A Study on the Shrink Fits and Internal Clearance Variation for Ball Bearing of Machine Tool using FEM

W. Kim, C. M. Lee and Y. K. Hwang

***Abstract*— System rigidity in machine tool is extremely important because the magnitude of deflection under load determines machining accuracy. The bearing stiffness is main factor that influence system rigidity. Therefore, bearing preload is needed to enhance system rigidity and to increase running accuracy. Bearing preload can be regarded as negative internal clearance. A proper amount of negative bearing clearance is desirable in order to stiffen the support of the spindle. However, inappropriate negative bearing clearance can cause excessive rolling contact stresses and eventually lead to bearing seizure. Therefore, Proper internal clearance have to be selected in order to prevent bearing seizure and to improve bearing stiffness.**

The bearing clearance is influenced by tight fit and thermal expansion during operation. The designer must take into account the reduction of clearance after installation to the interference fits, and thermal expansion must be considered. The purpose of this study is to grasp the internal clearance variation and behavior of a bearing which is a deep connected with fatigue life of bearing and performance of spindle through FEM(Finite Element Method). Finite element analysis is performed by using commercial code ANSYS according to variation of thermal condition and rotational speeds. This paper presents correct negative internal clearance according to temperature during operation. Furthermore, interrelation between thermal expansion and contraction are presented to maintain adequate contact force in spindle system. The influence of the centrifugal force and Internal clearance variation of bearing is studied to operating rotational speed.

***Index Terms*— Bearing internal clearance, Preload, High speed spindle, Tight fits, Shrink fit, Thermal expansion,**

I. Introduction

Recent trends of machine tools are high speed, high precision, high rigidity and unmanned automation. Of those, high speed spindle is rapidly being developed for productivity improvement. In addition, researches on the high rigidity of the spindle system have been carried out to ensure the high quality of the product. The rotation precision of the machine tool is a critical factor for the processing precision, and one of the causes that influence the factor is the motion error of the bearing that supports the spindle [1]. Rolling bearings are most frequently used for the spindle of the machine tools.

For successful bearing operation, care must be taken to specify tolerances of the appropriate fits between the bearing bore and shaft seat. It is important that rotating shaft always be tightly fitted into the bearing bore, because a loose fit will damage the bearing bore as well as the shaft seat. And the bearing also has internal clearance between the ball and the race way. The internal clearance of the bearing is generally reduced by the shrink fit and the thermal expansion due to the temperature difference between the temperatures of the inner ring and outer ring during operation. If the internal clearance of the bearing becomes smaller than specified, the breakage of oil film and seizure due to excessive contact stress may lead to the reduction of the life of the bearing, and even spindle vibration and noise [2]. Therefore, the preload is initially applied to improve the rotating precision by increasing the rigidity of the spindle system and preventing the vibration.

That is, the rigidity and rotating precision of the spindle system are improved and the excessive clearance of the bearing is prevented by the negative initial clearance between the rolling body of the bearing and the surface of the race way [3].

Thus, in terms of the machine tool bearing, clearance, fitting and the selection of preload value are very important. They are correlated with the temperature and rotation speed during the spindle operation, however, it is difficult to select the initial values. Especially, the higher speed of the spindle leads to the larger influence of thermal deformation and centrifugal force, so the selection of the values may depend on experiences instead of on theory [4].

In this paper, a finite element model is established to examine the influences of thermal expansion and centrifugal force on the preload for the bearing, fitting and clearance variation, and these influences are analyzed by FEM to study the fitting of the bearing and internal clearance variation, which are directly connected with the life of the bearing and the performance of the spindle.

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To predict deformation between the bearing and the spindle, transient thermal analysis of the spindle and the inner ring of the bearing are carried out by frictional heat generation on the contact surface of the bearing the transient thermal analysis.

In addition, thermal-structure coupled analysis and non-linear structural analysis is performed to analyze clearance variation of the bearing by the preload and centrifugal force applied to the bearing.

II. Theory of Heat Generation and Shrink Fit

The precision of rotation of the machine tool is a critical factor for the processing precision, and one of the causes that influence the factor is the motion error of the bearing that supports the spindle. Fig. 1 shows the interaction force between the spindle and the bearing.

