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Original article

Spherical contact mechanical analysis of roller cone drill bits journal bearing

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ABSTRACT

Fang contact model is introduced to analyze stress of the spherical fixed ring journal bearing. Developed calculation programs in the MATLAB software which are utilized to calculate the contact characteristics of roller cone drill bits spherical fixed ring journal bearing. In addition, effects of external load, radius clearance values, and material parameter on the mechanics performance were investigated. The results show that the value of external load has a direct pronounced effect on the contact characteristics of journal bearing. There is a significant positive correlation between contact pressure and external load, radius clearance value, and the Young's modulus of material. However, there is an evident negative correlation between contact radius of journal bearing and radius clearance value, and the Young's modulus of material. The smaller radius clearance value of journal bearing is, the more centralized contact region will be, so the corresponding contact pressure will be higher. From the perspective of reducing friction and wear, we need select the materials which have high strength and good toughness. Not only might this can improve the wear resistance, it also effectively decreases the contact pressure. In this case, we can prolong the service life of roller cone drill bits journal bearing.

1. Introduction

The problem that life of roller cone drill bits journal bearing doesn't match the cemented carbides is restricting the life of roller cone drill bits. At present, the bearing that extensively used for roller cone drill bits is journal bearing. The downhole complicated conditions and uneven bearing load will further cause the journal bearing failure [1–3]. In order to prolong the journal bearing's life, so many experts and scholars have gotten a lot of academic research results through their shared efforts. Chen proposed a kind of variable curvature of roller cone drill bits journal bearing [4]. This new kind of structural design can improve the bearing friction properties of the friction pairs. Huang et al. analyzed the failure journal bearing of roller cone drill bits, which shows that the load in the bearing is excessively and extremely uneven. Higher temperature will reduce the metal material surface strength and abrasion resistance. Moreover, the uneven shaking of roller cone drill bits in the course of working will bring the bearing uneven stress [5,6,7]. So the optimization and improvement of roller cone drill bits journal bearing are particularly significant.

The principal failure modes of journal bearing are adhesive wear and abrasive wear [8–13]. Wear and tear will damage the surface quality of the material. Ability of abrasion resistance determines the journal bearing's life of roller cone drill bits. In order to reduce friction and wear, we need to enlarge the contact region and enhance the wear resistance. He et al. proposed a kind of spherical fixed ring journal of roller cone drill bits (ZL201320364808.9) [14]. This is a newly-designed idea. There is a spherical fixed ring in the big journal bearing which is made of cemented carbide after carburizing and quenching, and being assembled in the big journal through thermal expansion method.

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At the same time, the inner hole of roller cone drill bits is being designed to be spherical accordingly (Fig. 1).

2. The load analysis of the bearing

Roller cone drill bits journal bearing has the following main parts: the big radial journal bearing, the smaller one, and two plane thrust bearing. The dimension of roller cone drill bits journal bearing is limited. Roller cone drill bits journal bearing is a special bearing, which is in a slow and overload condition. Zhang et al.'s experiment confirmed that the load in the $II^{\#}$ roller cone drill bits journal bearing is the largest, and the journal bearing's wearing rate is the biggest [15,16]. The failure of bearing speeds up the overall failure of roller cone drill bits. In terms of many experts and scholars' academic research achievements, the distributed forces in the journal bearing can be simplified as a concentrated force (Fig. 2). To calculate those forces, we get the formulas as follows [5,15,16]:

$$\begin{cases} F_{r1} = 9800 \times \alpha_{123} \times 0.9 \times \sin\beta \times \omega = 8820\omega\alpha_{123}\sin\beta \\ F_{r2} = 9800 \times \alpha_{123} \times 0.1 \times \sin\beta \times \omega = 980\omega\alpha_{123}\sin\beta \\ F_a = 9800 \times \alpha_{123} \times \cos\beta \times \omega = 9800\omega\alpha_{123}\cos\beta \end{cases} \tag{1}$$

The friction torque along the circumferential of the bearing:

$$M_n = F_{r1} \times f \times R_{j1} \times F_{r2} \times f \times R_{j2} \tag{2}$$

where F_{r1} is the radial force in the big journal; F_{r2} is the radial force in the smaller journal; F_a is the force in the thrust bearing; ω is the external load in the roller cone drill bits journal bearing; β is the angle degree between bearing axis and the roller cone drill bits journal bearing axis; R_{j1} and R_{j2} are the radii of the big journal and the smaller one, respectively; f is the friction coefficient between the bearing friction pairs.

