Computational and Experimental Investigation of Thermal Generation in CNC Milling Machine Spindle Bearing with the Oil-Air Lubrication Method

Duc-Do Le
School of Mechanical Engineering, Hanoi University of Science and Technology, Vietnam
do.leduc@hust.edu.vn

Van-Hung Pham
School of Mechanical Engineering, Hanoi University of Science and Technology, Vietnam
hung.phamvan@hust.edu.vn

Tuan-Anh Bui
School of Mechanical Engineering, Hanoi University of Science and Technology, Vietnam
anh.buituan@hust.edu.vn (corresponding author)

Received: 9 November 2023 | Revised: 1 December 2023 | Accepted: 10 December 2023

 DOI: https://doi.org/10.48084/etasr.6603

ABSTRACT

This study investigates the thermal generation dynamics in the spindle unit of a CNC milling machine. The main objective is to analyze the heat transfer from the bearings to the housing during operation, using simulations and experiments. An air-oil-cooled lubrication system is employed, which enables the airflow to dissipate some of the heat produced. Before conducting the experiment, heat generation and transfer are accurately predicted. The air-oil mixture, formed by pressurized air atomizing oil droplets, is effective in cooling high-temperature regions. A spindle ER16-80SK 24k is integrated with a CNC machine for real-time data acquisition, including parameters such as spindle speed and temperature. The results show significant temperature rises in all bearings, which reach a steady state after an hour of operation. There are noticeable differences in range, from 6.1% to 43.4%, between the experimental and simulated maximum temperatures, indicating possible real factors not considered in the simulation. The environmental impacts of oil particle emission are also discussed, which require proper ventilation management during operations. This research provides valuable insight into the thermal dynamics of CNC milling machine spindles and establishes a solid basis for further research and development in this important field of machining technology.

Keywords-CNC machining; spindle unit; thermal generation; temperature monitoring; air-oil mixture lubrication

I. INTRODUCTION

Modern manufacturing requires high-speed machining, which allows for the creation of complex and advanced products [1]. The elevated rate of spindle rotation also results in increased thermal generation, which can impact rigidity and lead to warping problems. As a result, various cooling and lubrication techniques have been suggested, such as the application of air-oil cooling, which can enhance the effectiveness of both lubrication and cooling. The spindle unit's stiffness is an important factor that influences the quality of machining in machine tools [2, 3]. However, when machining at high speeds, heat is produced, lowering the stiffness or increases the deformation of the spindle [4-7]. Hence, a variety of methods for lubrication and cooling have been suggested to reduce thermal production at bearings, such as the use of grease, oil splatter, oil fog, and a combination of air and oil [8]. Research has indicated that the pattern of temperature change over the course of operation was comparable between empirical and computational simulation studies when all the bearings of the CNC spindle unit were lubricated using grease [9]. The authors used ANSYS software to model the spindle unit and applied boundary conditions based on experimental data. They found that the maximum temperature rise occurred at the front bearing near the tool tip due to high contact pressure and friction. They also observed that the temperature distribution was uneven along the spindle axis due to heat conduction and convection. A more efficient method of lubrication and cooling that saves lubricant and is favored in modern machining industry is oil-air mixture lubrication [10]. Oil-air mixture lubrication consists of injecting small droplets of oil mixed with air into the bearing gap. The oil droplets provide lubrication while the air provides cooling. Oil-air mixture lubrication has several advantages over grease lubrication, such as lower friction coefficient, higher heat dissipation capacity, better lubrication performance at high speeds, and longer service life [11, 12]. Several studies have investigated the effect of oil-air mixture lubrication on thermal generation in spindle bearing units using numerical simulations. Authors in [13] modeled the heat transfer process and examined the thermal coupling using finite element analysis. They considered different parameters such as oil-air ratio, injection pressure, injection angle, and spindle speed.

