Analyzing the Effects of Lubrication Techniques on CNC Spindle Bearing Heat: An Experimental Investigation

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ABSTRACT

The machining ability and accuracy of a machine are determined by parameters such as the stiffness and load capacity of its spindle unit. In addition, the effectiveness and technique of lubrication and cooling can significantly affect the operational characteristics of the machine spindle. The current study investigated the effects of two different lubrication methods, grease and air-oil mixture, on the temperature which is generated at the spindle bearings of a Computer Numerical Control (CNC) machine. The temperature distribution and rise rate of the bearings were measured using a thermal imaging camera and thermocouples. The results indicated that the air-oil mixture method was more effective in dissipating heat and reducing the temperature of the bearings than the grease method, due to the direct cooling provided by the air-oil mixture to the bearing balls, resulting in improved lubrication efficiency and heat exchange with the environment. Compared to the grease lubrication method, the temperature of the bearings was lower by 7°C to 9°C depending on the position of the bearing on the CNC spindle. Therefore, it is recommended to use the air-oil mixture lubrication method, especially for high-speed processing on CNC machines. However, the discharge of oil particles from the ventilation system should be carefully controlled. Overall, the findings offer valuable insights into optimizing lubrication methods for CNC machines to enhance processing quality and reduce the impact of temperature on the bearing performance.

Keywords-spindle bearing; lubrication method; temperature distribution

I. INTRODUCTION

The demand for high-speed machining has risen in modern manufacturing as it enables the production of complex and advanced products [1]. However, the high spindle rotation speed generates more heat, which can lead to stiffness and deformation issues. To address this problem, several cooling and lubrication methods have been proposed, such as air-oil cooling, to improve lubrication and cooling efficiency. The stiffness of the spindle unit is a crucial factor affecting the machining quality of machine tools [2, 3]. High-speed machining is necessary in order to produce more complex products. However, it generates heat and reduces the stiffness or increases deformation of the spindle [4-7]. Various methods have been proposed to enhance the efficiency of lubrication and cooling systems, and among them, grease and air-oil mixture lubrication have been studied using numerical simulations [8]. On the other hand, a study conducted in 2021 indicated a similarity in the trend of temperature variation over working time between experimental and numerical simulation studies when lubricated with grease in all bearings of the CNC spindle unit [9]. Various lubrication methods have been developed to minimize heat generation at bearings, including grease, oil splash, and oil mist. Among these methods, liquid droplets have been identified as a promising option for enhancing lubrication and cooling, due to their effective convection and heat transfer properties [10]. A mixture of oil-air is a more effective lubrication and cooling method that saves lubricant and is preferred in modern machining industry [11, 12]. Authors in [13] investigated the effect of heat on machining accuracy, simulated the heat transfer process and analyzed thermal coupling using finite element analysis [13]. The cooling capacity of the spindle cooling system was also simulated, and the parameters provide a reference value for actual model building. Authors in [14] conducted a study investigating the performance of high-speed spindles using oil/air lubrication, with a focus on the effects of various lubrication parameters and preloads on temperature increase, thermal deformation, and static stiffness. The study applied the Taguchi method to determine optimal lubrication conditions that minimize temperature increase and provide a useful tool for designing high-speed spindles with sufficient static stiffness [14]. Authors in [15] investigated the film-forming behavior under oil-air lubrication and oil-jet lubrication. Their results showed that oil-air lubrication has a higher oil supply efficiency and slower reduction in film thickness in starved regime, due to the contribution of micron-order oil droplets that improve oil supply efficiency [15]. Additionally, lubricating oil can be supplemented with additives to enhance lubrication efficiency, reducing friction and component wear within the machine [16].

