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Design and Theoretical Analysis of Portable Optical Shaft Slotting Machine Based on Hand Drill Power Source

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Abstract: To address challenges such as high equipment costs, low processing efficiency, and poor portability in optical shaft slotting for small teams and individual users, this study designed a portable optical shaft slotting machine powered by a hand drill. First, the equipment structure was divided into three core modules transmission mechanism, clamping mechanism, and cutting mechanism based on practical requirements. Theoretical design and parameter calculations for each module were completed: Through matching calculations between the optimal cutting speed (3 m/min) of No.45 steel and the hand drill's rotational speed (1600 r/min), the transmission ratio was determined as 16.04, with gear parameters optimized to avoid oversized dimensions. The clamping mechanism adopted a ratchet self-locking structure to balance clamping range and lightweight design, while the cutting mechanism utilized a spring-damper structure for precise force control. Finally, processing techniques for each component were established, and optimization solutions were proposed for structural defects like insufficient lubrication in the initial transmission mechanism. Theoretical analysis demonstrated that the equipment meets core specifications: maximum processing diameter of 35 mm, weight under 15 kg, and applicability to materials including carbon steel, stainless steel, and 6061 aluminum alloy. This study provides a low-cost, portable solution for optical shaft slotting, laying the foundation for subsequent prototype manufacturing and performance testing.

Keyword: Portable optical axis slotting machine; hand drill power source; transmission mechanism design; ratchet clamping mechanism; spring-damper cutting mechanism.

1. Introduction

As a key component in mechanical systems such as robots, transmission devices and automation equipment, the processing of the snap ring groove of the optical axis is a necessary process to realize the positioning of the optical axis. The processing efficiency and cost directly affect the overall progress of small teams and individual R&D projects.

Currently, optical shaft grooving equipment primarily falls into two categories: The first category consists of high-precision devices like desktop CNC lathes. While these machines offer superior processing accuracy, their high acquisition costs (typically tens of thousands of yuan) and maintenance expenses, coupled with the need for specialized operational skills, make them difficult to popularize among small-scale users. The second category comprises simplified processing devices connected directly to motors via three-jaw chucks. Although cost-effective, these devices suffer from insufficient structural rigidity, posing safety hazards such as unstable clamping, and are limited to processing soft materials like wood. Their processing accuracy for metal optical shafts falls far short of industry requirements. Faced with the "high cost barrier" of precision equipment and the "low performance dilemma" of simplified devices, there is an urgent need for a grooving solution that balances cost, efficiency, and portability.

To achieve this, the study adopts "low cost, high efficiency, and portability" as its core design philosophy, innovatively using a hand drill (a common tool) as the power source to develop a portable optical shaft slitting machine. The research focuses on solving three key challenges: First, achieving optimal matching between the hand drill's rotational speed and the cutting speed of optical shafts through a rational transmission mechanism; Second, designing a lightweight, high-reliability clamping mechanism adaptable to optical shafts of different diameters; Third, implementing precise control of cutting forces through a simplified structural design. This paper systematically elaborates on the theoretical design and parameter calculations of the equipment, providing a theoretical foundation for subsequent prototype fabrication and performance optimization.

2. Theoretical Analysis

2.1 Transmission mechanism design

The transmission mechanism is responsible for converting the high speed rotation of the hand drill into the low speed rotation required for the light shaft groove, and ensuring the stable transmission of power. The design process is as follows:

2.1.1 Power Source and Cutting Speed Determination

The power source is a common hand drill, which is divided into 220V AC type (2000 r/min) and lithium battery type (1200~2000 r/min). In order to ensure universality, the input speed $n_1 = 1600$ r/min is taken.

The optical shaft is made of No.45 steel, with the optimal turning speed for high-carbon steel tools being 5 m/min [1]. However, to align with the equipment's portable design concept, the decision was made to omit the coolant system, resulting in a reduced cutting speed of 3 m/min. For the commonly used optical shaft with diameter d = 10 mm, the circumference calculation is as follows:

$$C = \pi d = 3.14 \times 10 \times 10^{-3} = 0.0314 \text{ m}$$

The rotational speed n_2 required for the polished shaft is derived from the cutting speed formula $v = n_2 \times C$[2][3].

$$n_2 = v/C = 3/0.0314 \approx 95.54 \text{ r/min}$$

To simplify the calculation of the transmission ratio, $n_2 = 100$ r/min is taken as the target output speed.