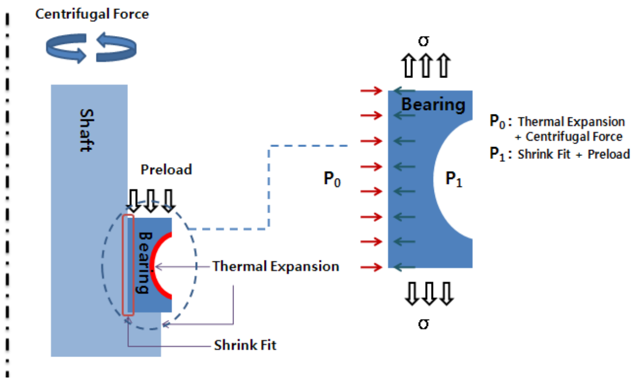

Fig. 1 Schematic Diagram of Spindle-Bearing System

A. *heat generation*

The heat generation can be calculated by two methods. In the first method, the heat from the angular ball bearing used in the spindle is calculated by adding: the heat by the spin moment and gyroscopic moment; the heat by applied load; and the heat by the kinetic friction torque determined by the viscosity and quantity of oil lubricant and the rotation number.

H_{spin} is the heat generated by the spin moment M_s, H_{gyro} is the heat from the bearing generated by the gyroscopic moment M_g, H_{load} is the heat generated by the applied load M_l, $H_{viscous}$ is the heat generated by the viscosity friction M_v. They are added as shown in Eq. 1 [5].

$$H_{total} = H_{spin} + H_{gyro} + H_{laod} + H_{vis\cos} \tag{1}$$

$$H_{vis\cos} = \frac{2\pi}{60} nM_v$$

$$H_{load} = \frac{2\pi}{60} nM_l$$

$$H_{spin} = \frac{2\pi}{60}(n_{si}M_{si} + n_{so}M_{so})$$

$$H_{gyro} = \frac{2\pi}{60} n_b M_g$$

$$M_l = f_l F d_m$$

$$M_v = f_v (V_o n)^{2/3} d_m{}^2$$

$$M_g = \frac{1}{10} m D_a{}^2 \omega_b \omega_c \sin\beta_m$$

$$M_s = \frac{3}{8}\mu_s Q a E(k)$$

The second method uses the fact that most of the bearing friction loss is converted into thermal energy in the bearing.

The heat generated by the frictional moment is shown in Eq. 2, where Q is the heat of the bearing, M is the frictional moment, μ is the frictional coefficient, P is the bearing weight, d is the inner diameter of the bearing, and N is the number of bearing rotation. The heat generation of the bearing is calculated by Eq. 2 in this study.

$$Q = (0.105 \times 10^{-6})MN \tag{2}$$

$$M = \frac{1}{2} P d \mu$$

B. *Shrink fit*

If the internal clearance of the bearing becomes smaller than specified, the breakage of oil film and seizure due to excessive contact stress may lead to the reduction of the life of the bearing, and even spindle vibration and noise. Therefore, the bearing whose clearance is suitable for the application must be initially selected.

δ is amount of the interference, R is the radius of the interfered section, and P is the pressure generated by interference [6].

$$\delta = \frac{pR}{E_o}\left(\frac{a_1^2 + R^2}{a_1^2 - R^2} + \nu_O\right) + \frac{pR}{E_i}\left(\frac{R^2 + b_2^2}{R^2 - b_2^2} - \nu_i\right) \tag{3}$$

$$p = \frac{\delta}{\frac{R}{E_o}\left(\frac{a_1^2 + R^2}{a_1^2 - R^2} + \nu_o\right) + \frac{R}{E_i}\left(\frac{R^2 + b_2^2}{R^2 - b_2^2} + \nu_i\right)} \tag{4}$$

III. FE- Model

In this study, the thermal and kinetic effects that the heat flow into the race way of the inner ring of the bearing that is fixed at the spindle has on the region in contact with the spindle are considered. A large quantity of heat is produced by the frictional loss according to the rotation of the bearing when the spindle starts, leading to the rapid rise of temperature in the spindle system. The resultant thermal deformation behavior of the spindle system is numerically identified. The heat generated during the operation is transferred from the inner ring to the spindle. The heat inflow, the contact thermal transfer coefficient and the forced convection by the cooling of the bearing are considered in the thermal deformation analysis. Through this process, the temperature distribution of the inner ring of the bearing and the spindle system is found, and the stress-strain analysis is performed with this temperature distribution as load condition.

To select the interference for keeping the precision of the spindle and the bearing under the allowed level the clearance variation of the bearing according to the preload and centrifugal force applied to the bearing is analyzed. A spindle with a 45mm-diameter and a maximum of 20,000rpm by a domestic spindle manufacturer, is modeled only for the spindle and the rear bearing section. ANSYS workbench is used for the analysis. Table 1 shows the properties of SCM415 and AISI 52100, which are used as the spindle and the inner ring of the bearing.

