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TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of Roller Cone Bit Bearing Based on Mechanics and Microstructure

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Abstract The service life of the roller cone bit mainly depends on the bearing. In order to figure out the cause and mechanism of bearing failure, mechanics and microstructure analysis of failed roller cone bit bearings are carried out. The results show that the bearing failure mainly includes wear (including adhesive wear and abrasive wear), plastic deformation, crack, fracture and burn. The main reasons for these failures are: abrasives and temperature rise caused by the cuttings and the lubrication failure; stress concentration, shock and vibration due to uneven load and fit clearance; and initial cracks or deficiencies because of unqualified surface treatment. In addition, investigation indicates that seal failure can bring degeneration on the bearing surface, which reduces the hardness of the bearing surface and thus accelerates the failure of the bearing.

Keywords Roller cone bit bearing · Failure analysis · Mechanics · Microstructure · Seal

Introduction

The roller cone bit is the main rock breaking tool in oil and gas drilling engineering, whose performance and service life directly affect the quality of the well, the drilling efficiency and the cost. With oil and gas exploration developing toward deeper and harder formations, drilling difficulties increase significantly, which puts forward higher requirements for the roller cone bit. Since the bearing cannot meet the requirements of strength toughness, temperature stability and low friction, 80% of roller cone bit failures are due to the early failure of the bearing system [1–3]. Therefore, it is necessary and urgent to conduct failure analysis of the roller cone bearing and to improve the service life of the roller cone bit.

Recent studies of the bearing mainly focused on dynamics, simulation analysis, material, processing and structural optimization. Bilgesu and Liu et al. analyzed the dynamics and vibration of the roller cone bit and bearing under the vibration load and established the prediction model of the bit life [4, 5]. Numerical methods for analyzing the contact pressure and optimizing of the cone bearing were presented by Marshek and He. Their research results were applied to the design of the cone bit bearing, making the contact pressure distribution of the roller bit bearing more reasonable [6, 7]. Hu et al. [8] carried out research on the processing and material of the bearing to improve the bearing wear resistance and impact resistance. Pearce and Antonescu et al. developed new structures such as floating bushing to make the loads applied on the bearing and cone more uniform [9, 10]. Zahradnik and Gillick, respectively, proposed sleeve and twin seal to improve the bearing reliability and performance [11, 12]. Halliburton Energy Services also invented optimized bearing structures for roller cone bit [13]. Huang et al. [14] provided a brief introduction about the bearing failure and proposed surface strengthening technology to improve the performance of the bearing. However, systematic failure analysis of the bearing from mechanics and microstructure perspective is still relatively lacking. Failure analysis of the bearing is the basis for improvement and application of the cone bit.

It is one of the urgent problems to be solved in oil–gas drilling engineering field to figure out the failure of the

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roller cone bit bearing and prolong its service life. In this paper, the failure modes of the cone bit bearing are classified based on mechanics and microstructure. Each failure mode is analyzed from macro- and microperspectives. Finally, impacts of the seal failure are discussed. This study will provide the theory and reference for the application and development of roller cone bit bearing.

Structure and Mechanics Analysis

As shown in Fig. 1a, the cone bit has three cones and three claws. There are four bearings between the claw and the cone, as Fig. 1b illustrates, the large radial bearing (purple), the small radial bearing (green), the thrust bearing (red), and the ball bearing (yellow).

During drilling process, the large journal is subjected to most radial load and circumferential friction load; the small journal mainly stabilizes the cone and withstands a small amount of radial load and circumferential friction load; the thrust surface is subjected to axial load and circumferential friction load when the cone is rotating; and the ball bearing withstands a small amount of axial load. The large journal and the small journal are subjected to very small axial loads which can be negligible. If these distributed loads are simplified as concentrated forces, we can obtain such forces as demonstrated in Fig. 2: the radial force applying on the large journal (F_{r1}), the radial force applying on the small journal (F_{r2}), the axial force applying on the thrust bearing (F_a), and the friction torque along the bearing circumference (M_n). These forces can be calculated as follows [15, 16]:

