Structure Design and Accuracy Analysis of High Precision Single Valve Spool Grinder

Kai Wang, Wanchen Sun, Qingtang Wu, and Dongyan Wang

Abstract**—**Aiming at the structure and accuracy of the single pump valve core grinder, the working process and structural characteristics of the core of the single pump were analyzed in this paper. The general structural design scheme of the grinder with the "L" type lathe bed and the high-precision motorized spindle as the sand wheel shaft and the CBN grinding wheel was put forward. Through the analysis of the grinding error, determine the error distribution principle. According to the characteristics of valve structure, characteristics and precision grinding, the errors are decomposed. And then, ultimately determine the range of error, to ensure that the total error can meet the processing requirements of grinder, laid the foundation for the following detailed design.

Keywords**—**Single pump valve core, Grinder structure, Precision analysis.

I. INTRODUCTION

PRECISION grinding machine tool is the key to ensure the smooth completion of the precision machining of the valve core, when the single pump valve core precision outer circle grinder is developed, the grinding scheme should be made according to the structure and material characteristics of the valve core, and then the overall structure layout of the precision grinder should be carried out in order to ensure the performance and accuracy of the grinder. In the precision valve core grinding process, the grinding wheel position with the valve spool moves around and before and after changes. This requires the work of moving the spool around the wheel table and the table before and after the move has a high linear accuracy, while the verticality of the two workstations must be high. At the same time must ensure that the workpiece shaft and the spindle of the grinding wheel must have a higher rotation accuracy. These key structures must be considered in the design of the grinding machine to ensure the overall accuracy of the grinding machine. This paper introduces the working process and structural features of the single pump spool, determines the key dimensional accuracy and shape accuracy of the spool. The overall design of each component of cylindrical pump of single pump spool was analyzed, and the accuracy range of each main component of grinder is analyzed and adjusted. According to the existing technical means, the precision of each moving part is determined.

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II. SPOOL WORKING PROCESS AND STRUCTURAL CHARACTERISTICS ANALYSIS

The spool is one of the two precision couplings of the unit pump. It is controlled by the solenoid valve to move left and right within the valve hole of the pump body, as shown in Fig. 1. When the solenoid valve is de-energized, the spool moves leftward under the action of the spool spring and opens the oil return passage. At the same time, the plunger moves downward to draw the fuel in the low-pressure chamber into the plunger chamber. When the piston reaches the bottom, it begins to move upward. At this time, the solenoid valve has not yet been electrified, and the spool is on the left side. The plunger in the monomer pump has started pumping oil, but the oil has returned to the low pressure cavity through the oil return passage, and there is no oil pressure in the high-pressure oil pipe. When the solenoid valve is electrified, the valve core moves to the right, the oil passage is closed, the oil pressure is quickly raised, and the high pressure fuel passes through the high-pressure oil pipe into the injector to make the oil spray. The electric solenoid valve is cut off, the valve core is moved to the left again, the oil channel is opened, the pressure is relieved quickly, and the injection is stopped. The duration of the power supply of the solenoid valve determines the time of the fuel supply, and the circulating fuel supply is indirectly controlled under the condition that the size of the nozzle is constant. In order to establish a reliable guarantee of oil, must ensure reliable sealing valve spool coupling, plunger, valve parts, the plunger is mechanical seal, which requires the coupling between the gap is small enough, at the same time for the spool coupling, the valve core conical surface and cylindrical surface must be coaxial with high precision. On the other hand, the speed of diesel engine design goals for 4200r/min, so the spool need to open and close 2100 times per minute, which determines the valve is working continuously in high frequency state, in order to meet the high precision, high strength, high wear, W6Mo5Cr4V2 is used as the core material. W6Mo5Cr4V2 steel is a W-Mo high-speed steel, carbide fine, uniform, high toughness, good thermal plasticity, its outstanding characteristic is with very high hardness, wear resistance and thermal properties is an ideal material for valve.