Table 1 Material property

Property	Spindle (SCM415)	Inner Ring (AISI 52100)
Young's Modulus(GPa)	205	210
Poison's ratio	0.29	0.3
Density(g/cc)	7.85	7.81
Thermal Conductivity(W/m-K)	44.5	45.6
Specific Heat(J/g-°C)	0.475	0.475

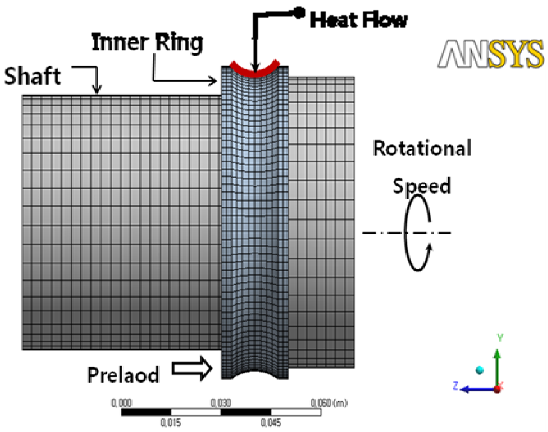

Fig. 2 FE-Model

Fig. 2 shows a finite element model to consider the thermal expansion by the heat from the inner ring of the bearing and the centrifugal expansion by the spindle rotation, which is modeled after being divided into two parts (the spindle and the inner ring of the bearing). The heat from the bearing is calculated by applying the bearing heating theory, and the heating part of the bearing is assumed to be the inner ring and the ball contact area to apply heat flow to the inner ring of the bearing.

It is also assumed that the heat from the bearing is divided equally into the inner ring and the outer ring, that is, the heat from the inner ring is 50% of the total heat. The cooling of the bearing is performed by air-oil lubricating method and by forced convection in the finite element model. To analyze the temperature distribution according to actual time, a transient thermal analysis is performed, and after the calculation considering the material properties and heat transfer rate, which are required for the heat transfer finite element analysis. The heat transfer rate is used as 283.0 W/m-K in the reference [7].

IV. Result

A. Transient Thermal Analysis

To consider the thermal expansion by the rotation of the spindle, an analysis is performed heat flow input for the bearing is shown in Table 2 and Fig.3.

Table 2 Heat flow input

Time (sec)	Rotation Speed (RPM)	Heat Flow(W)
900	5,000	9.78
1,800	10,000	32.11
2,700	15,000	77.185
3,600	20,000	132.61