$$F_{r1} = 9800 \times \alpha \times 0.9 \times \sin\beta \times F_z = 8820\alpha F_z \sin\beta$$
$$F_{r2} = 9800 \times \alpha \times 0.1 \times \sin\beta \times F_z = 980\alpha F_z \sin\beta$$
$$F_a = 9800 \times \alpha \times \cos\beta \times F_z = 9800\alpha F_z \cos\beta$$
$$M_n = F_{r1} \times f \times R_1 + F_{r2} \times f \times R_2$$

where β is the angle between the bearing axis and the roller cone bit axis, α is the load distribution coefficient, F_z is the external load applying on the roller cone bit, f is the friction coefficient, R_1 is the radius of the large journal, and R_2 is the radius of the small journal.

The three cones of the roller cone bit are not completely symmetrical, and the arrangements of the teeth are not identical, so the loads applied on the bearing are uneven. The working conditions of the cone bit in the bottom hole are very complex. The bearing suffers axial vibration load, torsional vibration load and lateral vibration load. These loads are random impact loads, and as the depth of the well increases, the loads also increase. Stress concentration generally appears on the large journal and roller bearings journal, due to the fit clearance, the uneven loads and the bearing structure.

The Main Failure Modes of the Roller Cone Bit Bearing

We dissected roller cone bits which were out of service. Based on mechanics and microstructure analysis, the failure of the cone bit bearings is classified into five modes.

Wear

Bearing wear includes adhesive wear and abrasive wear, accounting for 60% of the bearing failure. Adhesive wear is the main mode of bearing wear and is sometimes accompanied by abrasive wear.

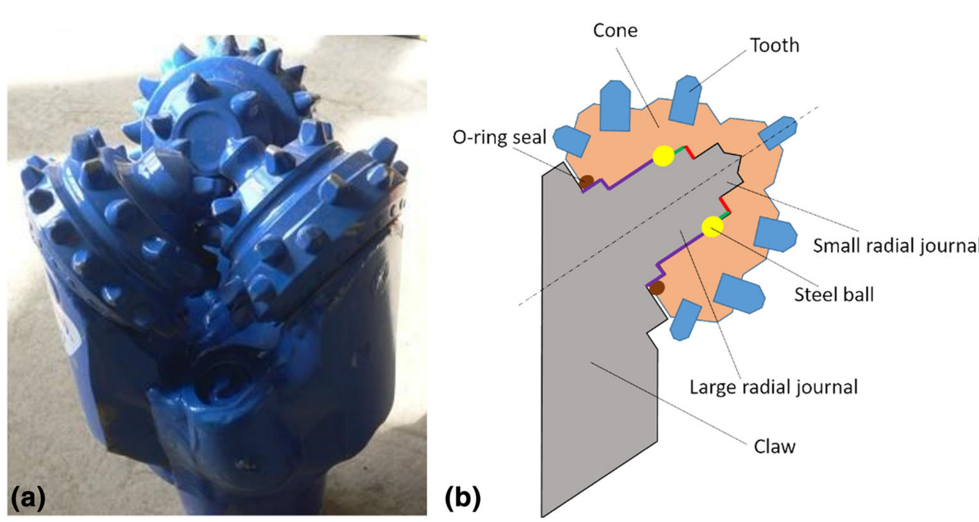

Fig. 1 The roller cone bit and the bearing (**a**) roller cone bit (**b**) schematic plot of the bearing

Adhesive Wear

As Fig. 3a shows, the adhesive wear mostly appears in the large journal of the bearing. As Fig. 3b illustrates, on the surface of a bearing with adhesive wear, there are obvious signs of strain, abrasion and some scratches. The main reason for the adhesive wear is that, with the increase in temperature and the lack of lubrication, the microregion of the bearing surface suffers degeneration softening, resulting in local welding. When the relative motion of the friction surfaces occurs, the bond points undergo deformation, fracture and material transfer under shear stress. When the bond points break, some of the fractures will fall off from the metal surface and become debris because of the friction torque M_n. Some fractures still attach to the journal to form a microscopic rough surface, and some slide on the surface.

