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Thermodynamic analysis of direct drive turntable

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Abstract

In this paper, the direct drive turntable of a five axis turn milling machining center is taken as the carrier to carry out the thermodynamic and heat transfer analysis. Through the analysis of the important components of heat generation torque motor and bearing, the heat and heat conduction are analyzed and calculated, and the convection heat transfer coefficient is calculated. The model of the turntable is established, and the heat distribution is obtained by finite element analysis, so as to improve the structure of the turntable The cooling system is used to improve the machining accuracy of the turntable.

Keywords

Direct drive turntable; thermodynamics; Thermal structure.

1. Introduction

Compared with the traditional worm and worm wheel turntable, the turn milling compound direct drive turntable has the advantages of high precision, fast processing, compact structure and low noise. The direct drive turntable forms a closed-loop control through the circular grating and encoder to control the rotation angle of the turntable, and uses the pneumatic locking device to control the spindle rotation, The torque motor directly drives the spindle and the table to rotate, which does not reduce the error through the mechanical structure. However, in this process, the relative motion of the rotor and stator of the torque motor and the inevitable friction and heat between the bearing and the spindle are generated. For the direct drive turntable, the fan cannot be added for the compactness of the structure, Therefore, the heat distribution is an important part of the accuracy analysis. Researchers at home and abroad have studied the way of generating heat of direct drive turntable. Jiang Xingqi and Ma Jiaju made thermal analysis on high precision angular contact ball bearing, deduced the condition factors related to bearing heat and friction, and pointed out the heat distribution of bearing[1]; Guo CE and sun Qinghong used the finite element method to carry out the thermal analysis of the machine tool spindle and optimized the heat dissipation module, which reduced the deformation of the spindle[2]; Feng Bo et al. Calculated the main heat generation part of the direct drive turntable, and proposed various ways of heat generation inside the motor and heat transfer[3]; Zhang Ai proposed the correlation between the heat generated by magnetic loss of motor and other conditions[4].

This paper mainly calculates the heat generated by the turntable, including the bearing and the machine tool motor, and calculates the heat transfer process of the turntable, including the heat transfer of the motor rotor and stator, the heat transfer of the bearing and the heat exchange between the air and the turntable, and obtains the heat distribution.

2. Heat generation and heat transfer of motor

The structure of direct drive turntable is simple, which simplifies the mechanical structure. The torque motor is directly connected with the spindle. Because the conventional heat dissipation method can not be used, the heat is transferred to other parts, resulting in the deformation of

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other parts and reducing the accuracy. The heating of the motor is mainly due to the mechanical loss, electrical loss and magnetic loss of the motor[3].

2.1. Heat generation of torque motor

The motor in this paper is gz6a 1705-54-200 W2 torque motor, which is used to generate heat. By inquiring the information of the motor, we can know that the rated power of the motor is 1.34kW, the[5] power factor of the torque motor is η=0.8, and the consumed power of the motor is calculated as 0.268kW through formula $H_f=P\cdot(1-\eta)$. During the calculation, all the consumed power of the torque motor is converted into heat generation, so the heat generated is ΔH=0.268kW. In this paper, the cooling oil is used to cool down, and the temperature of the cooling oil at the oil inlet is about 20℃, The temperature measured at the oil outlet is 33℃, so the temperature difference is f_c=13℃. The density of the cooling oil is ρ=852kg/m^3 and the specific heat capacity is C_p=1993J/kg·℃, Through the query formula, we can know that:

$$\Delta H = Q\cdot\rho\cdot C_p\cdot\Delta t_f \tag{1}$$

Among: Q is the flow rate of cooling oil per second,therefore,Q=1.214×10^{-5}m^3/s.

The cross-sectional area and length of the cooling tank are A=28.274mm^2 and L=1m, respectively,thus, The flow rate is:

$$u=\frac{Q}{A}=\frac{1.214\times10^{-5}}{28.274\times10^{-6}}=0.429m/s$$

The heat transfer of the cooling oil flowing in the mounting sleeve is forced convection heat transfer. The heat transfer conditions of the cooling oil will be affected by its flow state. The main reason is that the liquid flow is turbulent flow or laminar flow. The judgment basis is Reynolds number Re[6], Re is dimensionless, and the calculation equation is as follows:

$$\mathrm{Re}=\frac{u\bullet D}{v} \tag{2}$$

Among: D is the qualitative scale of geometric features,The geometric feature of the cylinder is the diameter of the outer circle:

$$D=\frac{4A}{U} \tag{3}$$

By calculating the kinematic viscosity of the coolant at room temperature is v=26.6×10^{-6}m^2/s. Its hydraulic radius is 1.5mm, Wet week U=A/R=18.849mm. Substituting R and u into equations 2 and 3, we get D=16.971×10^{-3}m.Re=96.766.

