Influence Study of Oil Film Thrust Bearing on Thermal Characteristics of High-speed Precision Roll Grinding Head

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Aiming at a kind of grinding head of high-speed precision roll grinder, its structure characteristics and heat source characteristics are analysed, and the characteristics of heat source is calculated. On these bases, the weakness of grinding thermal characteristics is found through the numerical analysis of thermal performance of roll grinding head, facing the thermal error of sensitive area, optimization method which unites multi objective and single objective are adopted to optimize the thrust oil film bearing of the roll grinding head, after that numerical analysis of thermal performance of roll grinding head is analysed. Analysis results show as follows: temperature of the optimized oil film thrust bearing is improved obviously. The oil film performance between the bearing and the main shaft is stability, and it has had effective prevent the phenomenon of metal dry friction happening. As a result, the grinding accuracy of the grinding roll is effectively improved.

Keywords: High-speed precision roll grinding head; Oil film thrust bearing; Thermal performance; Optimize design

1 Introduction

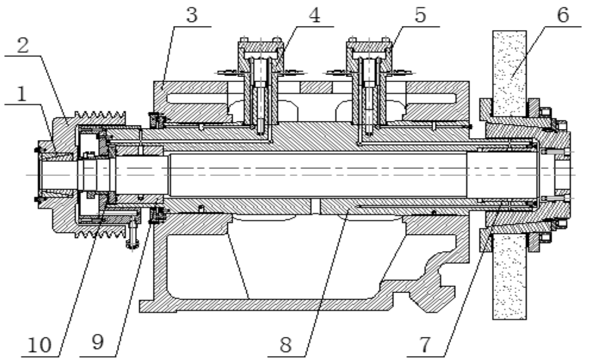
Roll grinder is an indispensable equipment in modern industrial production, mainly used in metallurgy, paper making, rolling and other industries [1-2]. Higher roll grinder precision is demanded to meet the demand for higher product quality. As high-speed and ultra-high speed grinding technology started late in China, the development of roll grinder in China is still in the stage of normal roll grinder.

High-speed and ultra-high speed grinding is attached great importance to by experts from around the word for its high production efficiency, low surface roughness, low grinding force, and high processing precision [3-4]. With the grinding speed increasing, the temperature of roll grinder also rises. The rising of temperature leads to deformation or expansion of machine tool parts, and eventually displacement between the work piece and cutting tool [5]. Micro machining is attaining accurate and reliable machining parameters, which can reduce tool wear and breakage to achieve higher productivity and quality at a lower cost [6]. Studies have shown that the error caused by thermal deformation is one of the main factors affecting the performance of precision machining tools, accounting for 40%~70% of the total machine tool error[7-8]. At present there are mainly two methods to reduce thermal error. The first method is to optimize the structure to achieve the best performance in the design process. The second is to detect and compensate the thermal error of machine tool in the machining process [9]. Now, the second method is widely adopted. Angelos P [10] presents a new hybrid model of precision grinding, which is about combination of the finite element and neural network. Wang Wei [11] presents a synthesis modelling method of geometric and thermal error. Due to the limitations of sensor technology and environment, it is not enough to accurately detect the machine error, so software alone can't meet the accuracy requirements of high-speed precision machine tools. In designing the structure, it is important to optimize the weak link. Jiao Yao [12] presents the thermal conduction analysis model based on thermodynamic theory and the structure optimization method of machine tools through finite element analysis.

This paper focuses on the grinding head of CNC high-speed precision roll grinder. Through analysis of its structure characteristics and working principle, a finite-element 3-D model is established while finite-element software is utilized to analyse its thermal performance and calculate the temperature field of the whole structure of the roll grinding head. Optimization method based on thermodynamic analysis of high-speed precision roll grinding head is presented to reduce the thermal error of machine tool and provide theoretical support for high-speed precision roll grinder.