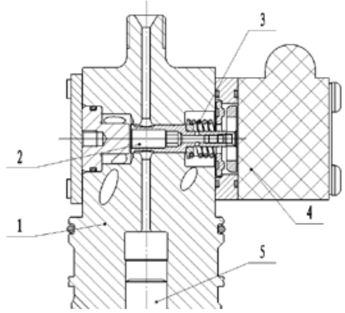

Fig. 1. Valve core working process diagram
1 Pump Body, 2 spool, 3 Spool, Spring, 4 Electromagnetic Valve, 5 Displacement Ram

As shown in Fig. 2, the outer structure of the spool is shown in Fig. 2. The axial size of the spool is very small, and the outer surface is composed of circular arc surface, conical surface and stepped cylindrical surface. Its main dimensions are linear precision, roundness and surface quality, roundness, runout and surface roughness of the conical surface. The coaxiality of conical and cylindrical surfaces must be considered in the design of grinding machine. The grinding process of the spool is generally the movement of the worktable left and right. At the same time, with the front and rear movement of the grinding wheel shaft table, the outer surface of the grinding wheel has a limited contact with the outer surface of the valve core, and the rotation of the sand shaft and the workpiece shaft makes the grinding wheel contact with the outer core of the valve core even. Therefore, it is necessary to ensure that the grinding machine two guideways have high linear operation accuracy and repeat positioning accuracy. Two guideways must have high vertical accuracy, grinding wheel shaft and workpiece shaft have high rotation accuracy.

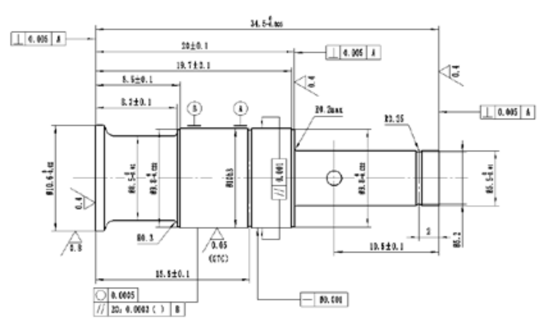

Fig. 2. Spool structure diagramdiagram

During the grinding process of the spool, in order to ensure a high coaxial accuracy of the conical surface and the cylindrical mask of the spool, the two clamping problem can not be generated in the grinding process. In order to ensure the clamping accuracy and the need of rotary drag, the inner side of the spool is designed as the inner six party structure shown in Fig. 3, so that the internal drive and rotation method is convenient to realize the rotation of the spool in the grinding process.

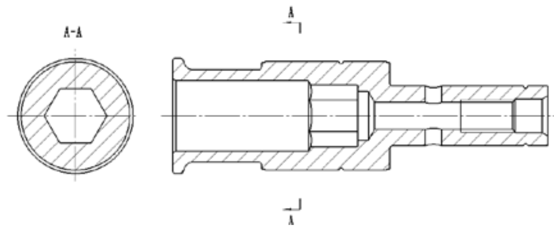

Fig. 3. Spool structure profile

III. Overall Structure Design of Precision Valve Core Outer Grinding Machine

According to the characteristics of the valve core material and structure, the overall structure of the grinder is designed, as shown in Fig. 4. The precision valve core cylindrical grinder mainly consists of the lathe body, spindle system, grinding wheel shaft system and the corresponding driving device.

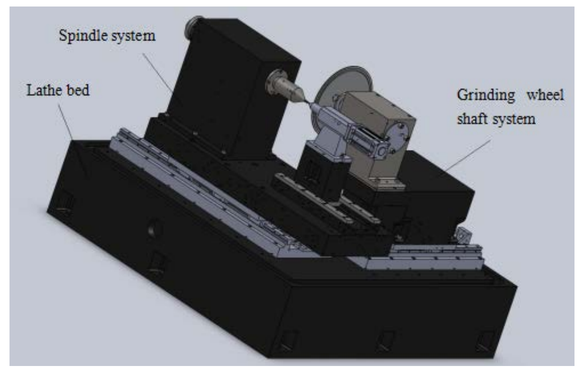

Fig. 4. Precision outer cylindrical grinder with single pump valve core

The structure of the lathe bed is shown in Fig. 5. The casting is made of HT200. The L shape structure is more favorable for the arrangement of spindle system and grinding wheel shaft system, so that the machine tool is compact and practical.

