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Effect of Magnetic Field on Dry Sliding Friction Mechanism of 1Cr18Ni9Ti

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Abstract:

The dry friction mechanism of paramagnetic austenitic metals under a magnetic-field may be different from general paramagnetic alloys because their magnetic properties with obvious work-hardening characteristics are changed during the dry sliding friction. The 1Cr18Ni9Ti (paramagnetic) is selected as the subject investigated to conduct dry sliding friction test via applying different magnetic field strength. Combined with the results of microscopic instruments SEM, EDS, XRD analysis, the magnetic field dry friction mechanism was explored. The results show that, the working hardening characteristics of austenite 1Cr18Ni9Ti change its magnetic properties. The friction surface and the subsurface layer form the rheological layer, which improved the hardness and magnetic permeability of the friction superficial-layer. As magnetic-field exerted, debris caused by wear is adsorbed on the friction superficies, and partially retained by magnetic attraction action, which prevents the direct contact between the matrixes of the friction pairs. The abrasive debris is easy to be refined by grinding, and the magnetic field is favorable to oxidation. Under combined action of magnetic field and friction heat and oxygen in the air, the oxide layer is formed. And the adhesion and adsorption between the abrasive debris and the substrate are strengthened, so that the wear rate is reduced. In this paper, the work hardening phenomenon of 1Cr18Ni9Ti is analyzed and studied, and the dry sliding friction mechanism of friction pair (high speed steel-1Cr18Ni9Ti) under the interference of magnetic field is discussed, which provides reference and theoretical support for the study of magnetic field dry tribology of friction pair composed of ferromagnetic alloy material and paramagnetic alloy material, as well as the friction pair composed of alloy materials with different magnetic properties.

Keywords*: Wear, Magnetic field, Paramagnetic; Rheological; Friction superficies.*

I. INTRODUCTION

With magnetic technology and magnetic materials developing, more and more parts are working and running in a magnetic field environment, whose tribological problems have attracted more and more attention [1-3]. Therefore, the study and improvement of tribological mechanism in a magnetic-field environment should become one of the important works of tribological researchers [4-6]. At the moment the study on friction behavior of magnetic-field of paramagnetic materials is rarely reported [7-12].

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The magnetic-field friction characteristics of ferromagnetic materials (medium-carbon-steel, 2Cr13, high-speed-steel [13-15]), paramagnetic materials (aluminum alloy [16]) and diamagnetic materials (CuZn [17]) have been studied by auctorial research group. Obviously, the magnetic properties of the above friction pair materials are relatively stable, that is, their magnetic properties remain unchanged under the action of friction and wear process. However, some alloys, such as the pure austenite alloys, whose magnetic properties of change during friction and wear. With pure austenitic stainless steel as the representative, it has obvious processing hardening characteristics. And it is found that the magnetic properties have changed significantly while the work hardening occurs. Therefore, this paper takes 1Cr18Ni9Ti austenitic stainless steel as the research object, whose dry friction mechanism under a magnetic field has been discussed mainly, rather than the wear resistance itself.

II. MATERIALS AND METHODS

2.1 Test Materials

The selection of pin samples is mainly based on their magnetic properties. The pin specimens are made of 1Cr18Ni9T stainless steel with high austenite content. The contact mode of pin and ring is shown in Fig. 1a. The size of the pin is Φ7mm × 15mm (Fig. 1b), and the hardness is HB165. The ratio of the relative permeability of 1Cr18Ni9Ti to high-speed steel (W18Cr4V) is 1:302 at normal state, and it has paramagnetism at normal state. The hardness of high-speed steel is HRC60. The chemical composition of pin-ring samples is shown in TABLE I [18].