2 Structure and working principle of high-speed precision roll grinding head

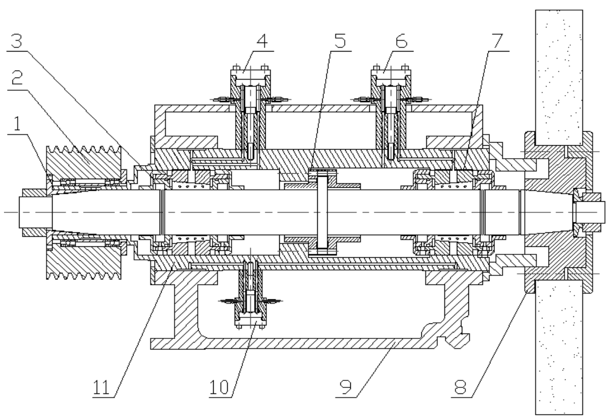
Fig. 1 shows the traditional low-speed roll grinding head model. Its working principle is as follow: The motor drives the pulley of the grinding head to rotate. Under the action of the expansion sleeve, the rotation of the pulley drives the rotation of the spindle, and the spindle rotates to drive the grinding wheel to realize the grinding process. In order to support the rotation of the spindle, the hydrostatic oil film bearings 7 and 9 are installed in the eccentric sleeve at both ends of the spindle. To effectively prevent direct metal friction between the spindle and the bearing, the hydraulic oil circuit supplies oil to the oil film bearings through the restrictor, forming a lubricant film between the spindle and the bearing. The eccentric sleeve method can realize the roller profile curve of the grinding head. The eccentric sleeve applies convex style and has a shoulder at both ends of the box, to prevent the eccentric sleeve's axial displacement. The bearing 10 prevent the spindle from moving axially. The hydrostatic bearing is used to support spindle, and the oil cavity of the bearing is filled with hydrostatic oil. The role of capillary chokes is to achieve pressure regulation and the oil supply. The traditional mechanism can achieve the running of the grinding wheel, at a low speed of only 30 m/s. Once the speed is greater than 45 m/s, the rolling head will lead to accidents of clamping shaft and combustion spindle.



1.power lock; 2.belt roller; 3.box; 4.front restrictor; 5.back hybrid bearing; 6.grinding wheel chuck; 7.back hydrostatic bearing; 8.eccentric sleeve; 9.front hydrostatic bearing; 10.hydrostatic thrust bearing

Fig. 1 *Structure of traditional low-speed roll grinding head*

Due to the limited grinding speed of the grinding wheel, the hydrostatic oil film can't meet the need for high-speed grinding. It is indispensable to change the original layout of normal hydrostatic oil film bearing. Thus, it is urgent to design a new hydrostatic bearing for high-speed grinding at speeds near 80 m/s [4]. Based on the characteristics of low speed roll grinding head, Fig. 2 shows the assembly of high-speed precision grinding head. Adjustable hybrid pressure oil film bearings 3 and 7, replace the hydrostatic oil film bearing of ordinary China-made roller head to support spindle rotation. Hybrid oil film bearing form eight wedge-shaped oil pockets through the interference fit of the four conical ribs and tapered bearing sleeve. To prevent dry friction of the bearing when starting and stopping, four hydrostatic cavities are opened on the inner wall corresponding to the four ribs. To prevent the spindle from moving, hydrostatic thrust bearing 5 is designed and installed in the eccentric sleeve.



1. unloading device; 2.belt roller; 3.front hybrid bearing; 4.front restrictor; 5.hydrostatic thrust bearing; 6.back restrictor; 7.back hybrid bearing; 8.grinding wheel chuck; 9.grinding head box; 10.down restrictor; 11.eccentric sleeve

