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A Method to Evaluate the Effects of Heat on a Spindle of a CNC Milling Machine

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Abstract— *The article presents the results of modeling the heat transfer process of the vertical main spindle of a CNC milling machine for evaluating the temperature change inside of the spindle unit when it is working at high speed level such as 11,000 rpm. The model is used to simulate the heat transfer from ball bearings to other components inside of the spindle unit and then transfer to the housing and convective heat transfer with the atmosphere from the housing. From the results of the simulation, the authors have evaluated the heat transfer rule inside of the spindle. The findings suggested a suitable lubrication method and nozzle arrangement to cool the spindle bearings and the locations of the heat sensors to investigate the real temperature of the bearing outer ring before the experiment.*

Keywords— *Heat transfer, heat distribution, vertical spindle, high speed, CNC milling machine.*

I. INTRODUCTION

Nowadays, with the development of science and technology, metal cutting machines are increasingly innovated, leaving a significant change in terms of product quality and productivity. To achieve an increase in productivity, the main spindle speed is one of the directions that scientists in the field are taking. However, high rotation speed of the spindle, along with the increase in temperature in the bearings, has led to a thorough inspection to ensure normal working conditions of the machine, as well as prolong the life of the machine. This also means the temperature increase in an operating spindle must be strictly controlled.

The heat generated in the bearings is the main heat source on the spindle [1]. The temperature of the spindle drive during operating is a factor that affects the precision machining of the machine. Errors caused by heat are reported up to 70% of the total number of errors in the machine tool, thus errors due to heat in the spindle need attention so as to reduce the errors proportion [2]. Objects such as load, and lubrication are important factors to reduce thermal errors of the main spindle when operating at high speed.

With the same belief, some authors have studied the heat of the spindle assembly in other conditions and speeds. This paper proposes a method for simulating the heat transfer process until it reaches the thermal equilibrium state and the layout of the lubrication and cooling device in a vertical main spindle of a CNC milling machine.

II. CALCULATION AND MODELING OF THE HEAT TRANSFER IN THE MAIN SPINDEL OF VERTIAL MILLING MACHINE

A. Experimental Setup

a) Experimental model

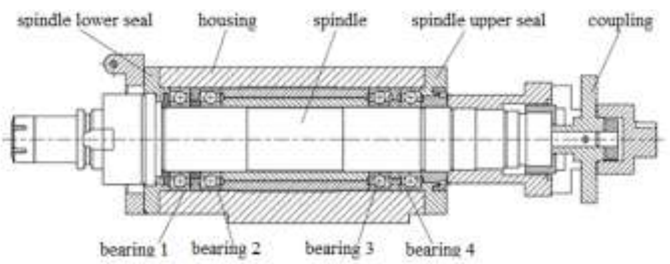

Fig. 1. Slice section of original main spindle.

To examine the thermal propagation of the spindle, the authors used the Takisawa MAC - V0 vertical spindle milling machine. The model consists of four 7010A ball bearings. The main vertical spindle works in the speed range from 3750 to 12000 rpm and will be tested at 11000 rpm from the condition of cutting C45 steel in two different lubrication conditions. The C45 cutting force in this article will be consider 100N. The spindle is made up of components made of Cr40 Steel and has spindle shaft components and flanges made of structural steel.

b) The temperature increase in an operating spindle measurement

During the process of cutting metal, the spindle will be influenced by two major sources of heat: the amount of heat generated by the metal removal process of the tool and the amount of heat generated by the direct contact of balls with the inner and outer ring of the bearing. It is assumed that the amount of heat generated during the removal of the material is transferred to the chip and is removed by air and coolant solution (if any) when the chip comes out. Therefore, the heat generated by the ball-bearing friction process is the main cause of thermal expansion in the spindle milling machine and is calculated by the following equation [4]:

$$H_f = 1{,}047 \times 10^{-4} nM \quad (1)$$

Where:

- n: the rotational speed of the inner ring of the ball bearing which is also the rotational speed of the main spindle (round per minute);
- M: The friction torque in bearing (N.mm)
- Hf: Heat energy generated (W)

The friction torque consists of two components: contact load torque and viscous torque:

$$M = M_l + m_v \quad (2)$$

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The load torque is primary caused by external force and can be approximately calculate by the experimental formula:

$$M_l = f_l P_l D_m \quad (3)$$

Where:

- $d_m = \frac{D+d}{2}$ (mm)
- P_1: dynamic load on bearings
  - At bearings number 1,2: $P_1(1,2) = 648(N)$
  - At bearings number 3,4: $P_1(3,4) = 534(N)$
- f_1: coefficient depends on ball bearing types and load types, $f_1 = 0.001\left(\frac{F_s}{C_s}\right)^{0.033}$