3. Hertz contact model

On the basis of photoelastic mechanical, Hertz proposed the two objects contact pressure distribution and deformation through researching the half space contact elastomer. It is necessary for Hertz contact model to make the following assumptions:

(1) The materials are homogeneous and isotropic;
(2) Contact surface is considered to be smooth, and the lubricating medium is ignored;
(3) Elastic deformation occurs only in contact region, conformed to the Hooke's law, and do not exceed the elastic limit of material;
(4) The size of contact region is so small compared with the two contact bodies.

In terms of the above assumptions, spherical fixed ring journal bearing approximately satisfies Hertz contact model. Contact region is a point without external load. Contact region turns into a circular region under the external load. And contact bodies only

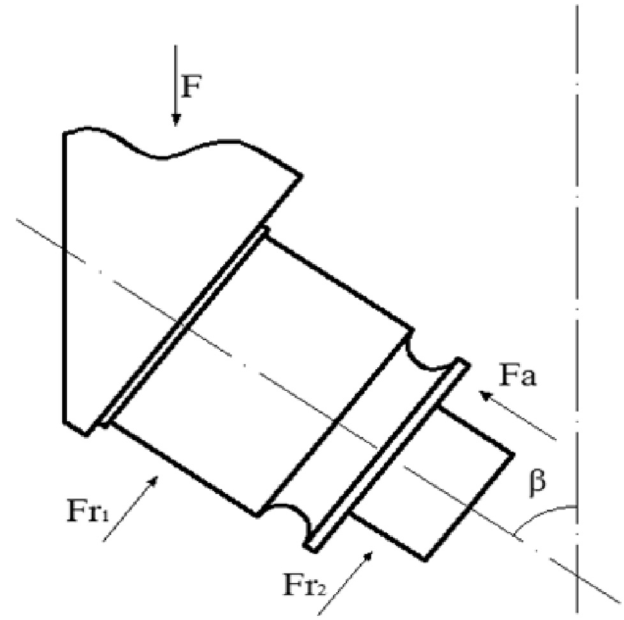
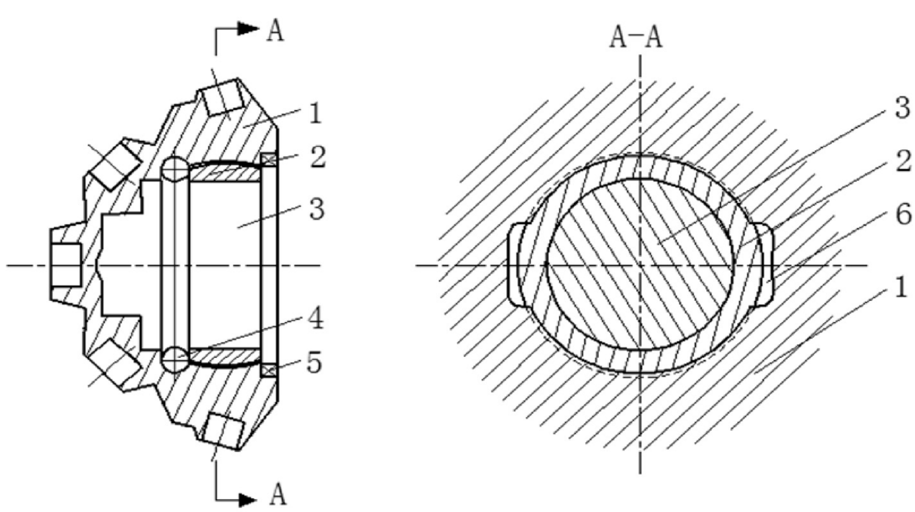


Fig. 2. Schematic diagram of the journal bearing forces.



1-roller cone, 2-spherical fixed ring, 3-journal, 4-steel ball, 5-seal ring, 6-assembling groove

Fig. 1. Structures of spherical fixed ring bearing of roller cone drill bits.

appear elastic deformation. The formulas can be expressed as follows [17]:

$$a = \left[\frac{3\pi F(k_1 + k_2)R_1R_2}{4(R_2 - R_1)}\right]^{\frac{1}{3}} \tag{3}$$

$$P_0 = \frac{3F}{2\pi a^2} = \frac{3F}{2\pi}\left[\frac{4(R_2 - R_1)}{3\pi F(k_1 + k_2)R_1R_2}\right]^{\frac{2}{3}} \tag{4}$$

$$\delta = \left[\frac{9\pi^2F^2(k_1 + k_2)^2(R_2 - R_1)}{16R_1R_2}\right]^{\frac{1}{3}} \tag{5}$$

where $k_1 = ((1 - \nu_1^2)/\pi E_1)$, $k_2 = ((1 - \nu_2^2)/\pi E_2)$; E_1, ν_1 are Young's modulus and Poisson's ratio of spherical fixed ring; E_2, ν_2 are Young's modulus and Poisson ratio of roller cone; a is radius of the contact region boundary profile; P_0 is maximum contact pressure; F is external load; R_1, R_2 are outer radius of spherical fixed ring and inner hole radius of roller cone; δ is approach of distant points in the two bodies.

