Study on Friction and Wear Properties of 23CrNi3Mo Carburized Steel under Water Lubrication

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Abstract — In this paper the friction and wear of 23CrNi3Mo carburized steel under water lubrication were studied. The friction and wear properties of carburized steel sliding with stainless steel, GCr15, Al\textsubscript{2}O\textsubscript{3} and ZrO\textsubscript{2} balls were analyzed by tribometer, 3-D topography and SEM. The results show that compared with other materials, ZrO\textsubscript{2} and carburizing steel have better tribological properties. Compared with Al\textsubscript{2}O\textsubscript{3}, the wear depth of carburized steel sliding with ZrO\textsubscript{2} is reduced by 41% at the load of 2 N and 50% at the load of 10 N. In the load range of 2N-10N, the wear rate of carburized steel is the lowest when rubbing with ZrO\textsubscript{2}, and it gradually decreases when the load increases. Combined with SEM and Raman spectrum analysis, Oxide film was formed on the surface of carburized steel during the sliding test of ZrO\textsubscript{2} and carburized steel. This oxide film was mainly composed of Fe\textsubscript{3}O\textsubscript{4} and Fe\textsubscript{2}O\textsubscript{3}, which effectively reduces the friction coefficient and wear rate of 23CrNi3Mo carburized steel under water lubrication.

1. Introduction
In recent years, the global consumption of lubricating oil has remained between 40-50 million tons and has a trend of increasing year by year\textsuperscript{[1]}. During the manufacturing and application of lubricating oil, a large number of pollutants enter the environment, causing air pollution and soil pollution. Pure water has received extensive attention due to its low cost, non-flammable and environment-friendly characteristics\textsuperscript{[2, 3]}. Using pure water instead of mineral oil as the transmission medium can effectively reduce the pollution of mineral oil for the environment. However, the materials applied to hydraulic equipment cannot be applied to water-powered equipment because the viscosity of pure water is much lower than that of mineral oil. Under the same clearance, the leakage of water is much higher than that of oil. The leakage will reduce the energy utilization of the equipment, and then affect the service life of the equipment. To reduce the leakage between clearance, water-powered equipment requires friction pair materials with better wear resistance. Metals, ceramics, and polymers are all considered to be suitable materials for water-powered equipment\textsuperscript{[4-6]}. For example, Danfoss in Finland has used metal and polyetheretherketone as friction pair to develop a plunger hydraulic motor. The core components of the water-powered rock drilling equipment produced by Peterstow use ceramic and carburized steel as friction pairs. Ravikiran et al. \textsuperscript{[7]} studied the tribological properties between Al\textsubscript{2}O\textsubscript{3} ceramics and steel under water-lubrication. This study had shown that at low speeds, hydroxides with antifriction properties were formed on the steel surface, while at higher speeds, water lubrication resulted in higher wear rates similar to dry friction. Wu et al.\textsuperscript{[8]} studied the friction and wear mechanism of ceramics in water lubrication, and the results showed that Al\textsubscript{2}O\textsubscript{3} and Si\textsubscript{3}N\textsubscript{4} formed Al(OH)\textsubscript{3} and Si(OH)\textsubscript{4} anti-friction and
wear resistance film. Although ceramics generated hydroxides friction-reducing film, but the ceramic particles worn off from surface caused severe abrasive wear. Therefore, the application of ceramics still needs experimental verification.

Carburizing process was widely used in the manufacture of hydraulic parts as it could improve the hardness and wear resistance of metals[9-11]. Carbon atoms entered in γ-Fe by diffusion. After quenching, the steel surface had excellent wear resistance and mechanical properties due to the formation of martensite. Under the condition of water lubrication, carburized steel showed different tribological properties when rubbing with metal or ceramics. However, there is a lack of systematic research on the tribological properties between carburized steel and different materials under water lubrication.

In this paper, the friction and wear properties between 23CrNi3Mo carburized steel and stainless steel, GCr15, Al2O3 and ZrO2 under water lubrication were investigated. By comparing the wear scar depth and friction coefficients of different friction pairs, the best anti-wear material suitable for 23CrNi3Mo carburized steel under water lubrication conditions was obtained. The wear scars were observed and analyzed to get the wear mechanism and tribochemical reaction during the sliding test between 23CrNi3Mo carburized steel and different materials. This research has significant guidance for the material selection of water-powered equipment.

