Effect of Sleeve Shrink-fit on Bearing Preload of a Machine Tool Spindle: Analysis using Finite Element Method

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Abstract

Shrink-fit is a well understood method of assembling precision sleeves on high speed Spindle. However, it is not well understood that how badly miscalculated interference value affects the performance of a spindle assembly. Authors here have made an effort to understand the behaviour of various values of interference and its effect on the practical performance as regards to machine tool spindle assembly application. A novel method is proposed to calculate and arrive at suitable and optimal interference values for spindle bearing assembly taking up the challenges as regards to mapping functional requirements and tolerances. In order to disallow axial movement of the bearing in a machine tool application sleeves are shrink fitted. Effect of hoop stress created causes the spindle to deform, very close to the sleeve. Local deformation of spindles directly affects bearing preload. Using FEA technique, a procedure is developed to calculate and optimise the required interference. A case study is presented to describe the entire process.

Keywords: Shrink fit, interference fit, bearing preload, FEM, parametric program, spindle

1. Introduction

In machine tool, spindle rigidity is the most important factor which influences the machining accuracy. The magnitude of deflection at the spindle under load determines the accuracy and surface finish of the component. The bearing stiffness is the important factor that affects the spindle rigidity. Bearing preload is used to enhance the bearing stiffness. Bearing preload can be stated as the negative internal clearance. A proper negative bearing clearance is required for the good bearing stiffness. However, smaller negative bearing clearance leads to breakage in lubrication film and seizure due to excessive contact stress which may reduce the life of the bearing. It may even increase spindle vibration and noise, as discussed by Y.H. Hwang et al [4]. Also, he validates the importance of selecting proper tight fit and clearance values and their effect on ball bearings [4].

Selecting the initial bearing preload value especially for the high speed machine tool spindles is difficult. Higher the speed of the spindle higher will be the heat generation and centrifugal force in the bearing. Hence, initial preload selected should compensate for the deformation due to thermal and centrifugal loads in the bearing. The initial preload values are selected most of the time based on experience; same was confirmed from the study carried by Hirasa wa et al.[5].

Extensive research has been carried out to understand the effect of shrink fitting of the bearing directly onto the machine tool spindle. W. Kim et al. [6] investigated in-depth using FEM; the displacements of bearing and spindle are analysed to find the variation of clearance in the bearing caused by the preload and centrifugal force on the bearing.

An important study but often overlooked is the effect on the preload of the bearings due to other adjacent assemblies that are shrink fit. For example, the shrink fit of sleeve to restrain the axial movement of the bearing. In this paper authors have put effort in developing better insight about the sleeve shrink fit and its effects. A proper interference fit is required to resist axial movement of the bearing. Smaller interference value reduces the axial stiffness of the assembly. Larger interference value causes the spindle to deform locally, thereby relieving the bearing creating gap between the bearing inner race and spindle.

In the practical scenario i.e. in an industrial environment assembly of sleeve also affects the bearing preload which in-turn affects performance of the entire spindle assembly unit. Hence a method is evolved to address the above issues and to arrive at an optimum interference value.

2. Spindle Assembly

In the present context a spindle assembly [7] is considered focusing on assembly of rear side bearing support and sleeve as shown in Fig 1 and Fig 2.
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Figure 1: Overall spindle bearing assembly

Figure 2: Rear side bearing and sleeve assembly

Figure 3: Special fixture for mounting outer race and to set the preload

2.1 Assembly process

Step 1: Spindle is kept on a special fixture

Step 2: Inner race of rear roller bearing is mounted in position. Bearing takes a location on the spindle taper.

Step 3: A special fixture as shown in Fig 3 is used to mount the outer race of the roller bearing on to the assembly by setting the radial preload value as 6-8 µm.

Step 4: Spacer value is obtained by measuring the distance between spindle step and the bearing face. Accordingly spacer is ground to that value

Step 5: Further whole rear bearing assembly is taken out to mount the ground spacer and then bearing set. Thus the bearing assembly is completed with the set radial preload.

2.2 Sleeve Assembly

In machine tool spindle the preloaded bearing is restrained axially by sleeves. The interference fit is achieved by shrink fitting a larger outer diameter of spindle into the smaller opening of the sleeve. The diametrical difference between spindle OD and the Sleeve ID is referred to as the interference fit.

To retain the radial preload of the assembled bearing it is necessary to shrink fit the sleeve. Sleeve bore is first ground to the pre-set value to achieve a calculated interference. Then sleeve is heated to assemble on to the spindle to complete the rear bearing assembly process.