4. Fang contact model

Fang contact model is based on many experts and scholars' academic research results [18–22]. It is a semi-analytical and semi-numerical model for non-conformal and conformal contact of a spherical surface. And it is not confined to the elastic half-space. Suppose that the contact region of spherical fixed ring is smaller than the overall size, the formulas can be expressed as follows [22]:

$$\begin{cases} P(r) = P_0\left(1 - \dfrac{r^2}{a^2}\right)^n \\ P_0 = (n+1)\dfrac{F}{\pi a^2} \\ \delta = 4(k_1 + k_2)BP_0a \\ a = \left[\dfrac{4BR_1R_2(k_1 + k_2)}{\pi(g\Delta R + C)}(n + 0.5)(n + 1)\right]^{\frac{1}{3}} \\ n = 0.5 - 0.24\exp\left[-15.08\left(1 - \dfrac{a}{R_2}\right)\right] \\ B = \dfrac{\sqrt{\pi}\Gamma(n+1)}{2\Gamma(1.5+n)}, \quad C = \dfrac{3.8304B(k_1 + k_2)F}{\pi R_2} \\ g(a) = \dfrac{2}{\pi} + \left(\dfrac{a}{R_2}\right)^2 \end{cases} \tag{6}$$

where P_0 is maximum contact pressure; a is radius of the contact region boundary profile; r is projected horizontal distance between the point on the surface and the symmetry axis; n is contact pressure distribution exponent; F is normal concentrated force; k_1, k_2 are parameters relate to Young's modulus and Poisson's ratios of the two isotropic materials; B is function determined by n and gamma function; δ is approach of distant points in the two bodies; Γ is gamma function; $R_i = (1,2)$ is outer and inner spherical radii; g, C are coefficient functions; R_1, R_2 are radii of the inner and outer spheres, respectively; $\Delta R = R_2 - R_1$. The Fang contact model sketch of complete spherical as is shown in Fig. 3. The calculation flow of Fang model as is shown in Fig. 4.

As shown in Fig. 1, outer diameter of spherical fixed ring $SR_1 = 31.32$ mm, inner diameter $R_3 = 25.025$ mm, axial length $L = 18$ mm, outer diameter of roller cone $SR_2 = 31.37$ mm. The material of spherical fixed ring is 18CrNiMo7-6 whose Young's modulus is 206 GPa, and Poisson's ratio is 0.3. The material of rock bit is 20Ni4Mo whose Young's modulus is 206 GPa, and Poisson's ratio is 0.285. In order to facilitate the analysis, in this paper, we ignore edge effects caused by the two bodies contact with each other, and tooth claw axis with inner-hole axis is not concentric during the working process. Friction coefficient is ignored; moreover, only vertical load is applied to the big journal.

5. Results and analysis

In the process of designing and manufacturing bearing, contact pressure calculation is of vital importance for wearing resistance and contact strength. Fang contact model and Hertz contact model are adopted to calculate the contact parameters of spherical fixed ring roller cone drill bits journal bearing. As shown in Fig. 5(a), with the increasing of the value of ΔR or external load, the contact pressure is sharply growing. Numerical simulations with radius clearance range from 0.05 to 1 mm were investigated. The contact pressure which is calculated by Fang contact model and Hertz contact model increases by 652.07% and by 505.81% respectively. Fig. 5(b) shows the relationship of external load with radius clearance is inversely proportional. The calculation results decrease by 63.54% and 59.35% respectively.

Define the relative error of contact pressure is ε_P, and relative error of the radius of the contact region boundary profile is ε_a:

$$\varepsilon_P = \frac{|P_{0.F} - P_{0.H}|}{P_{0.H}} \times 100\% \tag{7}$$

$$\varepsilon_a = \frac{|a_F - a_H|}{a_H} \times 100\% \tag{8}$$

where $P_{0.F}$, $P_{0.H}$ are maximum contact pressures; a_F, a_H are radii of the contact region boundary profile; F denotes results coming from Fang contact model; H denotes results coming from Hertz contact model.

