Preparation of titanium alloy outer ring self-lubricating spherical plain bearing by two-step extrusion forming process

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Research Article

Keywords: Self-lubricating spherical plain bearing, Extrusion forming process, Titanium alloy, Precision forming

Posted Date: March 22nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1449521/v1

Abstract

Self-lubricating spherical plain bearing is a key component widely used in aerospace field. The spherical plain bearing made of titanium alloy has lighter weight and better corrosion resistance. In order to manufacture the outer ring of self-lubricating spherical plain bearing with titanium alloy, a two-step extrusion forming process was proposed. Taking GE15DE1TK spherical plain bearing as an example, the finite element simulation model of the forming process was established, the forming test was carried out, and the outer ring of self-lubricating spherical plain bearing made by TC4 titanium alloy was successfully prepared. The results show that the forming defects such as over extrusion and insufficient extrusion can be improved by optimizing the die structure, the size of outer ring blank and the lubrication conditions. The forming parameters for GE15DE1TK spherical plain bearing are given. The prepared spherical plain bearing can be used directly without other processes to correct no load rotational breakaway torque.

Introduction

Self-lubricating spherical plain bearing has the advantages of large bearing capacity, long service life, compact structure and maintenance free. It is a key supporting component of many important equipments, and it is widely used in aerospace fields such as aircraft control system, landing gear and rotor system[1–3]. Bearing companies such as Kamatic and RBC carried out research on the design and manufacturing technology of self-lubricating spherical plain bearings as early as the 1950s, with mature design methods and manufacturing processes[4]. In recent years, with the increasing service demand of marine and aviation aircraft, the self-lubricating spherical plain bearing has been in service for a long time in the marine atmospheric environment. Hence bearing is prone to corrosion, locking and other failure forms, which seriously affects the mobility and safety of aviation aircraft, and puts forward higher requirements for the lightweight and corrosion resistance of self-lubricating spherical plain bearing[5, 6].

Titanium alloy has excellent properties such as low density, high specific strength and corrosion resistance. It is widely used in structural parts such as aircraft fuselage and engine. It is the preferred material for lightweight self-lubricating spherical plain bearing[7, 8]. However, titanium alloy has large yield ratio, narrow plastic deformation range and small elastic modulus, so the forming accuracy is difficult to control[9]. In order to realize the precision forming of titanium alloy, there are two common processes: precision forging and isothermal superplastic forging, which are mainly used for the development of gas cylinders and tanks in the aerospace field[10]. Such as, Ti-6A1-4V and Ti-5A1-2.5Sn Eli titanium alloy pressure vessels; 0t4-1 and BT5-1 fuel tanks in progress detector; Ta7 Eli titanium alloy cryogenic gas cylinder in xx-3a and xx-5 launch vehicles[11]; Ti-6A1-4V titanium alloy N2H4 fuel tank[12].

However, these titanium alloy precision forming processes need to be heated to more than 700℃. Due to the material characteristics of titanium alloy, titanium alloy cold formed components are generally found in single curvature parts with large bending radius and easy to form[13]. The self-lubricating layer is adhered to the outer ring of self-lubricating spherical plain bearing before forming. The titanium alloy outer ring must be formed at room temperature in order to ensure the self-lubricating performance and bonding performance of the self-lubricating layer.

In addition, in the existing extrusion forming process of self-lubricating spherical plain bearing, the self-lubricating gasket is often over extruded[16, 17], which reduces the service life and the self-lubricating effect of the bearing[18, 19]. After the bearing is formed, the rotational breakaway torque of the bearing needs to be further adjusted with the help of other processes, which increases the production cost[20], Therefore, the existing forming process needs to be further improved to be suitable for the forming of titanium alloy outer ring self-lubricating spherical plain bearing. Due to the above limitations, the precision forming process of titanium alloy outer ring at room temperature is very difficult, and there are few research reports.

In this paper, a two-step extrusion forming process was proposed, the forming characteristics and outer ring deformation law of the process were analyzed by means of finite element simulation and experiment, the main factors affecting the forming results were determined, and the forming process parameters were optimized, the self-lubricating spherical plain bearing with titanium alloy outer ring was prepared by forming test. It provides theoretical and data support for the development of titanium alloy outer ring self-lubricating spherical plain bearing.

Forming Principle Of Two-step Extrusion Forming Process

The forming model is shown in Fig. 1. The main forming parts include: upper die, bearing outer ring bonded with gasket, bearing inner ring and lower die. The working surface of the upper die is a conical surface with a certain angle(α), and the maximum cone diameter(s) needs to be determined according to the size of bearing. The main dimensions of the outer ring blank include: height(H), outer diameter(D), inner diameter(d), gasket thickness(h), In order to facilitate the processing and bonding of the gasket, the shape of the outer ring blank was designed as a circular ring, and the inner ring and the lower die do not participate in the deformation.