Because the Reynolds number is less than 2200, it can be judged as laminar flow. Because the turbulent flow is chaotic, its heat exchange capacity is also strong. Compared with laminar flow, the heat distribution of turbulent flow is more uniform, and the temperature exchange of laminar flow is more stable. The main heat is adsorbed on the layer close to the heat source. Therefore, for laminar flow, turbulent flow is easier to exchange heat, with smaller thermal resistance and larger heat transfer coefficient, It can be known from literature[7] that when the coolant is oil, the temperature difference is small, and the temperature difference is about. It can be seen from the above that the heat exchange between the cooling oil and the mounting sleeve belongs to forced convection, and the diameter of the cooling pipe of the mounting sleeve is also small, so the liquid is strictly laminar flow. After the liquid is heated by the heat source, the calculation method is as follows:

$$Nu_f=1.86(\mathrm{Re}\cdot pr_f\cdot D/L)^{1/3} \tag{4}$$

To use this formula 4, the following conditions need to be met:

$$\mathrm{Re}\cdot pr_f\cdot h_{\mathrm{gap}}/L>10\text{; }\mathrm{Re}=13\sim2030\text{; }Pr_f>0.6$$

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It can be seen from the above that it fully meets the requirements of Reynolds number,Pr_f is Prandtl multidimensional number, which can represent the physical properties of fluid, and its calculation expression is [8]：

$$\mathrm{Pr}_f = \frac{c_p \cdot \rho \cdot v}{\lambda} \tag{5}$$

λ is the thermal conductivity of the liquid, The thermal conductivity of the cooling oil is λ=0.123W/(m·K). Further calculation shows that:Pe_f=367.237,Nu_f=59.741.

It can be seen from the previous paper that the forced convection exists between the coolant and the tube wall of the motor, so the heat transfer coefficient of the laminar flow can be calculated h_w[8]：

$$h_w = Nu_f \lambda / D \tag{6}$$

$$h_w = 1224.691$$

2.2. Heat transfer between motor and air

In addition to the above-mentioned heat transfer to the coolant, the heat generated by the motor also has two parts of heat transfer, one part is transferred to other parts, and the other part is transferred from the motor rotor to the air in the motor. There are mainly two heat transfer modes between rotor and internal air, namely convective heat transfer and radiation heat transfer, so the heat transfer coefficient between rotor and air can be expressed as follows [8]：

$$a_t = 28(1+\sqrt{0.45u}) \tag{7}$$

Among：a_t is the heat transfer coefficient between rotor and air,W(m·K)；u Is the axial speed of the rotor,m/s；u=πnd/60；d is the average diameter of the rotor end,d=0.125m.

Thus, u can be calculated and then a_t can be obtained.

3. Heat generation and transfer of bearings

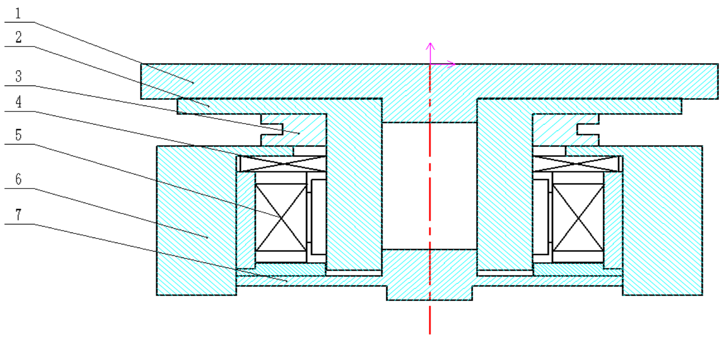
3.1. Heat generation analysis of bearing

