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optimal lubrication condition
oil-air lubrication
high speed spindle

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AN EXPERIMENTAL STUDY ON THE DETERMINATION OF OPTIMAL LUBRICATION CONDITIONS IN A HIGH-SPEED SPINDLE

The heat generation inside spindles becomes a major factor that limits the allowable maximum rotational speed in machine tools and decreases the cutting quality. It is necessary to accurately estimate the temperature distribution in spindles caused by the heat generation in bearings and its heat transfer characteristics in order to perform the high-speed and high-precision in high-speed spindles. In addition, an accurate correction process is required according to the results of the estimation through investigating the thermal deformation error. A commercial program, MINITAB, was used to establish an experiment plan that analyzes the heat generation characteristics of the spindle system according to the operation and lubrication conditions of the spindle. Also, the change in the outer ring temperature of bearings was measured according to the experimental plan. After establishing a response surface model using the results of the experiment, the estimation equation of the quadratic polynomial model was proposed for determining the optimal lubrication condition. A verification experiment was applied to verify the accuracy of the experimental equation determined by the estimated regression model and the experimental value used in the estimation of the regression model.

1. INTRODUCTION

The application of high-speed spindles represents a wide scope. In this application, high-speed spindles in the field of machine tools have been considered as one of the most complicated technologies that require the rotational accuracy and the acceleration and deceleration characteristics of a spindle including high-speed rotational characteristics. In the spindle used in recent machine tools, the necessity of ultra high-speed spindles has been continuously increasing due to economic and environmental reasons. In the case of the fields of aircraft parts and semiconductors, high-speed machining has been carried out using the spindle speed more than 2 million DmN.

The high-speed in spindles significantly increases the contact pressure occurred inside bearings that is generated by centrifugal force and that becomes a major cause in heat

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generation inside spindles. The heat generation inside spindles becomes a major factor that limits the allowable maximum rotational speed in machine tools and decreases the cutting quality. It has been reported that about 70% of the factors that affect the static and dynamic position errors in spindles were caused by such heat generation.

Thus, it is necessary to accurately estimate the temperature distribution in spindles caused by the heat generation in bearings and its heat transfer characteristics in order to perform the high-speed and high-precision in high-speed spindles. In addition, an accurate correction process is required according to the results of the estimation through investigating the thermal deformation error.

Wu et al. [1] performed the study that analyzes the influence of preload on the thermal deformation of oil-air lubricant spindles. Choi et al. [2] analyzed the thermal characteristics in spindles according to the change in the viscosity and flow rate in high-speed spindles through a computational experiment. Kim et al. [3] performed the study that analyzes the influences of the supplied flow rate and number of rotation in spindles on the temperature increase in bearings and its thermal distribution. Also, Kwon et al. [4] analyzed the thermal characteristics of spindle systems according to the cooling conditions of bearings and jackets. However, these studies represented certain limitations in the analysis that investigates the influence of each lubrication condition on the heat generation of spindle systems only and lacks in the study that determines its optimal lubrication condition.

Thus, in this study, we analyze the influences of the supplying interval of lubricating oil and supplying air pressure and spindle rotational speed on the heat generation characteristics of bearings and investigate the optimal lubrication condition that minimizes the heat increase in bearings. Therefore, we measured the change in the temperature of bearings according to the change in lubrication conditions using a high-speed spindle and analyzed the measured data using a statistical method.

2. EXPERIMENTAL DEVICES AND METHODS

Fig. 1 illustrates the experimental set-up for determining the lubrication condition of spindle bearings. The experimental devices consist of the spindle system, cooling device, lubricant device, and temperature sensor unit.

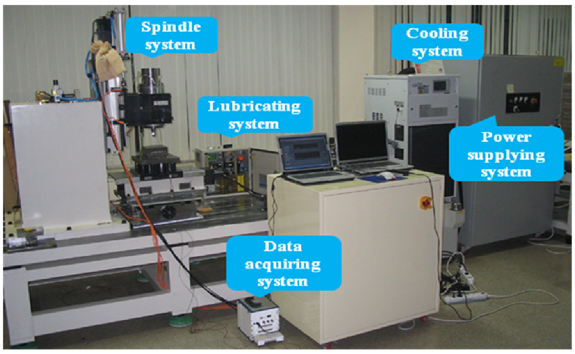


Fig. 1. Experimental set-up

The spindle system applied in this experiment was a high-speed system that is a motor included operation system and represented a tandem arrangement of bearings at the front and rear sides, respectively. Tab. 1 shows the specification of this spindle system.