The forming principle is shown in Fig. 2. The positioning mandrel is used to fix the position of the inner and outer rings of the bearing, the upper die moves up and down according to the specified forming distance to realize the first forming, then the outer ring is turned over 180° and repositioned on the lower die, and the upper die moves up and down again to realize the second forming.

As shown in Fig. 3, referring to the dimensions of GE15DE1TK spherical plain bearing, a two-step extrusion forming process finite element model was established by DEFORM3D software. The outer ring material was TC4 titanium alloy, and the mechanical property parameters are shown in Table. 1. The stress-strain curve of TC4 was measured through the tensile test, as shown in Fig. 4. The finite element model was axisymmetric mode and the outer ring has large deformation, so the elastic-plastic model was adopted. The friction was set as coulomb friction model. The element type was tetrahedron, with 5012 elements and 5248 nodes.

Table 1
TC4 mechanical property parameters

Material	Young's modulus(Gpa)	Poisson's ratio	Density(g/cm^3)
TC4	109	0.34	4.44

Analysis Of Main Factors Affecting Forming Results

Figure 5 shows bearings with good forming quality and typical defects. Common forming defects include insufficient extrusion, over extrusion, etc[21].These defects can affect the rotational breakaway torque of the bearing and reduce the service life of the bearing. Titanium alloy has large yield strength and small elastic modulus. These forming defects are more likely to occur in the cold forming process. The die structure, forming distance and outer ring blank size directly affect the deformation process of titanium alloy. For the extrusion process, the deterioration of lubrication conditions in actual production was also prone to forming defects[22], Under high forming pressure, it is difficult to ensure good lubrication conditions between the blank and the die, while poor lubrication will increase the wear of the die and workpiece. Therefore, the lubrication condition is also an important factor to be considered. It can be determined that the main reasons affecting the forming results are: die structure, forming distance, outer ring blank size, lubrication conditions.

The influence degree of each factor on the forming result was analyzed by orthogonal test, and the forming distance(L), die angle(α), inner diameter(d), thickness of out ring(t), friction coefficient(f) was set as the influencing factors. $L_{16}(4^5)$ orthogonal test table was adopted, and four levels were set for each factor, as shown in Table. 2, Table. 3. In this paper, the track radius of the inner surface of the outer ring was used as the forming quality evaluation index[23]. The schematic diagram of the track radius of the inner surface of the outer ring is shown in Fig. 6.

$$F_{err}=\frac{\sum_{i=1}^{n}\left|R_i-R_j\right|}{n} \quad i=1,2,3,\ldots n.$$

Where: R_i is the radius of the inner surface of the outer ring after forming; R_J is the target value of inner surface radius, which is equal to the sum of inner ring radius and grasket thickness, and the grasket thickness is set as 0.4mm[24]; F_{err} indicates the forming accuracy. The smaller F_{err} is, the closer radius of the inner surface after forming is to the target size, so the forming accuracy is higher.

Excessive forming force can improve the design requirements of forming equipment and die, which is not conducive to the precision forming of bearing. The maximum forming pressure is selected as the second evaluation index.

The orthogonal test results were analyzed by the method of range analysis.

$$T_i = \max\left\{\bar{K}_{im}\right\} - \min\left\{\bar{K}_{in}\right\}$$

Where: $\bar{K}_{im}$ is the average value of the evaluation index at a certain level of a factor, $\bar{K}_{in}$ is the average value of the evaluation index at other levels of a factor, and T_i is the difference between the average value of the maximum evaluation index and the average value of the minimum evaluation index at all levels under a factor. The greater the T_i value, the greater the impact of the factor on the evaluation index.

Table 2
Level-Factor

Level	Factor				
	Forming distance(mm)	Angle of die(°)	Internal diameter(mm)	Thickness(mm)	Friction coefficient
1	2	40	23.8	2	0.2
2	3	50	24.3	3	0.3
3	4	60	24.8	4	0.4
4	5	70	25.3	5	0.5

Table 3
$L_{16}(4^5)$orthogonal test

No.	Forming distance (mm)	Angle of die (°)	Internal diameter (mm)	Thickness (mm)	Friction coefficient	Ferr (mm)	Max forming pressure (kN)
1	2	40	23.8	2	0.2	0.183	95.11
2	2	50	24.3	3	0.3	0.138	204.74
3	2	60	24.8	4	0.4	0.5	185.85
4	2	70	25.3	5	0.5	0.931	176.47
5	3	40	24.3	4	0.5	0.288	505.87
6	3	50	23.8	5	0.4	0.389	555.94
7	3	60	25.3	2	0.3	0.57	61.2
8	3	70	24.8	3	0.2	0.473	62.02
9	4	40	24.8	5	0.3	0.512	729.5
10	4	50	23.8	4	0.2	1.153	338.89
11	4	60	25.3	3	0.5	0.08	188.32
12	4	70	24.3	2	0.4	0.13	59.38
13	5	40	25.3	3	0.4	0.809	384.33
14	5	50	24.8	2	0.5	0.674	162.85
15	5	60	24.3	5	0.2	1.093	274.49
16	5	70	23.8	4	0.3	0.645	156.06

