Optimal Design of the Process for Self-lubricating Spherical Plain Bearings Based on Finite Element Analysis

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Abstract. As a key technology for forming of self-lubricating spherical plain bearing, extrusion forming process affects general performances of self-lubricating spherical plain bearing. In order to solve the problems of insufficient force of the extruder and material accumulation of outer ring blank in the extrusion process of wide series and large bearing, a scheme of machining extrusion groove on outer ring blank is put forward, and taken numerical simulation by explicit dynamic finite element code LS-DYNA. Effective plastic plain and effective stress and bearing osculation after springback are investigated as well as applied extrusion force. The experimental results show that the bearing osculation can meet the requirement after machining extrusion groove on outer ring blank, meanwhile, a smaller extrusion force is needed in the extrusion forming process.

1. Introduction

Self-lubricating spherical plain bearing is mainly composed of outer ring, inner ring and maintenance-free PTFE liner embedded in an organic resin matrix, it has some advantages such as high impact resistance, high bearing capacity, high corrosion resistance and high wear resistance, so it is applied in field of aviation, aerospace, water conservancy facilities, military machinery and other engineering fields. The most important quality index of self-lubricating spherical plain bearing is the bearing osculation between the spherical mating surfaces of inner ring and outer ring, it is the standard for the uniformity of the gap between the inner and outer rings which has a great impact on its service life.

As an important forming method for manufacturing self-lubricating spherical plain bearing, extrusion forming is responsible for the general performance of bearing. Due to the design of die, the process parameters of extrusion forming and the complicated metal flow mechanism, it’s difficult to get the ideal spherical surface of outer ring during the practical manufacture process to ensure the bearing osculation. For the extrusion forming process, an iteration process is used to obtain suitable design of die and process parameters. In the meantime, the process of optimizing bearing osculation is more difficult.

At present, the extrusion forming process has been studied in the method of finite element by academics. Yang et al. made some researches, found the advantages of two-way extrusion forming process relative to one-way extrusion forming process; Orsolini et al. created two-dimensional (2-D) axisymmetric model and three-dimensional (3-D) model of extrusion forming process respectively, obtained the results that the difference in simulation less than 1%, and the reliability of the model was
verified by theory and experiment; Wu et al. combined the FEA, neutral network and genetic algorithm to develop a method for the design of the optimal shape of an extrusion die, improved the bearing osculation.

In order to solve the problems of insufficient force of the extruder and material accumulation of outer ring blank in the extrusion process of wide series and large bearing, the extrusion groove of outer ring blank is machined to complete the extrusion forming process. The finite element modeling and simulation of the extrusion forming process of self-lubricating spherical plain bearing with the extrusion groove are carried out by explicit dynamic finite element code LS-DYNA. And determine the final shape of the outer ring after springback, bearing osculation, extrusion force and other information of interest. The experimental results show that the scheme with extrusion groove can meet the product quality requirements.

2. Finite element model of extrusion forming process

2.1. Method of extrusion forming process

The wide series of bearings selected in this paper is shown in the schematic diagram as Figure 1, the outer ring blank is machined with an arc-shaped extrusion groove, the groove depth is 0.42mm, the arc radius is 43.78mm, outer diameter of outer ring blank is 29.67mm, and its internal diameter is 23.05mm. The liner is attached to the inner surface of the outer ring blank, the thickness is 0.375mm. The outer diameter of inner ring is 22.30mm, and its internal diameter is 12mm.

As shown in Figure 2, the self-lubricating liner is attached on the inner cylinder surface of the processed outer ring blank, and then the processed floating mandrel is placed in the inner ring, and the outer ring blank is placed outside the inner ring. And the mandrel, together with the inner and outer rings, is placed in the lower die; when the upper and lower dies are closed, the inner ring and outer ring are respectively positioned by the upper and lower dies, the outer ring and the self-lubricating liner are tightly wrapped in the inner ring to complete the extrusion forming.
2.2. Establishment of finite element model

In order to facilitate the observation of the details of the extrusion, a 1/2 three-dimensional (3-D) finite element model is used to simulate the extrusion forming process and as shown in Figure 3. The finite element model consists of dies and bearing parts, including upper and lower dies, outer ring blank, liner and inner ring. The upper and lower dies are assumed to be rigid bodies, and load is applied to the upper and lower dies during the extrusion simulation.