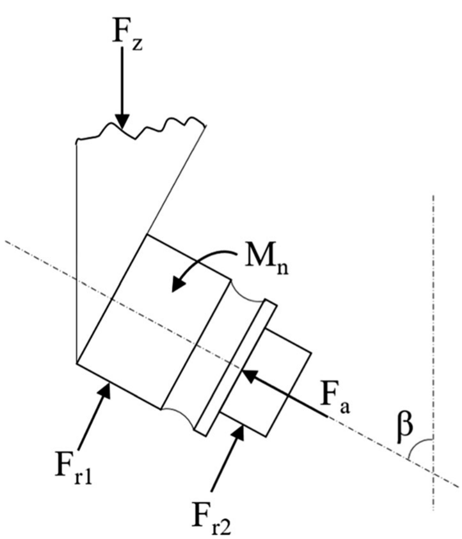

Fig. 2 Forces applied on the bearing

Abrasive Wear

Abrasive wear mainly occurs on the large journal and thrust bearing surface under the action of load F_{r1} and F_a. Specific morphology of the abrasive wear: (1) there are wide scratches along the circumference (Fig. 4a), (2) these scratches are long, parallel and in different depths as shown in Fig. 4b. Abrasive wear is mainly due to cuttings and fluid entering the bearing system to produce abrasive wear after the seal has failed. Besides, the debris generated in adhesive wear can also become abrasives to cause abrasive wear. With more abrasives and higher temperatures, the abrasive wear will be more severe.

Plastic Deformation

As shown in Fig. 5a, b and c, the plastic deformation is located in the root and load region of the large journal and the slide of the ball bearing. Figure 5a illustrates that there are two long and deep furrows at the root of the bearing. At the load (F_{r1}) region of the large journal (Fig. 5b), there are many pits of different sizes, and the depth of the pit is up to 0.16 mm. As Fig. 5c demonstrates, in the slide of the ball bearing, there is an arc protrusion produced by squeezing of the F_a. Figure 5d, e and f shows the microstructures of the plastic deformation. Microstructures indicate that furrows and fragmentations are generated by excessive stress concentration and repeated rolling compaction. Due to stress concentration, high temperature and lack of lubrication, the bearing surface suffers degeneration softening and serious plastic deformation like the pits and the fragmentations. The pits generated at the root of the bearing are because of the fit clearance between the bearing and the cone. Such fit clearance can cause serious vibration and large force concentration at the root. Some material cannot bear the load and peel off from the body, as shown in Fig. 5f. In plot (e), the materials peel off and form area A,

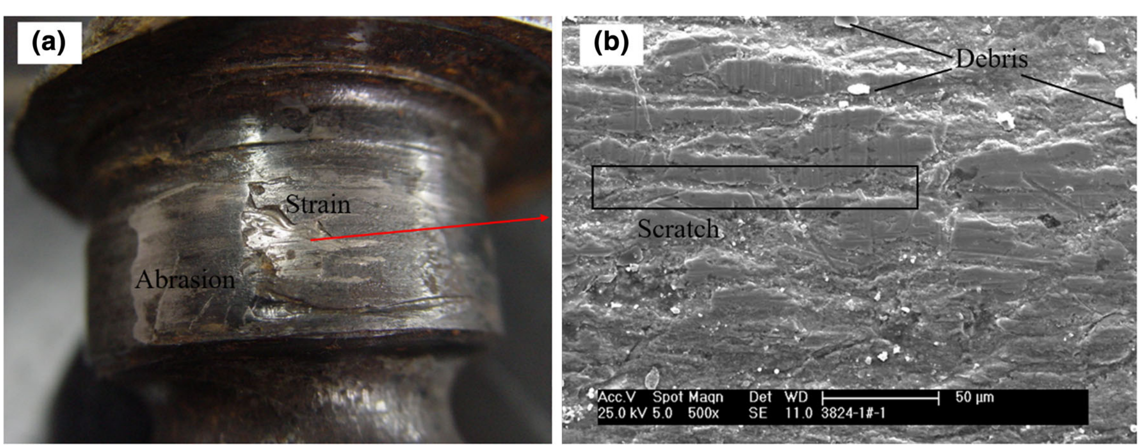

Fig. 3 Adhesive wear of the bearing (**a**) macro-morphology (**b**) enlarged view

and area B waits for its turn. The materials peel off layer by layer. The arc protrusion in the ball bearing is mainly due to the partial grinding and squeezing when the bearings deviate from the track with rocking and vibrating of the bearing.