The influence of various factors on the forming accuracy and maximum forming force range is shown in Fig. 7. It can be seen from the figure that the order of forming accuracy T_i is: forming distance > outer ring blank thickness > friction coefficient > inner surface diameter > die angle. The order of forming pressure T_i is: outer ring blank thickness > die angle > forming distance > friction coefficient > inner surface diameter. It shows that the biggest factors affecting forming accuracy and forming pressure are forming distance and outer ring blank thickness respectively. Due to the coupling effect of various parameters, it is difficult to quantitatively analyze the influence of various factors on the deformation in the orthogonal test results. Therefore, the key factors are quantitatively analyzed through single factor experiment.

Influence Of Forming Distance And Die Angle On Forming Results

The lateral displacement of the outer ring under different forming distances and die angles is shown in Fig. 8. Compared with figure a and b, after the forming distance increases from 2mm to 5mm, the maximum transverse displacement of the inner surface of the outer ring increases from 0.74mm to 2.85mm, indicating that increasing the forming distance can significantly increase the lateral displacement of the outer ring, The maximum lateral displacement of the inner surface in Fig. 8(c) is 0.39mm, which is smaller than that in Fig. 8(a), indicating that increasing the die angle will reduce the lateral displacement of the outer ring, Therefore, a small die angle should be used to match a small forming distance, and the inner diameter of the outer ring can be designed to be close to the outer diameter of the inner ring. Insufficient extrusion defects are easy to appear under this cooperation (Fig. a and Fig. c). When the forming distance is large, selecting a smaller die angle is easy to produce over extrusion defects (Fig. b). The extrusion degree at both ends of the outer ring can be improved by increasing the inner diameter of the outer ring or increasing the die angle (Fig. d).

The relationship between forming distance, forming accuracy and forming pressure under two die angles is shown in Fig. 9. It can be seen from the figure that when the die angle is 70°, with the increase of forming distance, F_{err} decreases from 0.907 to 0.233, indicating that increasing forming distance can improve forming accuracy. When the die angle is 60°, the F_{err} decreases and then increases. The forming accuracy with the forming distance of 4mm is the highest, and the F_{err} is 0.08. The reason may be that insufficient extrusion is caused by too small forming distance under the same die angle, and over extrusion is caused by too large forming distance. Both cases will reduce the forming accuracy. Therefore, reducing the die angle can obtain the best forming accuracy under small forming distance.

When the die angle is 60°, the forming pressure will increase significantly with the increase of the forming distance before the forming distance is 4mm, which mainly comes from the friction between the outer ring and the die and the plastic deformation of the outer ring itself. The larger the forming distance is, the greater the forming pressure is required, and the maximum forming pressure after 4mm is basically the same. The reason may be that the contact area between the outer ring and the die is no longer increased, and the friction force does not increase significantly after the outer ring is deformed. When the die angle is 70°, the forming force changes less before the forming distance is 4mm. The reason may be that the lateral displacement of the outer ring is small under such conditions and there is no large bending deformation. When the forming distance is increased, the bending deformation of the outer ring increases significantly, resulting in a significant increase in the forming pressure. When the die angle increases from 70° to 60°, the forming pressure increases by about 30%. Reducing the die angle will significantly increase the forming pressure.

Influence Of Outer Ring Thickness And Forming Distance On Forming Results

The lateral displacement of the outer ring under different outer ring thickness and forming distance, as shown in Fig. 10, the maximum lateral displacement of the middle part of the outer ring in Fig. 10(a) is

0.22mm, and the maximum lateral displacement of both ends is 1.33mm. With the outer ring thickness increases to 5mm, the maximum lateral displacement of the middle and both ends are 0.63mm and 1.48mm respectively (Fig. b). It shows that the thickness of the outer ring is small, the blank is easy to deform, and the diameter of the outer ring will be reduced after the bearing is formed. The use of thinner outer ring blank can reduce the reduction of diameter, and can cooperate with the smaller inner diameter of outer ring to ensure the rotational breakaway torque of bearing. It is easy to produce over extrusion defects when cooperating with large forming distance (Fig. c). With the thickness of the outer ring increases, the part in contact with the die will produce large plastic deformation (Fig. b and Fig. d). On the whole, the outer ring blank will produce large upsetting deformation, which is easy to produce insufficient extrusion and asymmetric defect (Fig. b and Fig. d). Therefore, on the premise of ensuring the machining allowance, the thinner outer ring blank shall be used as far as possible.

