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Study on Fretting Wear Properties of High Speed Diesel Engine Roller Tappet Material Cr12W Steel

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Abstract. The cam and tappet are key components of the internal combustion engine valve train system. Due to the alternating high-frequency cyclic of high contact stress, the cam and tappet are prone to abnormal wear and failure. In this work, Cr12W steel was selected as the material of the roller tappet in valve train. Then, it was treated by ion nitriding treatment. The fretting wear tests were carried out under laboratory conditions. The wear mechanisms of nitrided and untreated specimens which rubbed with GCr15 steel were investigated under dry friction and oil lubrication, respectively. It is found out that the predominant wear mechanisms of nitrided specimens under dry friction are slight abrasive wear and adhesive wear, whereas under oil lubrication, it is mainly spalling. The wear mechanisms of untreated specimens under dry friction are identified as adhesive wear and oxidative wear, while it is mainly abrasive wear under oil lubrication.

1. Introduction

Diesel engines have high thermal efficiency, high power, and low fuel consumption. According to statistical results, diesel engines save more than 25% of fuel consumption compared with general gasoline engines, and more and more agricultural vehicles and even passenger cars start to use diesel engines [1]. However, with the development and innovation of the modern automobile industry, new energy vehicles have begun to appear in daily life. Government and people pay more and more attention to the environmental protection and fuel consumption, leading to a severe challenge to the traditional internal combustion engine industry. Since the internal combustion engines have been used for more than 100 years, the early failure caused by friction and wear of components has become a serious waste of resources [2].

The cam and tappet are the key components of the valve train system. The cam profile controls the movement of the tappet and it is closely related to the timing of the engine. During the normal operation of the engine, a certain extent of elastic deformation occurring in different parts of each component would result in the increase of the contact gap between the components, leading to a severe vibration and noise. The tappet suffers the alternating high-frequency cyclic of high contact stress as well as the tangential force during the cam motion, which easily cause abnormal wear on the top surface of the tappet [3]. With the development of current high-speed diesel engine, there is a problem of serious wear and premature failure of the working surface of the tappets, so that the intake valves and exhaust valves cannot be opened and closed in time. As a result, the aeration performance of the engine is reduced and the safety and stability of the whole machine are seriously affected.

Many scholars have carried out many bench tests and numerical simulation analysis to find the cause of failure of the tappet. Nayak et al. [4] used finite element analysis, AVL TYCON simulation program and typical tribological principles to estimate the wear position and attrition rate of the tappet. Wang et al. [5] analyzed the wear phenomenon of the cam and tappet using an agricultural diesel engine. They proposed some methods to reduce the wear and designed the test scheme to verify. However, there are few reports and publications about the fretting wear properties of the tappet.

In this work, Cr12W steel was selected as the base material of the roller tappet. This type of material has the characteristics of high strength, high toughness and good wear resistance [6,7]. Then, it was treated by ion nitriding treatment. The application of ion nitriding technology can form a hardened protective layer on the surface of the material. It will enhance the wear resistance and corrosion resistance of the material. Thereby the service life of the components will be prolonged.

Studies have shown that if friction and wear can be effectively controlled and reduced, not only it can reduce fuel consumption and maintenance costs, but also the service life of the valve train system components can be greatly improved [8]. The fretting wear properties of the nitrided Cr12W steel were investigated under laboratory conditions. This study will provide a direct design reference and theoretical support for the optimization of the roller tappet.

2. Materials preparation

The chemical composition of the Cr12W steel is shown in Table 1. A strip of 100×20×20 mm was cut from the steel bar blank and then the heat treatment was performed, the heat treatment process is shown in Figure 1. The heat-treated strip was cut into a number of 8×8×8 cubic samples, and their surface were polished with 180 mesh, 360 mesh, 600 mesh, 800 mesh, 1000 mesh, 1500 mesh, and 2000 mesh waterproof abrasive paper, respectively. After the sanding is completed, it is polished using a nylon fabric and a polishing agent in order to make the approximately same surface roughness of 3.2 Ra.

The polished samples were placed in the absolute ethanol solution for an ultrasonic cleaning. Take some samples to treat by traditional industrial gas nitriding, NH_3 gas was selected as a nitrogen source. The ion nitriding process is shown in Figure 2. After the surface of the samples are nitrided. they can be used as a test material after thorough ultrasonic cleaning in the absolute ethanol solution and drying.

