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Reduced Friction and Excellent Anti-Wear Performance of QBe2 Beryllium Bronze against 38CrMoAlA Steel in Pneumatic Downhole Motor under Grease Lubrication

Chenfan Liang [1], Jing Zhou [1,2,*], Yu Wang [1] and Zhijian Peng [3,*]

[1] Key Laboratory on Deep GeoDrilling Technology of the Ministry of Natural Resources, School of Engineering and Technology, China University of Geosciences, Beijing 100083, China
[2] China National Administration of Coal Geology, Beijing 100038, China
[3] School of Science, China University of Geosciences, Beijing 100083, China
* Correspondence: zhoukeke2003@163.com (J.Z.); pengzhijian@cugb.edu.cn (Z.P.); Tel.: +86-10-82321954 (J.Z.); +86-10-82320255(Z.P.)

Abstract: To improve the service life of the newly designed pneumatic downhole motor, a kind of commercially available lithium complex grease was used to help avoid the rapid wear-induced failure of the dynamic seal of pneumatic downhole tools in operation. The investigation on the tribological behaviors of QBe2 beryllium bronze and 38CrMoAlA steel tribo-pairs in pneumatic downhole motor revealed that under lubrication, the instantaneous friction coefficient and wear volume became very low, showing greatly reduced friction and excellent anti-wear performance. Compared with the case without lubrication, the adhesive wear mechanism and ploughing effect of the tribo-pairs were significantly alleviated. Moreover, Cu and Fe were oxidized to form composite oxides between the frictional surface, further improving the lubrication effect between the QBe2 beryllium bronze and 38CrMoAlA steel. Notably, the test could be operated stably for more than 150 h under lubrication, fully reaching the requirement of pneumatic downhole tools under actual drilling conditions. These results provide a solid support for the practical application of the reported pneumatic downhole tools.

Keywords: friction; lubrication; QBe2 beryllium bronze; 38CrMoAlA steel; wear mechanism

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1. Introduction

Gas drilling is a unique method for directional drilling driven by air or gas as the drilling fluid, which does not contaminate the cores, cutting or formations. However, without the lubrication and cooling effects of mud, it will result in rapid and excessive wear-induced failure of the rotor and stator of the dynamic seal in the downhole pneumatic drilling motor [1]. Therefore, introducing air and gas drilling into the directional drilling market requires the development of a more reliable downhole pneumatic drilling motor.

In our previous work, a new type of pneumatic downhole motor was designed (see Figure 1), and the contact load and surface roughness of the stator were optimized for the steel–copper hard-soft tribo-pairs in the pneumatic motor [2,3]. In this pneumatic downhole motor, four copper rods were used as the transition components to separate the stator and rotor to convert the steel–steel friction into steel–copper friction, thus effectively reducing the wear between stator and rotor. However, copper alloy as the transition part has some shortcomings that cannot be ignored in practical application. Specifically, copper is easily scratched and transferred to the surface of steel because the former has a relatively low hardness. Thus, although the new type of pneumatic downhole motor is designed to reduce the wear of the stator and rotor, the copper rods are used only as a replacement. As a matter of fact, extending the life of the copper rods can also reduce the number of drilling trips and improve the efficiency of drilling. Hence, it is of great significance to explore a suitable way to further reduce the wear of the copper rods to prolong the life of the pneumatic downhole tool.

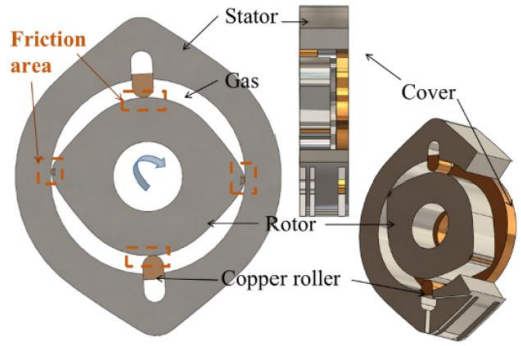


Figure 1. Schematic diagram of the designed pneumatic downhole motor with a steel–copper seal.