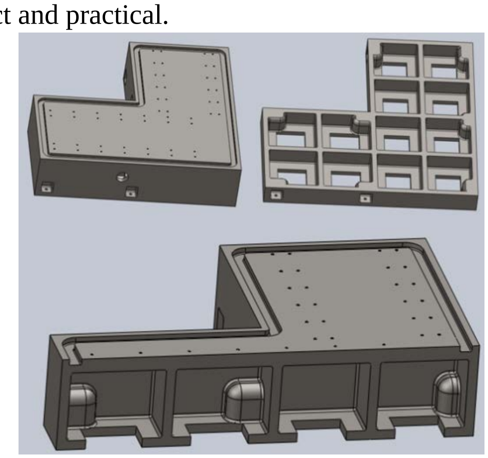

Fig. 5. Machine tool structure diagram

The spindle system consists of a spindle box, a tail top, a worktable, and a Z axis guide (left and right motion). The spindle box and the tail top are installed on the worktable to form the clamping and positioning unit of the valve core. The worktable is connected by the bolt to the Z axis guide, and the Z axis guide is linked to the bed through the bolt, as shown in Fig. 6.

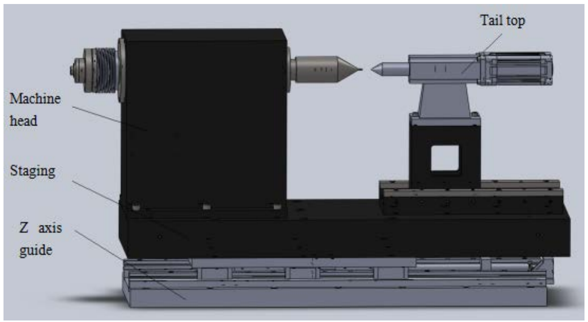

Fig. 6. Spindle system composition

The grinding wheel shaft system is composed of an electric spindle, an axle box of a grinding wheel and a X axis guide (front and back motion).A CBN grinding wheel with a diameter of 400mm and a 180# ceramic binder with a width of 4mm is used as a grinding tool. The grinding wheel is driven directly by a high precision electric spindle. Not only the precision is ensured, but also the intermediate transmission is reduced. The electric spindle is installed in the axle box of the grinding wheel, and the axle box of the grinding wheel is connected with the X axis guide rail through the bolt. The X axis guide is linked to the bed by a bolt, as shown in Fig. 7.

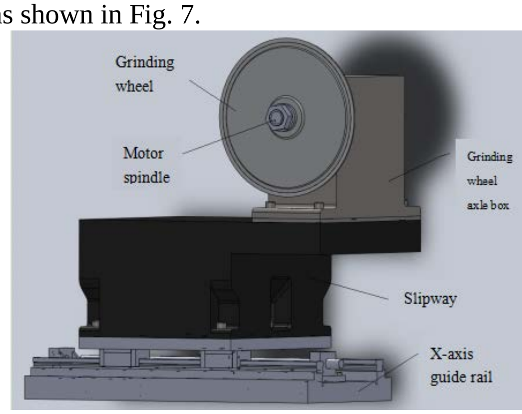

Fig. 7. Grinding wheel shaft system composition

IV. Error Analysis of Grinding Machine

The precision of the grinding machine is an important factor that can realize the precision grinding of the valve core, and is the main technical parameter to evaluate the precision of the equipment. The purpose of the analysis is to determine the accuracy of equipment precision various error analysis confirmed that the reasonable error value assigned to the balance system and the components, so that the machine can meet the requirements of the overall, while avoiding various systems and parts processing, debugging too difficult or cannot realize the problem.

The overall accuracy of the equipment comes from the accuracy of the subsystems and the core parts of the subsystem. For the precision spool grinder, the core components include the X axis linear guide, the Y axis linear guide, the workpiece shaft and the grinding wheel shaft. Only these high-precision moving parts can be developed, and the high-precision grinding equipment can be debugged through high-precision assembly. Therefore, high-precision parts processing and reasonable high-precision assembly and debugging methods are the important foundation for high-precision grinder.