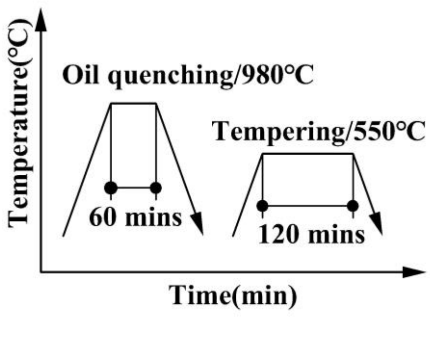

Figure 1. Heat treatment process.

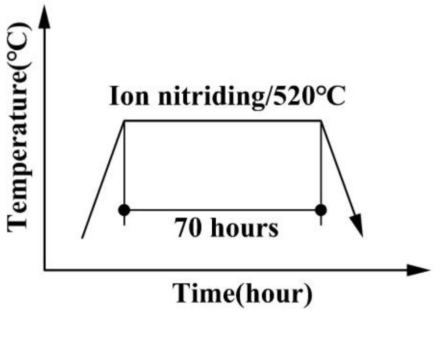

Figure 2. Ion nitriding process.

Table 1. Composition of Cr12W (wt%).

Element	C	Cr	Mo	Si	P	S	W
Content	2.00~2.30	11.00~12.50	≤0.35	≤0.40	0.03	0.03	0.60~0.90

3. Fretting wear test method

The fretting wear test was performed using a friction and wear tester (SRV IV, Optimol, Germany) at room temperature. The upper sample is a standard GCr15 steel ball (in a diameter of 10 mm and hardness of 62~63 HRC) equipped in the test machine. The lower sample is a cube in the dimension of 8×8×8 mm. During the fretting wear test, the upper specimen is fixed by a designed holder and driven by a servo motor to perform the reciprocating sliding motion. The lower specimen is fixed by a special holder. The contact type of the upper and lower specimens is ball-to-surface contact. The test machine motion model and the experimental cabin configuration are shown in Figure 3 and Figure 4, respectively. The lubricant selected for the test was Diesel Lubricating Oil (Great Wall CD 15W-40), which applicable temperature is from -20 °C to 40 °C. The fretting wear test parameters are listed in Table 2. After test, the surface wear morphology of the samples were observed by a scanning electron microscope (Quanta 200, FEI, Netherlands), and the wear mechanisms were analyzed and discussed.

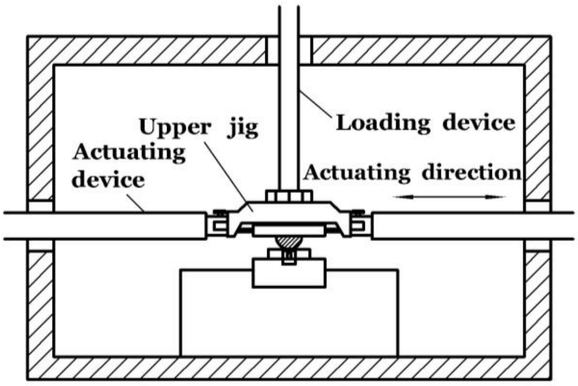

Figure 3. Motion model of the testing machine.

Figure 4. Experimental cabin configuration.

Table 2. Fretting wear test parameters.

Load (N)	Time(s)	Frequency (Hz)	Stroke (μm)	Sample	Condition
50	1800	20	200	nitrided	dry
				untreated	dry
				nitrided	lubrication
				untreated	lubrication

4. Results and discussion

4.1. Physical properties

The microstructure of the cross-sectional nitrided layer is shown in Figure 5. The matrix structure mainly consists of eutectic and reticulate ledeburite. The distribution of the tissue in the brighter nitrided layer is uniform and the particles are fine. There are many high hardness and stable nitrides distributed in the nitrided layer. After ion nitriding treatment, the maximum hardness of the surface layer of the material is 1050 $HV_{0.2}$, while the hardness of the substrate material is 470 $HV_{0.2}$. The maximum hardness of the surface layer is 2.23 times of the hardness of the substrate material. The change in hardness from the nitrided surface to the substrate was measured at intervals of 10 μm as shown in Figure 6. It can be found that the hardness of the nitrided layer changes rapidly with the nitriding depth. The effective depth of the nitrided layer is about 160 μm. This may lead to a large difference in performance at different depths of the nitrided layer. Besides the matching section between the matrix structure and the nitrided layer may become weaker and its performance may become poorer [9]. In the process of friction, the nitrided layer fell off, which weaken the friction and wear resistance of the material.