As is well known, adding a sufficient amount of lubricant is an efficient way to reduce the wear between tribo-pairs. At present, various liquid oils are the most widely used lubricants. For example, Liu et al. evaluated the tribological performance of a steel/steel (SAE52100) contact under the lubrication of a room-temperature ionic liquid of alkylimidazolium tetrafluoroborate by an Optimol SRV oscillating friction and wear tester in air and a CZM vacuum friction tester in low vacuum with a pressure of 1×10^{-3} Pa. Their results indicated that the proposed ionic liquid exhibited excellent friction-reduction and anti-wear performance, both in air and vacuum, which were superior to the conventionally used phosphazene (X-1P) and perfluoropolyether (PFPE). During friction, the ionic liquid forms a surface protective film mainly composed of FeF_2 and B_2O_3, which contributes significantly to the low friction and wear [4]. Jisheng et al. used a conventional wear machine with a rotating pin-on-plate like-on-like configuration to investigate the sliding tribological behavior of 817M40 steel under the action of a formulated commercial gear lubricating oil, revealing that no wear of nickel–chromium–molybdenum steel was observed under full-fluid film-lubricated sliding, and polishing by mild abrasive and mild adhesive wear mechanisms took place under mixed lubrication [5]. Yeong et al. investigated alkylimidazolium tetrafluoroborates as the lubricant in a variety of contacts including steel/steel, steel/aluminum, steel/copper, steel/SiO_2, Si_3N_4/SiO_2, steel/Si (100), steel/sialon ceramics and Si_3N_4/sialon, showing excellent friction reduction, anti-wear performance and high load-carrying capacity. In particular, in the case of steel/copper, a very small friction coefficient of 0.025 was reported when 1-hexyl-3-methylimidazolium tetrafluoroborate was used [6]. In summary, liquid oils played an important role to reduce the friction and wear between the surfaces of tribo-pairs.

However, pneumatic downhole motors generally work in a relatively dry environment, so it is more appropriate to use greases instead of liquid oils for lubrication. Unlike liquid lubricants, lubricating greases have a higher consistency, more possibly displaying a good sealing function [7,8]. As a semi-solid colloidal dispersion system, lubricating greases can maintain their shape and adhere to the surface of metal components in a static state without flowing or slipping off at normal temperature. When the temperature is high or the external force exceeds a certain limit, they can flow like a liquid in order to reduce the friction and wear between the surfaces of tribo-pairs. When the shearing action stops, they can restore a certain consistency. Specifically, grease contains two main components: base oil as a fluid lubricant and thickener for thickening the base oil to a certain consistency [9]. The lubricating function of greases is strongly determined by the base oil and thickener, which could deposit on the worn surface during the friction process, forming a boundary protective film [10]. Therefore, lubricating greases have been also widely applied to many fields owing to their special fluidity and excellent friction-reducing and anti-wear properties.

Moreover, considerable efforts have been made to elucidate the role of greases on the friction-reduction of metallic materials. For example, Wang et al. examined the tribological properties of plasma nitrided bearing steel under the lubrication of borate ester (B-N) additive, indicating that the friction coefficient and wear scar diameter of the nitrided

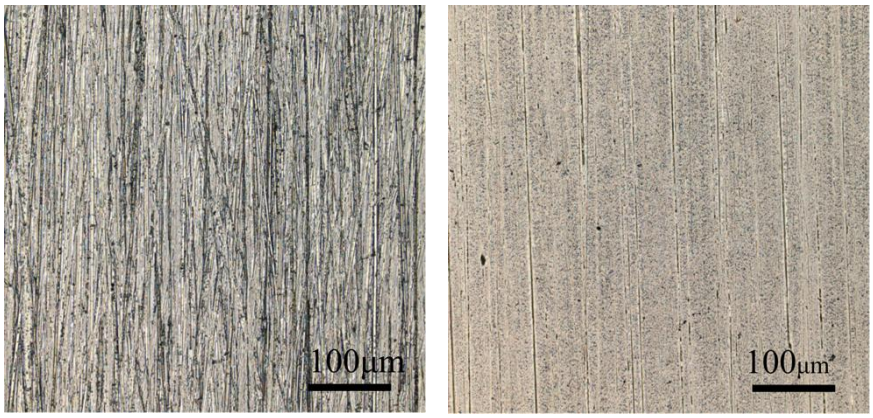
steel could be reduced by 34% and 45%, respectively, when 1.25 wt% of B-N additive was used. The main mechanism of this effect was attributed to the fact that such additive could produce a tribo-film containing a higher content of B-N on the surface of nitrided steel [11]. Blanchet et al. investigated the tribo-pairs of C95500 aluminum bronze blocks against nitrided 4140 steel by block-on-ring method under the lubrication of M28 grease, A33 grease or the 50/50 mixture (in mass) of both greases, revealing that the steady-state wear factor (the slope of wear volume vs. the product of sliding distance and normal load, mm^3/Nm) of the aluminum bronze blocks in the presence of A33 grease was lower than that in the presence of M28 grease under the same loads. Additionally, the wear factor under the lubrication of the 50/50 grease mixture generally acquired an intermediate value compared with those when the neat greases were used separately [12]. In a word, greases can play a critical role in reducing the coefficient of friction and wear volume, and protecting the metal surfaces of the tribo-pair. However, the application of lubricating greases in pneumatic downhole motors has not been reported.