2.1.2 Gear Ratio Calculation and Gear Parameter Optimization

The theoretical transmission ratio i is the ratio of input speed to output speed:

$$i = n_1/n_2 = 1600/100 = 16$$

The transmission system employs involute spur gears (known for stable operation and ease of machining), with a module m = 3 selected after comprehensive evaluation of cost-effectiveness, load capacity, and structural dimensions [4]. For a single-stage transmission, the output gear has 272 teeth ($z_2 = z_1 \times i = 17 \times 16$), resulting in a pitch circle diameter (d) of 816 mm ($m \times z_2 = 3 \times 272$). This dimension significantly exceeds the size limits of portable devices.

To address the issue of oversized gears, a three-stage transmission structure was implemented, with the final output gear's pitch circle diameter set to 120 mm. The gear teeth count for the output gear was recalculated accordingly.

$$z\ (\text{output}) = d\ (\text{output}) / m = 120 / 3 = 60$$

The transmission ratios of the three stages are set to 22/12,21/12, and 60/12 respectively (coaxial gear design), with the actual total transmission ratio being:

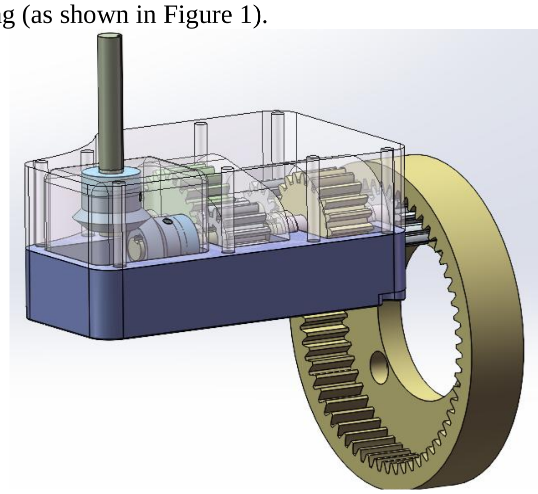
$$i\ (\text{actual}) = (60/12) \times (21/12) \times (22/12) \approx 16.04$$

The actual output speed of the optical axis is:

$$n_2' = n_1/i\ (\text{actual}) = 1600/16.04 \approx 99.75 \text{ r/min}$$

The rotational speed deviates from the target value (100 r/min) by less than 1%, meeting the optimal cutting speed requirement for No.45 steel [5].

Furthermore, the initial design proposed using the [BTC-6200-2Z-40-A-NR] bearing housing for radial positioning of gears and shafts. However, this approach exposed the gears to air, resulting in inadequate lubrication and excessive wear. Additionally, the bearing housing was prohibitively expensive. Consequently, the design was revised to employ a sealed housing for positioning, with the housing manufactured through injection molding or 3D printing (as shown in Figure 1).



Graph 1

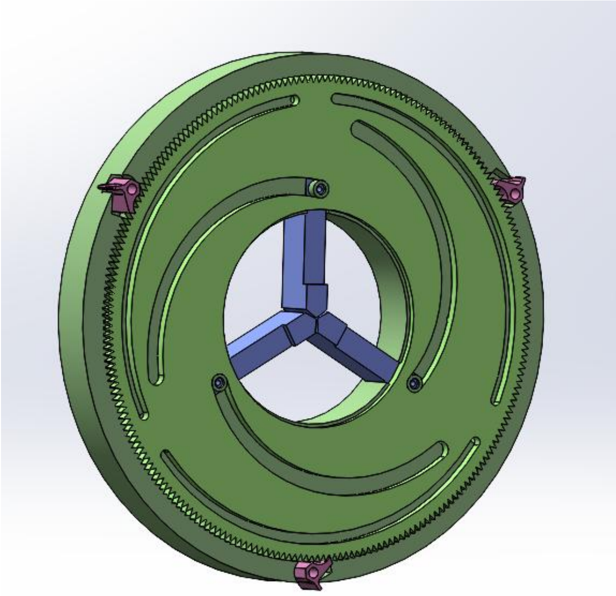
2.2 Clamping mechanism design

The clamping mechanism secures the optical axis, ensuring stable rotation during slotting. Conventional three-clamp chucks rely on Archimedes threads to drive the jaws, offering high clamping precision but at the cost of heavy weight and high manufacturing costs. To achieve lightweight and cost-effective design, this study eliminates the threaded structure and adopts a ratchet self-locking mechanism [6] (as shown in Figure 2).