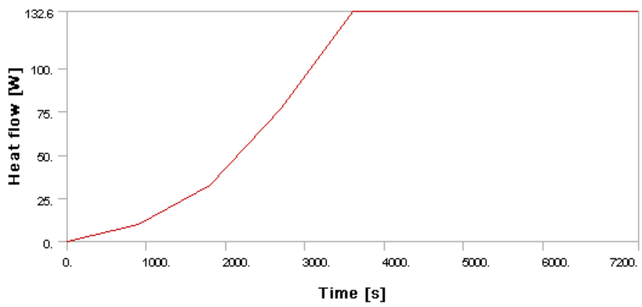

Fig. 3 Heat flow input with time

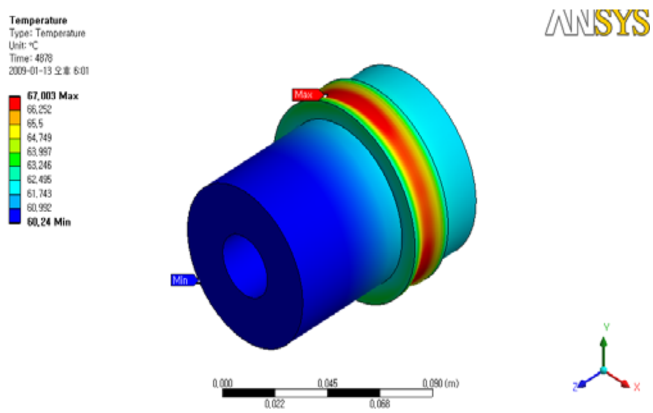

Fig. 4 Temperature distribution by the transient thermal analysis

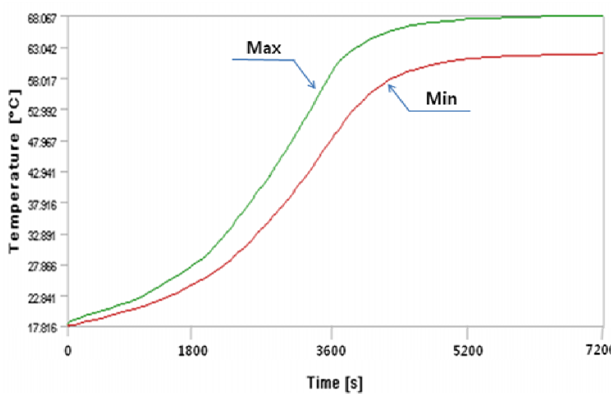

Fig. 5 Temperature variation with time

Figs. 4 shows temperature distribution by the transient thermal analysis. Fig. 5 shows Temperature variation with time . The highest temperature is 68°C, which is observed in the inner ring according to the rotation of the bearing ball. The lowest temperature is 60°C at the end of the spindle. Through this analysis, it is found that the heat from the spindle-bearing system can be estimated, and the interference between the spindle and the bearing increases according to the thermal displacement variation by the generated heat. It seems that this comes from the difference between the thermal expansion coefficients of the inner ring of the bearing and the spindle.

Table 3 Result of the thermal-structure coupled analysis

	Displacement[㎛]	
	Max	Min
Inner Ring	26.2	20.7
Spindle	27.0	2.7

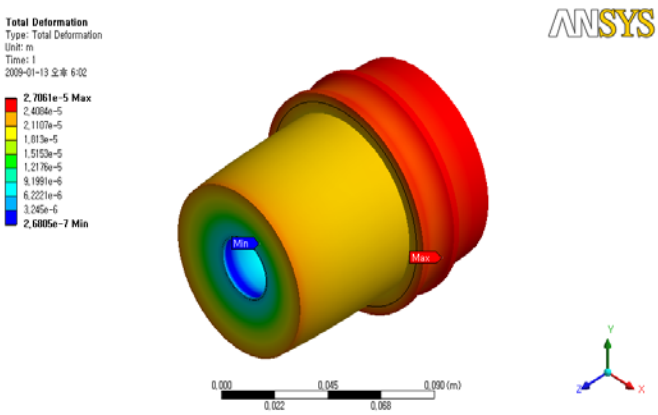

Fig. 6 Displacement of thermal-structure coupled analysis

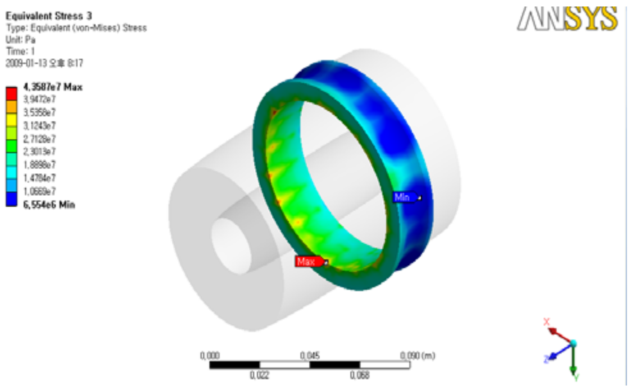

Fig. 7 Thermal stress of inner ring

Fig. 6 shows the results of the Thermal-structure coupled analysis, wherein the thermal displacement of the bearing-spindle system is found by applying the results of the transient heat transfer analysis. Table 3 shows maximum and minimum displacements of the spindle and the inner ring. The minimum displacement of the inner ring is generated at the region in contact with the spindle, and the maximum displacement of the spindle is generated at the region in contact with the inner ring. Therefore, it can be concluded that the thermal expansion of the spindle is larger than that of the inner ring. Fig. 7 shows the thermal stress of the inner ring, the maximum stress appears at the region in contact with the spindle. Accordingly, it seems that the interference of the bearing and the spindle will increase due to the thermal expansion of the spindle. In addition, the contact angle will decrease since the radius curvature of the rolling surface of the inner ring increases due to the thermal expansion of the spindle and the inner ring of the bearing in the bearing clearance.

B. Non-Linear Structural Analysis

The displacements of the bearing and the spindle are analyzed to find the variation of clearance in the bearing caused by the preload and centrifugal force on the bearing. To observe the change in the interference of the bearing, the directional deformation of radius is measured for the contact region between the spindle and the bearing, as shown in Fig. 8

The directional deformation of spindle at the side surface of the bearing, to which the preload is applied, is measured to examine the change in the bearing clearance. Table 4 shows the results of the displacement analysis according to each given conditions of the bearing-spindle a system. δ_b is direction deformation at the side surface of inner ring, δ_i is direction deformation of inner ring, and δ_s is direction deformation of shaft.