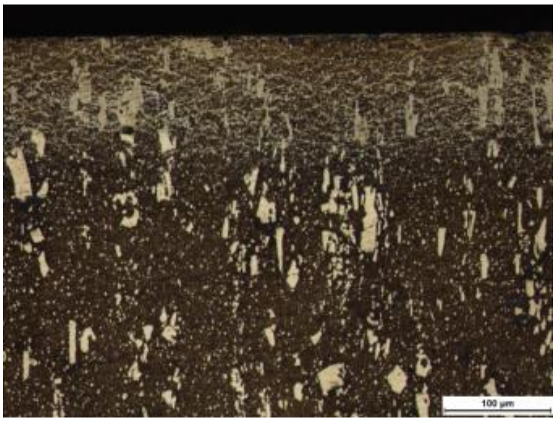

Figure 5. Microstructure of cross-sectional nitrided layer.

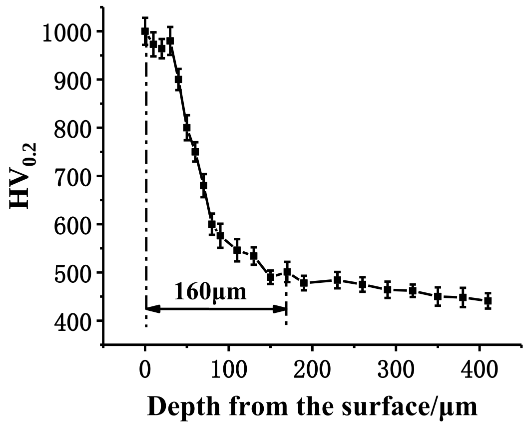

Figure 6. Microhardness distribution of cross-sectional nitrided layer.

4.2. Friction and wear properties

4.2.1 Friction properties.
The friction coefficient curves of nitrided specimens and untreated specimens under dry fretting wear and oil lubrication conditions are shown in Figure 7. The average friction coefficient and the standard deviation of the friction coefficient under each test condition were calculated respectively, as shown in Table 3. The average friction coefficient under various test conditions were investigated. The average friction coefficient of nitrided specimens under dry friction and oil lubrication conditions were lower than that of untretaed specimens. Under dry friction condition, the average friction coefficient of nitrided specimens were 10.58 % less than that of the untreated specimens. In addition, the average friction coefficient of the nitrided samples under oil lubrication were 4.91% lower than that of the untreated samples. The average friction coefficient under oil lubrication condition are much lower than that under dry friction condition. Under oil lubrication condition, the average friction coefficient of nitrided samples are reduced by 83.93 %, and the average friction coefficient of untreated samples is reduced by 84.89 %. It can be seen that with oil lubrication test condition, there is little difference between the nitrided specimens and the untreated specimens. For the same coordinate system, the friction coefficient curves of nitrided specimens under dry friction and oil lubrication conditions are respectively below that of untreated specimens. The standard deviation of nitrided specimens under oil lubrication condition is the smallest, and the friction and wear status are also stable from the graph. Comparing the friction coefficient curve under the two test conditions, it can be found that there is a steep peak in the initial stage of wear. This is mainly due to the fact that the rough peaks of the microscopic surface are in contact with each other, resulting in mechanical occlusion fracture or local cold welding [10]. The friction coefficient curve under oil lubrication condition also has a steep slope, but this steep slope is much smaller than that under dry friction condition. This is mainly due to the lubricating effect. In addition, the friction pairs can quickly come to a stable wear stage, and the friction coefficient is also quickly stabilized [11]. Under dry friction condition, the friction pair of the nitrided sample is in the running-in stage, which the wear debris falls off to form a three-body wear state. The grinding debris plays a role of ploughing. With the break and fracture of the nitrided layer, the friction coefficient rises rapidly. In the later stages of wear test, the oxide film provides a certain protective effect on the worn surface, which reduces the wear loss between the friction pair. The

friction coefficient curve tends to be stable, and the rate of change of the friction coefficient at the end of wear test is lower than that in the initial test stages.