2. Experimental materials and methods

2.1 Sample preparation
The material used in this experiment was 23CrNi3Mo, and its chemical composition is shown in Table 1:

| Element | C   | Si  | Mn   | Cr  | Ni  | Mo  | P   | S   |
|---------|-----|-----|------|-----|-----|-----|-----|-----|
| Content | 0.25| 0.2565 | 0.6455 | 1.272 | 2.9285 | 0.246 | 0.0105 | 0.003 |

23CrNi3Mo used in the test was carburized at 850 °C for 18 hours. After carburizing, the prepared sample was quenched to form martensite, and then the sample was tempered at 270 °C to improve the toughness. A wear-resistant carburized layer was formed on the surface of 23CrNi3Mo after heat treatment.

Cutted the prepared sample into 20mm×10mm×3mm small pieces by wire cutting machine, grinded and polished the surface of these small pieces. The polished sample was putted in acetone for ultrasonic cleaning 15 minutes to remove impurities and oil.

2.2 Experimental method
The friction and wear properties of 23CrNi3Mo carburized steel under water lubrication were tested by MFT-EC4000 reciprocating tribometer. Four different kinds of balls with diameter of 6mm, made of ZrO2, Al2O3, GCr15 and stainless steel, were selected for sliding test. The test parameters were as follows: the load of 2 N, 5 N and 10 N, the frequency of 2 Hz, and the test time was 30min. During the whole test, the carburized steel and the corresponding ball were immersed in distilled water.

The hardness gradient of carburized steel was tested by TIME-6610M hardness tester. The load was 200g and the load duration was 10s. Test one point every 0.1mm. Zeta-200 three-dimensional surface profiler produced by Zeta company of the United States was used to test the surface profile of wear scar and its minimum resolution is 0.013 μm. The wear trace morphology was tested by JEM-7200F scanning electron microscope (SEM) produced by Oxfrod company, and the element composition in the wear trace morphology was analyzed by EDS (X-Max50). Renishaw invia Raman spectrometer was used to test the types of compounds in the wear marks. The wavelength of 633nm was used in the test process, and the test range was 50-1200cm^{-1}. 

3. Results and discussions

3.1 Microstructure and hardness gradient of 23CrNi3Mo carburized layer

The microstructure and hardness distribution of the carburized layer are shown in Figure 1. Figure 1(a) shows the overall morphology of the carburized layer, in which the bright white region is the high-carbon martensite in the carburized layer. Some studies had proved that when the carbon content was higher than 1wt%, the steel formed brittle and hard acicular martensite during the quenching process. Figure 1 (b) shows the microstructure of region A (as shown in Figure 1 (a)), which is characterized by obvious acicular martensite, and the thickness of acicular martensite is about 200 μm. The microstructure shown in Figure 1 (c) is the region B shown in Figure 1 (a). The microstructure in this area has obvious plate-like characteristics, so it is lath martensite. Because the carbon content in the carburized layer decreases with the increase of the distance from the surface, the carbon content in region B far from the surface is smaller than that in region A, and lath martensite will be formed in the quenching process. The hardness gradient of carburized layer is shown in Figure 1 (d). According to the hardness gradient, the acicular martensite with high surface carbon content have the characteristics of high hardness, and its hardness value remains between 620-650 HV. With the increase of surface distance, the hardness of carburized layer gradually decreases and finally stabilizes at about 460 HV. The influence area of carburized layer is within 2.5mm.

3.2 Tribological properties of 23CrNi3Mo carburized layer

Figures 2 (a), (b) and (c) show the friction coefficients of carburized steel and different materials under water lubrication, in which the loads are 2 N, 5 N and 10 N respectively. The friction coefficient between ZrO₂ and carburized steel exhibits the lowest value (μ=0.235) at the load of 2 N and compared with GCr15, the friction coefficient of ZrO₂ was reduced by 31.7%. When the load increase to 5 N, the friction coefficient of ZrO₂ and Al₂O₃ are the same, both of which are 0.159 and compared with GCr15, the
The friction coefficient of ZrO$_2$ and Al$_2$O$_3$ ceramics are reduced by 18.0%. The friction coefficient of Al$_2$O$_3$ is the lowest at the load of 10 N, and its value was 0.186. According to the relationship between friction coefficient and load shown in Figure 2 (d), the friction coefficient of GCr15 and Al$_2$O$_3$ decreased with the increase of load, and the friction coefficient of stainless steel and ZrO$_2$ is less affected by load, maintained at about 0.288 and 0.292 respectively.