Table 1. Specification of the spindle system

Item		Specification
Bearing	Front	Angular contact ball bearing (ø50, 2EA)
	Rear	Angular contact ball bearing (ø45, 2EA)
Lubricating method		Oil-air lubrication
Motor		16kW/40,000rpm

The supplying interval of lubricating oil and supplying air pressure can be arbitrarily controlled using the DIP switch and air pressure controller of the lubricant device (PRELUB ST MV0 by GMN).

A commercial program, MINITAB, was used to establish an experiment plan that analyzes the heat generation characteristics of the spindle system according to the operation and lubrication conditions of the spindle. Also, the change in the outer ring temperature of bearings was measured according to the experimental plan.

A RSM(response surface method) was used to make the experiment plan. This method obtains the relationship between response and description variables through some experiments or simulations as polynomials. Then, it determines a level combination in description variables, which maximize or minimize the value of response variables, and optimizes a specific characteristic as a statistical manner.

The experimental variables were determined as tube length, supplying interval of lubricating oil, supplying air pressure, and rotational speed based on the results of the previously performed experiment [5] and the reference [1-3]. In these variables, the tube length was applied as a fixed value determined by 2meter based on the experiment [5], and other variables were varied. Tab. 2 shows the factors and levels used in this experiment.

Table 2. Experimental conditions for RSM

Factor	Level
Supplying interval of lubricating oil [min]	2, 4
supplying air pressure [bar]	3, 5
Rotational speed [rpm]	10000, 30000

The temperature was measured using a T-type thermo couple that can be used to the range by 0~100°C. Also, the measurement was performed by contacting the contact point of the thermo couple to the outer ring of the bearing directly through a pre-processed hole for measuring the outer ring.

For maintaining the experimental condition as the same figure, the experiment was carried out after cooling the object in order to recover the initial temperature of the outer ring after completing an experiment stage with a specific experimental condition.

3. RESULTS AND CONSIDERATION

3.1 REGRESSION MODEL ESTIMATION

After establishing a response surface model using the results of the experiment, the estimation equation of the quadratic polynomial model for the response value using a model fitting process. Also, an estimation model was determined as a perfect form of quadratic polynomial that considers the response surface for all factors in order to establish a response surface model and predict regression equations. Then, the validity of the regression model selected by using a residual analysis and a coefficient of determination was investigated. As the selected model is not appropriate, the model was re-established through the reduction of the response surface model that pulls the terms, which represent no significances in the ANOVA(analysis of variance) table.

The response surface model for the heat generation of bearings was obtained by pulling the interaction effect between the supplying interval of lubricating oil* supplying air pressure and the supplying air pressure*rotational speed that represents no significance with the square terms of the supplying interval of lubricating oil and rotational speed. It is considered that the regression model, which finely follows the normal distribution obtained from the results of the residual analysis and selects the coefficient of determination by 98.4%, was a proper model.

The experimental equation that is able to estimate the heat generation of bearings according to the combination of the lubrication conditions determined from the established regression model, such as supplying interval of lubricating oil, supplying air pressure, and rotational speed, can be expressed as equation (1).

$$\Delta T=12.796+0.0014R-6.6819L-3.0275A+0.6002L^2+0.2772A^2+0.6039LA \tag{1}$$

where ΔT is the heat generation of bearings presented by ℃, L is the supplying interval of lubricating oil presented by min, A is the supplying air pressure expressed by bar, and R is the rotational speed presented by rpm.

3.2. REGRESSION MODEL VERIFICATION

A verification experiment was applied to verify the accuracy of the experimental equation determined by the estimated regression model and the experimental value used in the estimation of the regression model. The verification experiment was performed for four processing conditions, which were arbitrarily defined, and the results of the experiment were compared with the estimated value obtained by the proposed experimental equation. The arbitrarily defined processing conditions are presented in Tab. 3. The experiment was repeated twice for each experiment condition for obtaining accurate results.