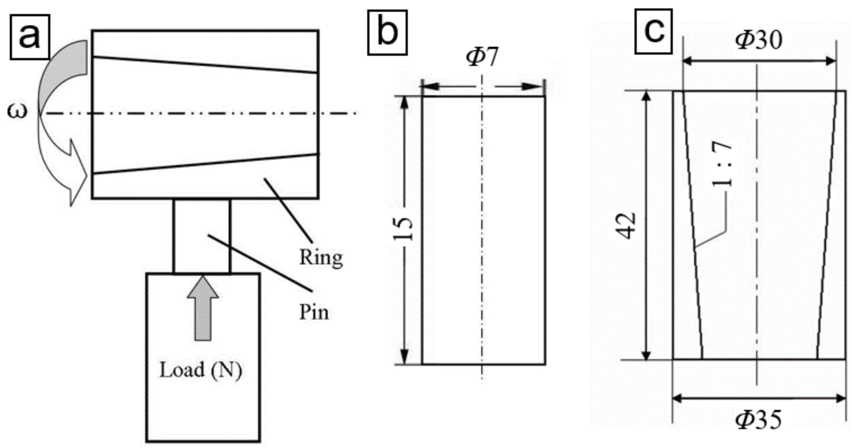

Fig 1: Diagrammatic sketch of the contact form (a), pin (b), and ring (c)

The material of friction pairs was selected. Considering that the size of the ring specimen (Fig. 1b) is large and the actual friction contact surface is narrow. It is difficult to carry out microscopic analysis. In order to facilitate the microscopic analysis of the friction superficies of pin specimens after the test and to explore the wear mechanism, the ring specimen must have a good wear resistance. High-speed steel [11, 14-15] is a tool steel, belongs to the ferromagnetic material, has high hardness and heat resistance and wear

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resistance. It can still maintain high hardness at high temperature (about 500 celsius degree). High-speed steel has a good processing properties, a good combination of toughness and strength, which is mainly used to manufacture high temperature bearings, complex thin edge, cold extrusion dies, as well as cutting tools of impact resistant metal. Therefore, high-speed steel (W18Cr4V) was selected as the material of ring sample with the size of φ35mm × 42mm (Fig. 1c). And its hardness is HRC60.

TABLE I. The composition of high-speed steel and 1Cr18Ni9Ti Stainless steel (percentage)

Pairs / Element	C	Si	Mn	Cr	Mo	V	W	Ni	P	Ti	Fe
1Cr18Ni9Ti	≤0.12	≤1.0	≤2.0	17-19	-	-	-	8-11	≤0.035	0.80	others
W18Cr4V	0.79	0.21	0.15	4.20	0.11	1.16	18.65	-	0.026	-	others

2.2 Methodology

Tribological tests were carried out on the MPV-1500 model tester improved. The contact form of pin-ring is put to use in the machine, which is loaded automatically by hydraulic pressure. It can realize automatic loading, unloading and CVT. The maximum load can reach 2.0 KN. The spindle speed is 80r/min~2400r/min, i.e. the linear speed is 0.146m/s~4.4m/s. The test condition is under sliding speed 0.6m/s and load 200N friction sliding running 15min continuously. To minimize errors, each experiment was done three times to calculate the average of the results.

The wear loss is obtained by measuring the weightlessness of wear. The pin and ring samples were weighed by an electronic balance BS210S with one thousandth accuracy. And the wear loss ΔW was calculated, and the wear rate ΔW’ was also calculated through referencing the formula (1).

The wear rate formula ΔW’ is:

$$\Delta W' = \frac{\Delta W_{Before} - \Delta W_{After}}{2\pi R n t} \tag{1}$$

Where, n is ring rotational speed (*r/min*), R is outer ring radius (*m*), $\triangle W$ is wear loss (*g*), t is friction lasted time (*min*).

The friction coefficient μ formula is:

$$\mu = \frac{M}{NR} \tag{2}$$

M is torque (N. m), N is normal pressure (N) applied on the pin specimen, R is ring specimen radius (m).

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Magnetic field is adjusted by changing the voltage of the energizing coil. Magnetic flux through pin cross section of the specimen was measured with a digital fluxmeter HT701. Magnetic field strength at cross section of specimen friction surface was calculated. After each test, the sample pins were demagnetized with a demagnetizer TC-2 model and cleaned with the absolute ethanol.