Spindle bearings are essential components in machine tools, and their performance can significantly impact the overall productivity and quality of the machining process. Proper lubrication is critical to ensure the smooth operation and extended life of these bearings. In recent years, various lubrication methods have been proposed and investigated regarding CNC spindle bearings, including oil, grease, and air-oil mixtures. However, the choice of lubrication method and the appropriate lubricant type can significantly impact the thermal and dynamic behavior of the spindle, affecting its load-carrying capacity, accuracy, and stability. Therefore, it is important to investigate the effects of different lubrication methods on CNC spindle bearing performance to optimize the machining process and improve overall efficiency. Although these methods efficiently lubricate and cool the bearings, they still face problems of inaccurate monitoring and control of ball bearings, which need further improvement. A lubrication system was developed for the bearings of the spindle unit of a high-speed milling machine to investigate and regulate the heat generation and transfer process during high-speed operation. The system combines the mechanical components with control, measurement, and monitoring features for the lubrication mode of the bearings of spindle unit. The integration of the mechanical system, control system, measurement system, and lubrication mode monitoring system is a key feature of this system. The functional requirements of the system were designed, including simulating the spindle unit's operation, ensuring sufficient stiffness, integrated space for lubrication, cooling, control, measurement, and monitoring systems, and providing sufficient lubricant to keep the bearing running smoothly, ensuring optimum temperature. The control, measurement, and monitoring system generate data for analysis by controlling the system. In order to identify the integration requirements, it is crucial to understand the heat generation and transfer mechanism within the spindle unit. This knowledge serves as the foundation for selecting specific and accurate system parameters.

In this study, the temperature of the spindle bearings in the CNC machine will be monitored using a sensor system and will be collected for processing to evaluate the quality of lubrication methods suitable for the working conditions of the spindle bearing unit. Two lubrication methods, grease and air-oil mixture, were performed at a spindle speed of approximately 7000 rpm for 1 h. The experiments were conducted under the same working conditions.

II. MATERIALS AND METHODS

The spindle unit generates heat which is transferred from the bearings to the housing. While using air-oil-cooled lubrication, a portion of the heat is absorbed by the air stream. However, with grease lubrication, some of the heat is transferred to the lubricant and then to the housing, which is eventually dissipated into the environment. Therefore, it is crucial to estimate the amount of heat produced within the spindle and the heat transferred through the bearings before constructing an experimental system for measuring the temperature of the spindle unit. To examine the effectiveness of the spindle unit's lubrication system, two lubrication techniques were utilized: (1) a water-cooled and grease-lubricated system, and (2) a high-pressure air-oil mixture system. The air-oil mixture will be generated by pumping oil from the tank into the mixer, where compressed air pressure will break it into small particles, creating a high-pressure oil force that can easily penetrate high-temperature areas. For the experiments, a CNC machine was integrated with a spindle ER16-80SK 24k that has a power capacity of 1.5 kW as depicted in Figure 1. The spindle is equipped with bearing of 7002 type and is driven by a three-phase asynchronous motor controlled by an inverter. The system monitors the spindle speed, current, voltage, torque, and alarm signals. Temperature sensors are attached to the bearings to collect real-time temperature data, which are saved in a computer for further analysis. A detailed schematic of the experimental air-oil cooling and lubrication system, including its components, is presented in Figure 2.

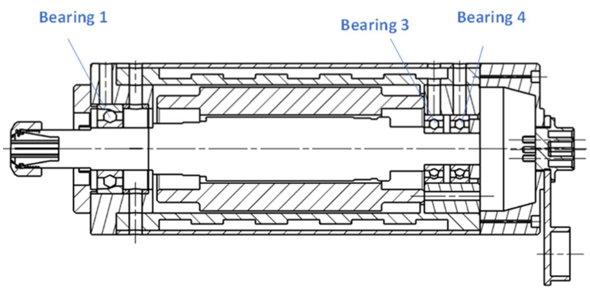

Fig. 1. Cross-section of the spindle unit.

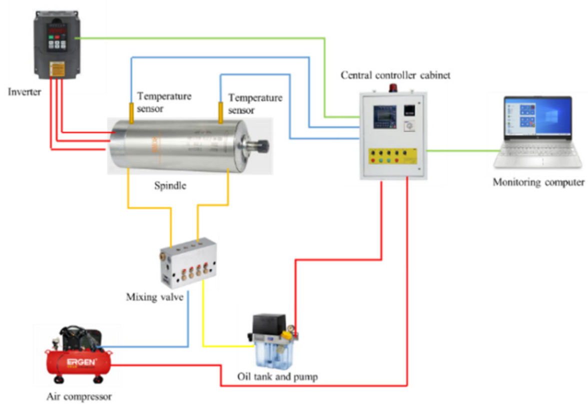

Fig. 2. A diagram illustrating the principle of the proposed air-oil cooling and lubrication system.