Because an in-depth understanding of the friction-reducing and lubricating effect of greases on the dynamic seals in pneumatic downhole motors is essential for its compelling design and optimization, so in this work the tribo-pairs of QBe2 beryllium bronze as the dynamic part and 38CrMoAlA steel for the static part were investigated by pin-on-plate sliding simulating tests under a lubricating condition. During the investigation, the lubrication effect of lithium complex grease (LCG) on the tribo-pairs of pneumatic downhole motors was examined. The results are discussed in terms of friction process, wear mechanism, and so on. Hopefully, the present work will provide a solid support for the practical application of the reported pneumatic downhole tools.

2. Experimental

2.1. Test Materials and Setup

QBe2 beryllium bronze and 38CrMoAlA steel were still used as the pin and plate, respectively, as in our previous work, in which their compositions and mechanical properties are also listed [2]. The roughness of steel plate used in the experiment is the optimal value of Ra = 0.231 μm and the roughness of QBe2 beryllium bronze pins is Ra = 0.096 μm as in our previous work [3]. The initial surface two-dimensional (2D) optical profilometer of the 38CrMoAlA steel plate and QBe2 beryllium bronze rod are presented in Figure 2.



(**a**) (**b**)

Figure 2. Surface 2D optical profilometers of the used 38CrMoAlA steel plate (**a**) and QBe2 beryllium bronze rod (**b**).

All the wear experiments were performed on a MMW-1 friction testing machine according to the standard of ASTM G99-04 [13], which was produced by Jinan Outuo Test Equipment Co. Ltd. (Jinan City, Shandong Province, China), as in our previous work [2]. The test rig, size of the pins and plates and their contact form are schematically illustrated in Figure 3. The plate is mounted on the lower specimen holder, which is pressed against

the load cell and kept stationary during the tests. The pin is fixed into the upper specimen holder, which is driven by a motor. After an axial load was applied onto the tribo-pair, the upper specimen slid against the lower one at a selected speed. As a result, the pin and plate remain with a flat-to-flat contact. The rotation speed is controlled by an AC motor, and the axial load is applied by the loading part. In addition, LCG, as the most prominent representative of soap-base greases [14], was applied in this experiment.

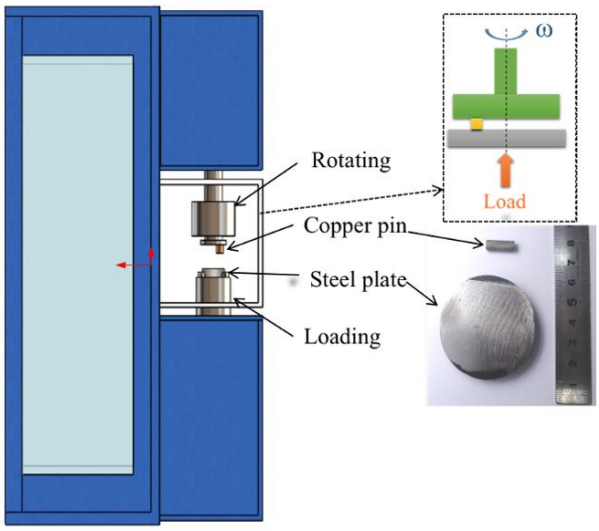


Figure 3. The MMW-1 friction and wear tribometer, and the settlement of specimens.

2.2. Wear Test and Sample Characterization

In practical drilling processes, the contact pressure and sliding speed between the stator and rotor are influenced by many factors, are commonly fall in the range from 0 to 3 MPa and from 1 to 4 m/s, respectively. Considering the specifications of the present pneumatic downhole motor and the simple experimental conditions for the designed dry sliding pin-on-disc tests, the vertical load was set in the range of 15 to 55 N. Meanwhile, a moderate rotation speed at approximately 300 rpm was selected. For the present sliding pin-on-plate test under a lubricating condition, a load of 45 N was applied on the basis of the optimized result of our previous work [2]. According to the actual working conditions, downhole tools should meet the life requirement for running about 150 h. Therefore, the tribological performance of the copper–steel tribo-pairs in pin-on-plate tests with LCG grease was evaluated via MMW-1 friction and wear tribometer under the applied load of 45 N at a speed of 300 r/min for 150 h. During the test, the friction torque signal was input to the recorder through the pressure sensor, and the friction coefficient μ was calculated by the computer linked to the tribometer using the following equation:

$$\mu = \frac{M}{F \times r} \tag{1}$$

where M is the torque (N·mm), F is the normal load (N) and r is the radius of tribo-pairs (mm).

Before characterization, the specimens were cleaned ultrasonically in baths of petroleum ether for 5 min. After drying, the weights of the samples were measured using an ESJ50-5 analytical balance (0.01 mg). Then, the wear volume (V) of the samples was calculated using the following equation:

$$V = \frac{m_1 - m_2}{\rho} \tag{2}$$

where m_1 is the mass of the sample before testing (mg), m_2 is the mass of the sample after testing (mg) and ρ is the apparent density of the samples (g/cm^3).