Fig. 2 *Structure of high-speed precision roll grinding head*

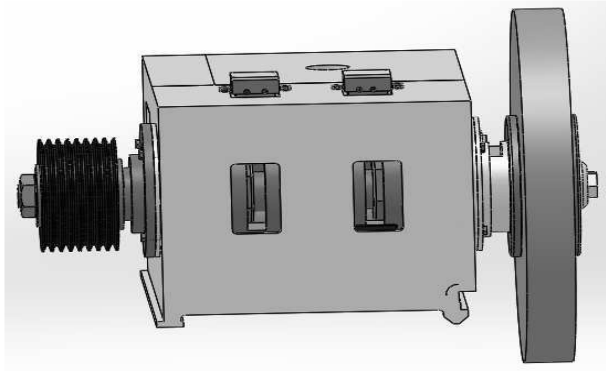


Fig. 3 *Three-dimensional structure of high-speed precision roll grinding head*

Fig. 2 and Fig. 3 show the grinding head model. Its characteristics are as follows: the belt wheel unloading sleeve lessens the influence of belt-tightening force on deformation of the spindle and improves the stability of the spindle. Motor-Worm Wheel-Worm-Eccentric method realizes the roller profile curve of the grinding head. When grinder works, the AC servo motor driven by the deceleration device drives ball screw nut, fork dial follow with the ball screw nut to do reciprocating motion. High-precision eccentric sleeve does tiny eccentric swing with outside diameter centre as fulcrum, so that there is no gap between the grinding wheel and the grinding surface. The transverse motion of work piece and the eccentric swing of eccentric sleeve lead to work piece interpolation motion, so that the grinding head can form a variety of roll profile curves. The entire grinding head is a closed-loop system, and has powerful compensation capacity, worm gear and eccentric sleeve-fork dial are adopted to achieve two-stage zoom high precision. Hydrostatic chamber is designed in the joint of the eccentric external cavity and the box, to reduce the friction between the eccentric sleeve and the box, at the same time improve the sensitivity of medium and high institutions. The high-speed precision roll grinding head is adjustable. Adjustable hydrostatic bearings supports the spindle rotation, while by adjusting the cover on both sides of the bearing, they enable the bearing body to move to the left or right, to strengthen the interference between the bearing tapered rib and the jacket. By squeezing the bearing body, changing the deformation of the recess of the bearing body, and changing the shape and size of the dynamic pressure chamber, the key purpose is to achieve adjustable bearing's support performance and to meet different grinding needs. With structural adjustment, the scope of grinding head is expanding to meet the needs for roll grindings of different loads and raise the market competitiveness of high-speed precision roll grinder.

3 Numerical analysis of the thermal field of high-speed precision roll grinding head

According to the finite element analysis theory, the finite element model of high-speed precision roll grinding head, as Fig.4 shows, is established. Finally, 20115002 mesh cells and 3310970 mesh nodes of the roll grinding head are acquired.

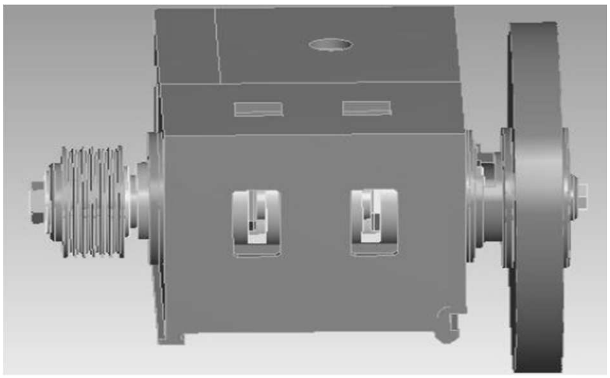


Fig. 4 *Finite element model of high-speed precision roll grinding head*

Set the material properties of the finite element model of the roller head in ANSYS. The calculated convective heat transfer coefficient is applied to the contact surface, and the initial temperature of the roller head is set 24 °C. Fig.5 shows the semi sectional drawing of steady state temperature field, and Fig.6 shows the temperature distribution of oil film bearing.

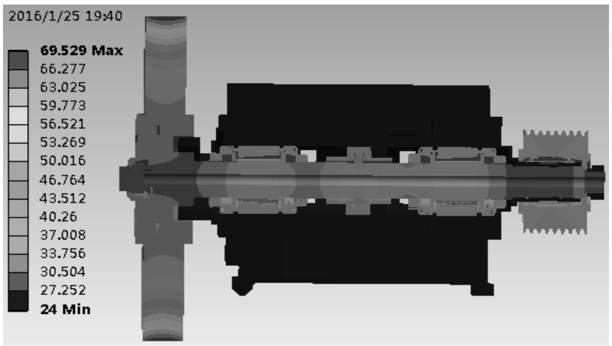


Fig. 5 *Temperature field of high-speed precision roll grinding head*

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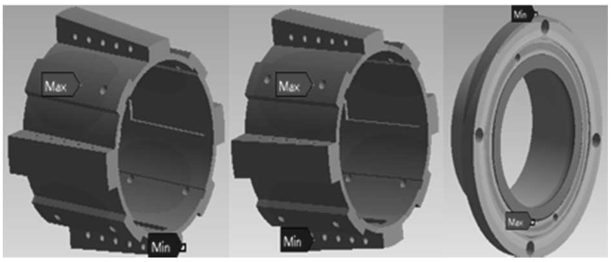