The relationship between the blank thickness of the outer ring and the forming accuracy and the maximum forming pressure under two forming distances is shown in Fig. 11. When the forming distance is 3mm, the forming accuracy decreases first and then increases. When the thickness is 3mm, the forming accuracy is the worst. The reason may be that when the thickness is less than 3mm, the bending deformation degree of the outer ring is large, and matching with a small forming distance can improve the forming accuracy. When the forming distance is 4mm, the forming accuracy first increases and then decreases, and the forming accuracy with a thickness of 3mm reaches the highest. The reason may be that if the outer ring thickness is too small at a large forming distance, it will produce transition extrusion, and then form over extrusion defects, which reduces the forming accuracy. Increasing the blank thickness can improve the over extrusion defect to a certain extent, so the forming accuracy is improved. With the thickness increases to 3mm, the outer ring will produce large upsetting deformation under the influence of large forming distance, resulting in the gradual reduction of forming accuracy. The forming accuracy is the highest when the outer ring thickness is 3mm and the forming distance is 4mm.

At the forming distance of 3mm and 4mm, with the increase of outer ring thickness, the maximum forming pressure increases from 93.48kN and 82.25kn to 516.13kN and 284.16kN respectively, indicating that increasing the outer ring blank thickness will significantly increase the forming pressure. The reason is that the bending deformation capacity decreases with the increase of the outer ring thickness, which increases the upsetting deformation and the contact area of the die. It increases the friction and leads to large forming pressure due to the titanium alloy is easy to bond with the die. When the thickness of the outer ring is less than 3mm, the difference between the maximum forming pressure of 3mm and 4mm is less than 20%. When the thickness of the outer ring reaches 5mm, the difference between the maximum forming pressure is about 80%, indicating that the greater the thickness of the outer ring, the more significant the influence of the forming distance on the forming pressure.

Influence Of Friction Coefficient And Outer Ring Thickness On Forming Results

The lateral displacement of the outer ring under different friction coefficients and outer ring thickness is shown in Fig. 12. In Fig. 12(a), the deformation size of the middle part of the outer ring is about 0.61mm, and the two ends are about 1.84mm. With the outer ring thickness increases to 4mm, the deformation size of the middle part is about 0.92mm, and the two ends are about 1.84mm (Fig. c). It shows that increasing the outer ring thickness will reduce the bending deformation degree of the outer ring and increase the diameter shrinkage of the outer ring. With the friction coefficient increases from 0.2 to 0.5, the deformation size of the middle part of the outer ring decreases from 0.61mm to 0.57mm (Fig. b). When the thickness is larger (4mm), the friction coefficient increases (Fig. d). The deformation sizes of both ends of the outer ring are 1.68mm and 1.96mm respectively, which reduces the symmetry of both ends. The reason may be that the larger friction coefficient enhances the upsetting of the outer ring.

The influence of friction coefficient on forming accuracy and maximum forming pressure under two kinds of outer ring thickness, as shown in Fig. 13. When the thickness of the outer ring is 3mm, the friction coefficient has little effect on the forming accuracy. However, when the thickness of the outer ring increases to 4mm, the forming accuracy decreases. The reason may be that increasing the thickness of the outer ring reduces the bending deformation of the blank, resulting in excessive outer diameter shrinkage, which reduces the forming accuracy. When the outer ring thickness is 4mm, the forming accuracy decreases first and then increases with the friction coefficient. The forming accuracy is the worst when the friction coefficient is 0.3, and the forming accuracy is higher when the friction coefficient is larger. This may be the result of coupling with other forming process parameters, indicating that the friction coefficient does not necessarily have a negative effect on the forming accuracy for the two-step extrusion forming process, This is a difference between this process and other processes[25].

When the outer ring thickness is small (3mm), the maximum forming pressure is positively correlated with the friction coefficient. When the outer ring thickness is large (4mm), the maximum forming pressure first increases significantly with the increase of the friction coefficient, but then decreases slightly after the friction coefficient is 0.3. The reason may be that when the outer ring thickness is large, the bending deformation of titanium alloy decreases and the plastic deformation increases. When the friction coefficient increases to a certain extent, it no longer plays a major role in the forming pressure. Considering that a large friction force will increase the wear of the die and reduce the service life. Therefore, it is necessary to improve the lubrication state between die and blank and reduce the friction coefficient.

Forming Test

According to the results of finite element simulation analysis, the optimized bearing forming parameters were determined: outer diameter 30mm, inner diameter 24.4mm, height 12mm, die angle 70°, forming distance 4.1mm. The forming equipment was TOX punch machine (maximum punching pressure 200kN), and the lubricating medium was graphite grease. Figure 14 shows the outer ring blank, die, and bearing samples after forming.

The bearing section and no load rotational breakaway torque are shown in Fig. 15. It can be seen that the bearing with non-optimized forming process parameters has serious insufficient extrusion defects, and the matching quality of the optimized bearing has been significantly improved. The no load rotational breakaway torque of the non-optimized bearing sample is less than 0.05N·m, and the optimized no-load starting torque is about 0.13 N·m, which meets the requirements of 0.05-0.5N·m in the standard. In the manufacturing process of existing self-lubricating bearings, rolling is generally required to adjust the no load rotational breakaway torque after bearing extrusion[26]. Compared with traditional processing methods, this process can directly prepare self-lubricating plain bearings that meet the requirements of no load rotational breakaway torque standards.