Although the existing literature has provided some insights into the lubrication and cooling methods for spindle bearing units, there are still some gaps and limitations that need to be addressed. Some studies have conducted experimental tests to validate the numerical results and to compare the performance of different lubrication methods under realistic conditions. For instance, authors in [14] conducted a study on the effectiveness of high-speed spindles using oil/air lubrication. Their research primarily delved into the impact of varied lubrication parameters and preloads on factors such as temperature elevation, thermal deformation, and static stiffness. Employing the Taguchi methodology, they identified the most favorable lubrication parameters that effectively minimize temperature escalation, offering valuable insights for crafting high-speed spindles endowed with adequate static stiffness. Similarly, authors in [15] scrutinized film formation under both oil-air and oil-jet lubrication systems. They found that oil-air lubrication has a better oil supply efficiency and slower decrease in film thickness in starved regime, because of the role of the micron-order oil droplets that enhance oil supply efficiency. Experimental research evaluating the effects of various lubrication and cooling methods pointed out the advantages and disadvantages of each method. In particular, the factors affecting the quality of lubrication are also clearly indicated in [16]. It was also recommended that additives can be added to the lubricating oil to improve lubrication efficiency, which can help to lower friction and component wear within the machine [17, 18].

Spindle bearings play a pivotal role in machine tools, exerting a substantial influence on the overall efficiency and precision of the machining operation. Their performance is paramount to achieving optimal productivity and impeccable quality in the process. However, spindle-bearings also generate heat due to friction and contact pressure. This generated heat has the potential to induce thermal deformations and diminish the stiffness of the spindle unit. Consequently, this could impede its load-bearing capabilities, accuracy, and overall stability. Thus, it becomes imperative to implement meticulous lubrication practices to guarantee the seamless functioning and prolonged lifespan of these bearings. Most numerical simulations have assumed ideal conditions and neglected some factors such as bearing clearance, preload, lubricant viscosity, and environmental temperature. Moreover, there is a lack of experimental studies that validate the numerical results and to compare the performance of different lubrication methods under realistic conditions. Therefore, future research should conduct more comprehensive and realistic numerical simulations and experimental tests to evaluate the lubrication and cooling methods for spindle bearings. Furthermore, future research should also explore other factors that may affect thermal generation in spindle bearing units, such as spindle geometry, material properties, tool wear, cutting parameters, and machining strategies.

This study focuses on the thermal generation in CNC spindle-bearing units under oil-air mixture lubrication by conducting experimental tests and numerical simulations. A custom-made lubrication system was designed and built for this purpose. The system integrated mechanical, control, measurement, and monitoring components to simulate the spindle unit's operation under different lubrication modes and parameters. The system collected data for analysis after each test run. The design of the system was based on the understanding of the heat generation and transfer mechanism in the spindle unit.

II. MATERIALS AND METHODS

Heat is generated by the spindle unit and transferred to the housing via the bearings. The airflow from the air-oil-cooled lubrication system can remove some of this heat. Before measuring the temperature of the spindle unit experimentally, it is important to predict the heat generation from the spindle and its transfer through the bearings. The air-oil mixture is produced by pumping oil from the tank to the mixer, where it is broken down by compressed air pressure, creating a powerful oil force that can reach high-temperature areas. A spindle ER16-80SK 24k, with a power capacity of 1.5 kW, was integrated with a CNC machine for the experiment, as shown in Figure 1. This spindle has 7002-type bearings and is driven by a three-phase asynchronous motor controlled by an inverter. The system monitors key parameters such as spindle speed, current, voltage, torque, and sends alarm signals when needed. Temperature sensors were attached to the bearings, allowing real-time temperature data collection, which is stored in a computer for further analysis.