In addition to the heating of the motor, there is also the friction between the bearing and the shaft. Each part of the bearing generates a lot of heat through friction and the impedance force of relative motion. According to different generation processes and principles, it can be roughly divided into five parts[9]: 1. The heat generated by the elastic hysteresis of the material. 2. Because the contact radius between the rolling element and the bearing ring is not uniform, and its angular velocity is equal, but the linear velocity is not equal. There is a small difference in the linear velocity at each point, so heat will be generated. 3. When the angular contact ball bearing receives the axial force, the rolling element may spin and produce friction. 4. The perfect rolling body should be pure rolling, but in the real state of motion, its motion is not pure rolling, but rolling and sliding, which will produce friction, but this friction is related to many parameters, so there is no effective calculation method. 5. The friction of lubricant is mainly divided into two parts, the first part is the heat generated by the internal friction of lubricant, the other part is the friction generated by the rolling element stirring the lubricant when rolling, so excessive lubricant will lead to the increase of heat.

In addition, excessive wear of the bearing will also lead to friction, which has a great impact on the accuracy of the turntable.

3.2. Calculation of bearing heat production

The bearing model selected in this paper is yrt100 P2 special bearing for high precision turntable. YRT turntable bearing can bear both axial force and radial force, and can support, rotate, drive and fix multi-functional bearings. The turntable will produce more heat when it works, so it needs to be checked.



1-rotating table 2-rotating spindle 3-turntable bearing 4-brake system 5-torque motor 6-mounting sleeve 7-flange plate

Figure 1 Structure diagram of direct drive turntable

shown in the figure above, the turntable bearing mainly bears the load from the rotary table, the rotary spindle and the processed workpiece. By querying the data, we can know that the material of the rotary spindle is 40Cr, the density is ρ=7.9g/cm^3, the calculated mass is 5.023kg, the mass of the rotary table is 7.9kg, and the maximum bearing capacity of the turntable is 60kg. The total axial load of turntable bearing is 72.923kg.

It can be known from reference[10] that the heating of turntable bearing mainly depends on the friction torque, and the two are proportional to each other. At the same time, according to palmgren's formula, the heat generation of bearing is generated by two parts, one is the bearing load, the deformation caused by the relative motion of rolling element and upper and lower rings, and the friction torque component related to sliding friction, The second part is mainly about the type, viscosity and amount of lubricant and the friction torque component related to the bearing speed, The sum of the two is the total heat production：

$$M=M_0+M_1 \tag{8}$$

The calculation of M_0 is mainly determined by the value of vn. At vn≥2000, $M_0=10^{-7}f_0(vn)^{2/3}D_m{}^3$ is used. On the contrary, when vn<2000,$M_0=160\times10^{-7}f_0D_m{}^3$ is used, where is the kinematic viscosity related to lubricant,n is the inner ring speed,v depends on the bearing design and lubrication mode, and f_0 can be obtained by looking up the table. D_m is the pitch diameter of the rolling bearing, so the data of the bearing are as follows:

Table 1 calculation of turntable M0

parameter	numerical value
Dm	142.5
F0	8
v	91.2
n	200
M0	3802.191

Query the working state of the turntable, the maximum speed is 200r/min, so it can be calculated vn=18240>2000, using the corresponding formula.

For the second part M_1, the calculation formula is as follows:

$$M_1=f_1P_1D_m \tag{9}$$

Among：f_1 is the coefficient of bearing type and load; P_1 is the equivalent load to determine the friction torque.

For the bearing, the load can be regarded as the axial force of the bearing：

$$P_1=F_1 \tag{10}$$

The acceleration of gravity is g=9.8m/s^2. It can be seen from the above that the axial force on the bearing is:

$$F_1=716.645N$$

Therefore, the relevant parameters of M_1 are as follows:

Table 2 Calculation of turntable M1

parameter	numerical value
Dm	142.5
F1	0.001
P1	714.645
M1	101.837

Therefore, the total friction torque is the sum of the two:

$$M_0+M_1=3904.028N/mm$$

According to palmgren's formula, when the rolling element and the inner and outer rings of the bearing move, the calorific value is calculated as follows:

$$Q=1.047\times10^{-4}Mn \tag{11}$$

Therefore, the formula is used to calculate:Q=81.756W.