The specific wear rates (W, mm^3/Nm) of the samples were calculated using the following equation:

$$W = \frac{\Delta W}{L \cdot \rho \cdot F} \quad (3)$$

where ΔW is the weight loss of the sample (mg), L is the sliding distance (m), ρ is the apparent density of the samples (g/cm^3) and F is the normal load (N). In this work, the densities of 38CrMoAlA steel and QBe2 beryllium bronze were measured as 8.7 and 7.85 g/cm^3, respectively.

The morphology of the sample surfaces was examined by 3D white-light interfering profilometer (SLCM, Olympus OLS4000), optical microscope (OM, Olympus SZX7) and scanning electron microscope (SEM, FEI Quanta 200 FEG). The elemental composition of the samples was measured by an X-ray energy dispersive spectrometer (EDX) attached to SEM, and the chemical state of elements on the surfaces was investigated by an X-ray photoelectron spectroscope (XPS, ULVAC-PHI PHI5000 Versaprobe III).

3. Results and Discussion

3.1. Coefficient of Friction and Wear Loss

Figure 4 shows the coefficient of friction between the copper–steel tribo-pair under the lubrication of LCG grease as a function of wear time. As the wear process proceeded, the coefficient of friction increased very slowly, revealing that the proposed tribo-pair operated very stably under the present lubrication conditions. Moreover, under the lubrication of LCG grease, even after 150 h of wear test, the maximum value for the coefficient of friction was 0.062 and the calculated average coefficient of friction during the whole process was 0.039, which is dramatically smaller than the minimum average coefficient of friction (0.197) of the same tribo-pair under the optimal load and stator roughness without lubrication in our previous study [3], indicating that the lubrication of LCG grease greatly reduced the friction and wear of the proposed copper–steel tribo-pair.

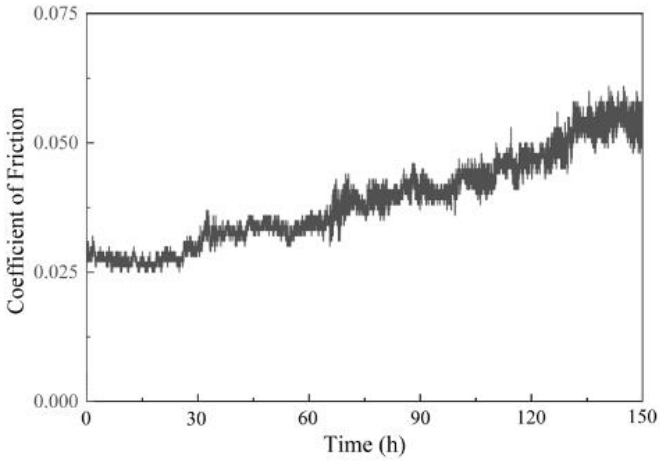


Figure 4. The coefficient of friction between the copper-steel tribo-pair under the lubrication of LCG grease as the function of wear time.

Table 1 shows the wear volume and specific wear rate of the tribo-pairs. The wear volumes of the QBe2 beryllium bronze pin and 38CrMoAlA steel plate were 9×10^{-4} and 4×10^{-4} mm^3, respectively. Their specific wear rates were 7.407×10^{-12} and 3.292×10^{-12} mm^3/Nm, respectively. In our previous work, without lubrication, the material removal (wear loss) mainly occurred on the softer QBe2 beryllium bronze pin of the tribo-pairs, and the QBe2 beryllium bronze pin presented the smallest wear volume of 3.47 mm^3 and the smallest wear rate of 2.42×10^4 mm^3/Nm [3]. Obviously, both values were greatly smaller than those for the tested tribo-pair without lubrication. Moreover, due to the presence of grease, the wear volumes of steel plate and QBe2 beryllium bronze pin were

almost negligibly small. That is to say, the lubrication of LCG grease effectively solved the problem that the wear process mainly had on the softer tribo-pair (copper) in our previous studies [2,3].

Table 1. Wear volume and specific wear rate of the proposed tribo-pair after 150 h of test.

	Wear Volume (mm^3)	Specific Wear Rate (mm^3/Nm)
QBe2 beryllium bronze	9×10^{-4}	7.407×10^{-12}
38CrMoAlA steel	4×10^{-4}	3.292×10^{-12}

3.2. Worn Surface of the Tribo-Pairs

Figure 5 displays typical SEM results on the 38CrMoAlA steel plates. As can be seen in Figure 5a, there were lots of scratches on the initial surface, which were caused by grinding with emery papers before the test. However, the worn surface of steel became smoother and the scratches were greatly flattened after the test (see Figure 5b).