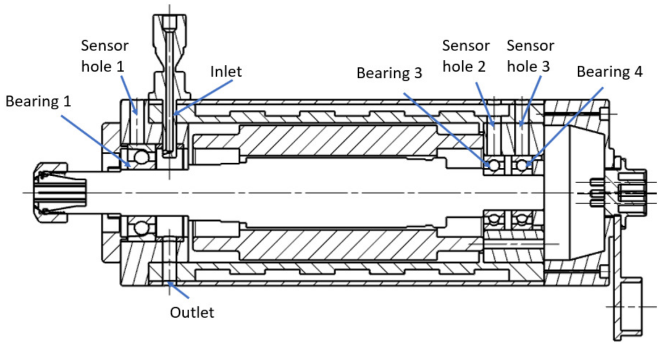

Fig. 1. Cross-section of the investigated spindle unit.

The ball rotates at a velocity of ωb, which is determined by the rotational speed (V) and the rotation diameter (D) [19]. The bearing generates heat mainly due to the load torque and the ball torque. The load torque is the torque exerted by the external load on the bearing, which creates friction between the balls and the races. The ball torque is the torque needed to rotate the balls around their own axes, creating friction. Both torques are influenced by the load, speed, cage design, and lubrication conditions of the bearing. Both torques increase with increasing speed and decrease with increasing lubrication efficiency. Hence, it is essential to optimize the lubrication conditions to minimize heat generation and enhance spindle performance. The experimental setup for measuring the temperature and the consumption current of the spindle-bearing unit is illustrated in Figure 2. The temperature sensors are fixed to the outer rings of the spindle unit to observe the lubrication condition and the heat production of the bearings. The consumption current is measured by an inverter, which sends the data to the controller. These data indicate the power losses and provide information about the overall efficiency of the spindle unit. Table I presents the experimental parameters for the air-oil mixture lubrication method, such as the oil-air ratio, the injection pressure, the injection angle, and the spindle speed. These parameters influence the lubrication and cooling performance of the air-oil mixture, as well as the thermal behavior of the spindle-bearing unit. The Table also displays the ambient temperature and air pressure of the environment, which are kept constant at 25 °C and 1 bar, respectively. The experiment will show how different lubrication methods and parameters affect the temperature rise and the consumption current of the spindle-bearing unit during high-speed machining. This will help the designer to compare and evaluate the performance of different lubrication methods and parameters, and to choose the best one for minimizing thermal generation and improving machining quality and efficiency.

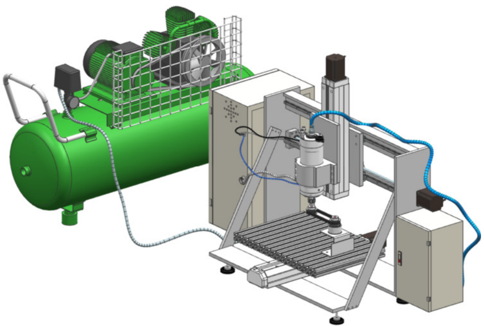

Fig. 2. Experimental system for spindle unit integration.

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

Specification	Value
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 spindle	16 N
Observation time	3600 s

The machine tool's spindle unit undergoes continuous lubrication and cooling through the air-oil method during operation. Maintaining optimal performance is contingent upon vigilant monitoring and upkeep of the lubrication status. This is done by monitoring parameters such as bearing temperature, oil level, air pressure, and spindle consumption current. To ensure proper oil flow and to optimize the lubrication and cooling process, the air pressure is kept at 7.5 bar. The other working parameters of the system are also presented in Table I. The spindle consumption current is carefully measured by an inverter, which sends the data to the controller. This preventive measure avoids system errors in case the required amount of lubricating oil is not supplied. If the bearing temperature and the consumption current increase to a predetermined limit, while all other conditions are satisfied, the system will shut down and trigger an alarm. The controller only allows the operation of the oil pump and the air valve when all criteria are met. For the numerical simulation of the lubrication and cooling process based on NX's software® using the air-oil mixture, Tona 68 lubricating oil with a kinematic viscosity of 68 mm^2/s at 40 °C was used. The spindle material was carbon steel C45. Using software, a heat transfer simulation model was created, consisting of 355,237 elements. The element sizes were automatically set as 3 mm, 6 mm, and 12 mm, depending on their location on the model, as shown in Figure 3.

