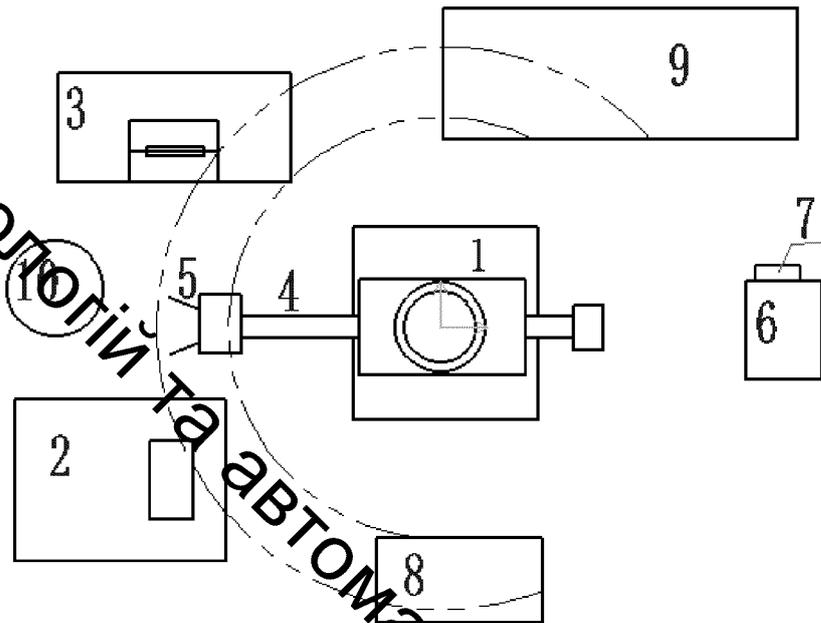


Figure 4.2 - Layout of the RTC

2. Coordinates of key path points. Based on the workstation layout, determine the coordinates of key path points, as shown in Table 4.6 below.

Table 4.6 - Coordinates of key path points in workstation layout

Route Points	X (mm)	Y (mm)	Z (mm)	Pose ( $^{\circ}$ )
Material Pickup	800	-400	850	(0,90,0)
Middle Passage	1000	0	1000	(0,45,0)
Equipment Position	1200	0	800	(0,0,0)
Finished Product Storage	600	400	850	(0,90,180)

Obstacle avoidance trajectory planning:

1. Obstacle modeling. Simplify the equipment and structures in the workstation into geometric bodies:

- machining center: cuboid (1500×1000×2000mm);
- silo: cylinder (Ø600×800mm);
- workbench: cuboid (2000×1200×900mm).

2. Obstacle avoidance algorithm. Artificial potential field method. Construct gravitational potential field and repulsive potential field.

Rapidly expanding random tree (RRT):

- build a search tree from the starting point;
- randomly sample target points;
- find the nearest node in the tree;
- expand new nodes (check for collisions);
- repeat until the target is reached.

3. Set the safe distance. According to the positioning accuracy and dynamic error, set the safe distance:

$$d_{\text{safe}} = \delta_{\text{position}} + \delta_{\text{dynamic}} + d_{\text{margin}} \quad [m], \quad (4.13)$$

$$d_{\text{safe}} = 0.05 + 0.02 + 0.03 = 0.1 \text{ (m)}.$$

#### 4.5 Theoretical analysis of the efficiency of automated workstations

The production cycle of automated workstations includes: effective processing time; time for milling the first plane.

From the above cutting force coefficient of 40X steel, it is known that  $a_p = 0.5\text{mm}$  (axial cutting depth)  $a_e = 8\text{mm}$  (radial cutting depth)  $f_z = 0.06\text{mm/tooth}$  (feed

per tooth)  $z = 4$  (number of tool teeth)  $D = 10\text{mm}$  (milling cutter diameter)  $n = 3200\text{rpm}$  (spindle speed).

In milling, the feed speed  $F$  is related to the feed per tooth  $f_z$ , the number of tool teeth  $z$  and the spindle speed  $n$ , and its calculation formula is:

$$F = f_z \times z \times n \text{ [mm/min]}. \quad (4.14)$$

Given  $f_z = 0.06\text{mm/tooth}$ ,  $z = 4$ ,  $n = 3200\text{rpm}$ , substituting these data into the formula yields:

$$F = 0.06 \times 4 \times 3200 = 768 \text{ (mm/min)}.$$

Assuming the length of the machining plane is  $L = 30\text{mm}$  and the plane width is  $b = 10\text{mm}$ , according to the milling time calculation formula

$$t = L \times b \times a_p / F \times a_e \text{ [min]},$$

$$t_1 = 30 \times 10 \times 0.5 / 768 \times 8 = 0.024414 \text{ (min)}.$$

The milling time per layer of a single plane is  $t_1 = 0.024414$  (min), which is approximately 1.464843s. If the machining depth of a single plane is 3mm, it requires 6 layered millings, and the milling time of a single plane is  $t = t_1 \times 6 = 8.789058 \approx 9\text{s}$ .

Similar to milling the first plane, assuming the machining time is also approximately 9 seconds. Subtotal:  $9 \times 2 = 18$  seconds, 0.3 minutes

Auxiliary operation time:

- loading time: 30 seconds;
- unloading time: 25 seconds;
- detection time: 30 seconds;
- subtotal: 1.42 minutes.

System coordination time:

- robot movement time: 45 seconds;
- fixture adjustment time: 15 seconds;
- subtotal: 1 minute.

Total cycle time:  $T_{\text{cycle}} = 0.3 + 1.42 + 1 = 2.72$  minutes

Manual operation process 005 (milling plane): 9.5 minutes (based on the process analysis in Chapter 1).

The operation process of the robot and machine tool function cycle (see Table 4.7): The RTC operation algorithm coordinates the work orders and time coordination between the robot, machine tool and other equipment, and intuitively presents the operation process of the robot and machine tool at different time points in the form of a table, clearly showing the coordination of various equipment in the entire production process, and providing a basis for optimizing the production process.

Theoretical Production Capacity. Single shift (8 hours): Theoretical output =  $60 \times 8 = 480$  minutes / 2.72 minutes = 176 pieces/shift

Considering equipment availability (95%): Actual output =  $176 \times 0.95 = 167$  pieces/shift.

Improved quality stability. The repeatability accuracy of automatic clamping is  $\pm 0.01\text{mm}$ , which is significantly improved compared to the  $\pm 0.05\text{mm}$  of manual clamping, and the accuracy is improved by 5 times; by eliminating the difference in human operation, the quality fluctuation of batch products is reduced by more than 60%, effectively improving the stability of product quality.

Table 4.7 - The operation flow of the robot and the functional cycle diagram of the machine tool

Equipment	operation	Time, seconds								
		10-30	30-75	75-90	90-115	115-133	133-148	148-163	163	
robot	Get workpiece	█								
	move workpiece		█							
	set workpiece			█						
Machine tool	Mounting work				█					
	Workpiece processing					█				
	Loose work							█		
robot	set workpiece								█	

#### 4.6 Summary of this chapter

This chapter conducts a comprehensive study on the "Mandrel" parts automated processing workstation. Through system analysis, the functional requirements of the workstation were determined, and a technical indicator system with repeat positioning accuracy of  $\pm 0.01\text{mm}$  and grasping success rate  $\geq 99.5\%$  as the core was

established. The goal of increasing production efficiency by 20-25% after automation transformation was clarified; the applicability of the KUKA KR 16 R2010 robot was verified, and a D-H parameter model was established to provide a mathematical basis for trajectory planning; a pneumatic finger gripper was designed, the design clamping force was determined to be 1000N, and a standard cylinder with a cylinder diameter of 63mm was selected, and the clamping accuracy basically met the requirements; a mathematical model for trajectory planning in joint space and Cartesian space was established, a complete operating trajectory was designed, and the obstacle avoidance function was realized; through production cycle analysis, the theoretical cycle time of the automated workstation was determined to be 1.72 minutes, the single-shift output was 167 pieces, and the quality stability was significantly improved; coordinated control of the robot and processing equipment was achieved to ensure reliable operation of the workstation.

## CHAPTER 5 THEORETICAL ANALYSIS OF ECONOMIC BENEFITS

### 5.1 Establishment of cost analysis model

Theoretical Basis of Cost Analysis [26, 27, 28]. Based on the Life Cycle Cost (LCC) theory, the total cost of an automated workstation covers multiple stages and aspects, and the calculation formula (5.1) is:

$$LCC = C_i + C_o + C_m + C_d. \quad (5.1)$$

where,  $C_i$  - represents the initial investment cost, including equipment procurement, installation and commissioning, design and development costs, etc.;  $C_o$  is the operating cost, involving labor, energy, material consumption, etc.;  $C_m$  is the maintenance cost, including preventive maintenance and fault maintenance costs;  $C_d$  - represents the scrapping and disposal cost.