Figure 2 Friction coefficient between carburized steel and SS, GCr15, Al$_2$O$_3$ and ZrO$_2$, a) 2 N, b) 5 N, c) 10 N, d) relationship between friction coefficient and load

Figure 3 shows the wear scar profile and corresponding wear rate of 23CrNi3Mo carburized steel and stainless steel, GCr15, Al$_2$O$_3$ and ZrO$_2$ under the load of 2 N, 5 N and 10 N. Compared with the other three friction pairs, the wear mark depth caused by the rubbing of Al$_2$O$_3$ on the carburized steel surface is the largest. For example, as shown in Figure 3 (a), under the load of 2 N, the wear scar depth caused by Al$_2$O$_3$ ceramic ball is 1.18 μm, which was much higher than that of stainless steel, GCr15 and ZrO$_2$. Because the hardness of Al$_2$O$_3$ is higher than that of carburized steel, so the wear mainly occurs on the carburized steel surface during the sliding test. Some small-size hard particles will be worn off from the Al$_2$O$_3$ ball and these hard particles will constantly rub the carburized steel surface to form furrows, so the depth of wear marks between carburized steel and Al$_2$O$_3$ small balls is large. The hardness of stainless steel is only about 210 HV, which is lower than that of 23CrNi3Mo carburized steel. Therefore, the wear of stainless steel ball is more serious, while the wear of carburized steel is relatively small. From the wear scar profiles shown in Figure 3 (a) - (c), the wear mark width of stainless steel is the largest, and with the increase of load, it increases from 338 μm at the load of 2 N to 618 μm at the load of 10 N. The wear scar profile between GCr15 and carburized steel is similar to that between Al$_2$O$_3$ ball and carburized steel. The wear mark profile caused by ZrO$_2$ on the carburized steel surface is similar to that of stainless steel, and both of the wear mark depth are shallow. The wear rate of carburized steel is shown in Figure 3 (d). When the load between 2 and 10 N, the wear rate of ZrO$_2$ exhibits the lowest value, and the wear rate tends to decrease with the increase of load. For Al$_2$O$_3$, the wear rate is high at
the load of 2-10 N. Especially, under the load of 10 N, the wear rate of Al₂O₃ increases significantly, and the wear rate is 4 times that of ZrO₂. 23CrNi₃Mo carburized steel rubbing with stainless steel also presents low wear rate, but the hardness of stainless steel is also low. Therefore, it can be inferred that the wear of stainless steel and carburized steel mainly occurs on the surface of stainless steel. In general, the following conclusions can be drawn: under the condition of water lubrication, the best material for matching with carburized steel is ZrO₂. As a ceramic material, ZrO₂ not only has good corrosion resistance and low wear rate, but also protects 23CrNi₃Mo carburized steel from serious wear.

Figure 3 Wear trace profile and wear rate of carburized steel under water lubrication. a) Wear trace profile of carburized steel under 2N load, b) wear trace profile of carburized steel under 5N load, c) wear trace profile of carburized steel under 10N load, d) relationship between wear rate and load of carburized steel under different material pairing under water lubrication