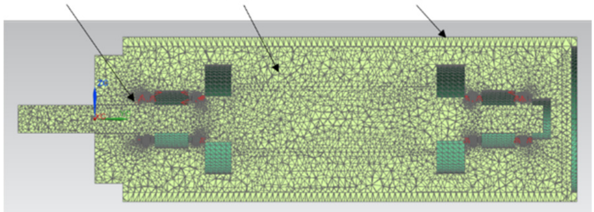

Fig. 3. The element mesh size of the simulation model.

III. RESULTS AND DISCUSSION

The assessment of the temperature generated at the bearings of the CNC milling machine spindle unit involved a comparative analysis between numerical simulations and experimental findings, conducted under identical operational parameters. The CNC milling machine spindle was configured to rotate at a constant speed of 7000 rpm. Subsequently, numerical simulations were performed, followed by the collection of experimental temperature data at the spindle bearings over a working duration of 1 hr. To facilitate this, temperature sensors were strategically positioned at the bearing locations to acquire the requisite experimental data. Figure 4 shows the heat generation in the bearings 1, 3, and 4 during operation. The Figure reveals that the temperature of all bearings increases rapidly from the start of operation until around 2250 s. Then, the temperature rise slows down and the temperature reaches a relatively stable level. After 1 hr of operation, the temperature changes slightly and stabilizes. However, the stable temperature value among bearings differs. The highest temperature, 45.6 °C, is observed at bearing 4, while the lowest temperature, which is 42 °C, is observed at bearing 3. This is the lowest temperature among the bearings of the main spindle unit. This can be explained by the fact that bearing 3 is closer to the nozzle that sprays the air-oil mixture than the other bearings. The temperature of bearing 1 is 44 °C, which is lower than bearing 4 and higher than bearing 3. This can be attributed to the fact that the nozzle that lubricates and cools with the air-oil mixture is closer to bearing 1 than to bearing 4.

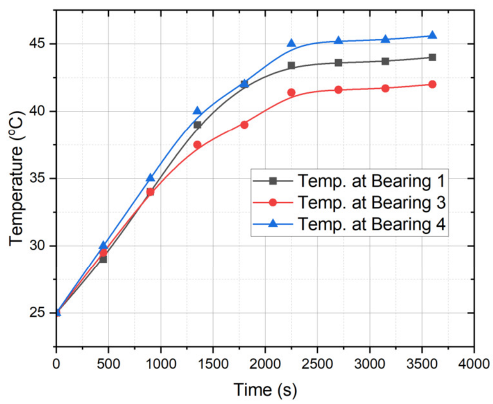

Fig. 4. Simulation data-based distribution of bearing temperature during 1 hr of spindle operation at 7000 rpm.

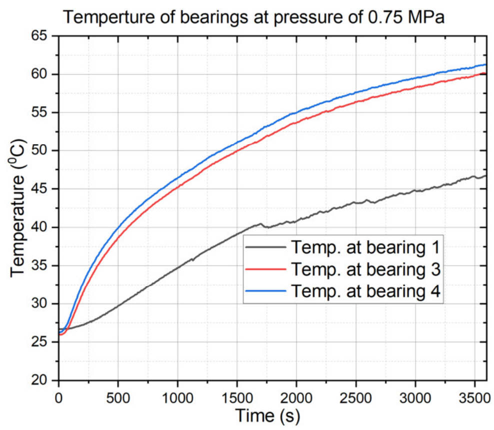

Fig. 5. Experimental data-based measurement of bearing temperature during 1 hr of spindle operation at 7000 rpm.