Crack

Figure 6a shows six obvious cracks on the surface of the large journal of the bearing, and such cracks are also appear on the surfaces of the small journal and the thrust bearing as Fig. 6b and c illustrates, respectively. These cracks are long and regular, and there is no crack source or extended tip. Moreover, cracks not only appear on the long-working bearings (Fig. 6a and b), but also on the bearing being processed (Fig. 6c). Plots (e) and (f) are the cracks of the plots (c) and (d), respectively. The cracks evenly distribute on the surface of the bearing. The width and length of the cracks are basically the same, and the depth of the cracks is shallow. Since cracks are present on both used and unused bearings, it can be inferred that the crack should be produced during processing rather than after the bearing has worked. The surface treatment of the bearing is first coating and then quenching. The thermal expansion coefficients of the bulk material and coating are different, which can cause cracks because of tensile stress after quenching. Wear and repeated rolling lead to the propagation and extension of the crack, causing the

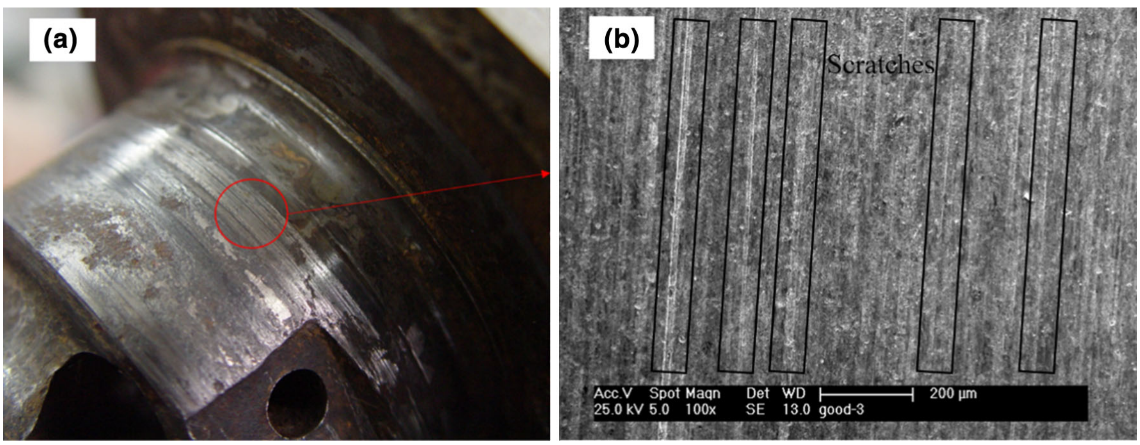

Fig. 4 Abrasive wear of the bearing (**a**) macro-morphology (**b**) enlarged view