Fig. 6 shows the relative errors between the Fang contact model and Hertz contact model. When ΔR = 1 mm and $F = 39.45$ kN, the contact pressure relative error is 4.36%, and the contact radius relative error is 2.06%. When $\Delta R = 0.05$ mm and $F = 39.45$ kN, contact pressure relative errors reach up to 29.55%, and the contact radius relative error is 12.15%. Those evidently show that the Hertz model is not appropriate for small clearance or large contact region which is consistent with the conclusion of Ref. [22]. Therefore, Fang contact model will be used to analyze the spherical fixed ring journal bearing of roller cone drill bits in this paper.

5.1. External load effect

In the process of mining the crude oil and natural gas, different weights on bit will be applied to journal bearing of roller cone drill bits according to different geological conditions. Therefore, when the weight on bit is changed, the external load on the journal bearing will also change. So it is necessary to research the influences of different external loads on the contact parameters of journal bearing (Table 1).

By keeping the parameters constant except external load, we will study the influences of the external load on the bearing contact parameters. As shown in Table 2, the bearing contact parameters under different external loads. With the increasing of the external load, the contact pressure and contact radius increase at the same time. When the radius clearance is 0.1 mm and

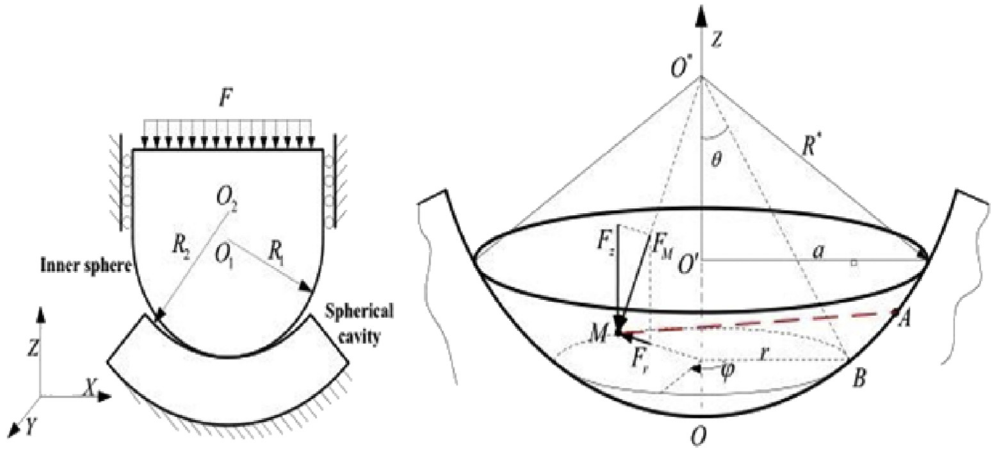


Fig. 3. Sketch of complete spherical in original Fang model.

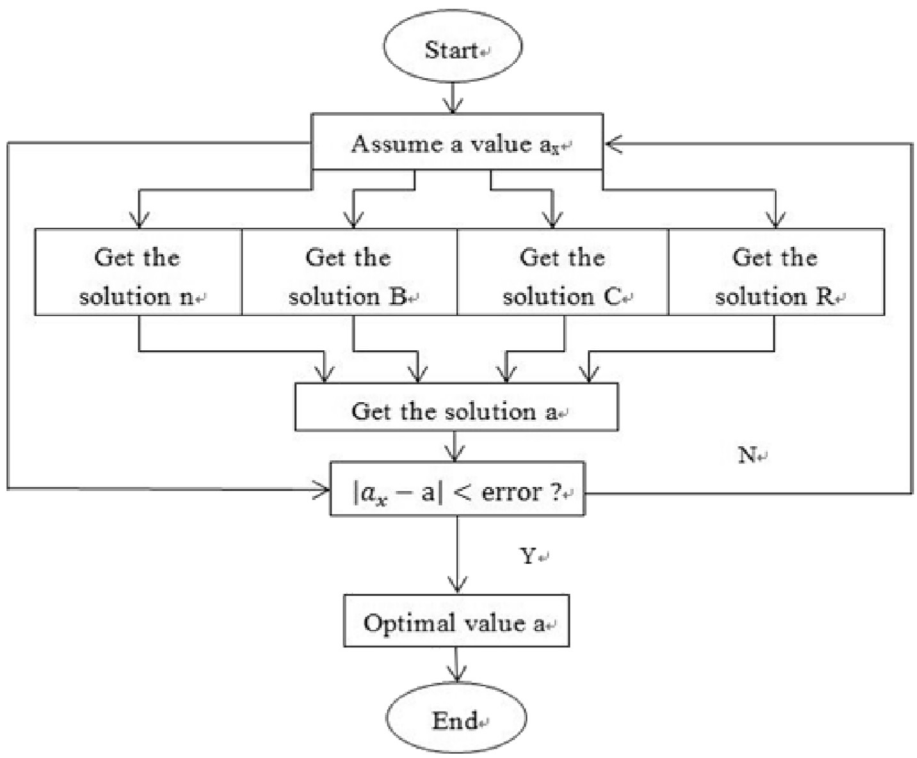


Fig. 4. Calculation flow diagrams of Fang model.