The experimental results concerning the heat generated at the rolling bearings of the spindle unit, depicted in Figure 5, demonstrate a correlation in the temporal temperature variations with those observed in the simulation. Initially, there is a prominent inclination for temperature to rise until approximately 2000 s of operation. Subsequently, this escalating trend begins to subside and stabilizes after roughly 1 hr of operation. This characteristic aligns with the simulation results. However, notable disparities exist in the maximum temperature values at different rolling bearing positions compared to the simulated values. Specifically, at bearing 1, the highest temperature recorded was 46.69 °C (corresponding to an increase of 6.1% compared to the simulated value). Similarly, at bearing 3, the maximum temperature reached 60.25 °C (equivalent to a 43.4% increase when compared to the simulation results). Furthermore, at bearing 4, the peak temperature was 61.38 °C (representing a 34.6% increase compared to the simulation results). These discrepancies suggest that the parameters employed in the simulation may not comprehensively encapsulate real-world factors, resulting in significant deviations. One plausible explanation may be an assumed higher working environment temperature in the simulation. Therefore, it is necessary to analyze the impact of other factors such as the environment and material parameters that closely match reality. This not only provides a foundation for augmenting, constructing, and refining the simulation parameters but also ensures that computational results under different lubrication modes closely emulate the actual operation of the spindle unit.

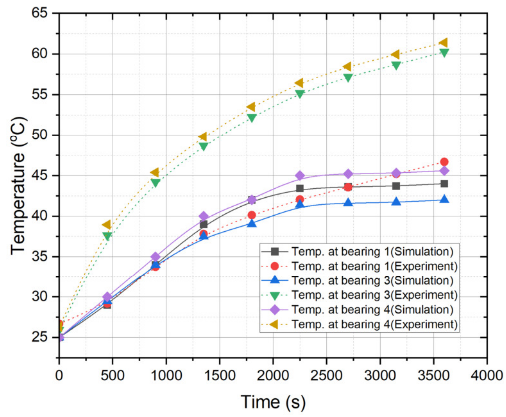

Fig. 6. Temperature comparasion between experiment and simulation at bearings.

The illustrative data in Figure 6 show the similarity of the temperature increase trend in the initial working phase as well as the temperature difference between the simulation calculation and the results measured from the experiment. Additionally, the data reveal that the temperature difference is more significant at bearings 3 and 4 than at bearing 1, indicating that these bearings are more affected by the position of the gas-oil mixture nozzle and the working time of the spindle-bearing unit.

The drawbacks of other lubrication methods have been overcome using an air-oil mixture for lubrication. The bearing is supplied directly with sufficient high-pressure lubricating oil, which permeates and deeply penetrates the friction areas. To safeguard against lubricant degradation over extended periods of operation, a continuous oil supply is diligently maintained. Notably, the primary thermal zone of the rolling bearing receives a direct infusion of lubricating oil, facilitated by compressed air pressure, thereby delivering immediate cooling to the bearing balls. This approach exhibits superior lubrication efficacy compared to methods employing indirect water cooling. The application of compressed air pressure effectively fragments oil particles into minute sizes, facilitating their ingress into frictional areas and thereby heightening lubrication efficiency. Furthermore, this pressure augmentation bolsters the efficiency of the heat exchange process with the surrounding environment. The air-oil mixture lubrication method emerges as a fitting choice, particularly for high-speed processing scenarios on CNC machines. Nonetheless, it is imperative to acknowledge its potential impact on the environment, given the discharge of oil particles post-lubrication. Thus, prudent consideration of ventilation system operation during processing is imperative.

Although there is a temperature discrepancy at the bearings of the CNC spindle between the simulation and experimental results, the simulation outcomes provide a general view of the temperature increase trend at the bearings during working stages. This can assist operators in designing appropriate lubrication regimes, ensuring system stability and the quality of the spindle unit's operation. Furthermore, experimental results are significant in evaluating the accuracy of the simulation, thereby helping designers adjust some simulation parameters or reconstruct the boundary conditions to closely match real-world working requirements. This task is still being researched and developed by our team, with the aim of constructing more suitable and realistic simulations. In addition, lubrication and cooling modes using an air-oil mixture are also being studied and experimental setups are being designed and constructed. These results will contribute to enriching lubrication and cooling modes in the field of mechanical engineering.