Figure 4 shows the wear scar on the carburized steel surface after sliding test with stainless steel, GCr15, Al₂O₃ and ZrO₂ balls, and the distribution of O, Cr, Fe and Ni elements across the wear scar. According to the SEM image, the wear mark width is basically consistent with that shown in Figure 3. The wear scar of carburizing steel rubbing with stainless steel is the widest, 440 μm. The wear scar width of carburizing steel rubbing with ZrO₂ shows the lowest value, only 190 μm. In addition to the different wear scar width, the wear mechanism is also different. It can be seen from Figure 4 that 23CrNi₃Mo carburized steel, rubbing with stainless steel, GCr15 and Al₂O₃, are mainly abrasive wear, and the oxygen content presents the highest value in the edge area of the wear scar because the wear debris will be continuously transfer to the edge from the center during the sliding test. The wear debris in the edge area will react with oxygen in water to form iron oxide. The wear scar of carburized steel rubbing with ZrO₂ is quite different from the other three kinds of wear scar, and a layer of black film forms on the surface. According to the line scanning of the EDS spectrum in Figure 4 (d), this film exhibits high level of O, so it’s a kind of oxide film. Therefore, it can be concluded that friction pairs of ZrO₂ and carburized steel are the best as oxide film forms on the friction surface.
The wear scar morphology of the ball at the load of 2 N is shown in Figure 5. The wear scar shape of stainless steel and GCr15 ball are regular circles with diameters of 440 μm and 329 μm respectively. The wear scar shape of Al₂O₃ and ZrO₂ ball are irregular circular, and their diameters are 245 μm and 201 μm respectively. The wear scar diameter of ZrO₂ ball exhibits the smallest value as the wear mechanism is different. Stainless steel and GCr15 are mainly worn by hard particles, and there were obvious furrows on their surfaces. The worn surface of Al₂O₃ ceramic ball shows different concave-convex morphology, which indicates that the material fell off from the Al₂O₃ ball surface. Due to the high hardness of Al₂O₃, the fallen Al₂O₃ particles were very easy to move back and forth on the carburized steel surface, resulting in deep furrows. The surface of ZrO₂ ceramic ball is relatively smooth. Therefore, The number of micro convex body on the ZrO₂ surface are small, which protect the carburized steel surface from the abrasive wear.
Figure 5 Wear scar on small ball surface at the load of 2 N, a) wear scar on stainless steel ball surface, b) wear scar on GCr15 ball surface, c) wear scar on Al$_2$O$_3$ ball surface, d) wear scar on ZrO$_2$ ball surface.

The surface wear morphology of carburized steel under 2 N is shown in Figure 6. Although the wear mechanism between carburized steel and stainless steel, GCr15 and Al$_2$O$_3$ ball are mainly abrasive wear, it could be seen from Figure 6 (a) - (c) that the surface morphologies of abrasive wear are quite different as the material properties of balls are different. The hardness of stainless steel is low. Therefore, even if some materials fall off from the surface of stainless-steel ball, it’s not easy to cause serious abrasive wear due to its low hardness. So, the furrows density of carburized steel rubbing against stainless steel is obviously low. Compared with stainless steel, GCr15 has higher hardness, so the furrows density on the carburized steel surface rubbing with GCr15 ball increases obviously, and these furrows are more deeper. Because the hardness of Al$_2$O$_3$ ceramic is much higher than that of carburized steel, so the hard particles fallen from Al$_2$O$_3$ ball surface cause serious abrasive wear on the surface of carburized steel as shown in Figure 6 (c). The particle in the red circle shown in Figure 6 (c) was Al$_2$O$_3$, which caused deep furrows on the carburizing steel surface. The wear scar of carburized steel and ZrO$_2$ ceramic ball is shown in Figure 6 (d). The wear scar surface was covered with a layer of oxide film, which protected carburizing steel surface$^{[12]}$. The oxide film cracked under the friction of ZrO$_2$ ball. With the expansion of crack, the oxide film fell off. When most of the oxide film fell off, the exposed carburized steel surface formed oxide film again. The wear between ZrO$_2$ ball and carburized steel is the mechanism of oxidation-fall off-oxidation.
Figuer 6 SEM image of carburized steel wear scar under 2 N (3000×). a) Wear scar of carburized steel sliding with stainless steel, b) wear scar of carburized steel sliding with GCr15, c) wear scar of carburized steel sliding with Al$_2$O$_3$, d) wear scar of carburized steel sliding with ZrO$_2$