Table 3 Experimental conditions of the verification experiment

Run order	Supplying interval of lubricating oil [min]	supplying air pressure [bar]	Rotational speed [rpm]
1	3	3	10000
2	3	5	15000
3	4	3	20000
4	4	5	25000

Fig. 2. shows the results obtained by the verification experiment and the experimental equation proposed in this study.

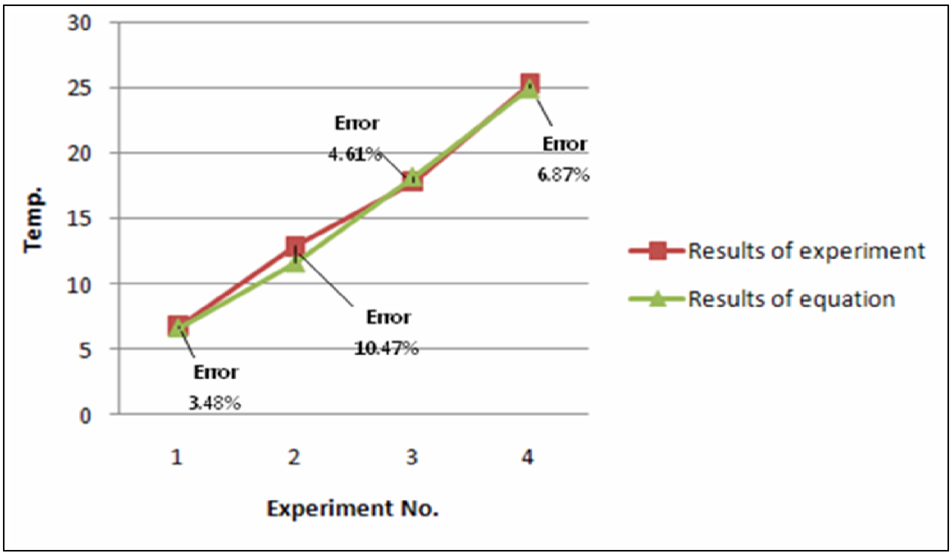


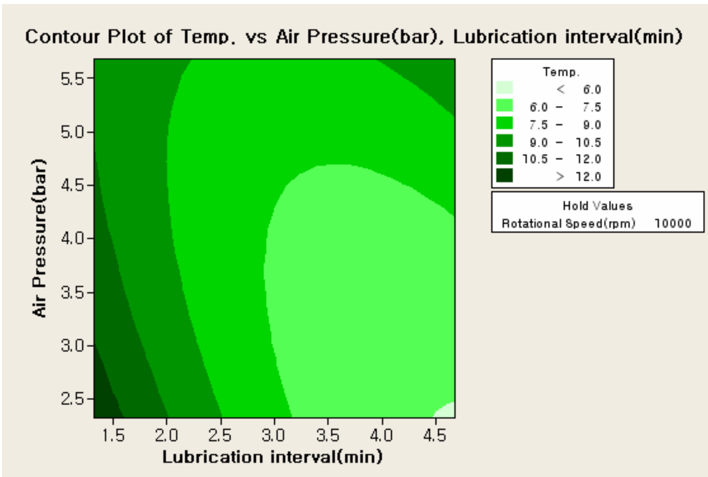
Fig. 2. Comparison plots between the verification experiment results and the suggested equation results

In the results of the experiment, it represented well agreements between the results of the experiment and the estimated values within 10% of the error for all conditions except for the run order #2. Also, the tendency presented in the results showed a same figure. Thus, it can be seen that the equation proposed by the estimated regression model is proper to the conditions.