A. Description of grinding error

According to the characteristics and properties of the error, there are two types of errors: system error and random error. System error is the inherent error of machine tools. The machining errors produced by machine parts during machining are the assembly errors when machine tools are assembled. This kind of error can be repeated in the same use and operation conditions, with high repeatability. The forms of system error include accumulative error, periodic error, reverse error and so on. Numerical results can be derived from mathematical models, or uniformity can be measured directly and regularly. By using the characteristic of systematic error, it can carry out off-line measurement. It can be corrected and compensated by off-line detection and open-loop compensation technology, so that it can be reduced and the accuracy of machine tool can be improved. The biggest characteristic of random error is randomness. Even under the same conditions of operation and operation, it cannot be reproduced. It is impossible to deduce mathematical models or get regular results, the measurement results can only be the state of discrete distribution, and the size is approximately determined by statistical method. In the grinding process, we can only reduce the influence of random errors on the machining accuracy of the machine by means of "online detection closed loop compensation". This method is very demanding for measuring instruments and measuring environment, and is difficult to be used and popularized in the production process. To sum up, the factors affecting grinding precision of the grinder can be described as shown in Fig. 8.

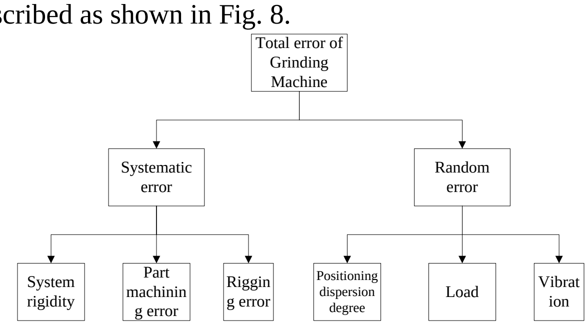

Fig. 8. Factors affecting grinding precision of grinding machine

The accuracy of grinder depends on the interaction of various factors, such as the technological shape, the quality of the surface and the position error caused by the location error of each part of the grinder system. The error of the control system contour following error and the numerical control difference compensation algorithm. In the actual operation process, the deformation due to the weight of the machine itself, load, speed, grinding internal heat source and environmental temperature changes caused by heat disturbance, all possible geometric deviation and motion error on the machine, thereby affecting the precision machine movement accuracy.

According to the factors that affect the error, the error is usually attributed to the design principle error, the machining error, the debugging error, the environment and the use error.

Design principle error. The design principle error includes design scheme error, mechanical structure error, part principle error, electrical principle error and so on. The error of design principle is different due to the different principle of the scheme when designing the precision grinding equipment. In the design process, we should give full consideration to the rationality of the design, the processing and debugging difficulty of the components, and so on, which are the main factors of the design alternatives.

Mismachining tolerance. After the completion of the design of the machine tool, the parts should be processed according to the design drawings. The machining error is the error generated in the machining process. Part processing error is the first source of machine tool error, which can only be controlled by making part tolerance. The higher the tolerance grade of the part, the more difficult the machining cost of the part is, so the tolerance range of the part should be reasonably chosen within the range of realizable and acceptable price.

Debugging error. Relative position errors, such as Perpendicularity Error, coaxiality error and parallelism error, are usually produced in the process of assembly, debugging and assembly of equipment components. Part deformation and internal stress are sometimes caused by improper assembly methods or other reasons. When the precision of position is very high, special adjusting device and proportional amplifying device are usually needed.

Environment and use error. In the process of the use of precision equipment, influenced by the objective factors, it is inevitably influenced by ambient temperature, humidity, pressure, vibration and other environmental factors. Though precision devices can be placed in constant temperature room, dust-free chamber, constant pressure chamber and set up isolation belt to reduce environmental impact, this effect can not be eliminated. During the use of machine tools, the movement of machine parts will cause machine vibration. This vibration will lead to intermittent contact between tool and workpiece, resulting in corrugation of the workpiece surface. The size accuracy of the workpiece can be affected seriously.

B. Sources of error

The sources of motion errors of machine tools include screws for driving straight lines, guides for supporting and guiding, spindle driving the workpiece, grinding wheel shaft for grinding wheels and parts for fixing and supporting. In the production and processing of these parts, the error of the component is caused by the inaccuracy of the geometric shape or size.