Viscous torque M_v is the torque caused by the viscousity of the lubricant:

$$M_v = 10^{-7} f_0 (\upsilon_0 n)^{\frac{2}{3}} d_m^3 \text{ with } \upsilon_0 n \geq 2000 \quad (4)$$

$$M_v = 160.10^{-7} f_0 d_m^3 \quad \text{with} \quad \upsilon_0 n \geq 2000 \quad (5)$$

Where:

- f_0: depends on ball bearing type and lubrication method. With axial thrust bearing and
  - grease lubrication $f_0 = 2$,
  - oil/air lubrication $f_0 = 1.7$
- υ_0 depends on temperature (cst) with 1 cst = 1 $\frac{mm^2}{s}$ = $10^{-6}\,\frac{m^2}{s}$

With the functions above, it can be seen that generated temperature depends significantly on viscosity of the lubricant. And this parameter decreases when temperature rise.

c) Convective heat transfer coefficient:

The convective heat transfer coefficient has been studied and determined as:

$$\alpha = \frac{N_u . \lambda_{fluid}}{h_{gap}} \quad (6)$$

Where:

- λ_{fluid} heat transfer rate of coolant air
- N_u Nusselt number
- h_{gap} diameter

Nusselt number can be calculated in various of methods according to boundary condition of the model. In this study, Nusselt number is calculated with Reynold number (Re) and Prandtl (Pr) and the following function [7]:

$$Nu = 0.133 Re^{\frac{2}{3}} Pr^{\frac{1}{3}} \quad (6)$$

Where:

$$Re = \frac{u_{fluid} . h_{gap}}{\upsilon_{fluid}} \quad (7)$$

$$Pr = \frac{c_{p\,fluid} . \mu_{fluid}}{k_{fluid}} \quad (8)$$

- u_{fluid}: main spindle speed
- υ_{fluid}: viscosity of fluid
- $c_{p\,fluid}$: specific heat of fluid
- μ_{fluid}: viscosity of oil

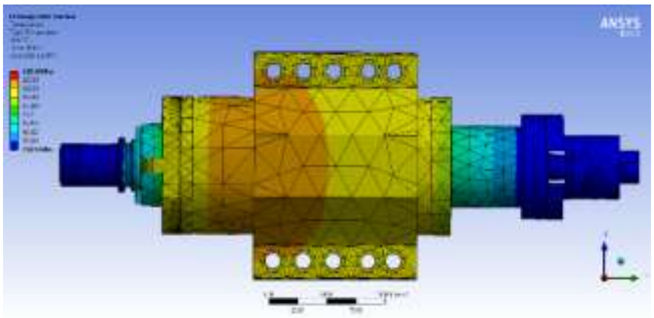
Function is applicable when $Re < 4{,}3.10^5$; $0{,}7 < Pr < 670$; with the convective heat transfer coefficient in the static part is $\alpha_1 = 9.7\,\frac{W}{m^2}$ [5] and the coolant air and air around the rotatory part is calculated as $\alpha_2 = 260.01\,\frac{W}{m^2}$

d) Calculation and simulation of grease lubrication of a high-speed spindle

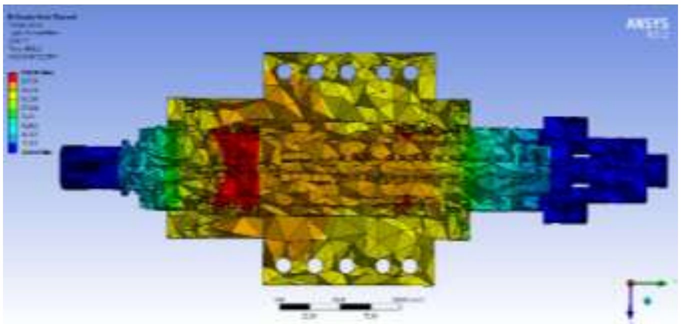
The heat generated in this lubrication method is shown in Table I. Simulation of heat transfer in the main spindle shows the distribution of heat transfer on the spindle from which we can determine the temperature distribution and the maximum temperature increase in the spindle; therefore, providing a cooling solution for the spindle.

TABLE I. Heat generated at each grease lubricated ball-bearing at 11000 rpm.

Ball-bearing No	#1	#2	#3	#4
40°C	761,27	761,27	756,78	756,78



a. Thermal distribution on spindle outer case.



b. Thermal distribution in the spindle components at the cross section through the center axis of the spindle.

Fig. 2. Heat distribution on grease lubricated spindle after 6000s operation time.