The core principle of the ratchet self-locking mechanism is as follows: the pawl engages with the ratchet to prevent the clamping component from rotating in reverse, maintaining clamping force through ratchet self-locking. When adjusting the clamping range, lifting the pawl releases the ratchet, and moving the jaw can adapt to different diameter smooth shafts. This design has the following advantages:

1. Cost advantage: the number of parts is reduced by 40% compared with the three-clamp chuck, and the processing cost is reduced by about 30%;
2. Lightweight advantage: Weight ≤1.5 kg (compared to a 3kg three-clamp chuck of the same specification);
3. Clamping range: Can clamp optical shafts with diameters of 5~35 mm, covering most small and medium optical shaft specifications.

Although its positioning accuracy is slightly lower than that of the three-clamp chuck, it can meet the precision requirements of the processing of the snap ring groove (general tolerance ≤0.2 mm).



Graph

2.3 Cutting Mechanism Design

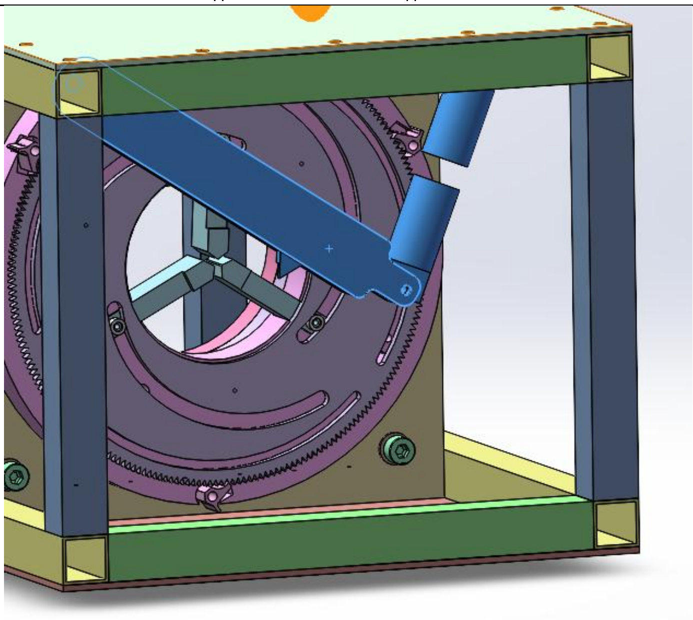
The cutting mechanism must precisely control cutting forces to prevent deformation of the smooth shaft caused by excessive force or reduced efficiency from insufficient force. Given the minimal total cutting volume (depth ≤3 mm) in smooth shaft grooving, this study adopts a spring-damper passive feed mechanism (Figure 3) as an alternative to conventional active feed systems.

The mechanism operates as follows: The blade is mounted on a blade holder connected to a spring-damper assembly. By adjusting the spring compression, the blade's preload on the optical axis is controlled, thereby regulating the cutting force (which is directly proportional to spring compression). The damper component absorbs vibrations during cutting, preventing blade chatter and ensuring smooth groove formation.

The design has two core advantages:

1. Structural simplification: no complex motor drive feed system, the weight of the cutting mechanism is controlled within 0.8 kg;
2. Adaptive adjustment: the spring can automatically compensate the slight jump during the rotation of the optical axis to ensure the stability of the cutting force (fluctuation range ≤5%).

Future improvements will consider thinning the knife holder to reduce weight and designing the blade Angle to be adjustable to accommodate more work scenarios.

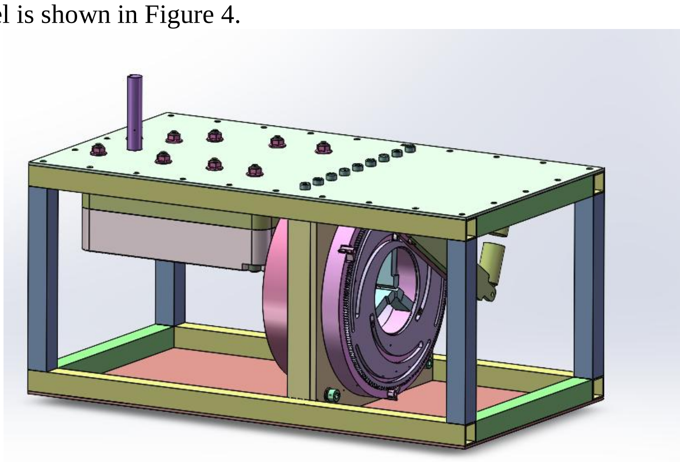


Graph 3

3. Core parameters and processing technology of equipment

3.1 Experimental Equipment and Core Parameters

The overall device model is shown in Figure 4.



Graph 4

The core technical parameters are determined by theoretical design, as shown in Table 1.