IV. CONCLUSIONS

This study presents a comprehensive investigation of the thermal generation dynamics in the spindle unit of a CNC milling machine using the oil-air lubrication method. The heat transfer from the bearings to the housing during operation is studied through a combination of computational simulations and practical experiments, providing valuable insights into the complex processes.

The results highlight the remarkable effectiveness of the air-oil mixture in absorbing and dissipating the generated heat, especially in high-temperature areas. A spindle ER16-80SK 24k is integrated with a CNC machine for experimental purposes, providing real-time data for analysis. The temperature trends in the bearings show a significant initial increase, followed by a steady state after one hour of operation. There are noticeable differences between the experimental and the simulated maximum temperatures, indicating that the simulations do not capture all the real factors. For example, the experimental temperature at bearing position 1 is 46.69 °C, which is 6.1% higher than the simulated value. Similarly, the maximum temperature at bearing position 3 is 60.25 °C, which is 43.4% higher than the simulation. The highest temperature at bearing position 4, 61.38 °C, is 34.6% higher than the simulation value. These results suggest the need for more realistic simulations in future studies. However, the study confirms the potential of the oil-air lubrication method in optimizing the spindle unit performance. The study offers practical insights for improving machining efficiency and quality, especially in high-speed machining scenarios. However, it is also important to consider the environmental impacts of oil particle emission, which require proper ventilation management during operations. This research significantly advances the understanding of thermal dynamics in CNC milling machine spindles, providing a solid foundation for further research and development in this critical domain of machining technology.

ACKNOWLEDGMENT

This research is funded by Hanoi University of Science and Technology (HUST) under project number T2021-PC-033.

REFERENCES

[1] X. J. Xuan, Z. H. Haung, K. D. Wu, and J. P. Hung, "Prediction of the Frequency Response Function of a Tool Holder-Tool Assembly Based on Receptance Coupling Method," *Engineering, Technology & Applied Science Research*, vol. 8, no. 6, pp. 3556–3560, Dec. 2018, https://doi.org/10.48084/etasr.2372.

[2] V.-H. Pham, M.-T. Nguyen, and T.-A. Bui, "Oil pressure and viscosity influence on stiffness of the hydrostatic spindle bearing of a medium-sized circular grinding machine," *International Journal of Modern Physics B*, vol. 34, no. 22n24, Sep. 2020, Art. no. 2040156, https://doi.org/10.1142/S0217979220401566.

[3] N. B. Serradj, A. D. K. Ali, and M. E. A. Ghernaout, "A Contribution to the Thermal Field Evaluation at the Tool-Part Interface for the Optimization of Machining Conditions," *Engineering, Technology & Applied Science Research*, vol. 11, no. 6, pp. 7750–7756, Dec. 2021, https://doi.org/10.48084/etasr.4235.

[4] A. Zivkovic, M. Knezev, M. Zeljkovic, S. Navalusic, and L. D. Beju, "A study of thermo-elastic characteristics of the machine tool spindle," in *9th International Conference on Manufacturing Science and Education – MSE 2019 "Trends in New Industrial Revolution,"* 2019, Art. no. 01009, https://doi.org/10.1051/matecconf/201929001009.

[5] L. Yu, Z. Xing, M. Gao, and L. Shang, "Research on the influence of spindle temperature rise of drilling and tapping machine on machining accuracy," *Journal of Physics: Conference Series*, vol. 1885, no. 2, Dec. 2021, Art. no. 022002, https://doi.org/10.1088/1742-6596/1885/2/022002.

[6] T. H. Le, V. B. Pham, and T. D. Hoang, "Surface Finish Comparison of Dry and Coolant Fluid High-Speed Milling of JIS SDK61 Mould Steel," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8023–8028, Feb. 2022, https://doi.org/10.48084/etasr.4594.

[7] A. D. Kara Ali, N. Benhadji Serradj, and M. E. A. Ghernaout, "Cutting Parameter Optimization based on Online Temperature Measurements," *Engineering, Technology & Applied Science Research,* vol. 13, no. 1, pp. 9861-9866, Feb. 2023, https://doi.org/10.48084/etasr.5348.