Screw error: commonly used lead screw is ball screw, it is a transmission original which transforms rotary motion into linear motion. Its error is mainly composed of screw rod's lead accuracy, wire and screw backlash, screw stiffness and prepress force.

Guide error: the guide rail has more structure forms, but in general, it is the accuracy error of the slider and the parallelism error of the slideway and the slider. Normal distribution of linear error of guide rail in normal condition.

Spindle rotation error: when the spindle of machine tool is rotating, the drift degree of the actual axis of rotation to the ideal axis of rotation is called the rotation error. In general, it is divided into three basic forms, namely, pure radial runout, pure axial movement and pure angle swing. In the process of actual processing, these three kinds of errors exist simultaneously, and the production error is also the superposition of the influence of the three forms. The radial runout plays a leading role in the grinding process, which directly affects the size and shape accuracy of the parts. The axial movement has little influence on the optical axis, but it affects the axial dimension precision of the ladder axis for the ladder axis. The pure angle swing can be eliminated by the method of dressing the top.

V. GRINDING ERROR DISTRIBUTION

According to the size accuracy and structural characteristics of the monomer pump spool, the design of the precision machining equipment for the single pump valve coupling is carried out. It is necessary to allocate the accuracy of the moving parts reasonably according to the existing technology and processing capability to meet the requirement of the spool processing.

The machining accuracy and assembly accuracy of the components with precise spool and cylindrical grinder will directly affect the machining accuracy of the spool, while the ultra precision linear moving parts and the rotary moving parts are the foundation for ensuring the extremely high form accuracy and surface roughness of the grinder. In the grinder structure, the linear moving part refers to the X axis guide and the Z axis guide, and the rotary moving part is the main shaft in the main spindle box of the grinder. So, the precision and performance of the machine tool are directly determined by the geometric accuracy of the X axis guide, the Z axis guide and the spindle. According to the needs of the main parts of the grinder and its processing capacity, the hydrostatic guideway and the hydrostatic spindle are used to meet the accuracy requirements of the moving parts of the grinder.

The systematic error of the main mechanical precision of the grinder is determined as shown in Table 1, according to the comprehensive balance of the design scheme, the processing means and the assembly capacity.

Table 1 Error table of mechanical precision system of valve core precision grinding machine

<table>
<tr><td rowspan="3">Component precision</td><td colspan="2">work-shaft</td><td colspan="2">grinding wheel spindle</td><td>X-axis guide</td><td>Y-axis guide</td></tr>
<tr><td>Radial runout</td><td>Axial runout</td><td>Radial runout</td><td>Axial runout</td><td>Straightness</td><td>Straightness</td></tr>
<tr><td>0.1μm</td><td>0.1μm</td><td>0.1μm</td><td>0.1μm</td><td>0.1μm /100mm</td><td>0.3μm /300mm</td></tr>
<tr><td rowspan="2">Precision relation</td><td>Workpiece axis and Z-axis parallelism</td><td>Wheel and X-axis perpendicularity</td><td>Verticality of X-axis guide and Y-axis guide</td><td>Wheel shaft and the workpiece shaft height difference</td></tr>
<tr><td>0.5μm</td><td>0.5μm</td><td>0.5μm</td><td>0.5μm</td></tr>
</table>

According to the law of error composition:

$$U = \sum_{i=1}^{m} E_i \pm \left(\sum^{p} \left|\Delta_n\right| + \left| \sqrt{\sum_{i=1}^{K} \Delta_i^2 + \sum_{j=1}^{L} \Delta_j^2} \right| \right) (1)$$

Of which:

U represents the total error;

Δn represents the indefinite length difference, may not consider temporarily, the definition is 0;

Δi represents the random error, can not be considered for the time being, defined as 0;

Δj represents system error;

Replace the value of each value (1), the limit error after the synthesis is as follows:

$U = 1.0677\mu m$

After the above calculation shows that the design parameters identified, the final did not reach the spool machining cylindricity less than 0.0005μm, straightness less than 0.001μm requirements. But through Fig. 2, we can see that the difference between the maximum radial diameter and the minimum diameter of the spool is only 5.1 mm, and the one-way feed rate is only 2.55 mm. Assuming that the remaining allowance of the spool semi finishing is 0.3mm, the maximum input of the X shaft is only 2.7mm, while the total length of the spool is only 34.5mm. The distance between the design of X axis guide rail and the Z axis guide rail is large. It is necessary to reduce the stroke and improve the accuracy of the straight line operation. Then,

X-axis guide：X-axis guide straightness 0.01μm / 10 mm.