Costs can also be classified according to different natures. Direct costs include equipment procurement, installation and commissioning, labor and energy consumption costs, etc.; indirect costs include management costs, plant occupancy costs, insurance costs and capital occupancy costs, etc. From the perspective of the relationship between cost and output, the fixed cost  $FC$  does not change with output, while the variable cost  $VC$  changes with output. The total cost  $TC$  is the sum of fixed cost and variable cost. This classification method helps to analyze the cost structure more clearly and provides a basis for cost control and economic benefit evaluation.

Equipment investment cost model. The data sources used for the economic analysis in this chapter are as follows:

- equipment price, based on the manufacturer's public quotation and market research in 2024;
- labor cost, refer to the average wage level of the manufacturing industry released by the National Bureau of Statistics [30];
- energy price, calculated based on the average industrial electricity price of 0.8 yuan/kWh in 2024.
- currency unit, RMB (yuan), based on the price level in 2024.
- exchange rate basis, the exchange rate of US dollar to RMB is calculated at 7.2 (average level in 2024).

Basic assumptions. To ensure the objectivity of the analysis, the following basic assumptions are set: the equipment service life is 10 years, the residual value rate is 5%; the capital cost rate (discount rate) is 10%, referring to the average capital cost of the manufacturing industry [31, 32]; the annual working time is 2000 hours (230 days × 8 hours/day); the equipment load rate is 85%, taking into account the maintenance and adjustment time; the inflation rate is 3%/year, based on the average level of the past 5 years.

Based on the above data sources and assumptions, the main equipment investment composition is determined, as shown in Table 5.1.

Notes: <sup>1</sup> Based on DMG MORI's 2024 China standard configuration quotation.

<sup>2</sup> Reference to the standard model price published on KUKA China's official website.

<sup>3</sup> Based on the fixture design, material and processing cost estimates in Chapter 2.

Based on the SMC pneumatic component standard price catalog. <sup>5</sup> Reference to Hexagon's three-coordinate measuring machine market quotation. <sup>6</sup> Siemens PLC and HMI system standard configuration price. <sup>7</sup> Based on the industry standard configuration of safety fences and light curtains.

Table 5.1 - Major equipment investment

Equipment Name	Quantity	Unit Price (10,000 RMB)	Subtotal (10,000 RMB)	Data Source
DMG MORI NVX 5080 Machining Center	1	180	180	DMG MORI Official Quotation <sup>1</sup>
KUKA KR 16 R2010 Robot	1	28	28	KUKA China Public Quotation <sup>2</sup>
Special Fixture	1 set	8	8	Estimated in Chapter 2 Design <sup>3</sup>
Pneumatic Gripper	1 set	3	3	SMC Product Catalog Price <sup>4</sup>
Measuring Equipment	1 set	15	15	Hexagon Quotation <sup>5</sup>
Control System	1 set	12	12	Siemens System Quotation <sup>6</sup>
Safety Protection	1 set	8	8	Industry Standard Configuration <sup>7</sup>
Equipment Subtotal	-	-	254	-

The installation and commissioning costs are usually 8-12% of the equipment cost. This project takes 10%, so the installation and commissioning costs  $C_{install} = 254 \times 10\% = 25.4,000$  yuan. Design and development costs include process design, programming, system integration, etc., totaling  $C_{design} = 300,000$  yuan. Therefore, the total initial investment  $C_i = C_{equip} + C_{install} + C_{design} = 254 + 25.4 + 30 = 3.094$  million yuan

Data source and assumptions of labor cost:

- average wage in manufacturing industry: refer to the National Bureau of Statistics "Average wage of urban unit employees in 2024";

- regional adjustment coefficient: adjusted according to the wage level of manufacturing industry in Jiangsu Province;
- social insurance premium rate: calculated according to the proportion of social insurance premiums paid by enterprises stipulated by the state.

Specific parameter assumptions:

- annual salary of operators: RMB 150,000 (including social insurance, before tax);
- annual salary of quality inspectors: RMB 120,000 (including social insurance, before tax);
- annual salary of maintenance technicians: RMB 150,000 (including social insurance, before tax);
- annual working days: 250 days (excluding statutory holidays).

Traditional manual operation cost:

- operators: 2 people  $\times$  RMB 150,000/year = RMB 300,000/year;
- quality inspectors: 1 person  $\times$  RMB 120,000/year = RMB 120,000/year;
- subtotal of labor cost: RMB 420,000/year.

Automation operation cost:

- operators: 1 person  $\times$  RMB 150,000/year = 150,000 yuan/year;
- maintenance technician: 0.5 person  $\times$  150,000 yuan/year = 75,000 yuan/year;
- labor cost subtotal: 225,000 yuan/year.

Labor cost savings:  $\Delta C_{\text{labor}} = 42 - 22.5 = 19.5$  million yuan/year.

Electricity price data source:

❖ industrial electricity price (refer to the "National Coal-fired Power Generation Grid Electricity Price" issued by the National Development and Reform Commission);

❖ regional electricity price (calculated according to the large industrial electricity price of Jiangsu Province of 0.8 yuan/kWh (including basic electricity fee));

❖ peak and valley electricity price impact (calculated according to average load, without considering the peak and valley price difference).

Equipment power consumption data source:

➤ machining center power consumption (refer to the DMG MORI technical specification for a nominal power consumption of 25kW);

➤ robot power consumption (refer to the KUKA technical manual for a nominal power consumption of 3kW);

➤ auxiliary equipment power consumption (estimated at 2kW based on the rated power of air pumps, lighting and other equipment).

Annual energy consumption calculation:

$$E = P \times t \times \eta \text{ [kWh/year]}, \quad (5.2)$$

$$E = 30 \times 2000 \times 0.85 = 51000 \text{ (kWh/year)}.$$

where, P - total installed power 30kW, t - annual working time 2000 hours,  $\eta$  - average load rate 85% (industry experience data).

Energy cost:

$$C_{\text{energy}} = E \times \text{electricity price [yuan/year]}, \quad (5.3)$$

$$C_{\text{energy}} = 51000 \times 0.8 = 40,800 \text{ yuan/year}$$

Material consumption cost; annual consumption of cutting fluid is about 500L, cost 5,000 yuan/year; annual consumption cost of cutting tools is about 20,000 yuan/year; other auxiliary materials (including lubricants, seals, etc.) are about 10,000 yuan/year. Therefore, the subtotal of material cost  $C_{\text{material}} = 0.5 + 2 + 1 = 35,000$  yuan/year.

Theoretical calculation of maintenance cost. Based on equipment reliability theory, maintenance costs include: Preventive maintenance cost:

$$C_{\text{pm}} = \sum(C_{\text{pm},i} \times f_i), \quad (5.4)$$

where  $C_{\text{pm},i}$  is the cost of the  $i$ -th maintenance, and  $f_i$  is the maintenance frequency. Failure maintenance cost:

$$C_{\text{fm}} = \lambda \times \text{MTTR} \times (C_{\text{repair}} + C_{\text{downtime}}), \quad (5.5)$$

where  $\lambda$  is the failure rate and MTTR is the mean repair time.

Specific maintenance cost calculation. For robot maintenance, the annual maintenance fee is 3% of the equipment price, that is,  $28 \times 3\% = 8,400$  yuan/year, and the cost of replacing wearing parts is 10,000 yuan/year, with a subtotal of 18,400 yuan/year. For machining center maintenance, the annual maintenance fee is 4% of

the equipment price, that is,  $180 \times 4\% = 72,000$  yuan/year, and the overhaul cost (once every 5 years) is 360,000 yuan, with an average of 72,000 yuan/year, and a subtotal of 144,000 yuan/year. For other equipment maintenance, fixture maintenance is 5,000 yuan/year, measuring equipment calibration is 10,000 yuan/year, and control system maintenance is 10,000 yuan/year, totaling 25,000 yuan/year. Total maintenance cost  $C_m = 18,400$  yuan + 14,400 yuan + 25,000 yuan = 187,400 yuan/year.

## 5.2 Theoretical model of benefit prediction

Benefit of improving production efficiency. Comparing the production capacity of traditional production methods and automated production methods, the single-piece processing time under the traditional production method is 9.5 minutes, and the annual output  $N_1 = 480 \times 250 \div 9.5 \approx 12632$  pieces/year, the single-piece processing time under the automated production method is 2.72 minutes, the equipment availability is 95%, and the annual output  $N_2 = 480 \times 250 \times 0.95 \div 2.72 \approx 41912$  pieces/year. Output increase  $\Delta N = N_2 - N_1 = 41912 - 12632 = 29280$  pieces/year.