The variation curve of forming pressure with forming distance in the test and simulation is shown in Fig. 16. It can be seen from the figure that the pressure-distance curve of the test and simulation is similar, which proves that the accuracy of the simulation is high. According to the change trend of forming force, the deformation process of the outer ring can be divided into three stages. In the first stage, the forming distance is 0-1.5mm and the forming force is about 60kN. At this stage, the contact part between the outer ring blank and the die will produce large plastic deformation. The dominant forming force is the deformation resistance caused by the plastic deformation of titanium alloy, and the forming force increases rapidly. In the second stage, the forming distance is 1.5-3.5mm, and the forming force is about 60-80kN. In this stage, the plastic deformation of the contact part between the die and the outer ring is reduced, and the outer ring blank mainly produces bending deformation. The bending resistance caused by the bending deformation of titanium alloy is the main factor to form the forming force in this stage. The third stage is that the forming distance is more than 3.5-mm. In this stage, the outer ring has produced large bending deformation. The inner liner of the outer ring contacts the bearing inner ring. The blank of the outer ring is extruded by the die and the bearing inner ring, resulting in large extrusion deformation resistance. This is the main factor of the forming force in this stage, and the forming force rises sharply.

The difference $\triangle R$ between the track radius of each point on the inner surface of the outer ring after forming and the target radius in the test and simulation is shown in Fig. 17.

$$\triangle R = R_i - R_j$$

Where: R_i is the track radius of each point on the inner surface of the outer ring after forming, i = 1,2,,, 20, and R_j is the target radius.

It can be seen from the figure that the track radius of the simulation is similar to that of the test, which proves that the simulation accuracy is good. After forming, the two ends of the outer ring are not symmetrical about the middle, which may be related to the change of the height and size of the outer ring during the two forming processes. It can be improved by adjusting the two forming distance. The track radius of the inner surface of the outer ring is slightly smaller than the ideal radius, which makes the gasket subject to certain extrusion deformation and ensures the no load rotational breakaway torque of the bearing. After the bearing is formed, it also needs to be machined. After machining (2-10mm), the extrusion deformation of the gasket is between 0 and 0.2mm.

Conclusions

In order to prepare titanium alloy outer ring self-lubricating spherical plain bearing, a two-step extrusion forming process was proposed, the finite element simulation model of the forming process was established, the influence of forming process parameters on the forming results was analyzed, and the forming test of titanium alloy outer ring self-lubricating spherical plain bearing was carried out. The main conclusions are as follows:

1)The new process can realize the forming of titanium alloy outer ring self-lubricating spherical plain bearing. The factors affecting the forming results mainly include: die structure, outer ring blank size, and lubrication conditions. The influence on the forming accuracy is forming distance > outer ring blank thickness > friction coefficient > inner surface diameter > die angle, The influence on forming pressure is as follows: blank thickness of outer ring > die angle > forming distance > friction coefficient > inner surface diameter. Taking GE15DE1TK titanium alloy self-lubricating spherical plain bearing as an example, its forming parameter is determined as outer diameter 30mm, inner diameter 24.4mm, height 12mm, die angle 70°, forming distance 4.1mm.

2)Large forming distance is easy to produce over extrusion defect, while small forming distance is easy to produce insufficient extrusion defect. It needs to be adjusted with other process parameters. The excessive thickness of the outer ring blank will reduce the bending capacity of the blank, produce the effect of upsetting and increase the forming pressure. On the premise of ensuring the machining allowance, the thickness of the outer ring blank should be reduced as much as possible. The large friction coefficient under the new process does not necessarily have a negative impact on the forming accuracy. In order to improve the service life of the die, the lubrication conditions should be improved as much as possible.

3)The forming pressure can be divided into three stages. The new process can control the extrusion amount of the gasket by optimizing the forming process parameters, and can directly prepare the self-lubricating articulated bearing that meets the standard requirements of no load rotational breakaway torque, without adjusting through subsequent processes.