3.3. Bearing heat transfer calculation

The lubrication mode of the turntable is oil air lubrication. Oil air lubrication is a new type of lubrication technology. Through compressed air and a small amount of oil to form an oil flow, the compressed air is continuously introduced to carry the oil to flow rapidly, so that the oil can slowly move forward in the case of compressed air. Under the action of air, the oil becomes uniform, continuous and thin, which can meet the complex working conditions[11]. In this technology, a small amount of oil is introduced into the rolling element and the inner and outer rings through compressed air for lubrication. Due to the use of a small amount of oil, it can be considered that the heat exchange only occurs between the bearing and the air. The atmospheric pressure is about 0.1013MPa, and the air lubricated by oil and gas needs a larger pressure. Generally speaking, the pressure of oil and gas nozzle is more than twice of atmospheric pressure, and it is turbulent, and the heat distribution is more uniform. In the process of injection, the speed of compressed air is set unchanged. Set the pressure of the compressed air outlet as 0.4MPa, the density of air at normal temperature and pressure as ρ_1=1.237kg/m^3, then the density of compressed air is ρ_2=4.88kg/m^3, the gas into the nozzle is 3×10^{-3}m^3, so the quality of compressed gas is:

$$m_2=\rho_2V_1=0.0146kg$$

The formula between the air velocity u_1 and the outlet velocity u_2 of a certain section in the pipe is (where the compressed air velocity of this section is 0.1m/s):

$$\frac{u_1}{u_0}=\frac{0.1}{\frac{ax}{D_0}+0.147}=0.134$$

Among: a is the experimental coefficient, which is 0.075; x is the distance between nozzle mouth and oil pipe mouth, which is 3 in this paper, and the diameter of nozzle D_0 is 1mm

According to the law of momentum, the momentum of oil and gas is approximately constant, The mass of oil and gas on this section is calculated as follows:

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$$m_1 = \frac{u_0}{u_1} m_2 = 0.109kg$$

Therefore, it can be calculated that the actual volume of gas under normal temperature and pressure is:

$$V_1 = \frac{m_1}{\rho_1} = 0.088m^3$$

The compressed air is ejected through the nozzle. In the process of ejecting, the compressed air is in a turbulent state. In addition, the compressed air is accompanied by an axial air flow. When the axial air flow quickly passes through the bearing, the flow area is:

$$A_{\alpha x} = 2 d_m \pi \Delta h \tag{12}$$

Among: d_m is the pitch circle diameter, as can be seen from the above d_m=0.142m, Δh are the gaps between the bearing inner ring and outer ring and its cage, which are measured to be Δh=0.001m. The results show that the flow surface of axial air flow through the bearing is as follows:

$$A_{ax} = 8.92 \times 10^{-4} m^2$$

The average velocity of compressed air in the bearing can be calculated by the above axial air flow and tangential air flow[13]:

$$\bar{u} = \left[\left(\frac{V_1}{A_{ax}} \right)^2 + \left(\frac{\omega \cdot d_m}{2} \right)^2 \right]^{1/2} \tag{13}$$

The angular velocity of the rotating spindle of the worktable is:

$$\omega = \frac{2\pi n}{60} = 20.944 rad/s \quad \bar{u} = 98.666 m/s$$

The lubrication mode of bearing is oil air lubrication. For oil air lubrication, which is a function of air velocity in bearing, the following formula is used to calculate its convective heat transfer coefficient:

$$\alpha = \left(c_0 + c_1 \bar{u}^{c_2} \right) \tag{14}$$

According to the reference[12], the three parameters are the experimental constants, and their values are 9.7, 5.33 and 0.8 respectively. Calculate out α=219.623W·(m^2·K)

4. Heat transfer calculation of direct drive turntable and air outside turntable

There are two parts in the heat transfer between the turntable and the outside air. The first part is the heat exchange through the rotating parts of the turntable, such as the rotating spindle and the turntable. The second part is the heat transfer to the non rotating parts through the heat generating parts, and then exchanges heat with the outside air.

There are three ways of heat transfer between objects: heat conduction, convective heat transfer and radiation heat transfer. The heat exchange between the turntable and the outside air is mainly through the latter two ways, and the two ways occur at the same time, which is called composite heat transfer. Because there is no interference of external force, the static part of the turntable is natural convection, and its heat transfer coefficient can directly reflect the degree of radiation heat transfer [13]. Turbulence and laminar flow will affect the convective heat transfer law.