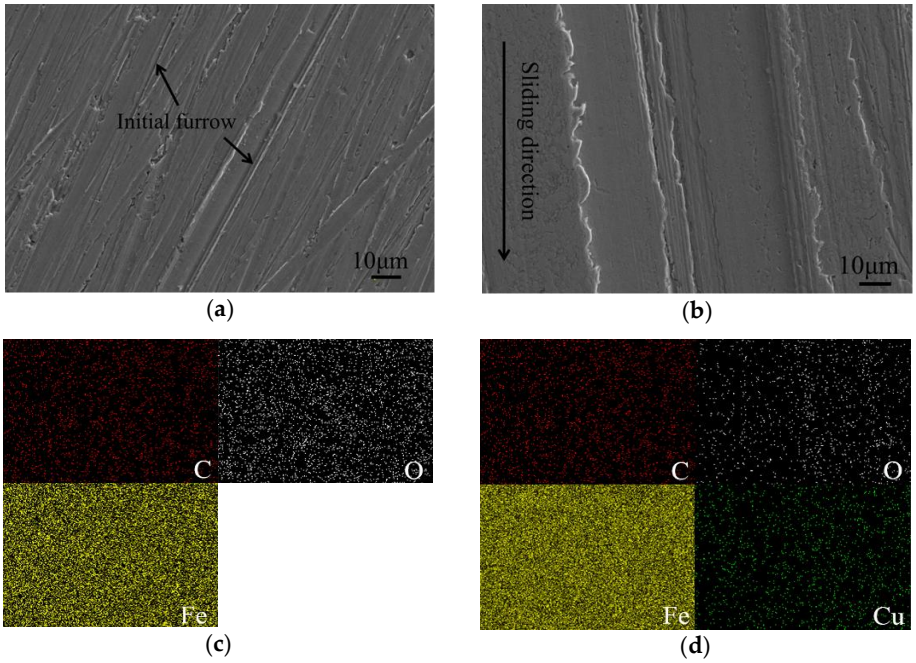


Figure 5. SEM results on the 38CrMoAlA steel plates: (**a**) on the initial surface, (**b**) on the worn surface, (**c**) mapping scanning results on the initial surface and (**d**) mapping scanning results on the worn surface.

When examining the compositions of the samples by EDX analysis, C, O and Fe elements were detected by mapping scanning on the initial surface (see Figure 5c), while Cu element was also detected by mapping scanning on the worn surface (see Figure 5d). Quantitatively, although there was still some wear debris transferred from QBe2 beryllium bronze pin into the steel plate, the transfer amount of QBe2 beryllium bronze pin was very low, compared with that in our previous dry sliding experiments without lubrication [3]. Above all, the wear behavior of the steel plate is similar to the mechanical polishing. With the extension of time, the surface became smoother, indicating that the tribo-pair would operate more steadily for a longer time under the lubrication of sufficient LCG grease.

Figure 6 exhibits typical SEM results on the QBe2 beryllium bronze pins. As shown in Figure 6a, the initial surface of the QBe2 beryllium bronze pins was smooth with some furrows after machining. However, the worn surface of the copper had a number of slight scratches, which was caused by the asperities of the steel plate (see Figure 6b). When examining the compositions of the samples by EDX analysis, C, O, Cu and Be elements

were detected by mapping scanning on the initial surface (see Figure 6c). Compared with the initial surface, very little Fe was detected by mapping scanning on the worn surface, revealing that the asperities on the steel plate might fall off due to the long-time fatigue wear and be transferred into the worn surface of QBe2 beryllium bronze pins (see Figure 6d).