1 Front hybrid bearing 2 Back hybrid bearing 3 Hydrostatic thrust bearing

Fig.6 *Static temperature distribution of oil film bearing*

It can be seen from Fig.5 and Fig.6 that when the high-speed precision roll grinding head is work at high speed, the belt roller, hybrid bearing, hydrostatic thrust bearing and grinding wheel chuck have higher temperature than other parts. The temperature of the belt roller and the grinding wheel chuck can meet the design requirements of the grinding head. Since the optimum temperature of the lubricating oil of the bearing is from 40 °C to 45 °C, and the temperature of hybrid bearing is less than 40°C, so it's within the range of lubricating oil temperature. The maximum temperature of hydrostatic thrust bearing is 47.5 °C, beyond the temperature range of the lubrication oil. Since the bearings are oil film higher temperature leads to lower lubricating oil viscosity. However, the temperature of thrust bearing is over 45 °C. If the roller grinding head works at such high temperature for a long time, lubricating oil viscosity will drop sharply, and the precision of the work piece will decline. Therefore, to lower the temperature of trust bearing and make it competent for the high-speed working condition of roll grinding head, hydrostatic thrust bearing should be optimized.

4 Optimization structure of thrust bearing of high-speed precision roll grinding head

From the analysis of steady-state temperature field of roll grinding head, it can be seen that, although the structural design of roll grinding head is rational, local temperature is still high. To get a more rational structure of roll grinding head, the thrust bearing structure should be optimized.

4.1 Adoption of the design variable in the structure of thrust bearing

As for high-speed precision roll grinding head, the main parameters affecting the performance of its thrust bearing are as follows: bearing diameter (D), diameter of sealing surface (D_i), supply oil pressure (P_s), dynamic viscosity of lubrication oil (η), radial clearance (h_0), and so on.

Among the parameters above, bearing diameter and seal surface diameter directly affect the axial loading capacity (W) and flow (Q) of thrust bearing, while diameter of sealing surface and radial clearance directly affect the friction power (N) and stiffness (J). When h_0 decreases, N and J will increase. When W increases, J will increase [4]. In conclusion, D_i and h_0 directly affect the performance of the bearing, thus diameter ratio of sealing surface and h_0 are selected as the design variables. Therefore, the design variables can be expressed by the following formula,

$$X = [a, D_2/D_1, D_3/D_1, D_4/D_1, h_0], \qquad (1)$$

Where: a is interpolation between D_1 and D.

4.2 Objective function of thrust bearing

Heat and temperature rise of the bearing are the key factors affecting the functioning of high-speed precision roll grinding head. Coordinating the relationship between loading capacity and friction power is key to the optimization design of the bearing. Therefore, the lowest friction power loss per unit loading capacity and the largest loading capacity are regarded as an objective function of optimization design, which can be expressed by the following formula:

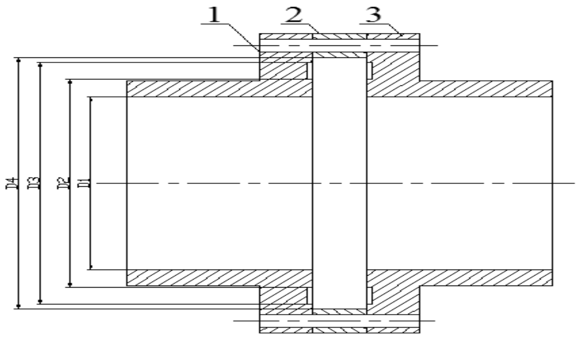
$$\min F(X) = [f(1), f(2)] = (N/W, 1/W), \qquad (2)$$

Where N is friction power; W is loading capacity.

N can be expressed by the following formula:

$$N = \frac{\pi^3 n_c^2 \eta}{28800 h_0}\left[\left(D_2^4 - D_1^4\right) + \left(D_4^4 - D_3^4\right)\right]\ [W], \quad (3)$$

As is shown in Fig.7, D_1, D_2, D_3, and D_4 are the diameters of structure of the bearing, which is made of the left bearing, the right bearing and the bearing bush. According to the value of each parameter, N can be figured out, and its value is 797.2W.



1.left bearing; 2.bearing bush; 3.right bearing

***Fig. 7** Structure of the thrust bearing*

W can be expressed by the following formula:

$$W = \frac{P_S \pi}{8\beta}\left[\frac{D_4^2 - D_3^2}{\ln D_4 - \ln D_3} - \frac{D_2^2 - D_1^2}{\ln D_2 - \ln D_1}\right] [N], \quad (4)$$

Where β is throttle ratio of capillary restriction. According to the values of each parameter, *W* can be figured out, and its values 2.47×10^4 N.