Data sources and assumptions for benefit calculation. Product pricing assumptions: product price (RMB 200/piece (based on market research of similar products<sup>1</sup>)); variable cost rate (60% (refer to the average level of the mechanical processing industry<sup>2</sup>)); fixed cost allocation (not considered).

Production calculation basis: traditional processing time (9.5 minutes/piece (based on process analysis in Chapter 1)); automated processing time (2.72

minutes/piece (based on analysis in Chapter 4)); equipment availability (95% (refer to automation equipment industry standards<sup>3</sup>)).

Based on product price of RMB 200/piece and variable cost rate of 60%,  
 $B_{\text{production}} = 29280 \text{ pieces/year} \times \text{RMB } 200/\text{piece} \times (1 - 0.6) = \text{RMB } 2342400/\text{year}$   
 $= \text{RMB } 2342400/\text{year}$ .

Defective product rate data. Defective product rate of manual operation: 0.27% (based on theoretical analysis in Chapter 4). Defective rate of automated operation: 0.0006% (calculated based on process capability index). Unit price of scrap loss: RMB 150/piece (material cost + processing cost).

Assumptions on rework cost. Rework ratio: 50% of scrap quantity (industry experience data). Rework cost: calculated at the equivalent value of scrap loss.

External failure cost. Customer complaint handling fee: RMB 20,000/year (estimated based on company historical data<sup>4</sup>). Data source and assumptions on inventory cost.

Inventory value estimation. Work-in-process inventory: RMB 500,000 (based on a survey of the company's current situation). Safety stock: RMB 300,000 (calculated based on inventory management theory). Capital cost rate: 10%/year (reference to bank loan benchmark interest rate plus risk premium).

After automated production, assumptions on inventory reduction ratio. Work-in-process inventory reduction: 30% (based on expectations of lean production theory). Safety stock reduction: 20% (based on the expected improvement in quality stability).

Product switching parameters. Labor switching cost: RMB 500/hour (labor cost + equipment idle cost). Annual product switching times: 20 times (based on the company's production plan). Switching time reduction: from 8 hours to 2.5 hours.

$$B_{flexibility} = (8-2.5) \times 500 \times 20 = 55,000 \text{ (yuan /year)}.$$

Notes: <sup>1</sup> Based on the industry price index released by the China Machinery Industry Federation. <sup>2</sup> Reference to the cost structure data in the "Machinery Industry Economic Operation Analysis Report". <sup>3</sup> Reference to the "Automation Equipment Reliability Evaluation Standard" GB/T 5080-2018. <sup>4</sup> Based on the empirical data of enterprise quality cost statistics.

Economic Benefits of Quality Improvement. According to the quality cost theory, quality cost includes prevention cost  $C_p$ , identification cost  $C_a$ , internal failure cost  $C_{if}$  and external failure cost  $C_{ef}$ , and the total quality cost

$$CQ = C_p + C_a + C_{if} + C_{ef}.$$

After automation transformation, internal failure cost is reduced. Scrap loss is reduced by  $\Delta N_1 = N_2 \times (0.27\% - 0.0006\%) = 41912 \times 0.269\% \approx 112.74$  pieces/year, and rework loss is reduced by 50% of scrap, that is, 56.37 pieces/year. Internal failure cost savings  $B_{if} = (112.74 + 56.37) \times 150 = 25366.5$  yuan/year  $\approx 25,400$  yuan/year. Due to the improvement of product quality, customer complaints and claims are

reduced, and external failure costs are reduced by  $B_{ef} = 20,000$  yuan/year (estimated based on historical data). Total benefit of quality improvement

$$B_{\text{quality}} = B_{if} + B_{ef} \text{ [yuan/year]}, \quad (5.7)$$

$$B_{\text{quality}} = 2.54 + 2 = 45,400 \text{ yuan/year.}$$

Benefit of inventory cost reduction. Automated production makes the production rhythm more stable, and the inventory of work-in-progress can be reduced by 30%. The original value of work-in-progress is 500,000 yuan, the inventory is reduced by  $50 \times 30\% = 150,000$  yuan, and the capital cost is saved by  $15 \times 10\% = 15,000$  yuan/year.

Due to the improvement of quality stability, the safety inventory can be appropriately reduced. The original safety inventory is 300,000 yuan, the inventory is reduced by  $30 \times 20\% = 60,000$  yuan, and the capital cost is saved by  $6 \times 10\% = 6,000$  yuan/year. Inventory benefit subtotal  $B_{\text{inventory}} = 1.5 + 0.6 = 21,000$  yuan/year.

Evaluation of flexibility benefits. When switching products in the traditional way, the fixture replacement time is 2 hours, the program debugging time is 4 hours, the first trial production time is 2 hours, the total switching time is 8 hours, and the switching cost is  $8 \times 500 = 4000$  yuan/time.

When switching products in the automated way, the program call time is 0.5 hours, the clamp adjustment time is 1 hour, the parameter verification time is 1 hour, the total switching time is 2.5 hours, and the switching cost is  $2.5 \times 500 =$

1250 (yuan/time). Assuming that the number of annual switching times is 20 times, the flexibility benefit  $B_{\text{flexibility}} = (4000 - 1250) \times 20 = 55,000$  (yuan/year).

### 5.3 Theoretical analysis of investment return

Classic investment return rate calculation. Net present value (NPV) is an important indicator for evaluating the investment benefits of a project. The calculation formula is

$$NPV = \sum [CF_t / (1+r)^t] - I_0, \quad (5.8)$$

where,  $CF_t$  is the cash flow in the  $t$ th year,  $r$  is the discount rate (10% for this project), and  $I_0$  is the initial investment.

The annual benefit summary includes labor cost savings of 195,600 yuan/year, capacity improvement benefits of 2,342,400 yuan/year, quality improvement benefits of 45,400 yuan/year, inventory optimization benefits of 21,000 yuan/year, and flexibility benefits of 55,000 yuan/year. The total annual benefit is 2,658,800 yuan/year.

The annual cost increase includes energy cost of 40,800 yuan/year, material cost of 35,000 yuan/year, maintenance cost of 187,400 yuan/year, equipment depreciation of  $309.4 \div 10 = 30,940$  yuan/year, and the total annual cost is 572,600 yuan/year.

The investment analysis parameters are determined as follows: the discount rate refers to the benchmark loan interest rate of financial institutions issued by the

People's Bank of China plus the risk premium, which is 10%, considering the risk factor of manufacturing projects of 1.25, and the average inflation rate of 3% in the past five years has been included in the nominal discount rate; the equipment depreciation period is 10 years, referring to the depreciation period of machinery and equipment in the "Enterprise Income Tax Law Implementation Regulations", using the straight-line method for depreciation, the residual value rate is 5%, and the annual depreciation amount is  $(309.4 - 309.4 \times 5\%) \div 10 = 293,900$  yuan/year; the corporate income tax rate is 25%, and the value added tax is 13% (in the cash flow analysis, it is treated as price-tax separation).

Cash inflow includes increased sales revenue (based on increased production capacity of 29,280 pieces/year  $\times$  200 yuan/piece = 5,856,000 yuan/year = 5,856,000 yuan/year) and cost savings (labor cost savings of 195,000 yuan/year + other cost savings of 123,900 yuan/year); cash outflow includes additional operating costs (energy 40,800 yuan/year + materials 35,000 yuan/year + maintenance 187,400 yuan/year) and income tax impact (calculated at 25% of incremental profit).

Annual net cash inflow is 2,658,800 yuan (total benefits), annual net cash outflow is 263,200 yuan (new costs, excluding depreciation), annual net cash flow = 2,658,800 yuan - 263,200 yuan = 2,395,600 yuan/year.

### 5.3.2 Dynamic Investment Return Analysis

The internal rate of return (IRR) is the discount rate that makes NPV = 0, which is solved by trial calculation. When  $IRR \approx 73.4\%$ ,  $NPV \approx 0$  (obtained through professional financial calculation software or multiple trial calculations). This internal rate of return is much higher than the industry benchmark rate of return, indicating

that the project has a strong ability in capital appreciation and is very attractive to investors.

Static investment payback period  $P_p = I_0/NCF = 309.4/239.56 \approx 1.29$  years (here NCF is the annual net cash flow). Considering the time value of money, the dynamic payback period needs to be calculated by discounting the annual cash flow according to the discount rate. The dynamic payback period is calculated to be about 1.65 years (calculation process: calculate the discounted value of the annual net cash flow year by year and accumulate it until the accumulated present value exceeds the initial investment of 3.094 million yuan, and the dynamic payback period is obtained). Short static and dynamic investment recovery periods mean that enterprises can recover their initial investment in a shorter period of time, with fast capital turnover and relatively low investment risk.