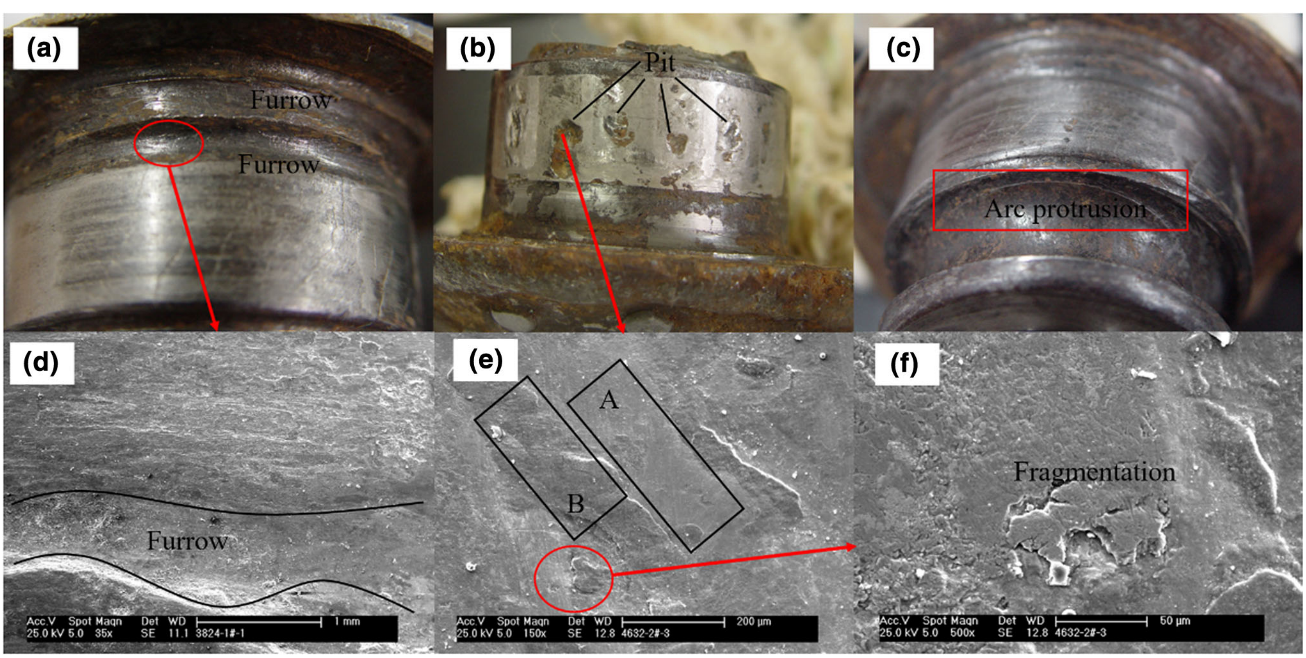

Fig. 5 Plastic deformation of the bearing

surfacing material to fall off, finally forming wide and shallow cracks.

Fracture

Fracture is a serious failure mode and probably leads to well accidents. From Fig. 7a and b, we can see that the bearing fracture is located at the minimum diameter of the ball bearing journal. Half of the bearing and the ball are stuck in the cone surrounded by compacted cuttings and mud. Figure 7c and d illustrates that the fracture surface is not very sharp, and there are many ripples, which indicate that the bearing fracture is a typical fatigue damage. The bearing suffers heavy load F_{r2} and acts like a cantilever beam, and the ball bearing journal is the weakest part of the bearing. The cone shakes as the fit clearance exits between the bearing and the cone, resulting in stress concentration and alternating load. Under the action of such fatigue load, the fracture gradually converges from the edge to the central region, leading to fracture of the bearing.

Burn

Burn only accounts for a small proportion of bearing failure and mainly appears on the large journal as the black blotch shown in Fig. 8. When the well depth reaches several kilometers, the temperature of the bottom hole is often above 100 °C [17]. Besides, the heat generated by the friction is hard to release as the bearing system is an enclosed space, so that the temperature of the sliding bearing friction pairs is very high. Once the viscosity of the lubricant reduces, or even the lubricant modifies, the bearing will work at very high temperature, and the surface material will generate such traces of burns.

Discussion

Failure analysis of the bearing indicates that temperature, lubrication and external mediums (drilling cuttings and fluid) play a very important role in the failure modes and service life of the bearing. The bearing seal greatly affects the temperature, lubrication and external mediums. The bearing seal separates the bearing and external mediums to prevent the drilling cuttings and fluid entering the bearing, and to maintain lubrication and heat dissipation for the bearing. The seal has a great influence on the performance of the bearing, as shown in Fig. 9a, a bearing with a good seal and Fig. 9b, a bearing with the seal failure. So it is important to discuss the effects of the seal on bearing failure.