Declarations

Fund

This study was supported by the Ministry of education's industry university cooperation collaborative education project fund. (Grant No. 202102009003)

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Song Zhao: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Visualization, Writing - Original Draft; **Xiao Yang**: Writing - Review & Editing, Methodology, Formal Analysis, Data Curation; **Changxin Liu**: Software, Conceptualization; **Abderrahim Ezzaid**: Writing – Editing, Investigation; **Bingli Fan**: Funding Acquisition, Project Administration; **Annan Sun**: Visualization; Validation; **Heng Wang**: Funding Acquisition, Resources; **Xiaowen Qi**: Funding Acquisition, Conceptualization, Supervision, Writing - Review & Editing, Project Administration

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Figures

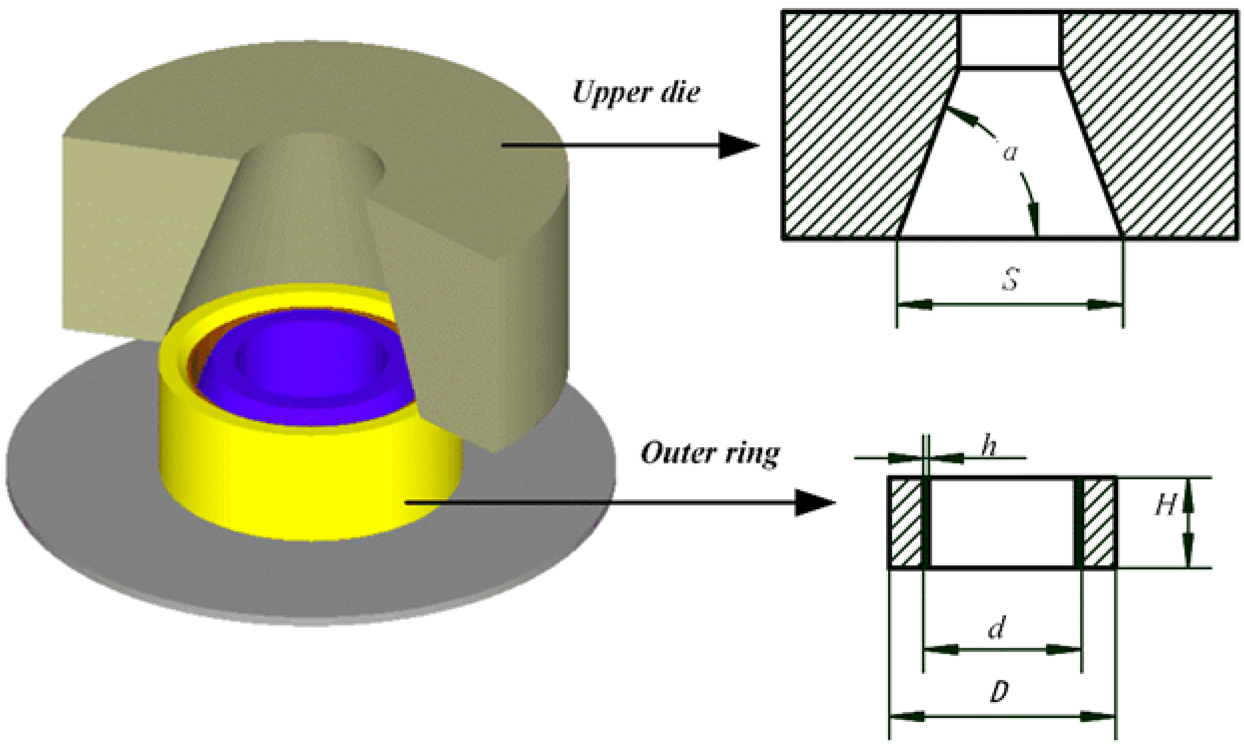

Figure 1