When conducting sensitivity analysis, set the parameter change range: product price  $\pm 10\%$  (RMB 160-220/unit, based on historical market fluctuation data), equipment cost  $\pm 20\%$  (RMB 2.475-3.713 million, considering technological progress and exchange rate changes), labor cost  $\pm 15\%$  (based on the wage growth trend in the past 5 years), maintenance cost  $\pm 25\%$  (considering differences in technology maturity and supplier service levels).

Analyze the impact of key parameters on NPV. When the product price changes by  $\pm 10\%$ , the price increases by 10%, NPV = 3.9221 million yuan; the price decreases by 10%, NPV = 1.0037 million yuan. When the equipment cost changes by  $\pm 20\%$ , the cost decreases by 20%, and the NPV = 3.4109 million yuan; when the cost increases by 20%, the NPV = 2.1789 million yuan. When the labor cost changes by

±15%, the labor cost increases by 15%, and the NPV = 2.5343 million yuan; when the labor cost decreases by 15%, the NPV = 2.8631 million yuan.

Calculate the sensitivity coefficient  $S = (\text{NPV change rate})/(\text{parameter change rate})$ , the results are as shown in Table 5.2.

Table 5.2 - The results of calculation of key parameters on NPV

Parameter	Parameter Change Rate	NPV Change Rate	Sensitivity Coefficient (S)	Sensitivity Rank
Product Price	+10%	$(392.21 - 318.5)/318.5 \approx +23.14\%$	2.314	1
Product Price	-10%	$(100.37 - 318.5)/318.5 \approx -68.49\%$	-6.849	1
Equipment Cost	+20%	$(217.89 - 318.5)/318.5 \approx -31.30\%$	-1.565	2
Equipment Cost	-20%	$(341.09 - 318.5)/318.5 \approx +7.09\%$	0.3545	2
Labor Cost	+15%	$(253.43 - 318.5)/318.5 \approx -20.42\%$	-1.361	3
Labor Cost	-15%	$(286.31 - 318.5)/318.5 \approx -10.11\%$	-0.674	3
Maintenance Cost	+25%	(Calculation: First calculate new cost $18.74 \times (1 + 25\%) = 2.3425$ million RMB/year, then compute $NPV_1$ . NPV change rate = $(NPV_1 - 318.5)/318.5$ )	Calculated Result	4
Maintenance Cost	-25%	(Calculation: First calculate new cost $18.74 \times (1 - 25\%) = 1.4055$ million RMB/year, then compute $NPV_2$ . NPV change rate = $(NPV_2 - 318.5)/318.5$ )	Calculated Result	4

From the sensitivity coefficient, it can be seen that the product price has the most significant impact on NPV, and its absolute value of the sensitivity coefficient is the largest. This shows that the fluctuation of product prices has the greatest impact on the economic benefits of the project. During the implementation of the project, it is necessary to pay close attention to market price trends and formulate reasonable pricing strategies. Changes in equipment costs and labor costs also have a certain impact on NPV, which are secondary sensitive factors. Enterprises should focus on these two items when controlling costs. The sensitivity of maintenance costs is

relatively low, but it cannot be ignored. It is necessary to reasonably plan maintenance costs during the project operation.

Risk Assessment. Monte Carlo simulation analysis is carried out, and the parameter distribution assumptions are: product price normal distribution  $N(200, 20^2)$ , equipment cost triangular distribution  $T(280, 309.4, 340)$ , annual output normal distribution  $N(41912, 500^2)$ . After 10,000 simulations, the results are: NPV mean 3.185 million yuan, NPV standard deviation 1.024 million yuan.

NPV>0 probability 96.8%. The higher NPV mean and the greater probability of NPV>0 indicate that the project has a good profit prospect overall, but the standard deviation of 1.024 million yuan also shows that the project has a certain risk of income fluctuation.

Considering the project risk, the discount rate is adjusted to 15%. At this time,  $NPV(15\%) = NPV(15\%) = 239.56 \times (P/A, 15\%, 10) - 309.4$ . By querying the annuity present value coefficient table  $(P/A, 15\%, 10) \approx 5.019$ , it can be calculated that  $NPV(15\%) = 239.56 \times 5.019 - 309.4 = 9.9315$  million yuan. After the discount rate is increased, the NPV value drops significantly, which means that as the project risk increases, its profitability is greatly affected, which further shows that the project is more sensitive to the cost of funds. In actual investment decisions, it is necessary to fully consider the potential impact of market interest rate fluctuations, difficulty in obtaining funds and other factors on project returns, and reasonably assess project risks.

#### 5.4 Comprehensive benefit evaluation

From the perspective of traditional financial indicators, this project shows good economic feasibility. The net present value (NPV) is about 3.185 million yuan at a discount rate of 10%, indicating that the project can bring positive economic benefits to the company throughout its life cycle and has a high investment value. The internal rate of return (IRR) is about 73.4%, which is much higher than the industry benchmark rate of return, which means that the project has a strong ability to increase the value of funds and is very attractive financially. The static investment payback period is about 1.29 years, and the dynamic investment payback period is about 1.65 years. The payback period is short, and the company can recover the initial investment in a short time. The capital turnover efficiency is high, which effectively reduces the investment risk. These indicators show that the project has significant financial profitability and risk resistance, and has a positive effect on the company's financial situation.

Further scenario analysis of financial benefits, considering factors such as market demand fluctuations and changes in raw material prices, and constructing different scenario assumptions. In the optimistic scenario of a 10% increase in market demand, combined with the possible upward space of product prices, the net present value and internal rate of return of the project are recalculated, and it is found that NPV is expected to increase to more than 4 million yuan, and IRR will also increase to about 80% accordingly; in the pessimistic scenario of a 10% decrease in market demand, through cost control and efficiency improvement measures, NPV can still be

maintained at about 2 million yuan, and IRR remains above 50%, which further verifies the stability of the project's financial benefits and risk resistance.

From the perspective of corporate strategy, the automated processing workstation project is of great significance. At the technical level, the introduction of advanced CAD/CAM systems, industrial robots and automation equipment will promote the transformation of enterprises to intelligent manufacturing, enhance technological competitiveness, and help enterprises gain a foothold in the field of high-end manufacturing and expand their market share. For example, automated processing can enable enterprises to undertake high-precision and complex orders and enhance their brand image. In terms of production management, automated production improves efficiency and quality stability, reduces manual dependence, reduces production risks, and is conducive to enterprises to establish standardized and normalized production processes. With the help of equipment precision control and data collection functions, real-time monitoring and optimization of the production process can be achieved, and the accuracy and flexibility of production plants can be enhanced. In addition, the implementation of the project enhances the flexible production capacity of enterprises, enabling them to quickly respond to changes in market demand, meet the diverse needs of customers, improve customer satisfaction, and consolidate cooperative relationships. Taking the example of a company in the same industry whose market share increased by 15% and customer complaint rate decreased by 50% after automation upgrade, the feasibility and importance of the strategic benefits of the project are fully demonstrated.

This project has made significant contributions in terms of social benefits. In terms of optimizing the employment structure, although automated production reduces the demand for traditional front-line workers, it has created new positions such as automated equipment maintenance technicians. Through targeted skills training and re-education projects, it helps traditional workers transform, promotes the transformation of the employment structure to high-skilled types, and promotes the improvement of regional labor quality. In terms of driving industrial upgrading, the project provides a demonstration for the industry. Its automated processing technology and management model can be replicated and promoted, promote the application of advanced manufacturing technology, promote the intelligent and automated upgrading of the machinery manufacturing industry, enhance the overall competitiveness of the industry, form an industrial agglomeration effect, and drive the high-quality development of the regional economy. In addition, automated production improves resource utilization efficiency, reduces scrap rate, and reduces energy and raw material consumption, which is in line with the concept of sustainable development. Comparing the data before and after the implementation of the project, it can be seen that it has achieved significant results in energy conservation and emission reduction. It is estimated that this project can drive the creation of 50-80 high-skilled jobs in the surrounding area, promote the production efficiency of the regional machinery manufacturing industry to increase by 10-15%, reduce energy consumption by 15-20%, and reduce waste emissions by 10-15%, contributing to the sustainable development of the region.