The calculation method of natural convection is[14]:

$$Nu = C\left(G_r \bullet \mathrm{P_r}\right)^n = CRa^n \tag{15}$$

Among: C、n is the parameter obtained by experiment, which can be found by looking up the table. When judging C and n, we can make a decision by calculating the reilly criterion. $Ra=G_r \cdot P_r$.where G_r is the Grachev criterion and P_r is the Prandtl number.

The formula of G_r is[15]:

$$G_r = \frac{g\alpha\Delta t l^3}{v^2} \tag{16}$$

Among: g=9.8m/s^2,α is the linear expansion coefficient of fluid, $\alpha=1/T_m$, $T_m=273.1+t_m$,t_m is the average value of the temperature of the external environment and the working temperature of the turntable. The external temperature is 20℃, and the temperature of the turntable is 45℃,so t_m=32.5℃,T_m=1/305.6℃$^{-1}$, when it is working. Therefore, Δt are the difference between the external environment and the working temperature of the turntable. Δt=25℃, l is the set size and v is the kinematic viscosity, through the measurement, we can know l=0.164m, at 32.5℃, the dynamic viscosity of air is 0.018715m·Pa·s=18.754×10^{-6}Pa·s, the relationship between dynamic viscosity and kinematic viscosity is $\eta=v\rho$,among:η is dynamic viscosity,v is kinematic viscosity, Density of dry air ρ=1.157kg/m^3, the kinematic viscosity can be calculated as follows: v=16.206×10^{-6}m^2/s, the Prant number of air is P_r=0.7, and the following can be calculated G_r:G_r=8.210×10^7.

The Rayleigh criterion can be calculated:

$$Ra = G_r \cdot \mathrm{P_r} = 5.747\times10^7$$

It is known from[16] that in the interval $10^4<Ra<10^9$, the values of C、n are 0.59 and 0.25 respectively, and the flow pattern of air is laminar flow, and the position of heat transfer is vertical flat wall, From this we can calculate Nu:

$$Nu = C\left(G_r \bullet \mathrm{P_r}\right)^n = 51.370$$

The natural convection heat transfer coefficient between the turntable and the air is as follows[8]:

$$h = \frac{Nu\lambda}{L} = 3.427$$

The thermal conductivity of the gas at 32℃ is about: λ=0.0263.

The heat transfer characteristics of the rotating part are similar to those of the bearing, and the convective heat transfer coefficient between the moving surface and the air is also used $\alpha=(c_0+c_1u^{-c_2})$. The measured data are the same as above, the average speed of the turntable is:

$$\bar{u} = \frac{\pi n d}{60} \tag{17}$$

Among: the maximum speed of direct drive turntable is calculated according to the maximum speed of torque motor, thus n=200r/min, and the diameter of the turntable is d=0.4m, the average speed is:

$$\bar{u} = 4.189m/s$$

Therefore, α=26.465W/ (m2·K).

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5. Finite element analysis of direct drive turntable

5.1. Model simplification and modeling

The heat distribution of direct drive turntable not only needs to calculate the convective heat transfer coefficient, but also needs to calculate the heat production of each part of the turntable, which is convenient to use the finite element analysis. When using ug10.0 three-dimensional modeling software to establish the model, it needs to simplify the model, and deal with the bolt, keyway, fillet and chamfer and other non critical details. After simplification, the key parts are as follows:

Figure 2 turntable model

The rotary table is made of HT200, the turntable bearing is made of GCr15, and the rotary shaft is made of 45 steel. The specific parameters are as follows:

Table 3 material properties of bearing, shaft and table

Material properties	HT200	GCr15	45
Young's modulus (Pa)	1.13E+11	2.19E+11	2.09E+11
Poisson's ratio	0.23	0.3	0.269
Density(kg/m3)	7.15E+3	7.83E+03	7.89E+03
Coefficient of linear expansion(K-1)	8.50E-06	1.20E-05	1.17E-05
Thermal conductivity(W/(mK))	39.2	44.0	48.0

5.2. Heat calculation

The main parts of heat generation of direct drive turntable are torque motor and bearing.