4.3 Constraint conditions of thrust bearing

According to the general design principle of ring thrust oil chamber, value ranges of the chosen design variables are as follows:

(1) Width of the bottom sealing surface

$$4 \le a \le 7\ [\mathrm{mm}], \quad (5)$$

(2) Diameter of sealing surface of thrust bearing

$$1.1 \le D_2/D_1 \le 1.25, 1.3 \le D_3/D_1 \le 1.45, 1.5 \le D_4/D_1 \le 1.8\ [mm], \quad (6)$$

(3) Radial clearance

$$0.02 \le h_0 \le 0.05\ [mm], \quad (7)$$

4.4 Multi-objective optimization design of thrust bearing

By analysing the design parameters of the bearing, it can be known that the mathematical model of the liquid thrust bearing belongs to non-linear constrained mathematical model, and its objective function is complex. So the genetic optimization algorithm is adopted.

At present, there are many multi-objective optimization algorithms. This paper adopts the gamultiobj function of MATLAB for multi-objective optimization design. Set the optimal front-end individual coefficient 0.4, population size 200, maximum evolutional generation 600, stopping generation 600, and fitness function value deviation 1e-100, draw picture of Pareto front-end. Run the function and the first front-end individual distribution picture is shown in Fig.8.

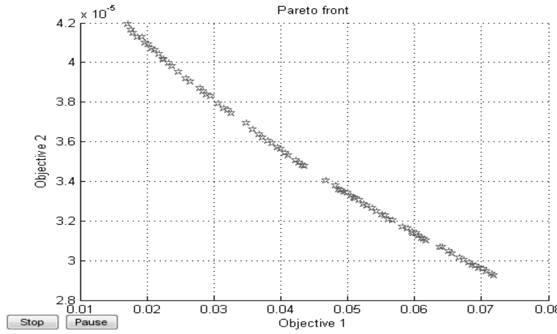


***Fig. 8** Static temperature distribution of oil film bearing*

It can be seen from Fig.8 that the distribution of the optimal solution of first frond-end is uniform and that objective function of *f*(1) and *f*(2) is mutual contradiction. When *f*(1) increases, *f*(2) decreases. Therefore, a reasonable result should be chosen as the result of the optimization analysis. As can be seen from the data, the optimal number of solutions is 80, which means there are 80 groups of solutions, and the population size is 200, so the optimal front-end individual coefficient takes effect. The individual is limited to the range of design variables.

Heat caused by the friction is taken away by the supply system of lubricating oil so that the temperature of the bearings can remain constant. Therefore, heat radiation of bearing oil cavity increases when flow of bearing oil cavity increases. The loading capacity of the bearing and the flow of oil cavity are regarded as objective function of optimization design to make single-objective optimization design, so the optimal solution group can be found among the 80.

4.5 Single objective optimization design of thrust bearing

Genetic algorithm has strong global search ability and weak local search ability, while non-linear programming algorithm has strong local search ability and weak global search ability. This paper adopts the advantages of algorithms, using genetic algorithm for global search, and non-linear programming algorithm for local search after certain groups are searched with genetic algorithm, so as to achieve global-optimization solution.

In order to turn multi-objective optimization design into single-objective, 1:1 weighted method for optimization design of the bearing is adopted. The objective function can be expressed by the following formula:

$$F(X) = \min(N + W), \quad (8)$$

Q can be expressed by the following formula:

$$Q = \frac{\pi h_0^3 P_S\left[\ln(D_2 D_4) - \ln(D_1 D_3)\right]}{6\eta\beta \ln(D_2/D_1)\ln(D_4/D_3)}\ \left[L\cdot s^{-1}\right], \quad (9)$$

According to the optimization objective and constraint conditions above, the program codes are compiled to implement the optimization design of the bearing by

MATLAB software. The initial setting of genetic algorithm parameters is as follows: evolutionary generations 40, population size 100, crossover chance 0.4, mutation chance 0.01. Set up the value ranges of variables for optimization design, then initialize population and calculate fitness iteratively with genetic algorithm. Set the current result of calculation as initial value and use linear programming function of MATLAB optimization toolbox for local optimization and regard the local optimal value as a new individual chromosome to evolve. Fig 9 shows the average function value and the changes of optimal individual function value of each generation in the optimization process.