The microstructures and microhardness of bearings with good seal or failed seal were analyzed. The original hardness of the bearing is generally within the range of HV700–800. Results show that the microstructure of the bearing with the good seal is tempered martensite as shown in Fig. 10a, and the microhardness is still at HV700–800. Microstructure and microhardness analysis demonstrates that the working temperature of the bearing with the good seal was below 200 °C, so the materials maintained the original microstructure and hardness. However, the tempered troostites appear in some microstructures of the

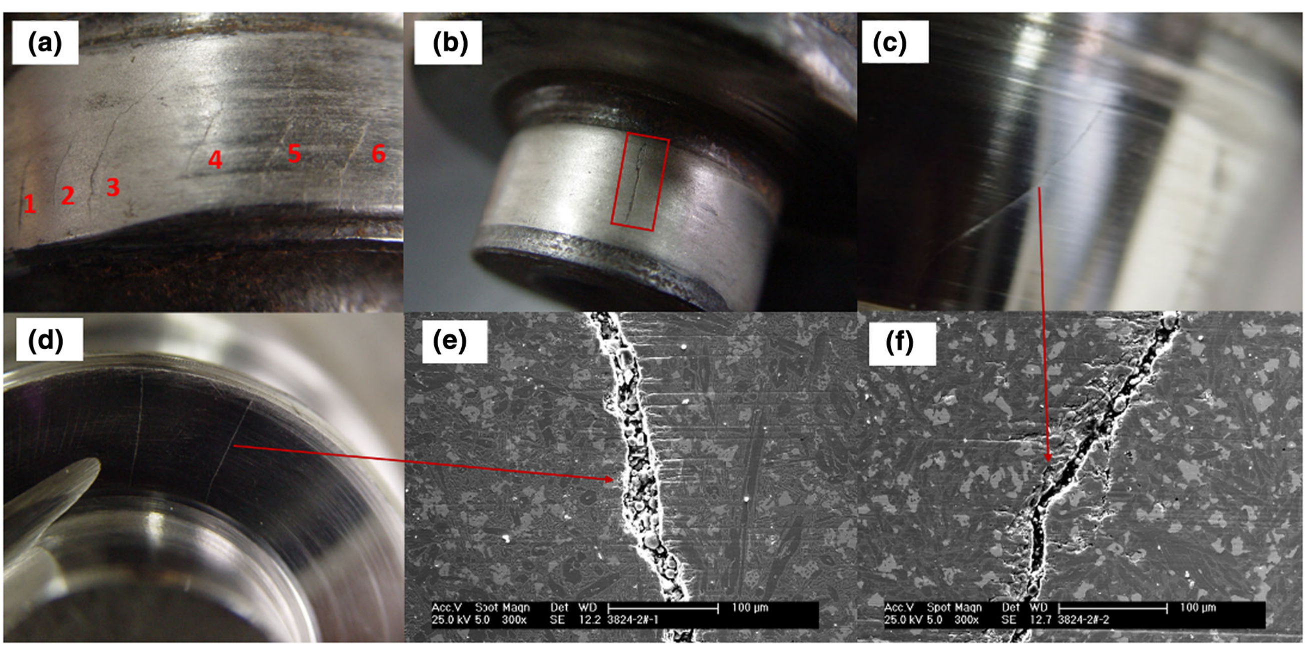

Fig. 6 Cracks on the surface of the bearing

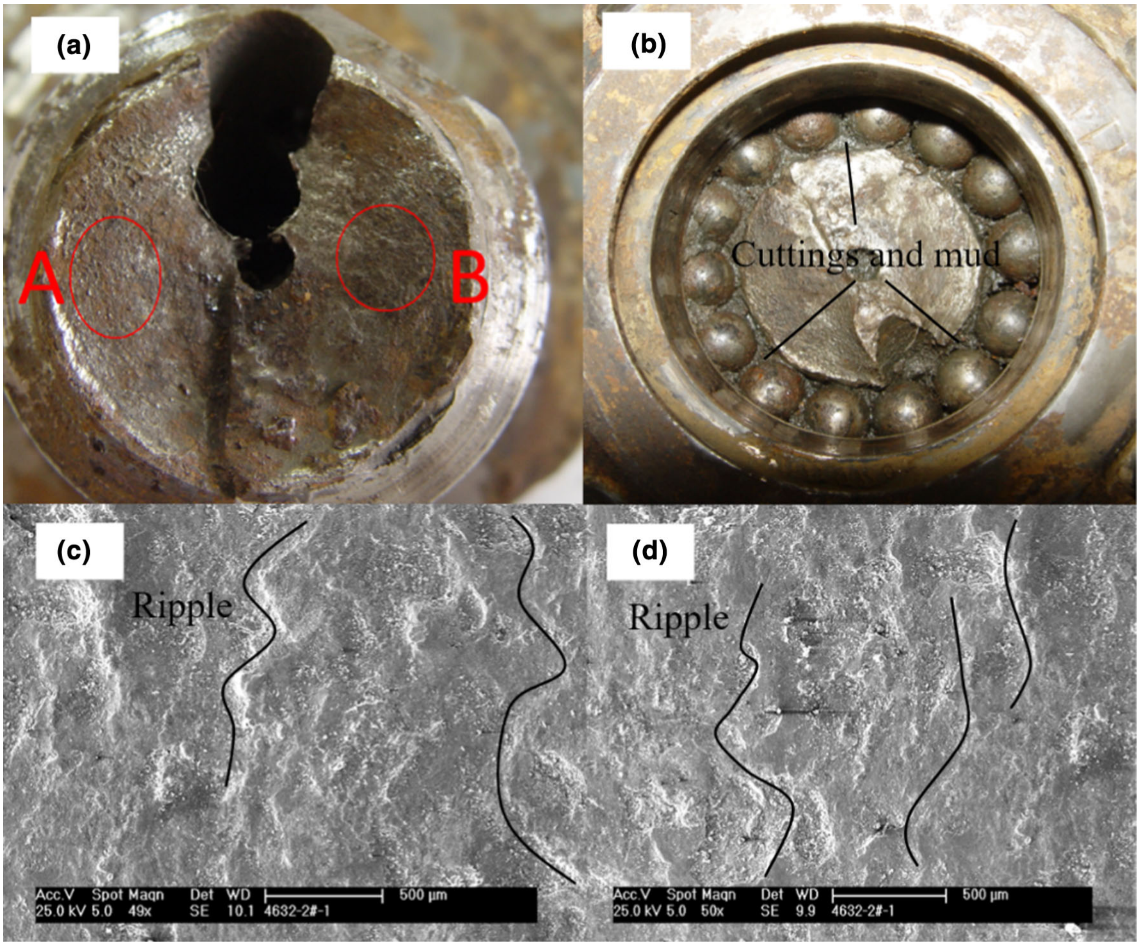

Fig. 7 Fracture of the roller cone bit bearing (**a**) bearing fracture (connecting with claw) (**b**) bearing fracture (inside the cone) (**c**) magnified plot in circle A (**d**) magnified plot in circle B

Fig. 8 Burn of the bearing

bearing with the failed seal, as shown in Fig. 10b, which indicate that the microhardness reduced to HV500–700. The tempered troostites are generally produced at the temperature of 300–500 °C. So local temperature of the bearing with failed seal exceeded 300 °C, and the tempered troostite generated in the metal organization of the bearing, which reduced the hardness of the surface structure, and thus accelerated the bearing failure.

Not all failed bearings generated tempered martensite, but all good-sealed bearings maintained the original material and hardness. Seal failure brings abrasive and lubrication failure, leading to serious wear and temperature rise. The service life of the bearing depends to a large extent on the service life of the seal.

The main reasons for bearing failures are as follows: abrasives and temperature rise caused by cuttings and lubrication failure; stress concentration, shock and vibration due to uneven load and fit clearance, and initial cracks