Forming model of self-lubricating spherical plain bearing

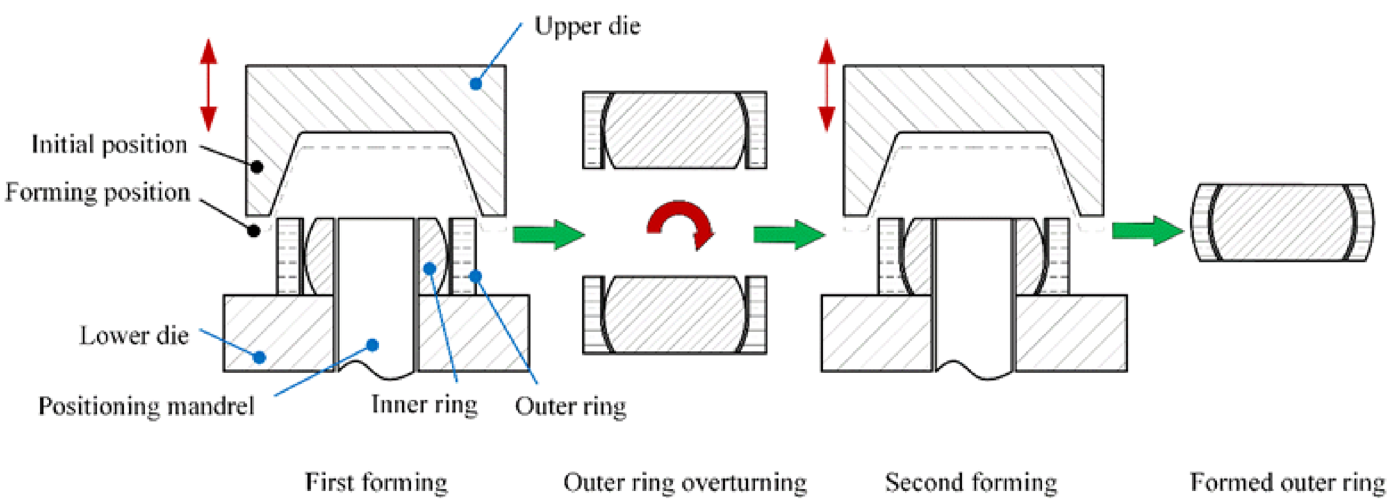

Figure 2

Principle of two-step extrusion forming process

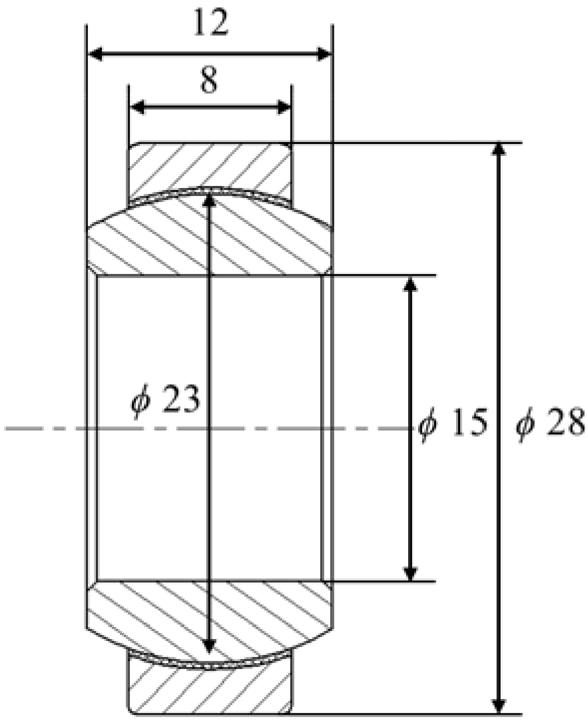

Figure 3

Dimensions of GE15DE1TK self-lubricating plain bearings

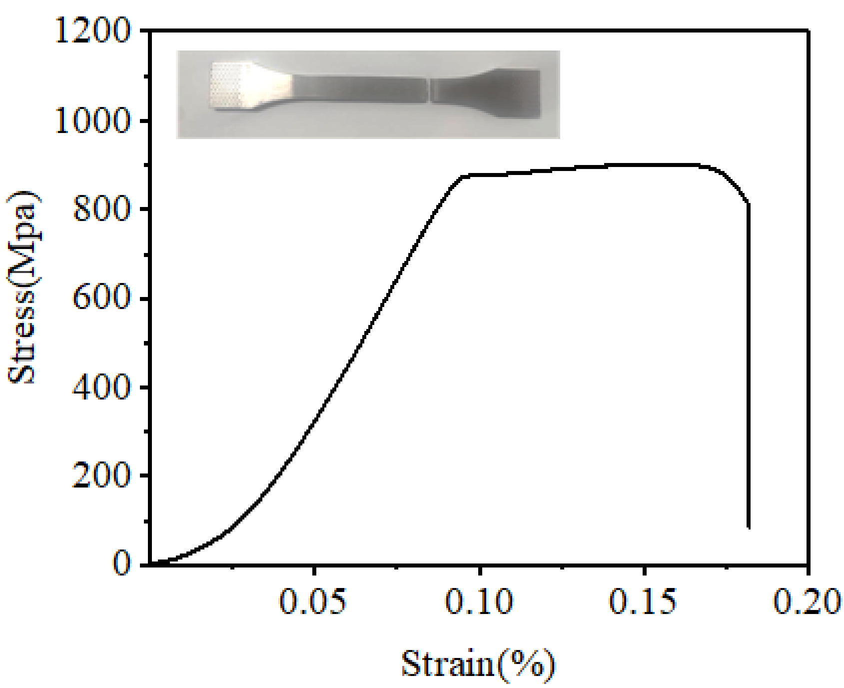

Figure 4

Stress strain curve of TC4

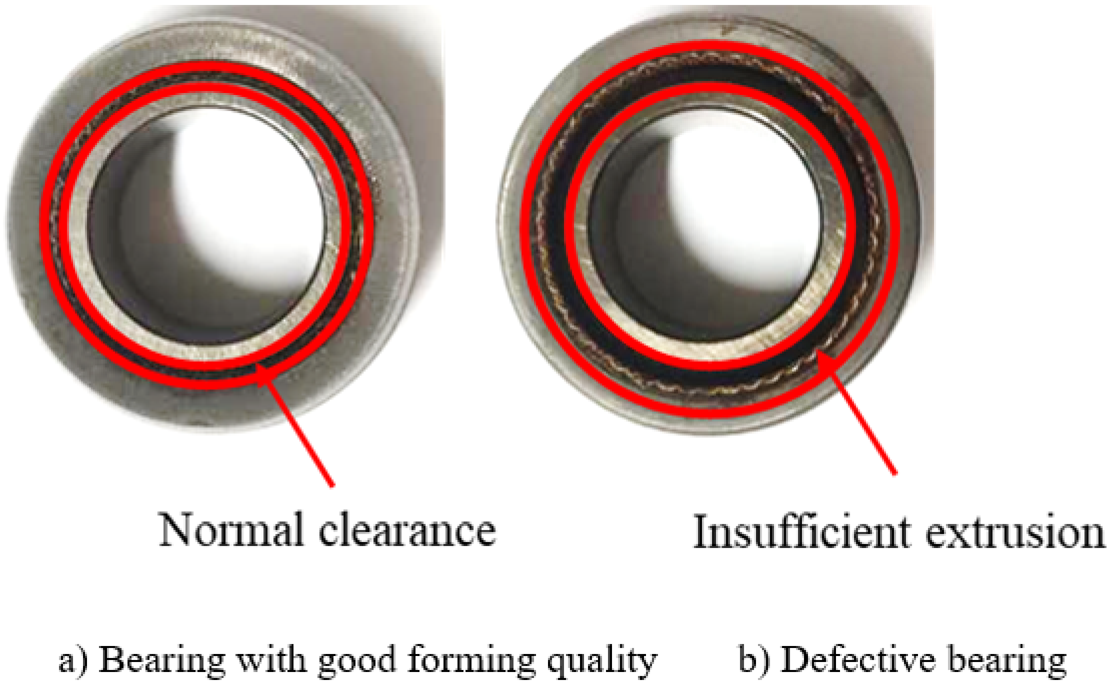

Figure 5

Formed bearings

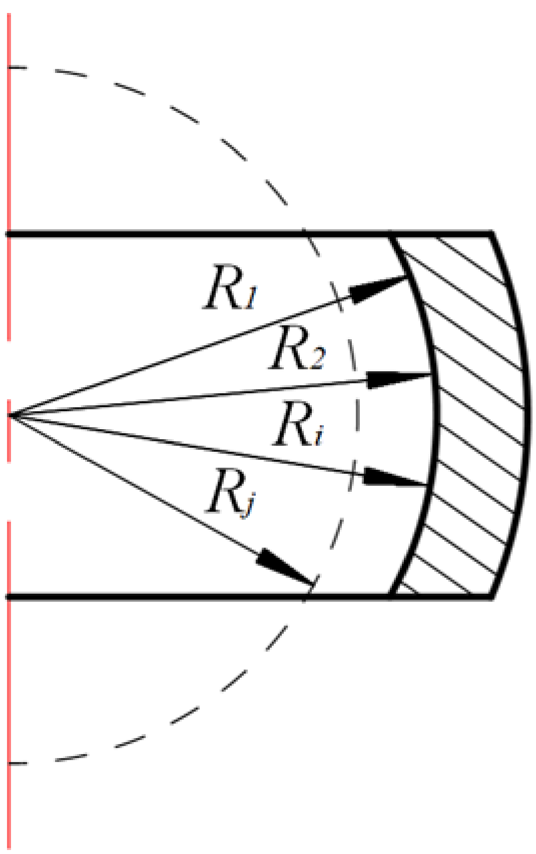

Figure 6

Schematic diagram of track radius of inner surface of outer ring

Figure 7

Influence of various factors(forming distance, die angle, inner diameter, thickness of out ring, friction coefficient) on forming accuracy and maximum forming force range

Figure 8

Lateral displacement of outer ring under different forming distance and die angle

Figure 9

Influence of forming distance on forming accuracy and forming pressure under different die angle