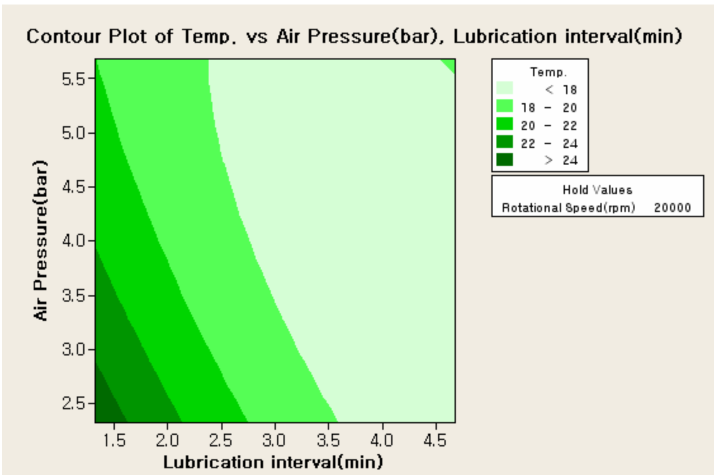
Therefore, it is verified that the heat generation equation of bearings proposed in this study is proper to within the range of applied lubrication conditions. Also, it is expected that it can be used to determine the optimal lubrication condition in the aspects of the pre-verification of the configured lubrication condition and the heat generation of bearings.

3.3. DETERMINATION OF THE OPTIMAL CONDITION

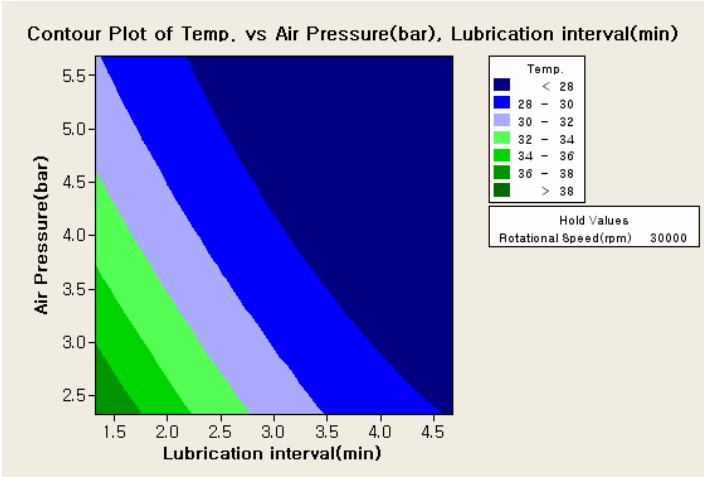
Contour plots were used to obtain the lubrication condition that satisfies the heat generation level of bearings required in a processing work using the estimated experimental equation. The contour plot based method represents the response curve for the combination of experiment factors and that shows the same response values for all points in contour lines. Also, it is useful to verify the desired response value and determine its condition.



(a) Rotational speed : 10,000rpm



(b) Rotational speed : 20,000rpm



(c) Rotational speed : 30,000rpm

Fig. 3. Contour plots according to the lubrication interval and air pressure

Fig. 3 represents the response values of the heat generation of bearings as the supplying interval of lubricating oil and supplying air pressure were changed while the rotational speed of the spindle was fixed as a specific level. In the case of the rotational speed of the spindle that was determined by 10,000rpm, it was possible to find a temperature range that satisfies the heat generation below 6℃. Also, in the case of the speeds that were determined by 20,000rpm and 30,000rpm, it was possible to determine the optimal levels of the supplying interval of lubricating oil and supplying air pressure below 18℃ and 28℃, respectively.

4. CONCLUSION

This study proposed an experimental equation for determining the optimal lubrication condition for an ultra high-speed spindle and analyzed the temperature change in bearings according to the combination of lubrication conditions based on the model established in this study. Based on the lubrication condition determined in this study, the conclusion of this study can be summarized as follows.

1. This study proposed an experimental equation that estimates the heat generation of bearings according to the change in the lubrication condition and rotational speed using a response surface method.
2. By using a contour plot method, the combination of lubrication conditions that satisfies a specific range of the heat generation of bearings was proposed.
3. The accuracy of the proposed experimental equation was verified through a verification experiment. In addition, based on the results of the verification, it is expected that the proposed equation can be used to determine the optimal lubrication

condition in the aspects of the pre-verification of the configured lubrication condition and the heat generation of bearings within the lubrication condition considered in this study.

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