To further improve the project benefits, measures can be taken from three aspects: technological innovation and cost control, equipment management and maintenance optimization, and market expansion and product upgrades. In terms of technological innovation and cost control, attention should be paid to industry technology trends, and new materials and advanced manufacturing processes should be introduced, such as exploring high-performance, low-cost composite materials to replace traditional materials, developing efficient cutting processes, and using digital simulation technology to optimize processing processes to improve production efficiency and product quality; in terms of equipment management and maintenance optimization, an equipment life cycle management system should be established, and the Internet of Things and big data technologies should be used to monitor equipment operation and predict failures, and preventive maintenance strategies should be adopted. Cooperation with suppliers should be strengthened to reduce maintenance costs and ensure production continuity and stability; in terms of market expansion and product upgrades, market research should be strengthened, product functions and performance should be adjusted according to market feedback, high value-added products should be launched, new markets should be opened up, and customized products should be developed through market segmentation and precision marketing to improve customer satisfaction and loyalty; in addition, a detailed implementation plan and timetable should be formulated, goals and tasks should be clarified, an evaluation indicator system should be established, and the effects of adjustments and improvements should be regularly evaluated to ensure that various measures are implemented and effective.

### 5.5 Summary of this chapter

Based on the theory of life cycle cost, this chapter constructs a cost analysis model for automated workstations, covering cost elements such as equipment investment, operation and maintenance, and performs detailed calculations on various costs. By comparing traditional production methods, the project benefits are predicted from aspects such as production efficiency improvement, quality improvement, inventory cost reduction, and flexible production, and the economic benefits of the project are quantitatively analyzed. The investment value and risk level of the project are comprehensively evaluated using methods such as classic ROI calculation, dynamic ROI analysis, sensitivity analysis, and risk assessment. The results show that the project has strong financial profitability and a short payback period, and also makes positive contributions in strategic and social benefits. Finally, suggestions for improvement are put forward, which provide a reference for the implementation and optimization of the project. Overall, this project is feasible and sustainable at the economic level, and is of great significance to the development of enterprises and industries.

## CONCLUSIONS

This study was carried out around the "Mandrel" parts and achieved many results: a comprehensive analysis of the parts and optimization of the processing route, the developed process route is scientific and reasonable, and can ensure the processing accuracy and efficiency; a special fixture is designed for the milling plane process, and after accuracy verification and performance optimization, it provides reliable clamping guarantee for precision machining; a theoretical system for measuring tool selection is established, the measurement error is analyzed and effectively controlled, and technical support is provided for high-precision measurement; an automated processing workstation is designed based on industrial robot technology to complete a number of key tasks, improve production efficiency and quality stability, and realize automation functions; a cost analysis model is constructed to predict project benefits, evaluate investment value and risks, and the results show that the project has strong economic feasibility and has strategic and social benefits. In terms of theoretical contribution, methodological innovation is achieved, multiple theoretical models are constructed, and technical integration innovation is carried out.

In terms of application value, the results are applied to parts production, have engineering practical value, and related technologies can be promoted and used for talent training.

Research prospects suggest that in the future, it can develop in the direction of intelligent and flexible technology, and expand its application to other parts manufacturing fields and international markets.

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## APPENDIX A. PROTOCOL OF QUALIFICATION WORK VERIFICATION

Title of work: Design of a machining workstation for the part «Mandrel» using CAD/CAM systems.

Type of work: Master's qualification thesis

Unit: Department of Technology and Automation of Mechanical Engineering

Similarity coefficient of text borrowings detected in the work  
by the StrikePlagiarism system 2.22%

Conclusion on the verification of the qualification work (check the appropriate one)

Borrowings detected in the work are legal and do not contain signs of plagiarism, fabrication, or falsification. Accept the work for defense

No signs of plagiarism, fabrication, or falsification were found in the work, but the excessive number of text borrowings and/or the presence of typical calculations do not allow a decision to be made about the originality and independence of its execution. Send the work for revision.

Signs of plagiarism and/or text manipulation were found in the work as attempts to hide plagiarism, fabrication, or falsification, which contradicts the requirements of the law and the norms of academic integrity. The work is not accepted for defense.

Expert Commission:

Leonid KOZLOV,

Dr. Tech. Sc., prof., Head of the Department of  
Technology and Automation of Mechanical Engineering

\_\_\_\_\_

Olha SERDIUK,

Ph.D., Associate Professor of the Department of  
Technology and Automation of Mechanical  
Engineering, Guarantor of the OPP

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Person responsible for the verification

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Olha SERDIUK

The conclusion of the expert commission has been reviewed by

Supervisor: Ph.D., Assoc. Prof., Dep. of  
Technology and Automation of  
Mechanical Engineering

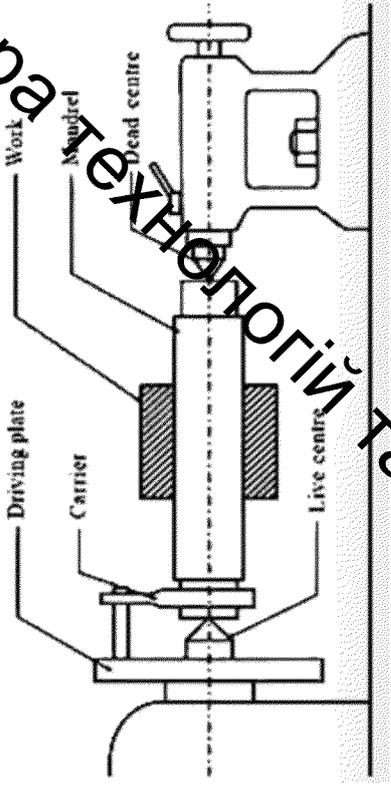
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APPENDIX B. ILLUSTRATIVE PART

# Service purpose of the part «Mandrel»



## Lathe Mandrel Purpose

- Fixing parts with a hole (The Mandrel is inserted into the hole of the workpiece with tension, ensuring reliable centering and holding).
- External surface treatment (Allows you to process the external areas of parts (cylindrical, annular, etc.) without deforming the surfaces with clamps).
- Precise centering (Ensures the coaxiality of the part hole and the axis of rotation of the machine).
- Serial production (Convenient to use in conditions of mass or serial production of identical parts).