From the thermal diagram (Fig. 2) of the spindle after simulation of heat transfer, it could be seen that the largest spindle heat zone is located in the bearing areas 1 and 2, specifically at 138.18 °C near the direct contact zone of balls with the inner and outer ring of the bearing. This is also the area where friction causes of heat on the spindle. From there we need to intensely cool the ball bearings of the spindle to ensure that the generated temperature does not affect the operation of the spindle.

e) Lubrication, cooling and temperature measurement system of the spindle:

After testing the temperature of the grease lubricated spindle, it is shown that this method of lubrication on the spindle does not meet the operating conditions at high speeds for lubrication and cooling. An oil/air lubrication system designed to meet the working conditions at 11000 rpm of the spindle has been proposed as shown in Figure 4.

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From Figure 1 it can be seen that four ball-bearings are arranged in one of the two-headed block types marked >> = <<. The ball bearings are currently lubricated with LGMT 2 oil which has a dynamic viscosity of 110 (cst) at 40 °C and 11 °C at 100 °C. With the layout of the bearings and lubrication with the oil, the maximum speed that the inner ring or main spindle speed can achieve is 12000 rpm is the upper limit recommended by the manufacturer and the temperature when the balance of the spindle is reached is very high. To ensure the operation of the spindle at that high speed, it is necessary to gain all the factors that avoid affecting the operation such as the gap between ball-bearings or lubricating and cooling ball-bearings in a reasonable way, ...

From the analysis in Section 2.4, it can be seen that the temperature is concentrated in the bearings 1 and 2. Hence, providing a minimum amount of oil for lubrication and cooling is involved. At the same time, in order to eliminate the gaps, the spindle is rearranged according to the other two-way block diagram as shown in Fig. 3, the layout is denoted by <=> <, the gap will be eliminated by the nut on the top of the main spindle.

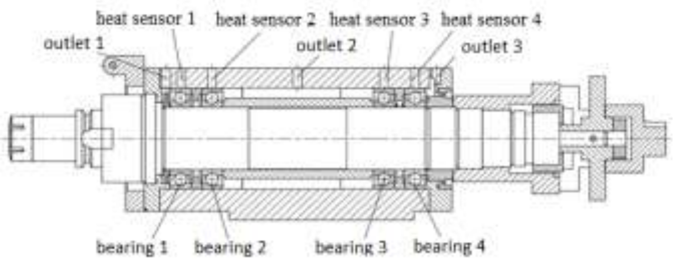


Fig. 3. Schematic illustration of air outlet and temperature sensor.

The current spindle cooling process will include internal cooling using an oil-lubricated system and convection heat transfer outside the main spindle. With this lubrication method, lubricating oil is periodically injected into the mixer, along with the compressed air. After the mixer, following the channels, lubricating oil and coolant gas are fed into the spindle through the pipe. At the outlet of the nozzle, gas will be torn oil into the fog to put into bearings which are rotating at high speed. The oil will cling to the ball, the inner and the outer ring of the bearing for lubrication, while the gas will pass through the surface of the balls, inner case, outer case as well as parts inside the tube to reduce heat and then follow the pipe to reach the outlet. The nozzles positions, air outlet, oil outlet and sensor position are presented in Figure 4.

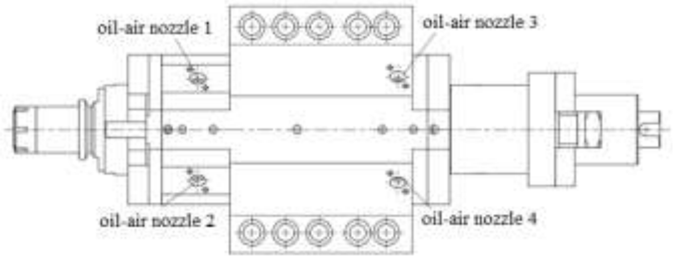


Fig. 4. Front projection of main spindle illustrates the schematic position of oil-air nozzles.

f) Simulation of heat transfer in the vertical spindle

ANSYS 17.2 was chosen to solve the heat transfer problem in the spindle, the temperature fluctuation in each region and across the spindle. The element type SOLID 87 is used in the simulation to model the temperature distribution field on the main spindle. The element types named CONTA174 and TARGE170 are used to simulate the links among the components in the spindle.

To ensure the ability to calculate and accuracy of the subject in the heat transfer simulation, the elements in the bearing area are divided smaller with 2mm element size, the vicinity and spindle cover are divided by 8 and 12mm respectively to reduce the calculation time. The finite element model for computation and analysis has a total of 287299 elements, as shown in Figure 5.