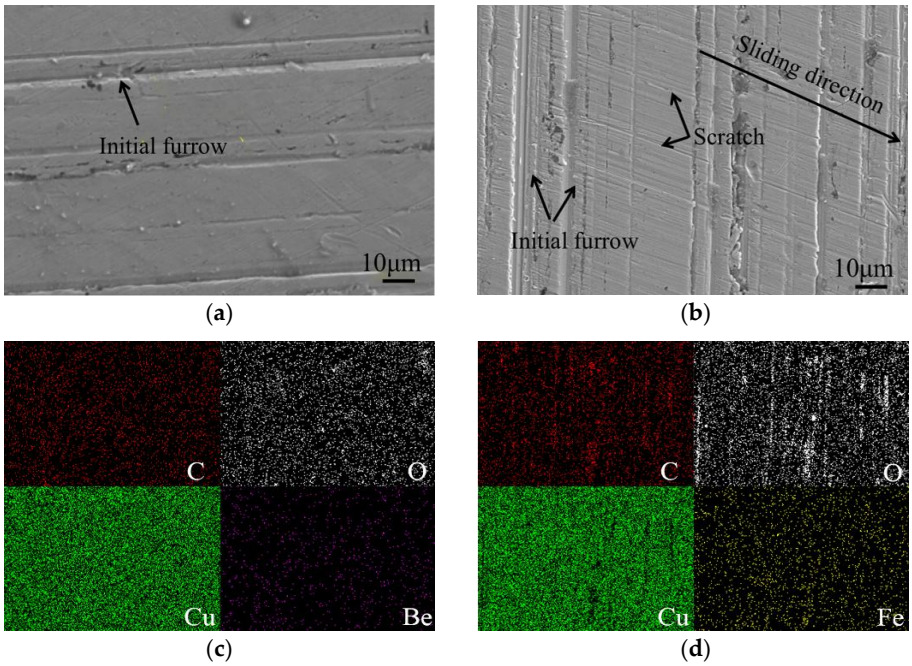


Figure 6. SEM results on the QBe2 beryllium bronze pins: (**a**) on the initial surface, (**b**) on the worn surface, (**c**) mapping scanning results on the initial surface and (**d**) mapping scanning results on the worn surface.

Figure 7 shows the SEM micrograph and mapping scanning results on the collected LCG grease after the wear test. By SEM imaging, no wear debris could be observed in the used grease (see Figure 7a), although Fe and Cu elements could be detected, which proves that the wear debris has actually existed in the grease (see Figure 7b) after the wear test. This result can be explained as follow. The amount of wear debris is very scarce and the size of wear debris was very small. Thus, during the wear process, the wear debris could be wrapped in the grease and crashed into powder by the repeated squeezing between the surfaces of the tribo-pair.

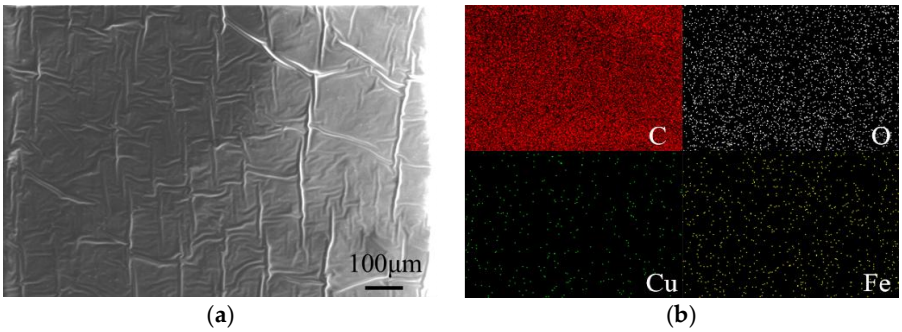


Figure 7. SEM results on the surface of LCG grease after the wear test: (**a**) SEM micrograph, and (**b**) mapping scanning results on (**a**).

In order to further investigate its chemical composition, XPS analysis was carried out on the LCG grease. Figure 8 displays the results of XPS analysis on the LCG grease. From the survey spectrum (Figure 8a), it is seen that Cu, O and Fe are detected, which are

consistent with the results by EDX analysis (Figure 7b). In addition, the peak of Ca 2p at 348.6 eV and the peak of Ti 2p at 450 eV could be identified, which come from grease. In the high-resolution spectrum of Cu 2p (Figure 8b), the characteristic peaks of Cu 2p3/2 were centered at 935.1 and 932.5 eV, respectively, which can be attributed to CuO, Cu_2O and elemental copper [15,16]. In the high-resolution spectrum of Fe 2p (Figure 8c), the peak of Fe 2p was located at 715 eV, from which it can be deduced that FeO [17] and Fe_2O_3 [18] were formed on the surfaces of the tribo-pair.

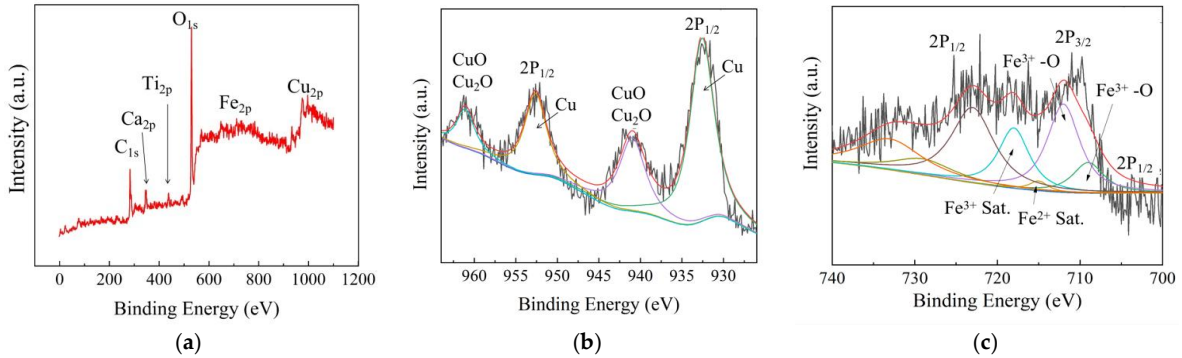


Figure 8. XPS analysis results on the LCG grease: (**a**) survey spectrum and the high-resolution spectra of (**b**) Cu 2p and (**c**) Fe 2p.