Z-axis guide：Z-axis guide straightness 0.05μm / 50 mm.

The perpendicularity between the center line of the grinding wheel shaft and the X-axis guide rail is 0.5μm, and the position relationship between the grinding wheel axis and the X-axis is shown in Fig 9.Because the installation position of the wheel dresser is on the spindle system worktable, no matter the relationship between the center line of the grinding wheel and the X-axis guideway, the contour line of the grinding wheel driven by the grinding wheel shaft is bound to be parallel to the X-axis guide rail after the dressing of the wheel trimmer, as shown in Fig. 10. The influence of the parallelism of the grinding wheel shaft and the X rail on the machining accuracy of the spool radial dimension is eliminated, and the influence of the deflection of the external wheel contour caused by the vertical axis of the grinding wheel axis and the X-axis rails on the machining accuracy of the spool core dimension still exists, cecause the axial dimensions of the spool are tolerances of 34.5 mm,tolerance range of 5μm, the deviation between the center line of the grinding wheel shaft and the X-axis guide rail and the deviation between the X-axis guide rail and the Z-axis guide rail are only 1 μm, which meets the requirements of machining precision.This wheel axis and X-axis parallelism error can be neglected.

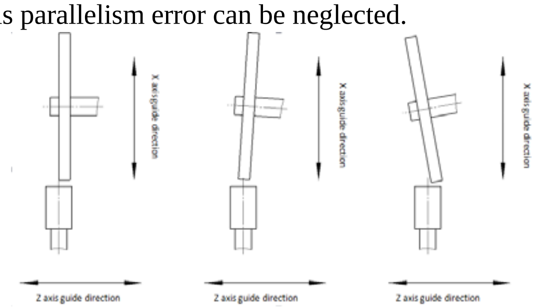

Fig. 9. Grinding wheel centerline and X-axis guide

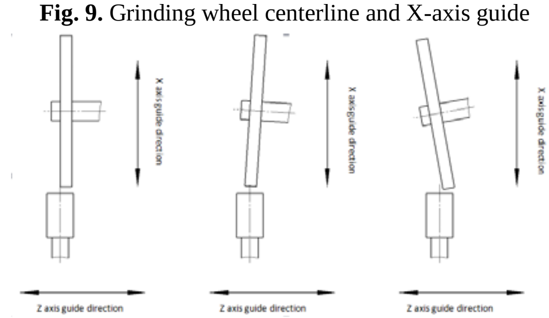

Fig. 10. Profile of grinding wheel after dressing with grinding wheel dresser

The perpendicularity between X rail and Y rail is 0.5μm. The main influence is the deflection of grinding wheel and the precise feeding of grinding wheel shaft. Through the above analysis of wheel dressing can know its impact on the wheel deflection is negligible, the precise feed for the wheel shaft can be compensated by the CNC system to eliminate the X-axis guide is not caused by the vertical feed error.

The difference between the centerline of the grinding wheel shaft and the center line of the main shaft of the spindle box is 0.5μm. The main influence is whether the feed value of the grinding wheel axis and the cutting amount of the spool are the same, which can be compensated and eliminated by the numerical control system.This will result in the elimination of the analytical error back into (1):

$U = 0.5409\mu m$

Has reached the spool of straightness requirements, but did not meet the requirements of the cylindrical degree, the problem is mainly concentrated in the spindle headstock spindle and Z-axis parallelism difference, the parallel to the value of 0.3μm, then

$U = 0.3641 \mu m$

Meet the requirements of spool machining accuracy.

VI. CONCLUSION

This paper focuses on the process and structure characteristics of valve core are analyzed, the overall design of single valve core parts precision machining equipment, gives the overall design scheme of the grinder and departments, according to the overall accuracy of the distribution principle of grinder was decomposed into the components of the accuracy requirements. It has set a foundation for further study.

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