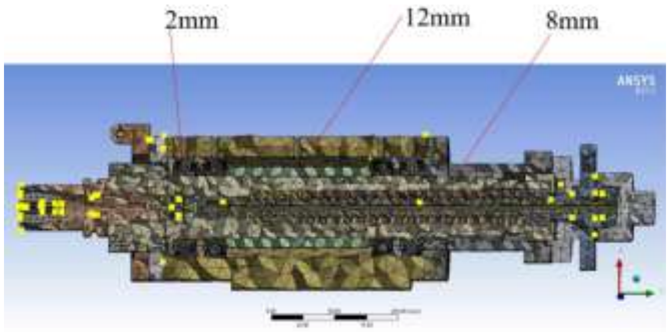


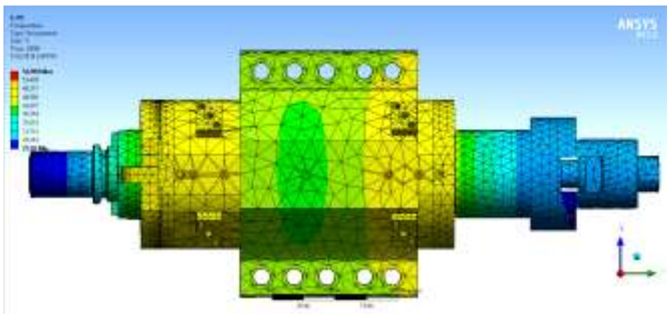
Fig. 5. The finite element model for analyzing heat transfer in the vertical spindle of a CNC milling machine.

TABLE II. Dynamic viscosity of oil by temperature.

Temp	Dynamic viscosity (mm^2/s)
25°C	155
40°C	68
60°C	29

TABLE III. Heat generated at each ball-bearing with oil/air lubrication at 11000 rpm.

Ball-bearing No	#1	#2	#3	#4
25°C	773,90	773,90	774,35	774,35
40°C	449,58	449,58	450,03	450,03
60°C	257,55	257,55	258,00	258,00



a. Thermal distribution on spindle outer case

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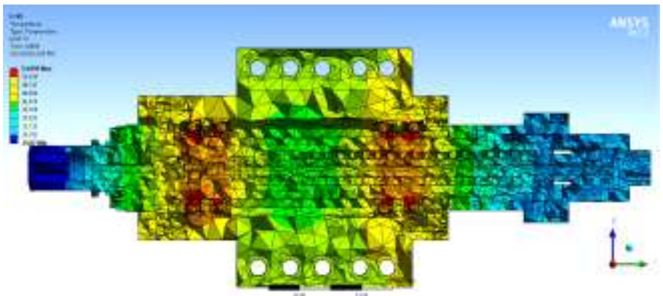

b. Thermal distribution in the spindle components at the cross section through the center axis of the spindle.

Fig. 5. Heat distribution on oil/air lubricated spindle after 6000s operation time.

III. RESULTS AND DISCUSSION

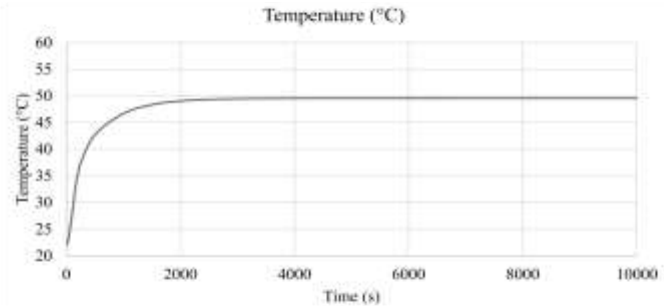

Fig. 6. Graph showing temperature rise over time.

From the graph, it was found that after a period of about 3,000s, the temperature of the spindle started to reach its thermal equilibrium and the temperature did not increase significantly after this period. This proves that the oil/air lubricated method at 11000 rpm for the spindle of the milling machine is more effective than the original grease lubrication method.

IV. CONCLUSIONS

In this paper, a heat model based on calculations by Bossman and Tu (1999) [5] has been developed and analyzed to evaluate the heat transfer characteristics of the spindle when operating at high speed. At the same time, the article also points out that comparing to the traditional grease lubrication method of the ball bearings, the oil/air lubrication system is more efficient in both cooling and lubricating for bearings in particular and the spindle in general.

Figures 4 and 5 show the temperature distribution field on the spindle in two lubrication modes, it can be seen that the temperature in the case of oil/air lubrication was significantly reduced compared to grease lubrication. In part, the viscosity of the oil is lower than that of the grease, and the rest is due to the cooling of the air.

The method that combine calculating heat and heat transfer simulation can be applied to other high-speed regions. The results of the article also indicate the method for conducting experimental equipment with the guideline of installation positions of oil/ air nozzles, heat sensors and outlets for air and oil.

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