external load is from 8.45 kN to 39.45 kN, the contact pressure peak increases by 85.98%, yet the contact radius only increases by 58.46%. The value difference of them is about 27%. Those show that the contact pressure is more sensitive to the external load.

5.2. Radius clearance effect

The radius clearance between the spherical fixed ring and roller cone has a significant influence on working performance. If the radius clearance is too big, eccentric wear of spherical fixed ring is more serious. On the other hand, if the radius clearance is small, the lubrication effect will be not good. In this paper, we keep the value of spherical radius R_1 constant to analyze the influence of radius clearance on the contact pressure through changing the spherical radius of the roller cone inner hole. Fig. 6 shows the curves of contact parameters under different radius clearance values.

Fig. 7(a) shows the contact pressure of spherical fixed ring under different radius clearance values. Fig. 7(b) shows that with the increasing of the external load, the contact radius increases rapidly. No matter how big or small the clearance is, as long as the external load increases, contact radius increases, too. When the radius clearance value is small enough, the contact area is bigger, and the corresponding peak of contact pressure is smaller after deformation. Fig. 8 shows the contact pressure of spherical fixed ring under different external conditions. If the contact pressure peak is small enough, the friction and wear of the contact region is not serious. In order to improve the reliability of the product, we must strictly control the radius clearance value during the designing and manufacturing processes of journal bearing.

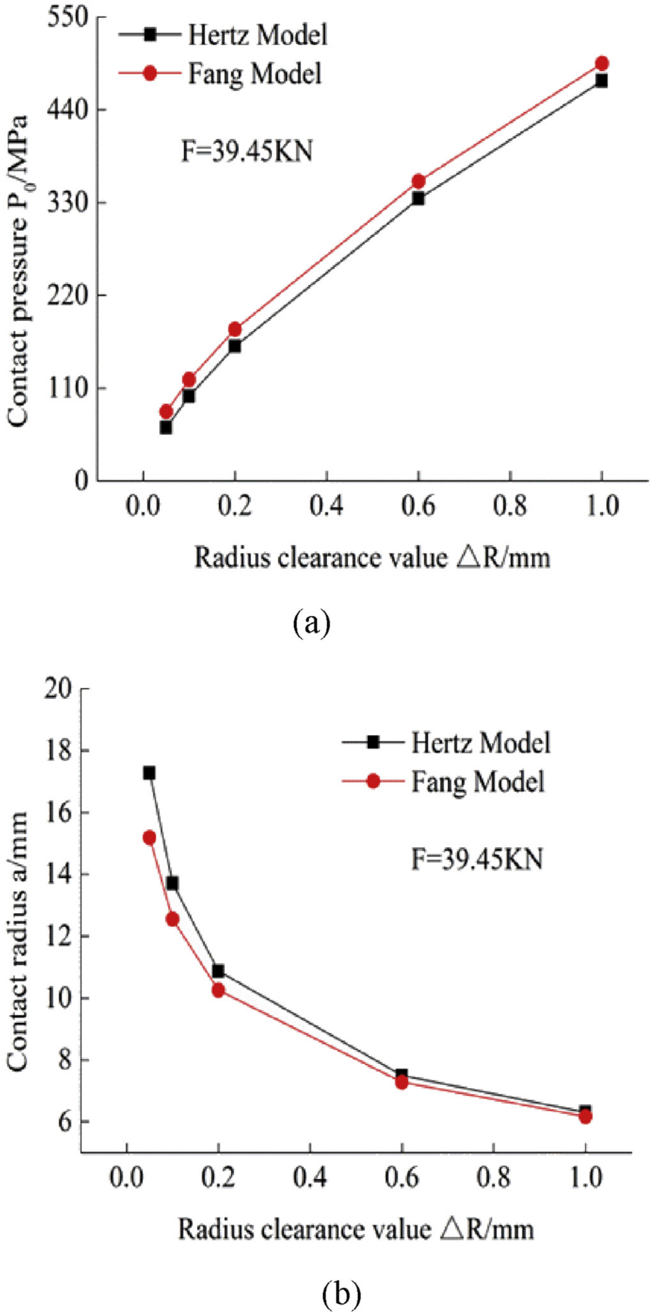


Fig. 5. The change tendency of radius clearance with contact pressure (or contact radius) under the Fang model and the Hertz model.