Figure 10

Lateral displacement of outer ring after forming under different outer ring thickness and forming distance

Figure 11

Influence of outer ring thickness on forming accuracy and maximum forming pressure under different forming distance

Figure 12

Lateral displacement of outer ring after forming under different friction coefficient and outer ring thickness

Figure 13

Influence of friction coefficient on forming accuracy and maximum forming pressure under different outer ring thickness

Figure 14

Outer ring blank, forming die and formed bearing

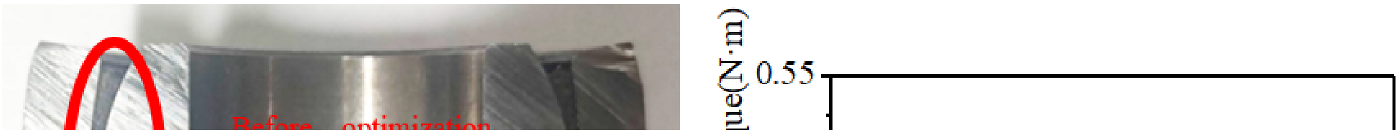

Figure 15

The bearing section and no load rotational breakaway torque

Figure 16

The variation curve of forming pressure with forming distance in the test and simulation

Figure 17

The difference between the track radius of each point on the inner surface and the target radius in the test and simulation