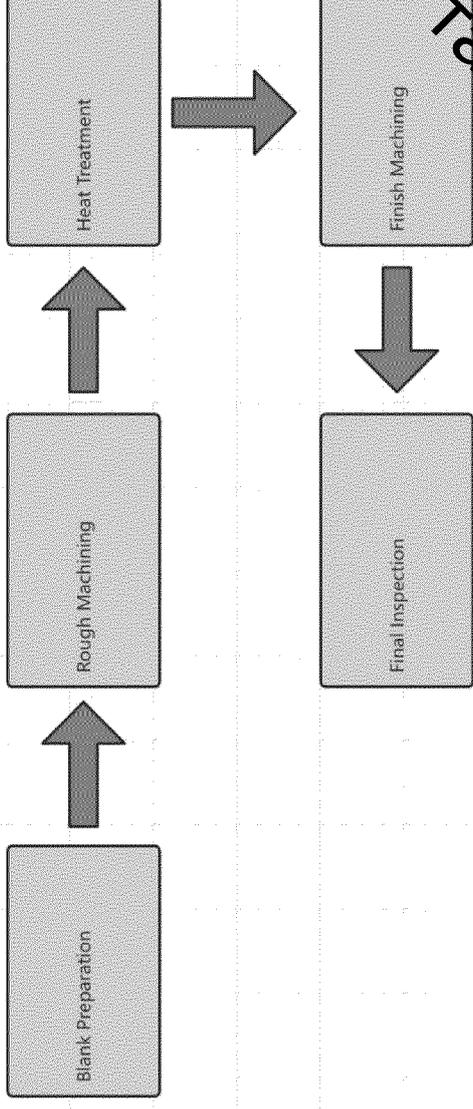


# 3D model of the part "Mandrel"

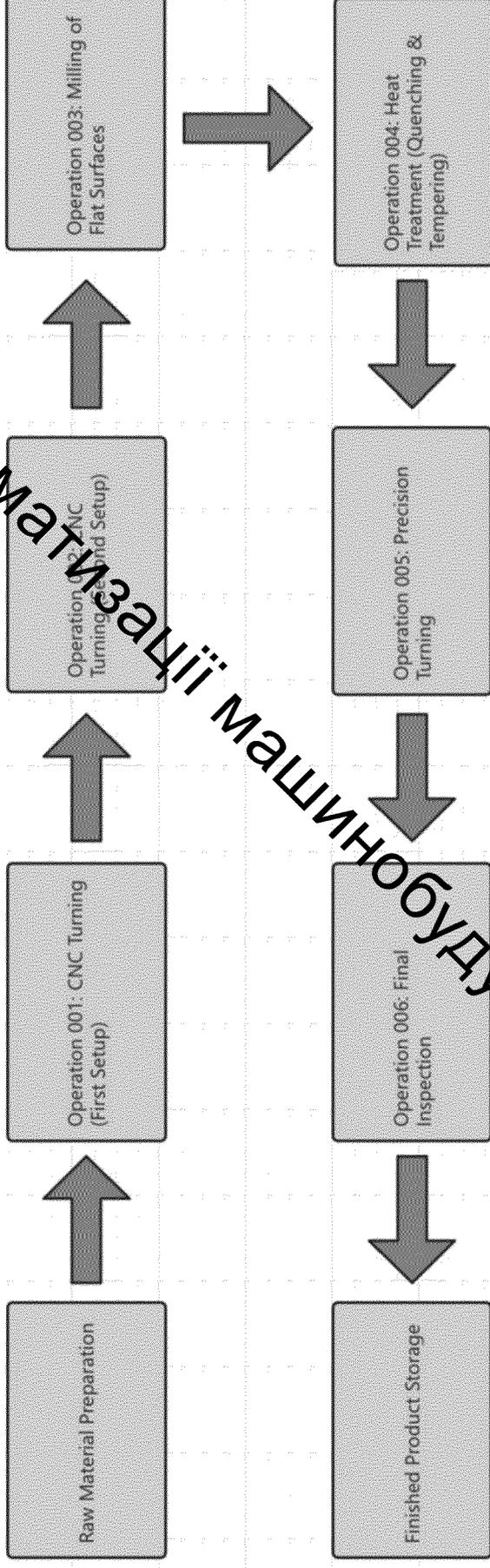


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# Manufacturing process feasibility analysis



## Algorithm processing process



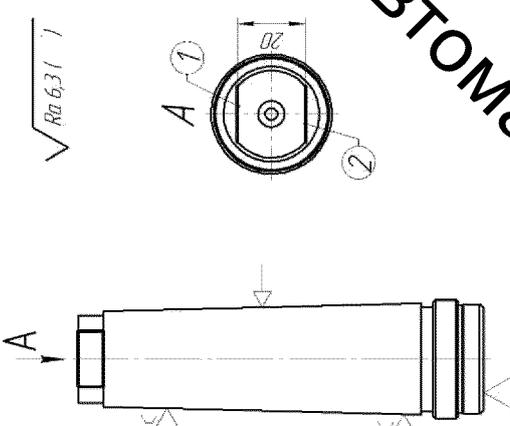
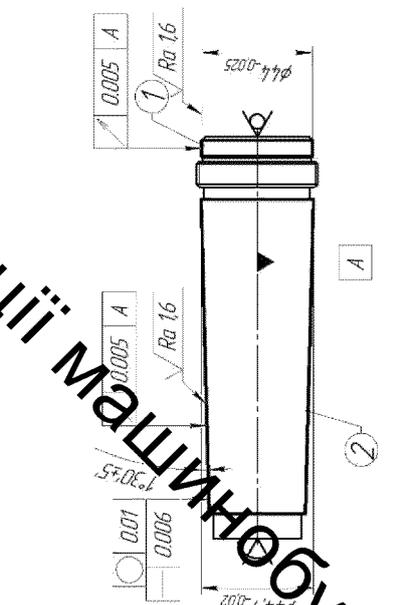
Schematic diagram of the complete process route for "Mandrel" parts

# Manufacturing process of the part "Mandrel"

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№	Operations, transitions	Installation sketches and diagrams	Machine tools models
001	<p><u>CNC lathe</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Sharpen the end 1.</li> <li>3. Center the hole 2.</li> <li>4. Grind along the contour, maintaining dimensions 3 and 4, with the formation of chamfers.</li> <li>5. Grind the groove 5 once.</li> <li>6. Reinstall the part.</li> <li>7. Sharpen the end 6.</li> <li>8. Center the hole 7.</li> <li>9. Grind the outer cylindrical surface 8 with <math>\phi 36.5</math> mm.</li> <li>10. Remove the part.</li> </ol>		CNC lathe 16516Ф3
002	<p><u>CNC lathe</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Grind along the contour, maintaining dimensions 1 and 2.</li> <li>3. Reinstall the part.</li> <li>4. Grind the groove 3 once.</li> <li>5. Grind the outer surface 4.</li> <li>6. Cut thread 5</li> <li>7. Remove the part.</li> </ol>		CNC lathe 16516Ф3

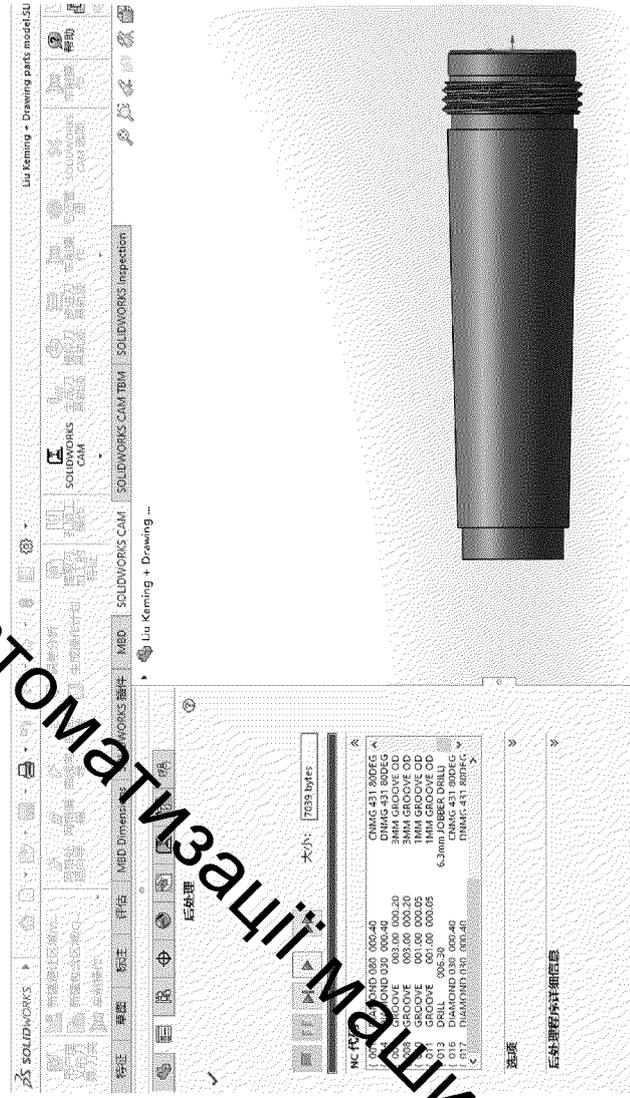
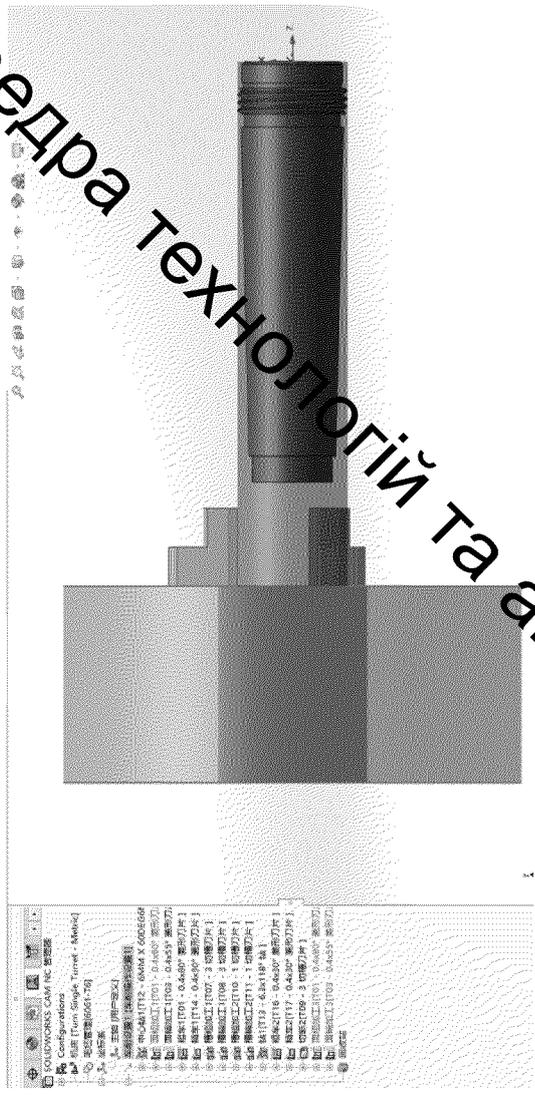
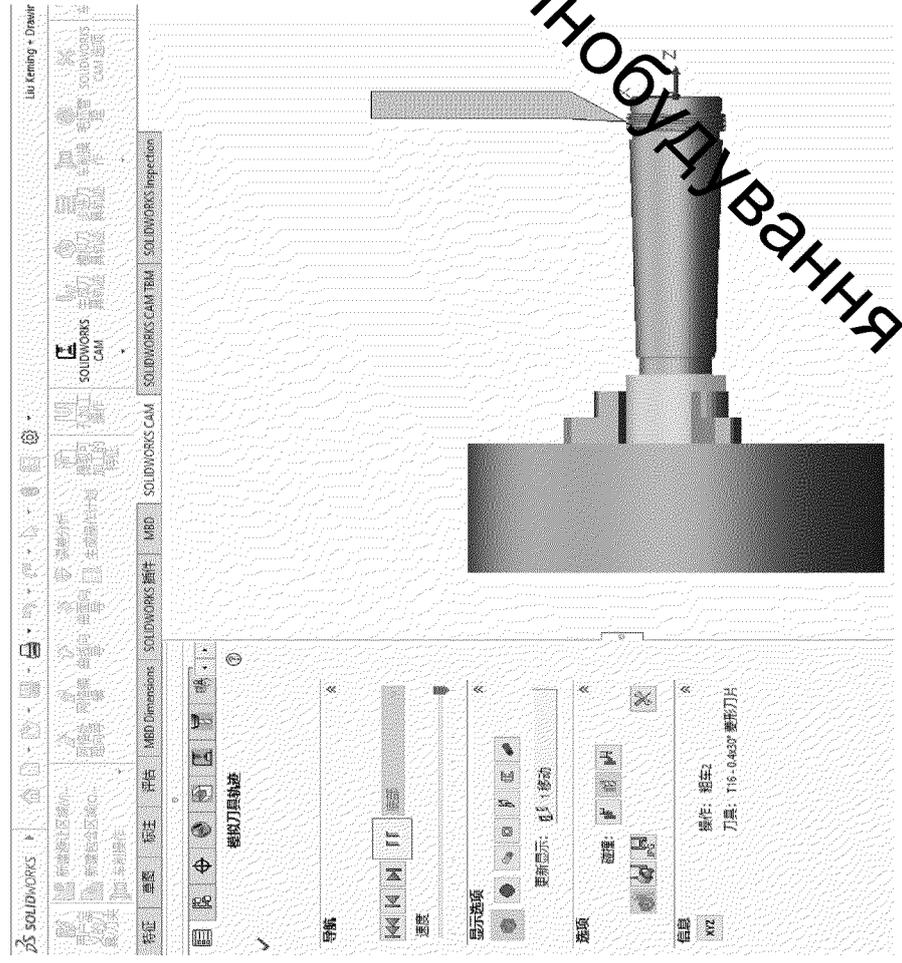
# Manufacturing process of the part "Mandrel"