The rated power of the rotary table torque motor obtained from the first chapter is 1.34kWnd its power factor is 0.8. Suppose that all the consumed power is converted into heat, the heat production of the stator and rotor is 268W and the heat production ratio of the stator and rotor is 2/3 and 1/3 respectively. Therefore, it can be calculated that the heat production of the stator is Q_s=178.667W, and that of the rotor is Q_r=89.333W. The calculation of bearing heat production is Q_B=81.756W. The convection heat transfer coefficient of motor and air is α_t=49.49W(m^2·K), and the convection heat transfer coefficient between bearing and air is α=219.623W(m^2·K) turntable rotating part and air α=219.623W(m^2·K).

The model uses the finite element software to divide the mesh automatically. The method of mesh division is to generate the mesh by tetrahedron and sweep method, to form hexahedral mesh on the scanned geometry, and to generate tetrahedral mesh on the mesh not swept. The number of grid cells generated is 87949, and the number of nodes is 52321. The specific figure is as follows:

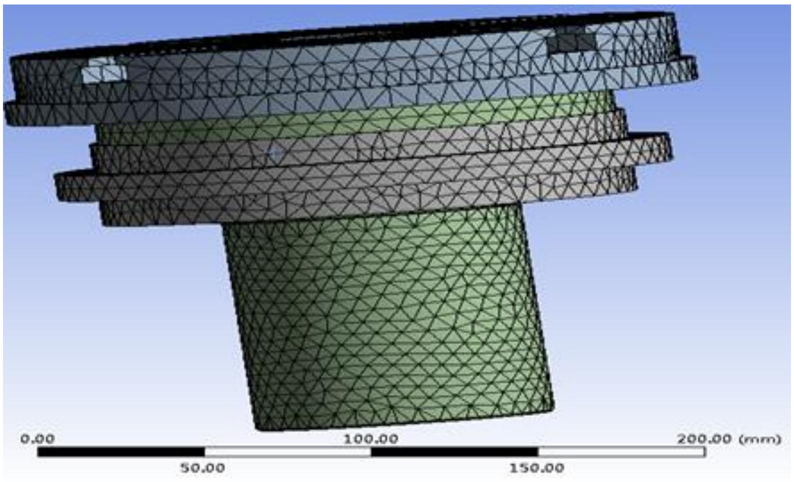

Figure 3 grid generation

Through the input of the above parameters, when the initial ambient temperature is 20℃ and the speed is 200r/min, the heat distribution of the rotating spindle, bearing and table is as follows:

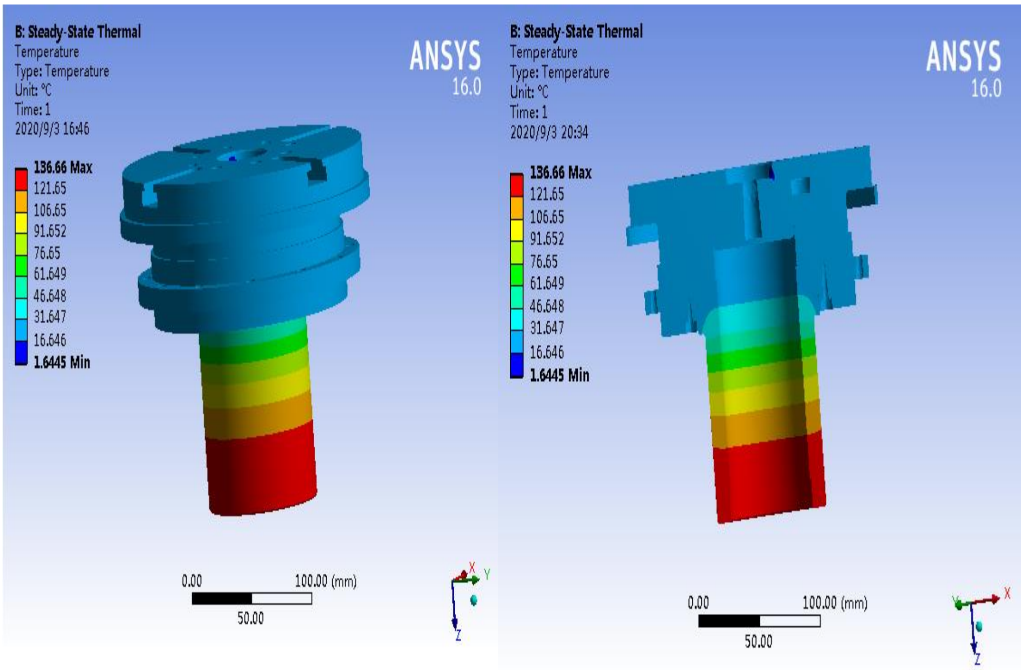

Figure 4 heat distribution of direct drive turntable

It can be seen from this figure that the heat generated by the bearing is small, so the heat of bearing and air has been discharged for the turntable. However, due to the large heat production of the motor, it can be found that the temperature of the spindle which rotates synchronously with the motor reaches 136.66℃, and the heat will accumulate on the rotating shaft driven by the motor. Only the air is used to remove the heat, and the heat is not released, and the heat transfer status of the spindle is poor.

5.3. Thermal structural coupling

The thermal analysis of the direct drive turntable is carried out. However, due to the different materials used in each part, the deformation of each part can not be seen directly by thermal analysis, so it is necessary to carry out thermal structure coupling analysis to calculate its thermal stress and thermal deformation and judge whether it can meet the requirements.

In ansys workbench 16.0, there are two kinds of thermal structural coupling methods, direct coupling and indirect coupling. The direct coupling needs to redefine the type of calculation

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element, and it needs to be changed to the element with temperature and displacement degrees of freedom, and it can be used for thermal stress and thermal strain structure; Indirect coupling needs to be carried out on the basis of thermal analysis. Since thermal analysis has been done, indirect coupling is selected as the coupling method. The thermal deformation and stress are analyzed. The results are as follows:

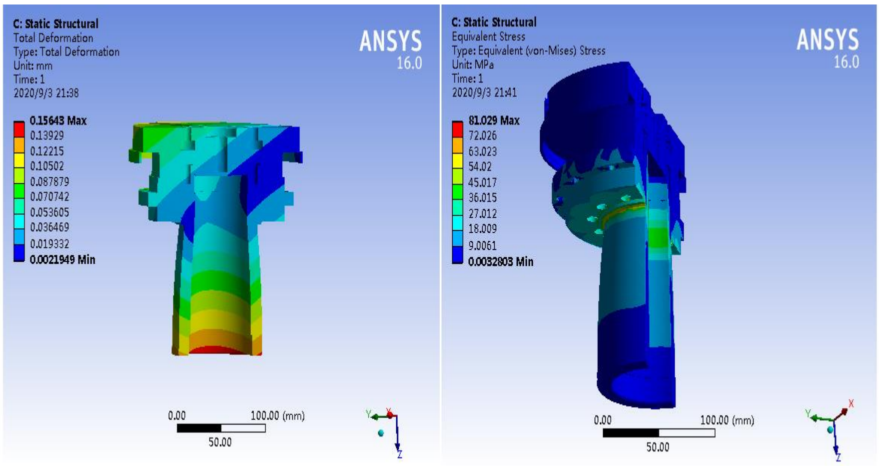

Figure 6 thermal deformation of direct drive turntable

From this figure, it can be seen that the thermal deformation mainly occurs on the main shaft, the maximum deformation has reached 0.156mm, and the rotating table has certain deformation.

The thermal stress mainly occurs in the contact part between bearing and spindle,The maximum is 81.029 MPa.

6. Conclusion

There are two parts of direct drive turntable, bearing and torque motor. Both of them are heated, but the calorific value is different. The maximum heat generation occurs on the rotating spindle, and the maximum temperature is 136.66℃. The temperature rise of the bearing is not high because it produces little heat.

Through the thermal structure coupling, the deformation and thermal stress can be seen directly. The maximum deformation is 156μm on the rotating spindle, and the maximum thermal stress at the contact between the bearing and the rotating spindle is 81.029MPa. Therefore, for the cooling of the rotating spindle and torque motor, the coolant system in the mounting sleeve should be used. In order to lubricate and cool the bearing, the oil-gas lubrication method is used, Good cooling effect can be obtained. Or the structure of the direct drive turntable can be improved without increasing the processing cost and reducing the dynamic and static characteristics.

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