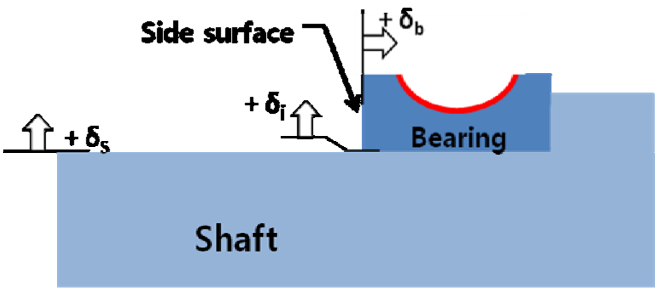

Fig. 8 Directional deformation values

Table 4 Results by structural analysis

Rotational Speed [rpm]	Preload [N]	Directional Deformation[㎛]		
		δ s	δ i	δ b
10,000	100	3.53	4.38	0.41
	200	4.52	4.89	0.43
	500	4.86	5.23	0.56
20,000	100	9.45	10.47	3.24
	200	11.78	12.16	3.91
	500	12.91	13.13	4.13

Fig. 9 shows the axial displacement at the side surface of the bearing according to the centrifugal force and preload. For 20,000rpm and a preload of 500N, the maximum displacement is 4.1㎛. The axial displacement increased as the rotation number and preload increased. It is found that the rotation number has more influence on the axial displacement than the preload. Then, contact angle between the bearing ball and the inner ring would increase due to the decrease of

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the radius curvature of the inner ring during the high speed rotation of the spindle. Therefore, the bearing clearance variation by centrifugal force must be considered at the initial design stage.

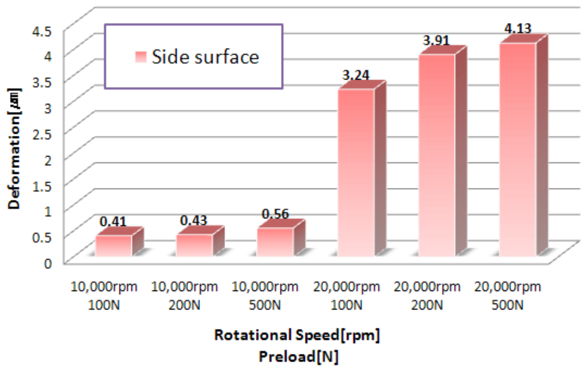

Fig. 9 Axial displacement at the side surface of the Bearing(δ_b)

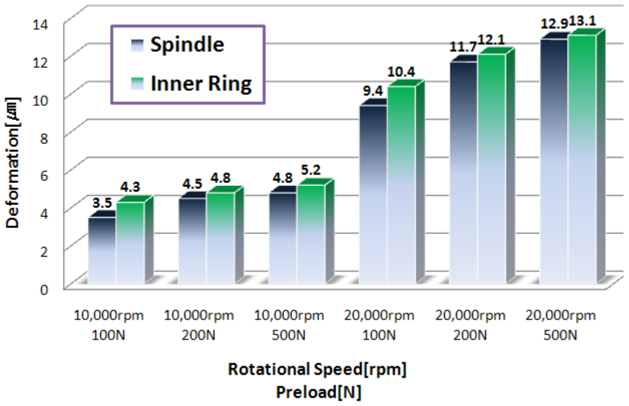

Fig. 10 Radial displacement at the spindle-bearing system($\delta s, \delta_i$)

Fig. 10 shows the radial displacement of the spindle-bearing system according to the centrifugal force and the applied preload. Junction region of the spindle and the inner ring clearance significantly increased as rpm increased, as with the axial displacement. The radial displacement of the inner ring and the spindle increased as the applied preload increased. However, the inner ring shows more centrifugal expansion. Accordingly, faster rotation of the spindle leads to less shrink fit of the inner ring, and it seems that the shrink interference must increase as the rotation speed of the spindle becomes higher, to prevent the slipping between the spindle and the inner ring of the bearing.

V. Conclusion

In this paper, a finite element model is established to examine the influences of thermal expansion and centrifugal force on the preload for the bearing, fitting and clearance variation and these influences are verified via analytical methods, to study the fitting of the bearing and internal clearance variation, which are directly connected with the life of the bearing and the performance of the spindle.

1) Finite element model is established to examine the influences of heat generation, revolution of spindle and the preload for the bearing.

2) Contact angle between the bearing ball and the inner ring is increased due to decrease of the radius curvature of the inner ring during the high rotation speed of the spindle.

3) Fitting interference between the spindle and the bearing increases according to the thermal displacement variation by the heat generation. Therefore, the fitting interference should be increased as the rotation speed of the spindle becomes higher.

4) Fitting interference is influenced by thermal expansion than centrifugal expansion by results of transient thermal analysis and non-linear structural analysis.

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