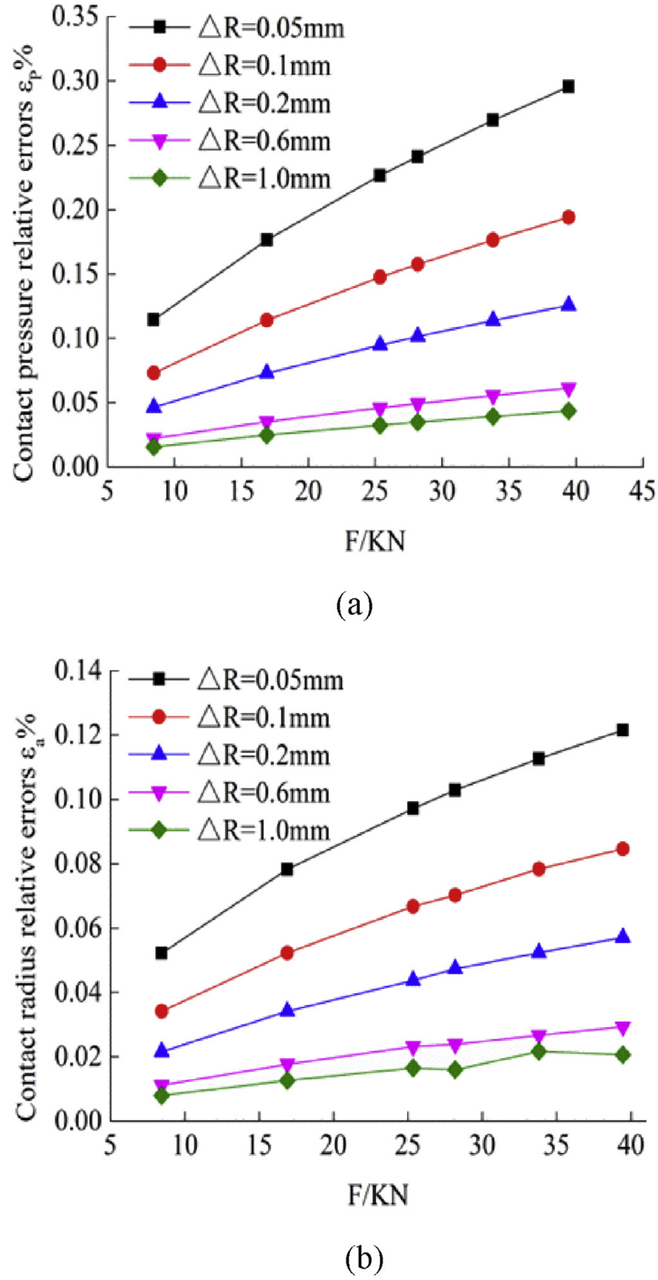


Fig. 6. Relative error between the Hertz model and Fang model.

5.3. Materials effect

Through failure analysis and experimental studying of the roller cone drill bits journal bearing, we can learn that the principal failure types are adhesive wear and abrasive wear. Whatever the material is, it has a big influence on the life of journal bearing. So we must choose the proper bearing friction pair materials. Common bearing materials are shown in Table 3. Keep the bearing dimension and external load constant while discussing materials impact on contact parameters. The calculating results of contact parameters are shown in Fig. 7.

Fig. 9 shows the contact pressure distribution under different bearing friction pair materials. Contact pressure has the characteristics of symmetrical distribution, and the contact pressure peak is in the center of contact region. As shown in Table 4, the different bearing friction pair materials have different contact parameters. When the beryllium bronze is used as bearing materials, the contact pressure peak is small. Yet when the cemented carbide is used as bearing materials, the contact

Table 1
The relationship of weight on the roller cone drill bits and the radial load in the big journal.

No.	1	2	3	4	5	6
WOB/t	3	6	9	10	12	14
Radial load in the big journal/kN	8.45	16.9	25.36	28.18	33.81	39.45

Table 2
Contact parameters of the journal bearing under different external loads.

No.	External load *F*/kN	Contact pressure peak P_0/MPa	Radius of contact region *a*/mm
1	8.45	64.35	7.92
2	16.9	84.17	9.79
3	25.36	99.26	11.04
4	28.18	103.7	11.39
5	33.81	112	12
6	39.45	119.68	12.55

Note: radius clearance $\Delta R = 0.1$ mm.