Both inner and outer rings and the liner are deformable bodies, they are meshed by using the SOLID164 element via the sweep mesh method, the upper and lower dies are set as rigid bodies, which are meshed by the same mesh method. The number of SOLID164 element is 570851 and the mesh of 3-D finite element model is show in Figure 4.
Figure 4. Mesh of the 3-D finite element model.

The plastic properties of the inner and outer rings of the bearing to analyse the deformation is
POWER_LAW_PLASTICITY, which is mainly used for metal plastic forming analysis. It provides
the elastic-plastic behavior of isotropic hardening, the effect of strain rate is described by a power
function constitutive relation including Cowper-Symbols multiplier. The function is as follows:

\[
\sigma = \left[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^p \right] k \left[ \varepsilon_e + \varepsilon_p^{\text{eff}} \right]^n
\]  

(1)

Where:
- \( \dot{\varepsilon} \) is strain rate,
- C and P are parameters of strain rate of Cowper-Symbols,
- \( \varepsilon_e \) is elastic strain,
- \( \varepsilon_p^{\text{eff}} \) is effective plastic strain,
- k is strength coefficient,
- n is hardening coefficient.

The material of liner is braided composite of PTFE and phenolic resin, the compression property
obtained by this material is similar to those of hyper elastic material, so the Mooney-Rivlin model is
chosen. This model is used to define incompressible rubber materials. The deformation energy density
function can be defined by:

\[
W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \left( \frac{C_{02}}{2} + C_{03} \right) \left( \frac{1}{I_3} - 1 \right) + D (I_1 - 1)^2
\]  

(2)

Where:
- \( D = \frac{C_{10}(5\nu - 2) + C_{01}(11\nu - 5)}{2(1 - 2\nu)} \),
- \( I_1, I_2, I_3 \) is invariants of strain,
$C_{10}, C_{01}$ are constant of Mooney-Rivlin.

The friction coefficient between the upper and lower die and outer ring blank is set to 0.15 (considering grease lubrication during processing). According to the experimental data, the frictional coefficient between the liner and inner ring is set to 0.10. The displacement boundary condition is symmetric boundary condition to ensure symmetric deformation.

In the simulation of extrusion forming process, the upper and lower dies are moved steadily at a speed of 2m/s to the intermediate plane, and the total displacement of die is 7.3mm. In order to obtain the precise ring shape of the outer and inner rings, the inner surface of the outer ring and the external surface of the inner ring should be further performed in the method of springback by removing the upper and lower dies.

3. Results and Analysis

3.1. Effective plastic strain and effective stress of inner and outer rings

In extrusion forming process, the plastic deformation of outer and inner ring after extrusion can be extracted from simulation via effective plastic strains. The effective plastic strains distributions of inner and outer ring after extrusion forming are in the form of contour plot in Figure 5. The maximum effective plastic strain of outer ring occurs in the top edge and the value is 0.4402. There is no plastic deformation in the inner ring and the value of effective plastic strain is 0 during the whole extrusion forming. Figure 5 clearly shows the final shape of the outer ring and at the end of extrusion forming process, the outer ring is shaped from a hollow cylinder to a portion of a hollow sphere. Due to the metal flow, the upper surface of the outer ring is changed from an originally horizontal plane to a tilted plane.

![Effective Plastic Strain Distributions](image)

(a) Outer ring.  (b) Inner ring.