[8] T.-A. Bui and Q.-T. Vu, "A Study on an Oil-Air Mixed Lubrication Monitoring System for Spindle Unit of CNC Milling Machine," in *Proceedings of the 2nd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2020)*, B. T. Long, Y.-H. Kim, K. Ishizaki, N. D. Toan, I. A. Parinov, and N. P. Vu, Eds. 2021, pp. 920-928.

[9] D.-D. Le, Q.-T. Vu, and T.-A. Bui, "Simulation and Experimental Study of Heat in Grease-Lubricated CNC Milling Machine Spindle-bearings," in *Proceedings of the International Conference on Advanced Mechanical Engineering, Automation, and Sustainable Development 2021 (AMAS2021)*, B. T. Long, H. S. Kim, K. Ishizaki, N. D. Toan, I. A. Parinov, and Y.-H. Kim, Eds., 2022, pp. 462-467.

[10] M. Handawi, A. E. I. Elshwain, M. Y. Noordin, N. Redzuan, and D. Kurniawan, "Comparison between Nitrogen-Oil-Mist and Air-Oil-Mist Condition when Turning of Hardened Tool Stainless Steel," *Applied Mechanics and Materials,* vol. 660, pp. 18-22, 2014, https://doi.org/10.4028/www.scientific.net/AMM.660.18.

[11] O. Maeda, Y. Cao, and Y. Altintas, "Expert spindle design system," *International Journal of Machine Tools and Manufacture*, vol. 45, no. 4, pp. 537–548, Apr. 2005, https://doi.org/10.1016/j.ijmachtools.2004.08.021.

[12] S. Li and Y. Wu, "A Study on Oil/Air Lubrication and Preload of a High Frequency Fully Ceramic Motor Spindle," in *2010 International Conference on E-Product E-Service and E-Entertainment*, Henan, China, Aug. 2010, https://doi.org/10.1109/ICEEE.2010.5661555.

[13] C. Zhao and X. Guan, "Thermal Analysis and Experimental Study on the Spindle of the High-Speed Machining Center," *AASRI Procedia,* vol. 1, pp. 207-212, Jan 2012, https://doi.org/10.1016/j.aasri.2012.06.032.

[14] C.-H. Wu and Y.-T. Kung, "A parametric study on oil/air lubrication of a high-speed spindle," *Precision Engineering,* vol. 29, no. 2, pp. 162-167, Apr. 2005, https://doi.org/10.1016/j.precisioneng.2004.06.005.

[15] H. Liang, D. Guo, L. Ma, and J. Luo, "The film forming behavior at high speeds under oil–air lubrication," *Tribology International*, vol. 91, pp. 6–13, Nov. 2015, https://doi.org/10.1016/j.triboint.2015.06.010.

[16] D.-D. Le and T.-A. Bui, "Analyzing the Effects of Lubrication Techniques on CNC Spindle-bearing Heat: An Experimental Investigation," *Engineering, Technology & Applied Science Research,* vol. 13, no. 5, pp. 11581-11585, Oct. 2023, https://doi.org/10.48084/etasr.6146.

[17] T.-A. Bui, V.-H. Pham, D.-T. Nguyen, and N.-T. Bui, "Effectiveness of Lubricants and Fly Ash Additive on Surface Damage Resistance under ASTM Standard Operating Conditions," *Coatings*, vol. 13, no. 5, May 2023, Art. no. 851, https://doi.org/10.3390/coatings13050851.

[18] T.-A. Bui and N.-T. Bui, "Investigating the Impact of Fly-Ash Additive on Viscosity Reduction at Different Temperatures: A Comparative Analysis," *Applied Sciences*, vol. 13, no. 13, Jan. 2023, Art, no. 7859, https://doi.org/10.3390/app13137859.

[19] T. A. Stolarski, Ed., *Tribology in Machine Design*. Oxford: Butterworth-Heinemann, 1990.