When analyzing a ball bearing, the parameters to be considered include ball diameter (*d*), rotational speed (*V*), and rotation diameter (*D*). The ball rotates at a velocity ω_b and the primary causes of heat generation in the bearing are the load torque and the ball torque [17]. The total heat generated can be estimated by:

$$H_f = \omega_b M_s \quad (1)$$

The angular velocity of the ball is denoted by ω_b. The torque generated in the bearing, which includes the torque caused by slip and the gyroscope of the ball, is denoted by M_s and is expressed as follows:

$$M_s = (M_{ds} + M_{gr})K \quad (2)$$

The coefficient *K* varies depending on the accuracy class of the spindle unit. The torque due to sliding can be expressed as:

$$M_{ds} = \frac{PD_0 z}{4d_b}\left(1 - \frac{d_b^2}{D_0^2}\cos^2\alpha\right)\left(r_0 B_0 - r_i B_i\right) f \quad (3)$$

The coefficient $B_0 = B_i = 1$ is determined by the geometry of the inner and outer rim of the bearing, while r_0 and r_i refer to the deformation of the inner and outer rim surfaces and α represents the contact angle, with f being the friction coefficient. The gyroscope torque of the ball is estimated by:

$$M_{gr} = \frac{\pi}{60} d_b^2 \frac{\gamma}{g} \omega_b z \sin\alpha \quad (4)$$

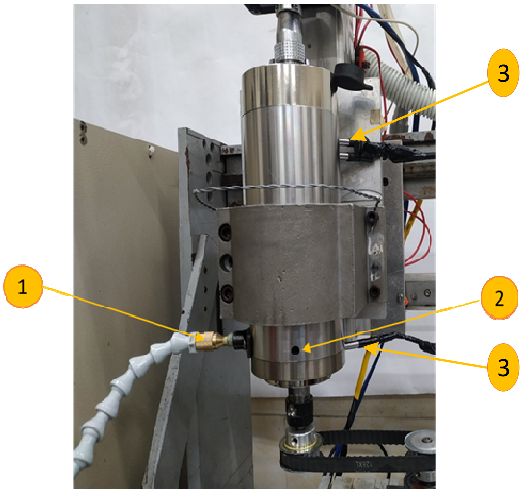

Fig. 3. Experimental system for spindle unit integration: (1) Air-oil supply, (2) air-oil vent hole, (3) temperature sensors.

Temperature sensors (Figure 3) are utilized to continuously monitor the spindle bearing's lubrication status, observe the temperature of the bearings, and record the spindle's consumption current value. The sensors are placed on the outer rings of the spindle unit while the consumption current is measured by an inverter and transmitted to the controller. The design parameters are used to set the working conditions with an assumption of ambient temperature at 25°C and assuming environment air pressure of 1 bar. The following section presents the experimental results for the temperature generated in the spindle bearings, and Table I lists the experimental parameters using the air-oil mixture lubrication method.

TABLE I. EXPERIMENTAL PARAMETERS OF THE AIR-OIL MIXTURE LUBRICATION

Air pressure	7.5 bar
Air flow rate	1200 l/hr
Oil flow rate	180 mm^3/hr
Oil type	Tona 68
Spindle speed	7000 rpm
Applied load on shaft	16 N
Observation time	3600 s

When using the air-oil lubrication method, the spindle unit of the machine tool is lubricated and cooled continuously during the operation. The lubrication status is monitored and maintained to ensure optimal performance. The system closely monitors parameters such as bearing temperature, oil level, air pressure, and spindle consumption current to assess the lubrication status of the spindle bearings. To optimize the lubrication and cooling process, the air pressure should be maintained at 7.5 bar to ensure proper shredding of the oil flow. An inverter is used to measure the spindle's consumption current, and the obtained data is transmitted to the controller to avoid system errors if the designed amount of lubricating oil is not supplied. If the bearing temperature rises, and the consumption current reaches a preset value while all other requirements are met, the system will shut down and an alarm will be triggered. The controller will allow the oil pump and air valve to operate only when all criteria are met.