It can be seen from Fig.9 that, when the population evolves to the 40th generation, function value converges to 2.6007, and the value can be achieved when design variables are respectively 6.4843, 1.1, 1.45, 1.5 and 0.05. Therefore, optimal solutions of design variables are 6.4843, 1.1, 1.45, 1.5, 0.05, and the best fitness is 2.6007.

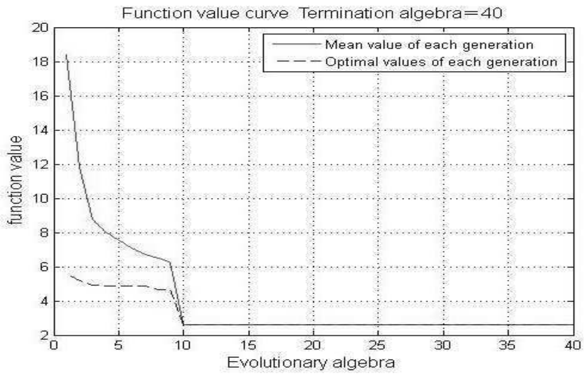


Fig. 9 *Optimize process of nonlinear programming genetic algorithm*

From analysis of the results of the two methods, it can be seen that, among the 80 groups of multi-objective optimization, the results of group 1, group 9 and group 57 are close to those of the single-objective optimization. Table 1 shows the relationship between bearing diameter and load capacity, flow rate and friction work.

Tab. 1 *Result comparison table of single-objective and multi-objective*

Parameters	Unit	Single-objective	Group 1	Group 9	Group **57**
Bearing diameter (D_1)	mm	106.5	106.4	106.4	106.5
Bearing diameter (D_2)	mm	117.1	117.0	117.1	117.2
Bearing diameter (D_3)	mm	154.4	154.2	154.4	154.5
Bearing diameter (D_4)	mm	159.7	159.5	160.8	172.4
Radial clearance (h_0)	mm	0.05	0.05	0.05	0.05
Loading capacity (W)	KN	23.9	23.8	24.2	27.9
Bearing flow (Q)	L/s	0.386	0.386	0.338	0.188
Friction power (N)	W	203.6	202.9	229.6	537.4

It can be seen from Table 1 that, the results of group 9 lie between those of group 1 and group 57, so the result should be either group 1 or group 57. Group 1 has the lowest friction power and loading capacity and the largest flow, while group 57 is opposite to first group. As the loading capacities of group 1 and group 57 are respectively 23.8KN and 27.9KN, the difference between the loading capacities of single-objective and group 1 is smaller than that between single-objective and group 57. The friction power of group 1 is less than half of that of group 57, while its flow is larger than twice that of group 57, so the result of group 1 is chosen as the result of optimization design. Structure parameters and performance index of thrust bearing are shown in Table 2.

Tab. 2 *optimization result table of oil film thrust bearing*

Parameters	Unit	Initial value	Optimization value
Bearing diameter (D_1)	mm	110	106.4
Bearing diameter (D_2)	mm	132	117
Bearing diameter (D_3)	mm	154	154.2
Bearing diameter (D_4)	mm	176	159.5
Radial clearance (h_0)	mm	0.05	0.05
Loading capacity (W)	KN	24.7	23.8
Bearing flow (Q)	L/s	0.125	0.386
Bearing stiffness(J)	N/m	9.5×10^8	1.03×10^9
Friction power (N)	W	797.2	202.9

It can be seen that from Table 2: bearing oil cavity is bigger after optimization; radial clearance almost remains constant; bearing loading capacity doesn't change much, it decreases about 3.6% from original 24.7KN to 23.8KN, it is reduced about 3.6%, the whole change is little. Bearing flow increases from original 0.125L/s to 0.386L/s. The increasing of bearing flow is beneficial to bearing cooling when the oil pressure keeps constant. Friction power decreases about 74.55% from original 797.2W to 202.9W. Therefore, through the optimization design of the bearing based on genetic algorithm, its overall performance is improved obviously.

5 Numerical analysis of thermal field of the improved roll grinding head

It can be seen from optimization analysis of the thrust bearing of roll grinding head that, bearing diameter changes greatly, leading to changes of friction power and bearing flow. Modify the structure of the thrust bearing, assemble the roll grinding head with 3-D software and transform it into finite-element model. Then set the finite-element model in ANSYS and reanalyse the steady-state temperature field of the grinding head. The steady-state thermal analysis results of the improved roll grinding head is shown in Fig.10, and the temperature rise of the improved hybrid bearing and thrust bearing is shown in Fig. 11.