III. TEST RESULTS AND DISCUSSION

Fig. 2 shows the microstructure of the longitudinal section of pin at magnetic field strength is B=214mT (×500 and ×1000, respectively). As shown in Fig. 2, there is a rheological layer on the subsurface of the friction surface. The analysis shows that the hardness of the pin is low under a normal condition, whose matrix is a paramagnetic material with austenite structure and very low magnetic permeability. The austenitic stainless steel has strong work-hardening characteristics. Under the action of fluctuating normal pressure and friction force, plastic deformation easily occurs on the friction subsurface (Fig. 2), resulting in a rheological layer, which can improve the magnetic permeability of the friction surface and subsurface of the sample pin [19]. In a magnetic field, its magnetism increases and has certain adsorption on the debris. Fig. 3 is an EDS energy spectrum analysis of the longitudinal section of the friction pin at B=214mT. From Fig. 3, the closer to the friction contact surface of the test piece, the more the content of oxygen element is. It indicates that the oxide layer is formed under the combined action of the friction heat effect and O2 in the air [20].

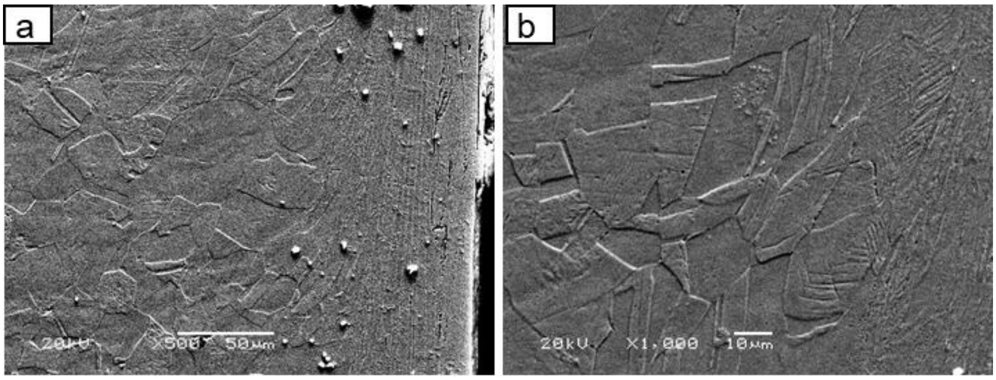

Fig 2: The microstructure of cutaway surface of friction subsurface of specimen pin (B=214mT): (a) ×500, (b) ×1000

Fig. 4 displays the wear rate changing trend of 1Cr18Ni9Ti pins when magnetic field strength changes. From Fig. 4, the wear rate decreases slightly as the magnetic field strength increasing. Fig. 5 is the electron microscope feature of the pin friction surface under the different strength of magnetic-field. Fig. 5 shows that there is a distinct furrow in Fig. 5a when there is no magnetic field. As magnetic field strength magnifying, morphology of friction surface looks smooth at B=116mT (Fig. 5b), and then debris adheres to friction surface at B = 260mT (Fig. 5c). In the process of friction and wear, the undulating normal pressure and friction force produce debris on the friction surface of specimen (Fig. 6). After the magnetic field is brought to bear on, pin matrix is strengthened, wear rate decreases as the increasing of the strength and hardness of the matrix. On the other hand, the contact surface absorbs

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debris. And some debris retains partly, which is not easy to fall off, and can prevent direct contact between friction pair and matrix, so that wear rate reduces. Therefore, in the wake of magnetic field strength increasing, wear rate of pins decreases, and the morphology of friction surface becomes more and more smooth.

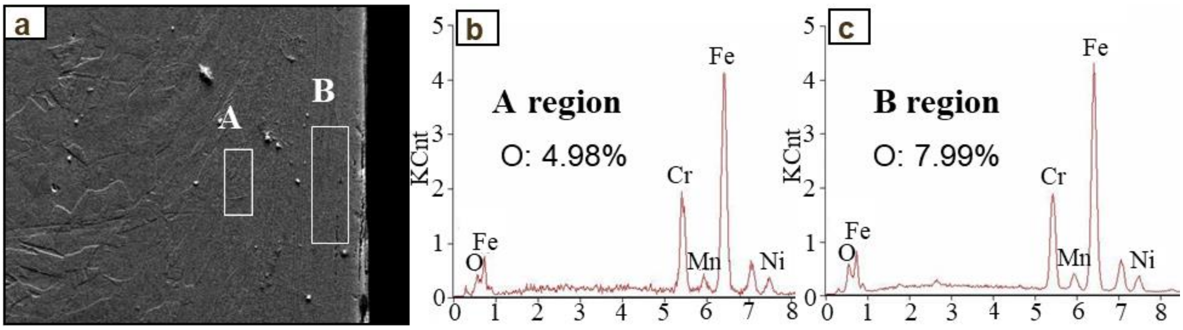

Fig 3: EDS analysis of sub section of friction subsurface (B=214mT): (a) SEM, (b) EDS (A region), (c) EDS (B region)