III. RESULTS AND DISCUSSION

To evaluate the temperature generated in the bearings of the spindle unit in the CNC milling machine using two different lubrication methods, i.e. grease and air-oil mixture, the experimental environment was maintained at constant working parameters. The spindle was set to rotate at a constant speed of 7000 rpm, and temperature readings were taken over a 1 hr period using temperature sensors located at the bearing locations. A numerical simulation study on lubrication using air-oil mixture and grease has been conducted, which shows that at the speed of 7000 rpm, the temperature at the main spindle unit is the lowest. On the other hand, the temperature at the roller bearing position increases sharply during the time interval from 0 to 2000 s and reaches a stable value after about 2250 s.

From the results shown in Figure 4(a), it can be observed that at the rotational speed of 7000 rpm, the temperature characteristic curves of the bearings have similarities to the numerical simulation results mentioned above. Bearings 3 and 4 have higher temperatures than bearing 1 due to the limitations in heat dissipation space. The temperature characteristic curves of the external area of the 3 bearings increase rapidly during the first 1000 s, then gradually increase. The temperature stabilizes after 3400 s, and the bearings gradually reach a state of thermal saturation that persists until the end of the experiment. It can be stated that the temperature increases after a certain period of operation, which reduces the viscosity of the grease, decreases the friction between the layers of lubricants in the bearings, leading to a decrease in the rate of temperature rise, and reaching a stable state.

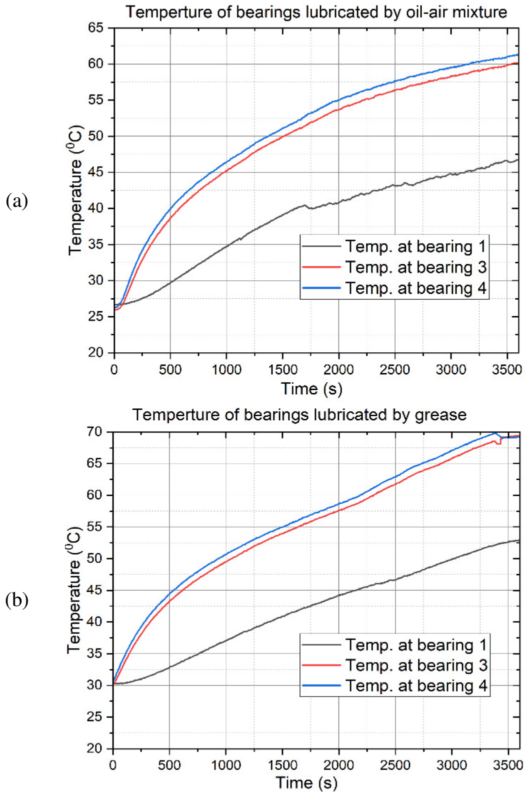

Fig. 4. The temperature at the bearings was measured during 3600 s of spindle operation at 7000 rpm using two different lubrication methods: (a) grease and (b) air-oil mixture.

The air-oil cooling lubrication method shows similar characteristics in the characteristic curve when compared to the grease lubrication method. However, the temperature rise rate is slower, indicating the effectiveness of the air-oil lubrication method. The air-oil mixture is easily able to fill the clearance between the relatively moving surfaces, and the high-pressure air-oil flow with continuous movement leading to better heat dissipation. Moreover, it is apparent that at bearing 1, direct cooling lubrication by air-oil mixture causes a significant decrease in temperature and slower temperature rise, with a maximum temperature difference of 7°C (about 14.5%) recorded compared to the grease lubrication method (as depicted in Figure 4(b)). When comparing the two lubrication methods, the maximum temperature difference values for rolling bearings 3 and 4 are about 7°C (about 11.5%) and 9°C (about 15%), respectively. However, these values were concentrated in the temperature range approaching stability, which is very significant in cases of long-term processing. The lubrication efficiency using an air-oil mixture will be better and contribute to reducing the influence of temperature on processing quality on the CNC machine.