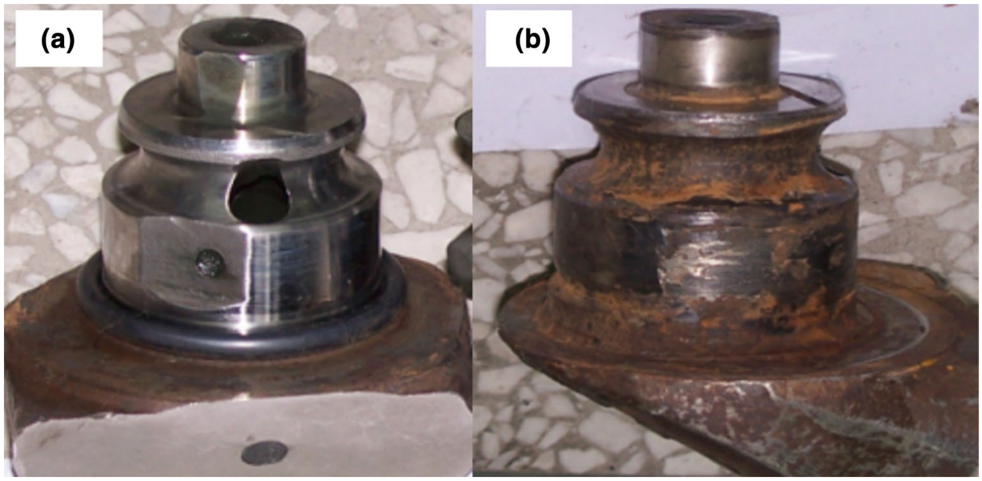

Fig. 9 Bearing (**a**) with good seal (**b**) with seal failure

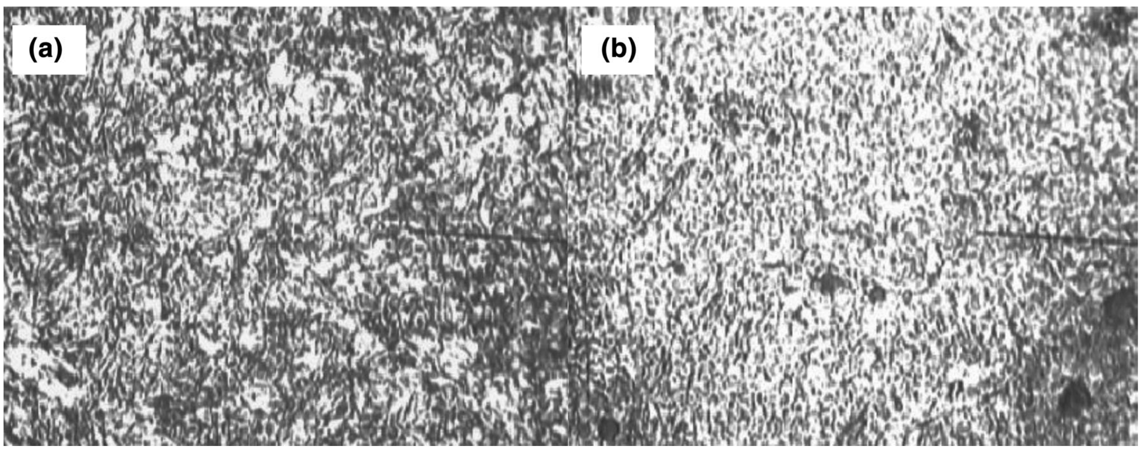

Fig. 10 Microstructures of (**a**) bearing with good seal and (**b**) bearing with failed seal

or deficiencies because of unqualified surface treatment. It is difficult to change the stress concentration, shock and vibration, as they are determined by the bit structure and the rock formation. Coating development requires new materials and a large number of new experiments, and fracture represents a minority of bearing failure. So the benefit of coating or processing improvement is very limited. Since seal is an important factor affecting the bearing life and there are a lot of existing seal technologies we can learn from, so improvement of seal is an effective way to prolong the service life of the bearing.

Conclusions

The main failure modes of the roller cone bit bearing include wear, plastic deformation, crack, fracture and burn, among which the wear is the majority. The main causes of failure include: (1) abrasives and temperature rise due to the cuttings entering the bearing subsystem and lubrication failure when the seal is poor or failed; (2) uneven load and fit clearance result in stress concentration, shock and vibration; (3) unqualified surface treatment leads to initial cracks or deficiencies. Improvement of the bearing should focus on the seal, the bearing structure and the processing three aspects, and improvement of seal is the most effective and reasonable way to prolong the service life of the bearing.

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