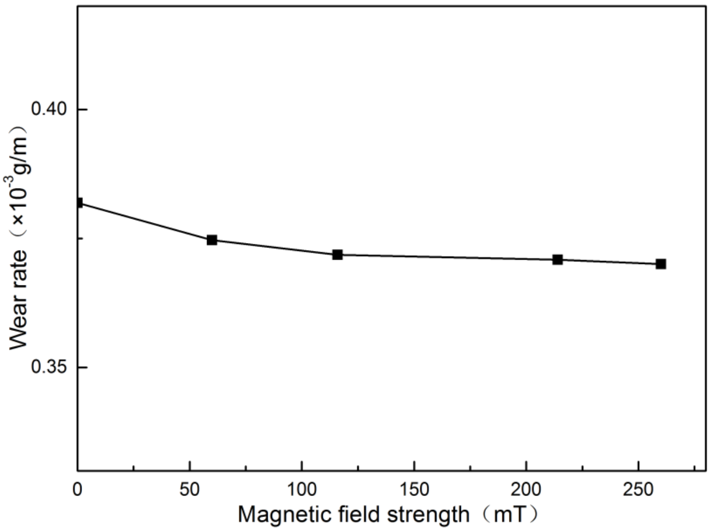

Fig 4: Effect of magnetic field strength on specimen pin wear rate

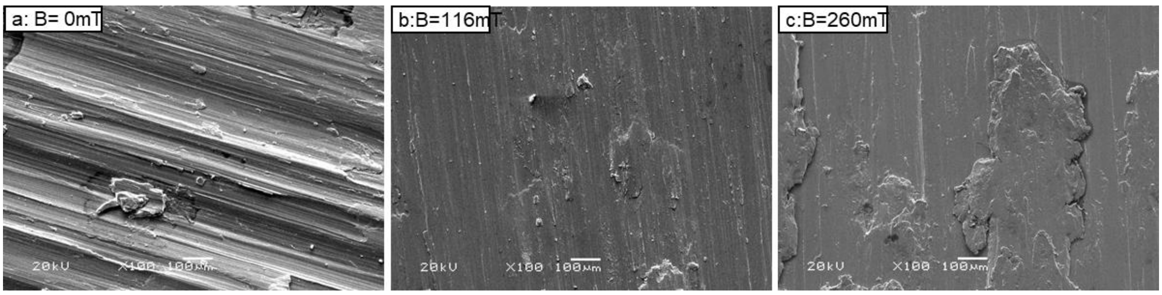

Fig 5: SEM appearance of friction surface with different strength of magnetic field：(a) B=0mT, (b)

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B=60mT, (c) B=260mT

Fig.6 shows the SEM morphology and EDS composition analysis of debris under different magnetic field strength. Compared with Fig. 6a, when magnetic field strength magnifies to B = 116mT (Fig. 6b), the size of the abrasive debris becomes smaller and finer, and the oxygen content of the abrasive debris increases obviously. Fig. 7 shows a XRD diffraction analysis of the frictional surfaces of different pin specimens under the magnetic field imposed. From Fig. 7, the formation of Fe2O3 and Fe3O4 increases with the increase of magnetic-field strenth. It should be known that the Fe3O4 can be generated only at a higher temperature. In the magnetic field environment, the pin sample has the ability to absorb and capture the debris, so that the debris takes part in the wear for a longer time, and slows down the heat dissipation; at the same time, it promotes the temperature of the friction surface, and the oxidation reaction proceeds in the positive direction, which promotes the oxidation.