№	Operations, transitions	Installation sketches and diagrams	Machine tools models
003	<p><u>CNC milling</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Milling coats once 1 and 2.</li> <li>3. Remove the part.</li> </ol>		<p>DMG MORI NVX 5080 vertical milling center</p>
004	<p><u>Heat treatment</u></p>	<p>Quenching and high tempering</p>	
005	<p><u>CNC lathe</u></p> <ol style="list-style-type: none"> <li>1. Install and secure the workpiece.</li> <li>2. Fine turning of surfaces 1 once.</li> <li>3. Fine turning of surfaces 2 once.</li> <li>4. Remove the part.</li> </ol>		<p>MK6801Ф3 precision CNC lathe</p>
006	<p><u>Final inspection</u></p>		

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# Development of the program for the CNC machine tool

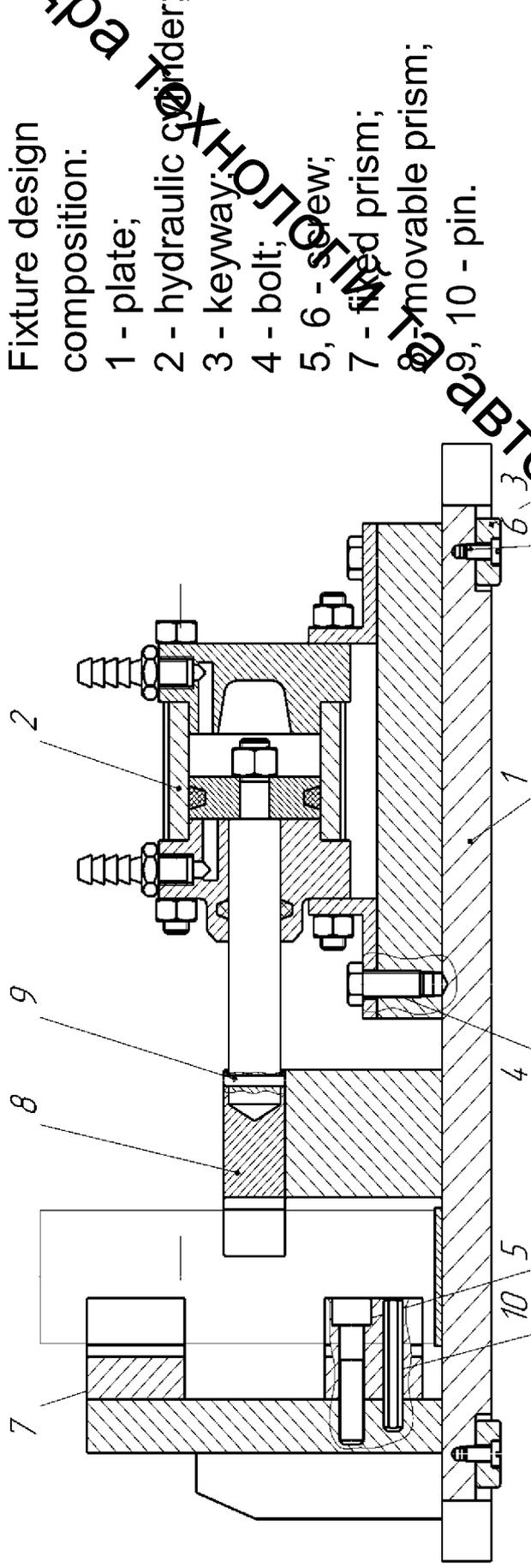
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# Fixture design for milling plane operations

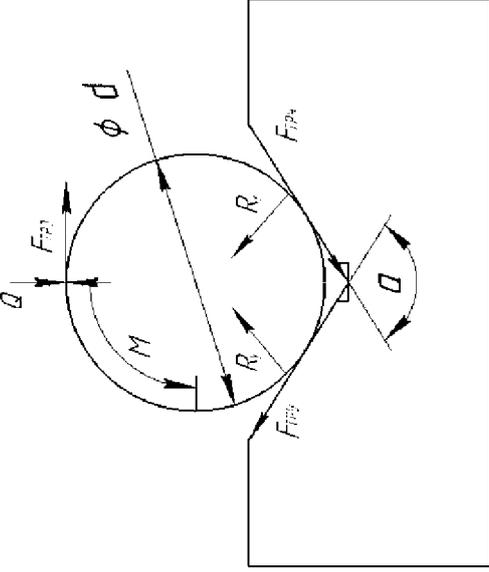
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АВТОМАТИЗОВАНОГО  
МАШИНОБУДУВАННЯ



Fixture design composition:

- 1 - plate;
- 2 - hydraulic cylinder;
- 3 - keyway;
- 4 - bolt;
- 5, 6 - screw;
- 7 - fixed prism;
- 8 - movable prism;
- 9, 10 - pin.