The wear scar of carburized steel at the load of 10 N under water lubrication are shown in Figure 7. By comparing Figure 5, it can be seen that the wear mechanism of carburized steel does not change with the increase of load. Stainless steel, GCr15 and Al$_2$O$_3$ are dominated by abrasive wear, while ZrO$_2$ generated oxide film at the beginning, and then the oxide film fell off. Figure 7 (a) - (c) show some black products form on the wear scar, which are oxide. With the increase of load, the contact pressure between the ball and carburized steel increased, leading to more heat and oxidation on the carburized steel surface. According to Figure 3, the wear scar depth between carburized steel and ZrO$_2$ doesn’t increase with the increase of load, because the oxide films didn’t completely fall off under 10N load. Although the coverage of oxide films on the wear scar under 10N load are lower than that under 2 N load (as shown in Figure 4 (d)), the oxide films still play the role of friction reduction and wear resistance.
Figure 7 Wear scar morphology of carburized steel rubbing with different materials under water lubrication at load of 10 N, a) stainless steel, b) GCr15, c) Al₂O₃, d) ZrO₂

For analyzing the types of oxides produced by friction between ZrO₂ and carburized steel, Figure 8 shows the Raman spectrum of carburized steel wear scar. According to Raman spectrum, the peaks of Raman from high to low are 659 cm⁻¹, 221 cm⁻¹, 291 cm⁻¹ and 404 cm⁻¹ respectively. The peak of 659 cm⁻¹ corresponds to the A₁₈ vibration of Fe₃O₄[13, 14]. As the highest Raman spectrum peak corresponding to Fe₃O₄, it can be explained that most of the tribochemical products between ZrO₂ and carburized steel are Fe₃O₄. The study had shown that Fe₃O₄ has good antifriction and wear resistance[15, 16]. The peaks of 221 cm⁻¹, 291 cm⁻¹ and 404 cm⁻¹ corresponds to the Fe₂O₃[17, 18]. In general, the oxide film composited with Fe₃O₄ and Fe₂O₃ would be formed on the wear scar carburized steel when it rubbed with ZrO₂. Because the Fe₃O₄ and Fe₂O₃ oxide film has good antifriction and wear resistance characteristic[19, 20], the matching of ZrO₂ and carburized steel is expected to become a good choice for water lubricating materials.
4. Conclusion

$23\text{CrNi3Mo}$ carburized steel has different tribological characteristics when it slides with stainless steel, GCr15, Al$_2$O$_3$ and ZrO$_2$ balls under water lubricated. The wear mainly occurs on the stainless steel if the carburized steel slides with stainless steel, so the wear scar depth of carburized steel is relative low, and the wear scar diameter of stainless-steel ball is large. Compared with stainless steel, GCr15 significantly increases the wear scar depth of the carburized steel, but the wear scar diameter of the GCr15 ball is smaller than that of stainless-steel ball. The wear scar depth sliding between Al$_2$O$_3$ and carburized steel is the largest under at the load of 2-10 N. However, the wear scar diameter of Al$_2$O$_3$ ball is much smaller than that of stainless steel and GCr15 ball. The wear between $23\text{CrNi3Mo}$ carburized steel and stainless steel, GCr15 and Al$_2$O$_3$ balls is mainly abrasive wear.

Under water lubrication, the tribological performance of ZrO$_2$ and carburized steel is better than that of the other three friction pairs. The wear rate between carburized steel and ZrO$_2$ is much lower than that of the other three friction pairs under 10 N load. Further study shows that the friction between ZrO$_2$ and carburized steel will form oxide films composed of Fe$_3$O$_4$ and Fe$_2$O$_3$ on the wear scar of carburized steel. Due to these oxide films, the direct contact between ZrO$_2$ and carburized steel is avoided. Because both Fe$_3$O$_4$ and Fe$_2$O$_3$ are good antifriction materials, the friction coefficient between ZrO$_2$ and carburized steel is stable at 0.23-0.24. The wear scar depth of carburized steel sliding with ZrO$_2$ does not increase significantly with the increase of load, and its depth remains at 0.8-1 μm in the range of 2-10 N load. The low wear rate of carburized steel sliding with ZrO$_2$ is attributed to its wear mechanism. The oxide film will crack due to the reciprocating motion of ZrO$_2$ ball on the carburized steel. With the expansion of the crack, the oxide film layer falls off, so the wear mark depth is related to the number of oxide film falling off. Under the load of 2-10 N, the oxide film in the wear mark of carburized steel did not completely fall off, so the wear mark depth is similar to the thickness of oxide film, which is about 1 μm. In general, for water lubrication, carburizing steel and ZrO$_2$ as the friction pair shows excellent tribological properties, which can be used in water-powered equipment.

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