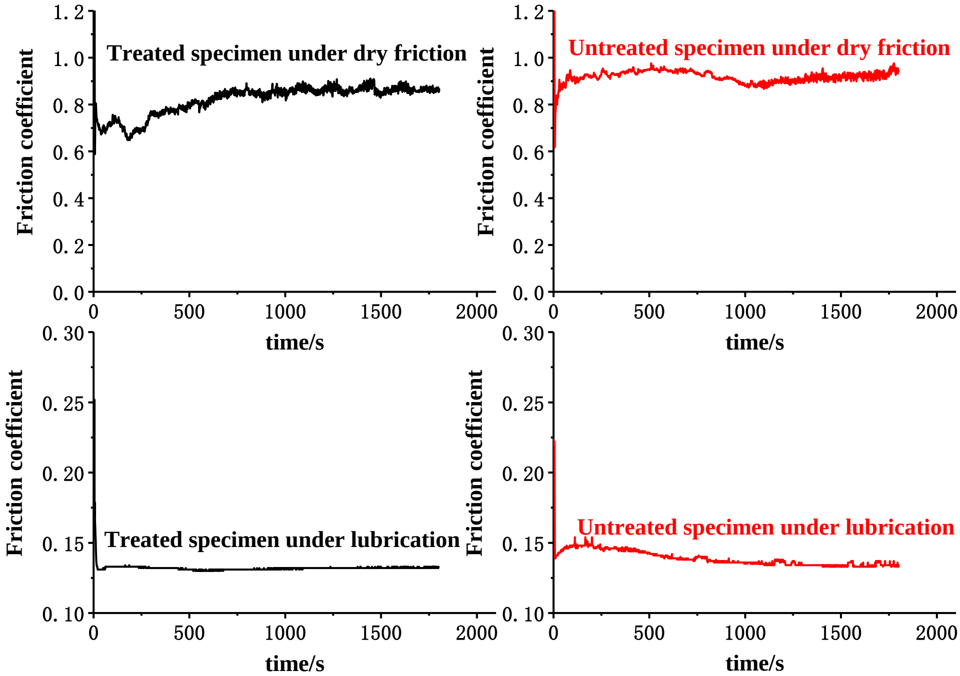

Figure 7. Friction coefficient curves of the test results.

Table 3. Average friction coefficient and standard deviation during the fretting wear tests.

Test conditions	Nitrided, dry friction	Nitrided, oil lubrication	Untreated, dry friction	Untreated, oil lubrication
Average friction coefficient	0.823	0.132	0.920	0.139
Standard deviation	0.070	0.005	0.040	0.007

4.2.2 Wear properties.
Figure 8 shows the surface wear morphology of the samples under each test conditions. Figure 8(a) shows the surface wear morphology of the nitrided samples under dry friction condition. Some slight furrows and adhesion are observed on the surface of the nitrided samples. Due to the hardness of the friction pair material is lower than that of the nitrided layer, the strength of the bonding point is higher than the strength of the friction pair material. When the bonding point is sheared, the soft metal will migrate to the hard metal surface, resulting in slight adhesive wear at the edge of the grinding spot and cold welding phenomenon [12]. Figure 8(b) shows the wear morphology of the untreated samples under dry friction condition. There is no furrow on the worn surface but adhesive wear occurs. Figure 9 and Table 4 show the results of the Energy Dispersive Spectrum (EDS) at the white wireframe in Figure 8(b). Based on the EDS results, the oxygen content of the worn surface is high, which can be inferred that oxidative wear occurs during the fretting wear test. Although the oxide films can reduce the wear loss between the friction pair, the oxide film continuously falls off and forms under the repeated action of the cyclic stress during the fretting wear progresses [13]. As a result, adhesive wear occurred on the worn surface. Therefore, the predominant wear mechanisms of the untreated samples under dry friction condition are concluded as adhesive wear and oxidative wear.

Figure 8(c) shows the wear morphology of the nitrided samples under oil lubrication condition. Less furrows could be found, but many fatigue micro-pits on the surface of the wear spot existed. Direct contact between the friction pair metal is prevented due to the presence of the lubricating oil film. Consequently, the wear resistance of the material is improved. It can be found that many cracks occurred around the fatigue micro-pits in Figure 8(c). On one hand, it may be the reason of the poor fluidity of the lubricating oil. On the other hand, the heat generated during the friction process couldn't be discharged in time. With the increase of surface temperature of the material, both the carrying capacity and the mechanical strength are declined. Cracks will firstly appear in the defects of the nitrided layer under the cyclic contact stress. These cracks are continuously extended and connected, causing the material to fall off and form a fatigue micro-pit. However, these fatigue micro-pits serve as storage lubrication, which reduced wear to a certain extent [14]. Therefore, the wear mechanism of nitrided specimens under oil lubrication condition is identified as spalling. Figure 8(d) shows the surface wear morphology of the untreated samples under oil lubrication condition. It can be seen that the surface of the wear spot is scratched, with a small amount of spalling and many micro-bulge. Because of the adhesion effect of the lubricating oil, the grinding debris can't easily discharge out of the contact surface. Therefore, the grinding debris acts as a third body to cut the surface of the material and fine furrows appear [15,16]. The wear mechanism is mainly identified as abrasive wear.