**Figure 5.** Effective plastic strain distributions of outer and inner rings.

The effective stress distributions of inner and outer ring at the end of extrusion forming are shown in Figure 6 (a) and (b) respectively. The maximum values of effective stress of outer and inner ring are 1147MPa and 623MPa. The outer ring is in contact with upper and lower dies in the extrusion forming process, and stress concentration happens in the external top of outer ring.
3.2. Springback Analysis of Outer Ring

After the extrusion is completed, relax the models by removing the dies for the springback of inner and outer rings. The plastic deformation remains, the elastic deformation completely disappears, the external side of the outer ring is shortened due to the elastic recovery, and the inner side is elongated due to the same reason which makes a greater springback at the end of outer ring.

The deformation of inner ring is small, and the springback of the external surface of the inner ring can be ignored. Figure 7 is a schematic diagram of the inner surface contour of the outer ring before and after springback, the maximum springback occurs at the end of the outer ring, the maximum displacement is 0.0734mm, and the minimum springback occurs at the waist of the outer ring, and the minimum displacement is 0.0001mm.

![Figure 7](image.png)

3.3. Measurement of Bearing Osculation

As one of the most important performance indexes of self-lubricating spherical plain bearing, bearing osculation is used to evaluate the uniformity of the spherical mating surfaces of inner ring and outer ring, and is the key factor to ensure the service life and running stability.
In the actual measurement, the bearing needs to be semi-divided, and then according to the national military standard GJB5502-2005 ‘Specification for low-speed swing self-lubricating spherical plain bearings’, use five-point uniformity test method to measure bearing osculation. The specific steps are as follows: Use resin to fix the bearing's inner and outer rings to prevent relative movement, then cut the bearing into two parts, grind and polish the split surface to obtain clear arc-curves of the inner and outer ring, and then measure the five assigned points by Industrial CT, t1-t5, as shown in Figure 8 (a) and (b).

Figure 8. Bearing osculation test.

Figure 9 shows the outline of inner surface of outer ring and external surface of inner ring which extracted from the model, after extrusion forming and springback, apparently, the end of the outer ring’s outline is warped, the overall outline is not perfect spherical surfaces, which will lead to wear of self-lubricating liner, abnormal sound and reduce the service life.

Figure 9. Final outline of outer and inner rings.

The bearing osculation is measured by the above method, and the experimental data are compared with the simulation result. A total of five samples are sampled and measured, due to manufacturing
batches and manufacturing deviations, the individual test results are different from the simulation results shown in Figure 10, but the overall results are consistent and meet the osculation requirements.

![Figure 10. Comparison of bearing osculation between experimental data and simulation results.](image)

3.4. Extrusion force

The extrusion force exerted on the dies is an important factor in the deformation of the outer ring blank of the bearing, Figure 11 compares the distribution of the extrusion force between the outer ring blank with and without the extrusion groove, two curves have the same rule, the extrusion force increases obviously in the later stage, and the deformation of the outer ring increases corresponding to the extrusion, the maximum extrusion force that with extrusion groove is 240kN, and the extrusion force that without extrusion groove is 469kN. Therefore, it can be seen that the scheme with the extrusion groove can not only meet the product osculation requirements, but also require smaller extrusion force. In practice, it also plays an important role in improving the wear of the dies and the metal flow of the bearing outer ring.

![Figure 11. Extrusion force versus displacement of die.](image)
4. Conclusion

Using explicit dynamic finite element code LS-DYNA to simulate the extrusion forming process of the bearing outer ring with extrusion groove, the distribution of equivalent stress and equivalent plastic strain in extrusion process are analyzed in detail, which provide theoretical guidance for extrusion forming process of self-lubricating spherical plain bearing. The springback of the bearing outer ring determines the final shape of the inner surface of the bearing outer ring, the maximum deformation caused by springback occurs at the end of outer ring blank, but the bearing osculation still can be ensured. On the premise of ensuring that bearing osculation meets the requirements, the scheme that the outer ring with the extrusion groove requires smaller extrusion force and optimizes the bearing extrusion forming process. The validity of the simulation results is verified by comparing the finite element simulation results with the experimental ones.

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