Figure 9 shows the 3D white-light interfering profiles of the steel plate and QBe2 beryllium bronze pins before and after the wear test. The roughness (Ra) of the initial steel plate surface, the worn steel plate surface, the initial QBe2 beryllium bronze pin surface and the worn QBe2 beryllium bronze pin surface were 0.231, 0.124, 0.095 and 0.181 μm, respectively. The surface roughness values of the samples were measured by using the stylus of the line roughness meter to directly cross the surface of the measured surface. As is seen, after the wear test, the surface roughness of the 38CrMoAlA steel plate was decreased during the wear test, because the asperities of the initial surface were removed due to the repeated grinding. Comparatively, the surface roughness of the QBe2 beryllium bronze pins became slightly larger after the wear test, which was caused by the mild ploughing effect from the asperities of the steel on the copper surface.

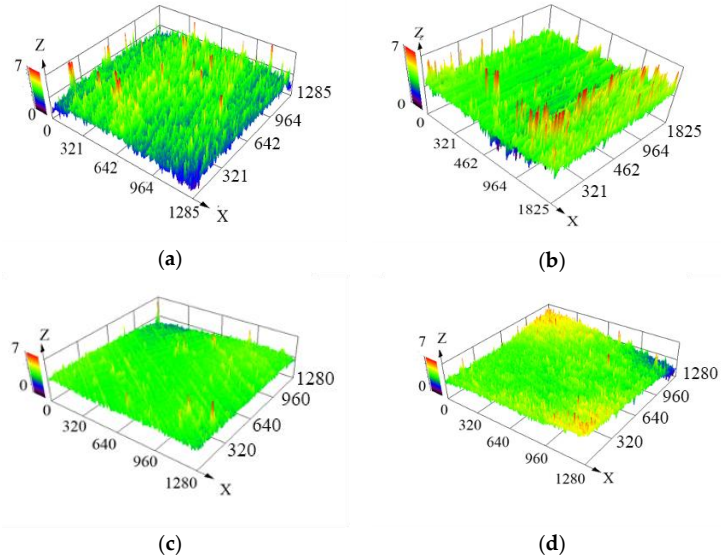


Figure 9. 3D white-light interfering profiles of the steel plate and QBe2 beryllium bronze pins: (**a**) on the initial surface and (**b**) on the worn surface of 38CrMoAlA steel plate, as well as (**c**) on the initial surface and (**d**) the worn surface of QBe2 beryllium bronze pin.

3.3. Friction and Wear Mechanism

As is well known, the coefficient of friction and wear volume are important indexes to evaluate the performance of tribo-pairs. The measured low coefficient of friction and wear loss of tested samples confirm that the proposed copper–steel tribo-pair can operate stably for at least 150 h under the lubrication of LCG grease. Moreover, it is also important to know the details why it can operate stably so as to improve the tribological property of the tribo-pairs. In the present case, in addition to the lubrication effect by the LCG grease, the reduction of the unit contact load and the oxidation of the tribo-pair surface also made positive contributions to the excellent performance of the proposed tribo-pair. Specifically, compared with the initial topography of 38CrMoAlA steel plate (see Figure 9), the surface roughness of the 38CrMoAlA steel was decreased after the wear test (from 0.231 to 0.124 μm), indicating that the asperities on the initial surface was removed during the test. As a result, the actual contact area increased, thus reducing the contact load per unit area. Additionally, the products of the oxidation reactions of the tribo-pair such as CuO, Cu_2O, FeO and Fe_2O_3 also play an important role in reducing friction of the tribo-pair [19]. In summary, the low coefficient of friction and wear loss are the result of the joint action of these factors.

The changes in coefficient of friction, wear volume and the micro morphology of the tribo-pair are related to the variation of wear mechanisms during the wear process. Figure 10 shows the schematic diagrams of the copper–steel tribo-pair under the lubrication of LCG grease as the function of wear time. At the beginning, the thickness of the lubricating film exceeded the height of the asperities, which completely separated the asperities to avoid them contact (see Figure 10a). With the consumption of lubricating grease, the thickness of the grease decreased (see Figure 10b). When the asperities on the surface were higher than the thickness of the grease, they would make contact with each other. At this time, local boundary lubrication would occur when these asperities contacted (see Figure 10c). As the lubricating oil film became thinner, there were more and more local boundary lubrication areas (Figure 10d). It can be predicted that the boundary lubrication would turn into dry sliding friction, but this phenomenon did not occur in this experiment.