## Benchmark transfer chain

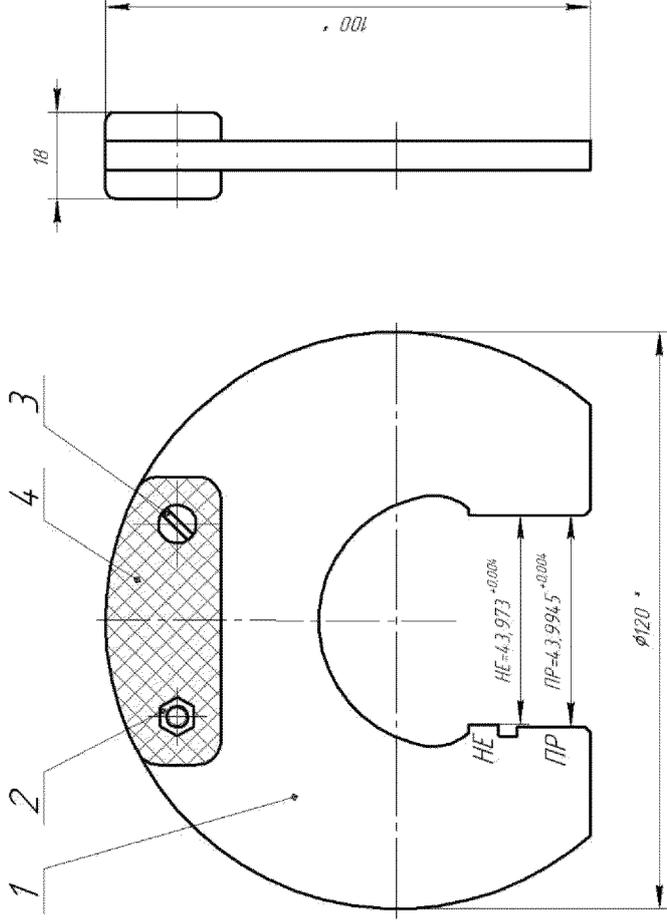


## Schematic diagram of V-block positioning

## Fixture design specifications

Index Item	Technical Requirement	Remarks
Positioning Accuracy	$\leq \pm 0.01$ mm	Radial and axial positioning
Angular Positioning Accuracy	$\leq \pm 0.1^\circ$	Control of relative angular alignment of two planes
Repeat Positioning Accuracy	$\leq 0.005$ mm	Consistency in multiple clamping operations
Clamping Force	2000–3000 N	Adjustable range
System Stiffness	$> 5000$ N/mm	Static stiffness indicator
Natural Frequency	$> 200$ Hz	Avoid resonance
Machining Accuracy Guarantee	Flatness $\leq 0.02$ mm	Key precision indicator
Applicable Workpiece Range	$\varnothing 30-40$ mm shaft-type parts	Consideration of general applicability

# Calculation and design of snap gauge for surface control $\varnothing 44h7$ mm



Result of design calculations for a snap gauge

Limit deviations for shafts with a diameter of 44 mm according to GOST 25347-82:

$es = 0$  mm;  
 $ei = -0,025$  mm;

Calculated limit dimensions and tolerances for a diameter of 44 mm:

$d_{max} = 44$  mm;  
 $d_{min} = 43,975$  mm;  
 $T_d = 0,025$  mm;

Limit deviations and tolerances for the manufacture of a snap gauge according to GOST 24853-81:

$H_1 = 0,004$  mm;  
 $Y_1 = 0,003$  mm;  
 $Z_1 = 0,0035$  mm;

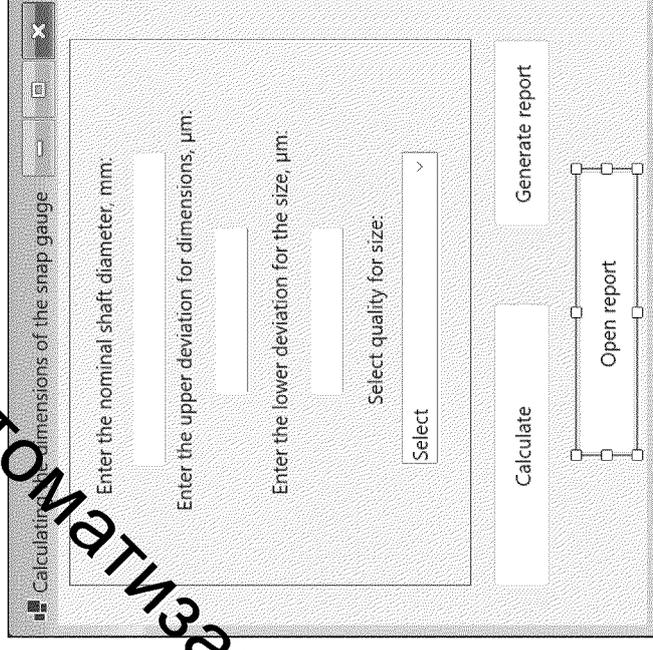
Parameters of the passage part of the snap gauge and wear:

$PP_{max} = 43,9985$  mm;  
 $PP_{min} = 43,9945$  mm;  
 $PP_{Zn} = 44,003$  mm;

Parameters of the impassable part of the snap gauge:

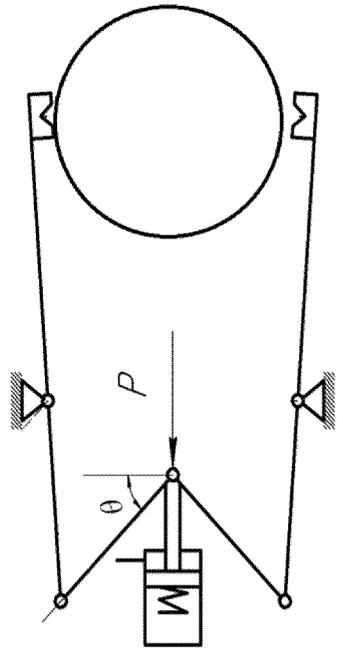
$HE_{max} = 43,977$  mm;  
 $HE_{min} = 43,973$  mm;

Publication: Poberezhets V., Hleba O., Piontkovych O. Application in C# programming language for automated selection of geometric parameters of a snap gauge. Collection of scientific papers of International Youth Scientific and Technical Conference «Young science - robotics and nano-technology of modern mechanical engineering». Kramatorsk: DSEA, 2025. P. 43-46.

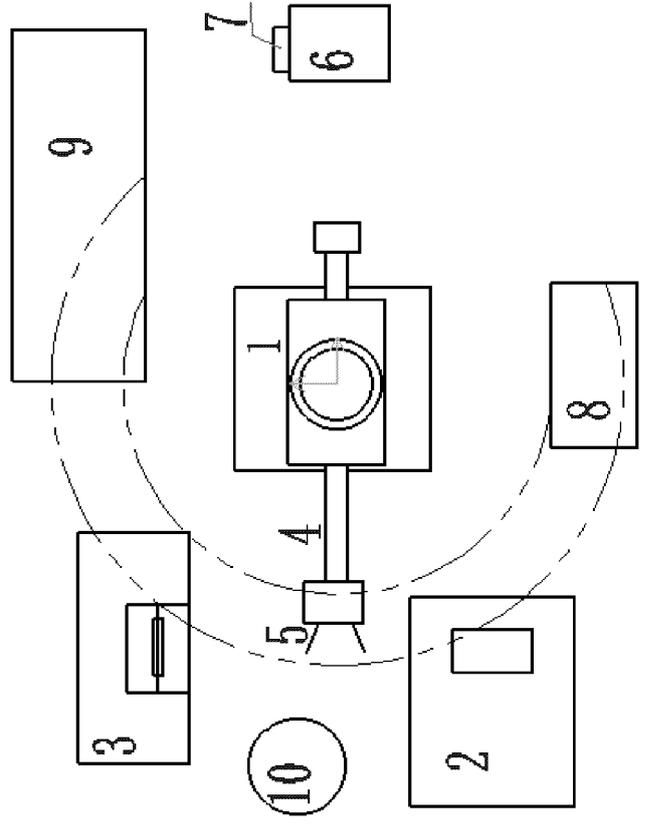


Appearance of the application for calculating snap gauge dimensions

# Improving the machining workstation



Schematic diagram of the design of the Industrial Robot's Gripping Device



Layout of the design of a machining workstation with an industrial robot

Equipment	operation	Time, seconds																			
		10-30	30-45	45-60	60-75	75-90	90-115	115-133	133-148	148-163	163										
robot	Get workpiece	hatched																			
	move workpiece				hatched																
	set workpiece					hatched															
	waiting work						hatched														
Machining	workpiece processing										hatched										
	Loose work																				
	set workpiece																				hatched

The operation flow of the robot and the functional cycle diagram of the machine tool

# Conclusions

This study was carried out around the "Mandrel" parts and achieved many results: a comprehensive analysis of the parts and optimization of the processing route, the developed process route is scientific and reasonable, and can ensure the processing accuracy and efficiency; a special fixture is designed for the milling plane process, and after accuracy verification and performance optimization, it provides reliable clamping guarantee for precision machining; a theoretical system for measuring tool selection is established, the measurement error is analyzed and effectively controlled, and technical support is provided for high-precision measurement; an automated processing workstation is designed based on industrial robot technology to complete a number of key tasks, improve production efficiency and quality stability, and realize automation functions; a cost analysis model is constructed to predict project benefits, evaluate investment value and risks, and the results show that the project has strong economic feasibility and has strategic and social benefits. In terms of theoretical contribution, methodological innovation is achieved, multiple theoretical models are constructed, and technical integration innovation is carried out.

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