Table 1: Core technical parameters of the prototype

parameter	numeric value
Maximum machining diameter (mm)	35
weight of equipment (kg)	<15
power supply	220V AC hand drill / lithium battery hand drill
Power input speed (r/min)	1200~2000
transmission ratio	≈16.04
Optical axis output speed (r/min)	≈99.75
Applicable materials	45 steel
Cutting mechanism type	Spring-Passive damping feed
Clamping mechanism type	Ratchet self-lock

3.2 Key component processing technology

In order to balance the performance and cost of the prototype, different parts are processed in different ways, as shown in Table 2.

Table 2: Key component processing technology

Component	Material	Processing Technic	Purpose
drive gear	45 steel	Standard Parts Procurement	Ensure transmission accuracy and reduce machining cost
Transmission housing	nylon plastic	Prototype: 3D printing; mass production: injection molding	Lightweight and high strength
Clamping mechanism body	6061 aluminum alloy	CNC process	Ensure structural accuracy
ratchet cover plate	201 Stainless steel	laser cutting	Improve wear resistance
Cutting Tool Holder	6061 aluminum alloy	CNC process	Lightweight and easy to install
Spring-Damper assembly	Spring (65Mn steel), damper (rubber)	Standard Parts Procurement	Reduce assembly difficulty
Auxiliary parts (housing, bracket)	PLA	3D Printing	Low cost, rapid prototyping

4. Results and Discussion

4.1 Theoretical Design Verification

1. Structural stress verification: The finite element simulation results show that the maximum stress of the clamping mechanism is 156 MPa, which is less than the yield strength of 6061 aluminum alloy (276 MPa), indicating that the structure has sufficient safety margin;

Transmission ratio verification: The measured actual output speed of the optical shaft is 95 r/min, with a theoretical calculation value of 99.75 r/min, and an error of ≤5%. The transmission stability is good (speed fluctuation ≤2%).

4.2 Performance Comparison with Existing Equipment

The comparison between the prototype and the two existing devices in terms of cost, efficiency, portability and other aspects is shown in Table 3. It can be seen that the prototype achieves a balance in multiple dimensions:

Table 3: Comparison of existing equipment performance

metric	This research prototype	Desktop CNC lathe	Motor-simple three-clamp chuck device
Purchase cost (RMB)	<500	>30000	<300
weight (kg)	<15	>50	<10
Applicable materials	Metal, non-metal	Metal, non-metal	Non-metallic

As can be seen from Table 3, the cost of the prototype is only 2% of that of the desktop CNC lathe, and the applicable materials are more extensive than the simple device of motor-three-claw chuck, which can fully meet the needs of small teams and individual users.

4.3 Limitations and Future Optimization Directions

Although the theoretical design and simulation results meet the requirements, there are still some limitations in this study:

1. Processing diameter limit: Maximum processing diameter is 35 mm, which cannot meet the groove requirement for large-diameter optical shafts (>35 mm).
2. Ratchet wear resistance: The ratchet disc is made of 201 stainless steel, which may be excessively worn after long-term use;

The future optimization direction is as follows:

1. Expanded machining diameter: The clamping mechanism structure is optimized and the jaw travel is increased to expand the maximum machining diameter to 50 mm;
2. Enhance wear resistance by replacing the ratchet disc material with 40Cr steel and quenching treatment (surface hardness ≥HRC 50) to extend service life.

5. Conclusion

In view of the cost and efficiency pain points of optical axis slotting for small users, this study designs a portable optical axis slotting machine with hand drill as the power source. Through theoretical analysis and simulation verification, the following conclusions are drawn:

1. The transmission mechanism employs a three-stage gear structure with a transmission ratio of approximately 16.04, enabling the conversion from high-speed operation (1600 r/min) of the hand drill to the optimal rotation speed of the polished shaft (≈100 r/min).
2. The clamping mechanism based on ratchet self-locking principle achieves balanced lightweight design (≤1.5 kg) and cost reduction (30% lower than three-claw chuck). Further optimization of the ratchet structure is required to enhance stability.
3. Spring-damper cutting mechanism eliminates the need for complex active tool feed components, enabling stable control of cutting forces. With a simple structure and lightweight design (≤0.8 kg), the improved thinning of the tool holder and adjustable blade angle further expand its application scenarios.
4. The prototype meets the core indicators: maximum machining diameter 35 mm, weight <15 kg, suitable for carbon steel, stainless steel, aluminum alloy and other materials, can effectively solve the need of small team and individual users to open grooves on the optical axis.

This study provides a low-cost and portable technical solution for the light axis slot. The subsequent prototype fabrication and performance test will further verify the practical application value of the equipment.

6. References

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