The samples treated by nitriding, under dry friction condition or oil lubrication condition, have a lower extent of wear than the untreated samples. The nitrided specimens have the best wear resistance under oil lubrication condition, and no adhesive wear or abrasive wear are observed. The wear mechanism is identified as spalling.

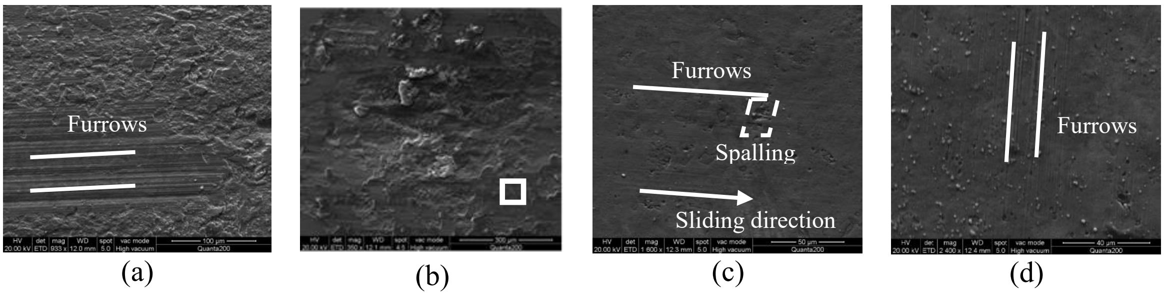

Figure 8. SEM micrographs of treated and untreated samples at different test conditions: (a) nitrided, dry friction, (b) untreated, dry friction, (c) nitrided, oil lubrication, (d) untreated, oil lubrication.

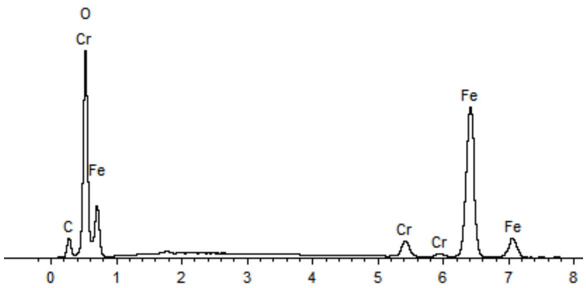

Figure 9. Surface energy spectrum results of untreated specimens after dry fretting wear test.

Table 4. EDS results of worn surface (Wt%).

Element	O	Cr	Fe	Mn
Worn surface	36.6	4.7	58.45	0.25

5. Conclusions

In this work, Cr12W steel was treated with heat treatment and ion nitriding treatment. The fretting wear tests were carried out under laboratory conditions. The fretting wear properties were discussed by observing and analyzing the friction coefficient curves and the surface wear morphology. Now come to the following conclusions.

(1) In this work, Cr12W steel was selected as the material of the roller tappet. The workblank was incubated at 980 °C for 1 hour and oil-quenched. Then it was tempered at 550 °C for two hours and air cooled. Subsequently, ion nitriding treatment was carried out. NH_3 gas was used as a nitrogen source. Specimens were incubated at 520 °C for 70 hours and cooled with the furnace. The maximum hardness of the nitrided layer is 1050 $HV_{0.2}$, while the hardness of the substrate is only 470 $HV_{0.2}$. The effective depth of the nitrided layer is about 160 μm.

(2) In the aspect of the average friction coefficient, the improvement of friction and wear resistance by the lubricating oil is similar on both samples. The wear is significantly reduced. The predominant wear mechanism of the untreated samples under dry friction is adhesive wear and oxidative wear, while under oil lubrication that is mainly abrasive wear.

(3) The friction coefficient curves of nitrided samples under dry friction and oil lubrication are relatively stable. The average friction coefficient is also smaller than that of untreated samples. The wear mechanisms of nitrided specimens under dry friction are identified as slight adhesive wear and abrasive wear, while under oil lubrication that is mainly spalling. When the nitrided samples are grinded with the GCr15 steel ball, the wear loss is lower than that of the untreated samples under the same test conditions. The nitrided samples show the best wear resistance under oil lubrication condition.

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