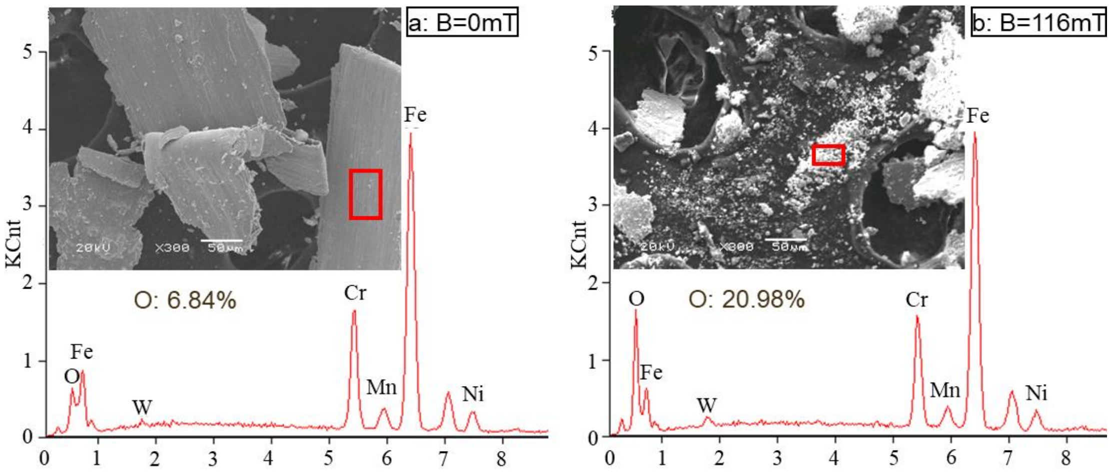

Fig 6: Debris SEM and EDS under different magnetic field strength：(a) B=0mT, (b) B=116mT

In order to approve that magnetic field can promote oxidation [21], a static experiment was carried out. The experimental results are shown (Fig. 8). It can be seen that the oxidation corrosion rate of medium-carbon-steel in magnetic field environment is more than that of no magnetic field environment, and humid environment can promote oxidation corrosion. It is basically confirmed that magnetic field environment can reduce the activation energy of oxidation and promote oxidation. The testing process is as follows: 1) Two samples with the same size and mass of 25.6240 g and 26.3490 g respectively were processed from the same medium-carbon-steel (ferromagnetism) and placed in a plastic cups separately, one of which was placed on a permanent magnet, and the two plastic cups were 2.5 meters apart. 2) Because the surface of the newly processed samples are relatively smooth, in order to promote its oxidation corrosion rate, the injector is first used to add 10 ml tap water to each plastic cup, then 10 ml medical H2O2 water is added separately. Subsequently, 5 ml tap water is added every other week to ensure that the sample is in a humid environment for 74 days. Then, the samples are taken out and put into each plastic sample bags for a demagnetizing treatment. The weights of the samples are weighed on one thousandth of the analytical balance, and their respective gain weights are calculated. 3) Return to

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the original plastic cup separately, no water is added, and exposed to air for 93 days. Take out the sample for demagnetization treatment, weigh them separately and calculate their weight gain. The result shows that, compared with no magnetic field, weight gain of sample under the magnetic field environment is 0.0273g higher in 74 days of wet environment and 0.0083g more in 93 days of dry environment, as shown in Fig. 8.