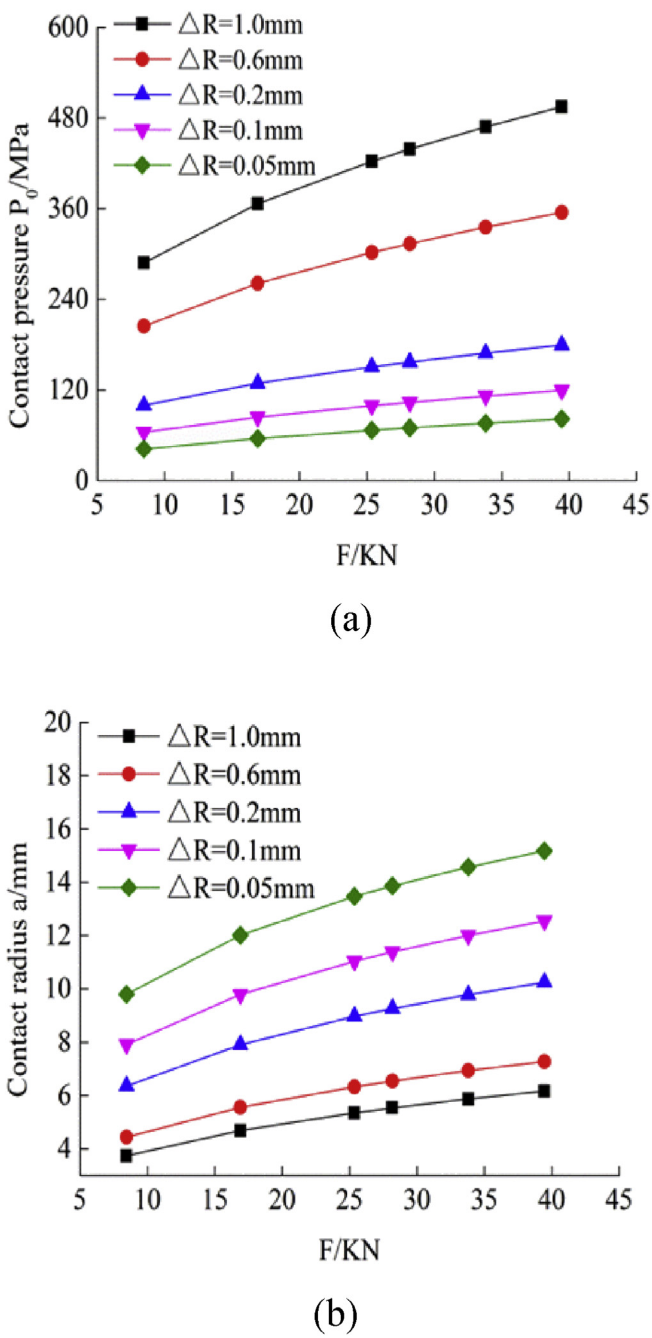


Fig. 7. The change tendency of external load with contact radius under different radius clearance values.