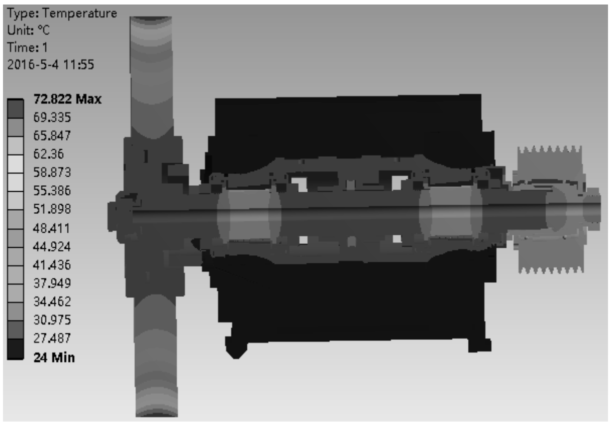
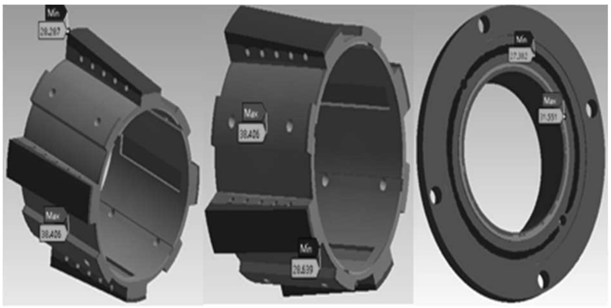


Fig. 10 *Temperature distribution of the improved high-speed precision roll grinding head*



1 Front hybrid bearing 2 Back hybrid bearing 3 Hydrostatic thrust bearing

Fig. 11 *Steady-state temperature distribution of the improved bearing*

It can be seen by analysing and comparing from Fig.5 and Fig.10 that the temperature distribution of the improved high-speed precision roll grinding head is more rational, and the temperature rise of the spindle is obviously ameliorated, especially hybrid bearing and thrust bearing. The temperature of the joint of the bearing and the spindle is 37°C~53°C before optimization design and 30°C~44°C after. Though the temperature change of the grinding wheel after optimization is not significant, the temperature of the grinding wheel chuck has been significantly reduced. Thus, thermal error of grinding wheel is reduced, and the machining accuracy is obviously improved.

It can be seen by comparing Fig.6 and Fig.11 that, after optimization design, the maximum temperature of front hybrid bearing is basically identical to that of back hybrid bearing. The maximum temperature, 38.4°C, is seen in the grooves between both oil holes. The maximum temperatures of both improved and original thrust bearings are seen on the bottom sealing surface of bearing oil cavity, from where high-temperature lubricating oil always streams out. At the same time, the axial pressure of the grinding head reduces the gap of the sealing surface and increases the pressure. Maximum temperature of the improved thrust bearing is about 31.6°C, at which , the viscosity lubricating oil is optimal and the performance of oil film between thrust bearing and spindle is stable. Thus metal dry friction between thrust bearing and spindle is effectively prevented.

In conclusion, after optimization, the maximum temperature of thrust bearing is significantly reduced; the influence that frictional heat of thrust bearing has on the spindle is reduced; the temperature of the bearing is within the optimal temperature range of lubricating oil; the structure of the oil film bearing is steady, thus the influence that axial movement of the spindle has on the grinding work piece is reduced, and the machining accuracy is obviously improved.

6 Conclusions

In this paper, the numerical simulation is used to analyse the thermal performance of high-speed precision grinding head. It can be seen that the temperature of oil film is on the high side, the oil film between bearing and spindle breaks easily, thus leading to metal dry friction between the bearing and the spindle. To reduce the influence of frictional heat on the thrust bearing, the thrust bearing needs to be structurally optimized. For this purpose, by analysing the influence of bearing parameters on its performance, the objective function of optimization design is found and then genetically coded with the single and multi-objective joint optimization method which is based on genetic algorithm. Then numerical analysis of thermal field of the improved roll grinding head is performed again. Analysis results show as follows: temperature distribution of the improved roll grinding head is more rational. The maximum temperature of the thrust bearing is significantly reduced. The viscosity of lubricating oil is within the optimal range. The performance of the oil film formed between thrust bearing and spindle is steady. Metal dry friction has been effectively prevented while the influence of thermal error on machining precision has been effectively reduced.

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