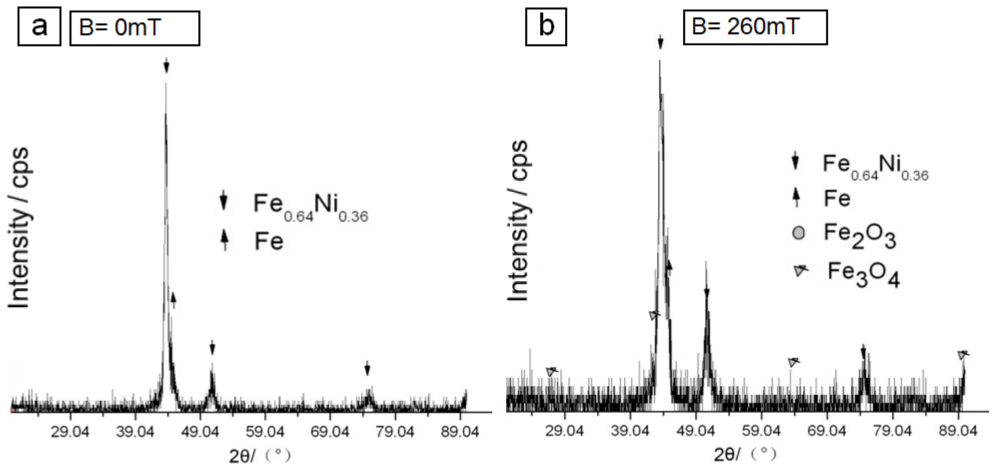

Fig 7: XRD diffraction analysis of pins friction surface under diverse magnetic field strength: (a) B=0mT, (b) B=260mT

The reason why the debris is adsorbed by the magnetic field on pins friction surface is. At first, under the action of normal pressure and friction force, plastic deformation of an austenitic-stainless-steel easily occurs on the friction subsurface because of its work hardening characteristics (Fig. 2), resulting in a rheological layer, which can improve its permeability. Second, the pin contains a high content of Fe. The friction heat will increase the temperature of the friction surface. And some of the wear debris will be oxidized, whose main components of the wear debris are Fe-Cr, FeO, Fe2O3 or Fe3O4 (Fig. 6). The Fe element belongs to a ferromagnetic material, while FeO, Fe2O3 and Fe3O4 belong to a ferrite (ferromagnetic material) generally. They can all be absorbed by magnetic field force. On the other hand, the superparamagnetic phenomena occur in the magnetic field when ferrite or other particles in the debris are repeatedly refined to nanometer size (Fig. 6b). (Magnetic nanomaterials [22, 23] have been used in many fields, such as biosensor technology, biomedicine and environmental engineering). The superparamagnetic phenomena can increase the magnetic permeability and magnetic induction intensity of the nano-scale abrasive debris by more than one order of magnitude, which makes it possible to be adsorbed by the friction surface greatly.

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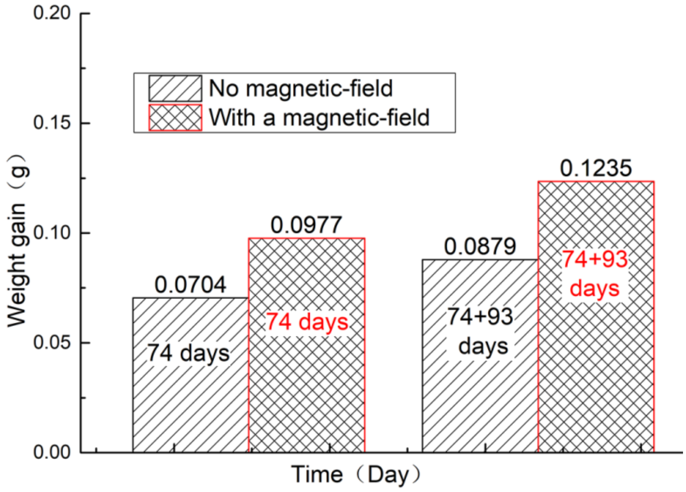

Fig 8: Weight gain of medium carbon steel with or without magnetic field

From Fig. 4 as magnetic field strength increasing, the wear rate decreases slightly and then tends to be gentle. On the one hand, the thickness of the rheological layer of the subsurface layer on the friction surface will not always increase when the applied load is unchanged. Compared with normal condition, magnetic permeability of subsurface layer of pin specimen will increase, but it will reach a stable state and no longer increase. Then, along with magnetic field strength increasing, magnetic-induction strength of the pin sample enlarges again. Because the permeability of the friction subsurface layer is almost constant and relatively small, the magnetic induction strength of the pin sample quickly reaches saturation. The bigger the magnetic field strength is, the thicker the oxide layer can be adsorbed. On the other hand, the magnetic attraction increases with magnetic field strength increasing because the bonding force between oxides themselves and the oxide and the matrix is fixed. Therefore, as magnetic field strength increases to a certain value, the thickness of the oxide layer enlarges some certain value, whose bonding can not withstand fluctuating normal pressure and friction shear stress, the oxide layer falls off and the thickness will not increase any more. Finally, the dynamic equilibrium is achieved. Therefore, in the wake of magnetic field strength increasing, wear-rate decreases only slightly, and then tends to be gentle.