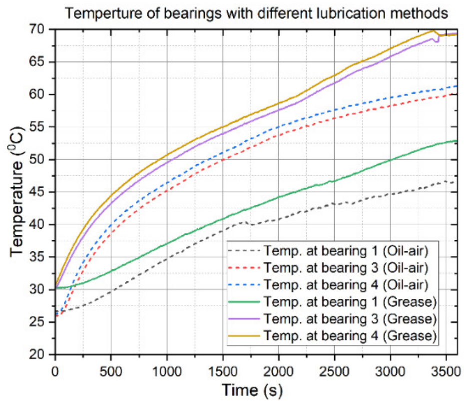

Fig. 5. Comparison of the temperature at the bearings for 2 lubrication methods during 1 hr of operation at 7000 rpm.

Figure 5 illustrates the temperature difference over time between the two lubrication methods. The temperature at the rolling elements is lower when lubricated with air-oil mixture than with grease. This can be explained by the higher viscosity of grease (15 mm^2/s) compared to oil (68 mm^2/s). Grease forms a thick layer around the ball, hindering its movement and increasing the friction between the moving surfaces. Furthermore, it takes time for the grease to reach the friction areas between the ball and the inner and outer races, resulting in slower lubrication efficiency than air-oil mixture. Moreover, the lubrication efficiency of grease decreases over time, significantly affecting the bearing performance. Therefore, when operating at higher speeds, using grease lubrication is not recommended due to its limitations.

Regarding the cooling performance, grease lubrication combined with water as a cooling agent is continuously pumped during operation. However, when the spindle operates for a long time, the temperature of the water increases, reducing the cooling efficiency. This issue largely depends on the optimization of the cooling pump system. Nevertheless, water only cools the outer race directly, while the main heat source is the inner ball, limiting the cooling capacity significantly.

On the other hand, the method of lubrication using an air-oil mixture overcomes most of the drawbacks of lubrication with grease. Enough lubricating oil with high pressure is directly supplied to the bearing, permeating and deeply penetrating the friction areas. Additionally, the oil is continuously supplied to prevent the degradation of the lubricant after prolonged use. With the help of compressed air pressure, the lubricating oil is directly transported to the primary thermal area of the rolling bearing, providing direct cooling to the bearing balls, resulting in better lubrication efficiency than the grease lubrication method combined with indirect water cooling. Indeed, the compressed air pressure will break down the oil particles into very small ones, making them able to easily penetrate frictional areas and improve the lubrication efficiency. This pressure also helps enhance the efficiency of the heat exchange process with the environment. Therefore, it can be said that the lubrication method using an air-oil mixture is encouraged to apply, especially in high-speed processing cases on CNC machines. However, it also shows certain limitations on the surrounding environment due to oil particles being discharged after lubrication. This requires attention to the operation of the ventilation system during processing.

The investigation on the impact of specific input parameters, such as the pressure and flow rate of the gas-oil mixture, on the lubrication quality of the spindle bearing unit is currently underway and will be presented in upcoming studies.

IV. CONCLUSIONS

In conclusion, the current experimental study aimed to evaluate the effectiveness of two lubrication methods, i.e. grease and air-oil mixture, on the temperature generated at the bearings of a CNC milling machine spindle unit. The results showed that the air-oil cooling lubrication method was more effective in dissipating heat, resulting in a slower temperature rise rate and a lower temperature at the rolling elements compared to the grease lubrication method. Moreover, the air-oil mixture provided direct cooling to the bearing balls, leading to better lubrication efficiency and heat exchange with the environment. Accordingly, the temperature of the bearings decreases from 7°C to 9°C depending on the position of the bearing on the CNC spindle compared to the grease lubrication method. Therefore, the lubrication method using an air-oil mixture is encouraged, especially in high-speed processing cases on CNC machines.

However, attention must be paid to the operation of the ventilation system during processing to mitigate the discharge of oil particles. Overall, the current study provides valuable insight into the optimization of lubrication methods for CNC machines in order to improve the processing quality and reduce the influence of temperature on the performance of the bearings.

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