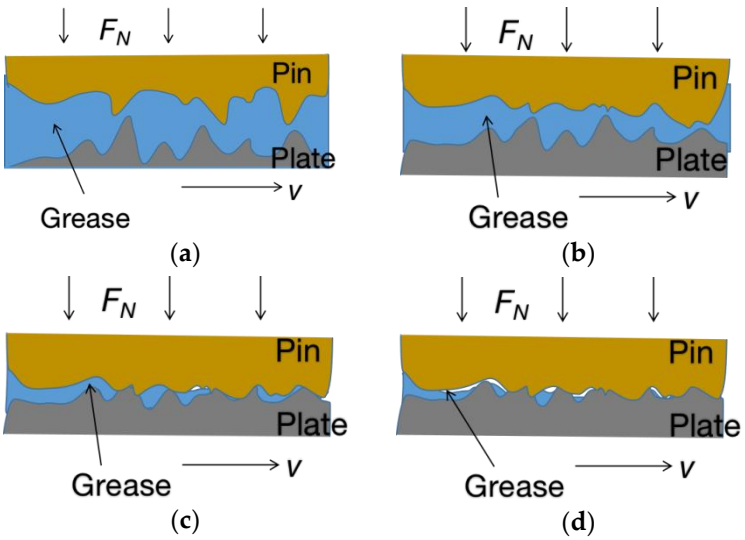


Figure 10. Schematic diagrams of the copper–steel tribo-pair under the lubrication of LCG grease as the function of wear time: (**a**) the beginning of the wear time, (**b**) the thickness of the grease decreased, (**c**) asperities contact and (**d**) the boundary lubrication period.

Interestingly, to accelerate the wear of tribo-pairs, the specimens after the wear test under lubrication for 150 h were ultrasonically cleaned, and then re-settled in the machine to carry out the wear test under the same conditions as used under lubrication. Astonishingly, because the wear volume of the pin specimen was too great, the wear rate was too high, and

the vibration of the tribo-pairs was too serious, the test machine was automatically stopped by sensor protection after about 50 h test. As a result, the coefficient of friction during the test fluctuated between 0.2 and 0.3, and the wear volumes and specific wear rates of the 38CrMoAl steel and Qbe-2 beryllium bronze pin were 899.625 mm^3, 439.872 mm^3, 2.8282×10^2 mm^3/Nm and 1.3833×10^2 mm^3/Nm, respectively (see Table 2). This result confirms again that the present copper-steel tribo-pairs could work well under lubrication conditions.

Table 2. Wear volume and specific wear rate of the proposed tribo-pair without lubrication for about 50 h test.

Sample	Wear Volume (mm^3)	Specific Wear Rate (mm^3/Nm)
QBe2 beryllium bronze	439.872	1.3833×10^2
38CrMoAlA steel	899.625	2.8282×10^2

Considering the tested tribo-pair in this work will be used in the newly designed pneumatic downhole tools, it would be better if the property of the tribo-pair could be examined in actual drilling. The test for 150 h in this study has fully demonstrated the importance of adding grease. In other words, adding grease once can guarantee that the tribo-pair will work steadily for at least 150 h, which can basically meet the average working time of downhole pneumatic drilling tools. Therefore, the only left issue is how to add grease in time between the tribo-pair for longer service.

4. Conclusions

In this work, pin-on-plate tests were performed to investigate the friction and wear behavior of 38CrMoAlA steel against QBe2 in pneumatic downhole tools under lubrication.

(1) The average coefficient of friction and the wear volume are very low, showing excellent anti-friction and anti-wear performance. During the test, the surface roughness of the steel plate was decreased, while that of the copper pin was slightly scratched by the asperities on the relative harder surface of the steel plate, thus resulting in a rougher surface. Cu and Fe oxidize and form composite oxides on the friction surface, which could reduce the friction of the contact surface.

(2) Compared with the dry sliding friction without lubrication, the performance of the present QBe2 beryllium bronze against 38CrMoAlA steel tribo-pair was greatly improved by adding LCG grease. The adding of grease could protect the copper components and improve the service life of the pneumatic downhole tool to 150 h, which can basically meet the requirements of working conditions in practical drilling. These results provide a solid support for the practical application of the reported pneumatic downhole tools.

Author Contributions: C.L.: literature surveying, drawing of figures and tables, design of experiments, data collection and analysis, writing of original manuscript; J.Z.: literature surveying, design of the experiments, revision and finalizing of the manuscript and supervision of the project; Y.W.: partial data collection and analysis, drawing of partial figures and tables, revision and finalizing of the manuscript; Z.P.: design of the experiments, revision and finalizing of the manuscript, and supervision of the project. All authors have read and agreed to the published version of the manuscript.

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