Fig. 9 is the altering of the friction coefficient with magnetic field intensity enlarging. From Fig. 9, at first the friction coefficient decreases, and then becomes gentle in the wake of magnetic field strength increases. The ring of pairs is made from high speed steel, whose hardness is bigger, and the hardness of the pin 1Cr18Ni9Ti is lower. In progress of friction and wear, when B = 0mT, the specimen pin friction surface has a large plastic deformation (Fig. 5a), resulting in a wider and deeper furrow. The friction contact surface meshes with each other with the larger convex and concave furrows, resulting in a big actual contact area and big friction resistance. Thus, friction coefficient at B = 0mT is larger. As magnetic-field exerting and increasing, some of the debris generated in the friction process is adsorbed in the friction contact surface and trapped in the furrows or spalling pits of the friction surface. The heat because of friction makes the debris self-generated into oxide. In the wake of magnetic field strength increasing, the friction surface will tend to smooth (Fig. 5). The higher the friction superficial layer temperature is [14], the more the oxides produced are (Fig. 7). Because of the lubrication of oxide layer,

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friction coefficient decreases along with the magnetic field strength enlarging. When oxide content form friction surface reaches a certain proportion, it will not increase any more. The friction coefficient tends to be flat while the relative stability value is maintained.

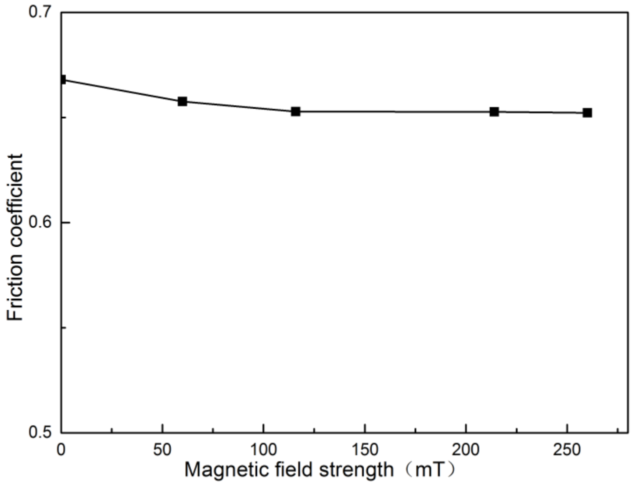

Fig. 9. Variation of friction coefficient with magnetic field strength enlarging

IV. CONCLUSION

(1) The austenite 1Cr18Ni9Ti pin has paramagnetism and obvious hardening characteristics. Under a normal condition, its permeability and hardness are low. The work hardening occurs during the friction and wear to form the rheological layer, which improves the hardness of the surface and subsurface layer. At the same time, the content of austenite phase in the friction subsurface layer decreases, the phase content of martensite and ferrite increases, that is, the ferrite phase increases, which increases the permeability of the friction subsurface layer and enhances the magnetic field's ability to absorb debris. At the same time, the magnetic strengthening effect occurs in the subsurface layer of the pin specimen under the magnetic field, which is beneficial to increase its strength and hardness.

(2) The work hardening and magnetic strengthening of the surface and subsurface layers of 1Cr18Ni9Ti pin are advantageous to decrease of wear rate, as well as the friction coefficient. The effect from the fluctuating positive-pressure and friction-force on the friction surface is bound to produce debris. When the magnetic field is brought to bear on, frictional contact surface absorbs debris under the magnetic field suction action, and makes some of the debris stay for a time, which is not easy to fall off. The abrasive debris is refined by repeated positive pressure and friction, which can enhance adhesion and adsorption, so that the oxidation is promoted. The abrasive debris is easier to form oxide layer, which can prevent the direct contact between the matrixes of the frictional pairs and reduce the wear rate.

(3) The bonding forces between the adsorbed debris themselves, the debris and the friction surface are relatively small and unstable, and similar ball action will occur, which is beneficial to reducing the

friction coefficient. It is generally believed that oxide (layer) also helps to reduce the friction coefficient.

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