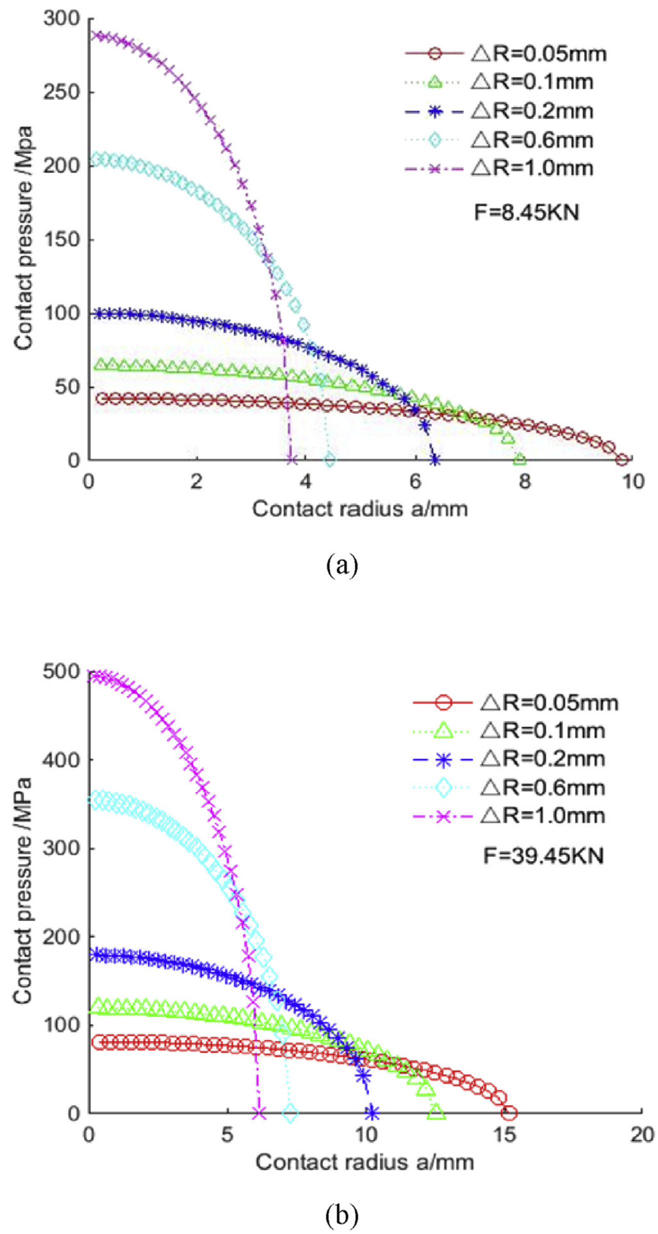


Fig. 8. Contact pressure distributions under different radius clearance values.

Table 3
Friction pair materials of journal bearing.

No.	Spherical fixed ring			Roller cone		
	Materials	Young's modulus *E*/GPa	Poisson's ratios *ν*	Materials	Young's modulus *E*/GPa	Poisson's ratios *ν*
1	Beryllium bronze	130	0.35	Beryllium bronze	130	0.35
2	Alloy steel	206	0.30	Alloy steel	206	0.30
3	Beryllium bronze	130	0.35	Alloy steel	206	0.30
4	Cemented carbide	535	0.25	Cemented carbide	535	0.25

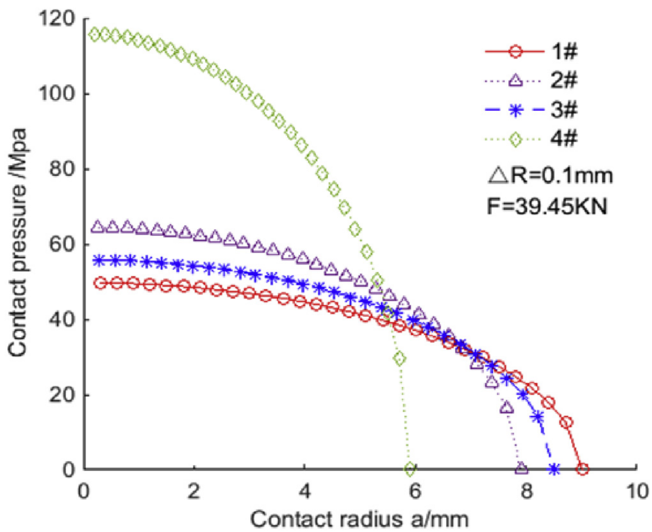


Fig. 9. Contact pressure distributions under different friction pair materials.

Table 4
Contact parameters of the journal bearing under different friction pair materials.

No.	Contact pressure peak P_0/MPa	Radius of contact region a/mm
1	49.69	9.01
2	64.54	7.91
3	55.82	8.50
4	115.85	5.90

Note: radius clearance value $\Delta R = 0.1$ mm, external load $F = 39.45$ kN.

pressure peak is so big. In other words, the smaller Young's modulus of bearing materials can reduce the contact pressure peak, yet it will also enlarge the bearing deformation and impact the bearing lubrication effect. So we choose the materials which have the characteristic of being flexible inside despite its hard show which can improve wear resistance, which, can reduce the contact pressure effectively as well as prolong the life of bearing.

6. Conclusions

(1) From the perspective of contact mechanics, the contact pressure distribution of spherical fixed ring roller cone drill bits journal bearing is discussed.
(2) The Fang contact model and Hertz contact model show that the spherical fixed ring is effective to reduce the stress concentration. The external load, radius clearance value and the Young's modulus of material have a significant influence on the work performance of roller cone drill bits.
(3) Different friction pair materials have different contact properties. From the perspective of reducing friction and wear, we should select the materials which have the characteristic of being flexible inside despite its hard show. In this case, not only can we improve the wear resistance, but also can effectively reduce the contact pressure peak. So we can prolong the life of bearing, improve the drilling efficiency and reduce the drilling costs.

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