2.3 Sleeve Shrink Fit Effect

The interference pressure developed causes the spindle to deform locally. The spindle deformation creates the gap between the bearing bore and the OD of the spindle thereby relieving the bearing. This removes the set preload and bearing will not take the load. Hence it is necessary to optimize the interference between the sleeve and the spindle.

3. Calculation of interference pressure

The contact pressure generated at the interference and the deformation at the interference can be calculated analytically for a cylindrical component with uniform geometry. Fig 4 shows the cross-section of two cylinders. The outer radius of the smaller cylinder is more than that of the inner radius of the larger cylinder by an amount δ.

The total deformation of inner and outer member can be expressed as [1]:

$$\delta_{total} = pRK_i + pRK_o$$  \hspace{1cm} (1)

Where the constant for the outside member, $K_o$, is defined as,

$$K_o = \frac{1}{E_o} \left( \frac{r_o^2 + R^2}{r_o^2 - R^2} + \vartheta \right)$$  \hspace{1cm} (2)
Similarly, for the inside member, $K_1$, is defined as,

$$K_1 = \frac{1}{E_1} \left( \frac{R^2 + r_i^2}{R^2 - r_i^2} + \theta_1 \right)$$

(3)

The total pressure generated by the interference is defined as

$$p = \frac{R}{E_2} \left[ \frac{r_i^2 + R^2}{r_i^2 - R^2} + \theta_0 \right] + \frac{R}{E_1} \left[ \frac{r_i^2 + R^2}{R^2 - r_i^2} + \theta_1 \right]$$

(4)

Using the said equations for the spindle under consideration values is calculated:

Deformations in inner and outer members are

$\delta_1 = 0.061 \text{ mm}, \quad \delta_o = 0.059 \text{ mm}$

And pressure generated at the interference is $p = 16.35 \text{ N/mm}^2$

Though analytical solution gives a rough estimate, in order to know the effect in the assembly condition it is preferred to do simulation using FEM technique.

4. Simulation through FEM technique

APDL (ANSYS Parametric Design Language) technique, available in ANSYS, has been used. APDL program gives the advantage of reduced lead time for modeling and analysis through several iterations.

The following FEM features are built into the APDL program:

- Geometric modeling and meshing.
- Applying boundary conditions and loads.
- Solving the algebraic equations for computing deformations, and
- Post processing for computing the deformation in spindle

Fig 5 and Fig 6 shows the pre-modeling sketch of the assembly that need to be analysed.

Using ANSYS spindle and sleeve are modelled with solid elements (refer Fig 7). The contact between the two is established using contact elements to transfer pressure load from sleeve to spindle and vice versa.

Thermal loads are applied to incorporate the physics of sleeve being heated and shrunk on to the spindle. It has been found that the deformation in the sleeve generates pressure at the contact pair there by deforming the spindle as shown in Fig 8.
5. Results and discussion

Fig 8 shows the deformation contour for 120 µm. Table-1 below gives the deformation results for spindle and sleeve with 120 µm and 20 µm interference fit at different locations as shown in Fig 9.

Table-1: Deformations for 120 µm and 20 µm interference fit

<table>
<thead>
<tr>
<th>Location</th>
<th>Radial deformation, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial interference value 120 µm</td>
</tr>
<tr>
<td>A</td>
<td>17</td>
</tr>
<tr>
<td>B</td>
<td>37</td>
</tr>
<tr>
<td>C</td>
<td>13</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
</tr>
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6. Conclusion

Initially 120 µm interference fit adopted.

1. For 120 µm interference fit, the maximum deformation of the spindle-shaft is at the sleeve-bearing interface (i.e., location B ref. fig-9). The deformation is 37 µm radially. Bearing preload got relieved and malfunction started.

After analysis and using experience 20 µm interference fit is adopted.

2. For 20 µm interference fit the deformation at location B is 6 µm radially. It is recommended to keep the interference below 20 µm radially it is found safe and bearing preload is not relieved.

Functionally we can infer:

a. Spindle is deformed due to shrink fitting causing relief to the preloaded bearing.

b. Above effect has taken place because of larger size sleeve that is shrunk over the spindle

c. Relief to preload can be avoided in two methods

i. Keeping the interference value below 20 µm radially.

ii. Increasing the spindle wall thickness and reducing sleeve thickness.

7. References

[1] Mechanical Engineering Design by J.E. Shigley
[8] Introduction to Finite Element Methods by Tirupathi R. Chandrupatla and Ashok D. Belegundu