Transitions of Wear Characteristics for Rubber/Steel Seal Pairs During the Abrasive Wear Process

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Abstract

Abrasive wear resulting from the microclastic rock is a common failure phenomenon in the drilling environment that often limits the sealing ability and the service life of seals. In this study, the friction and wear process of fluoro rubber (FKM) seals against 304 stainless steel (SS304) after one single entry of SiO_2 abrasives were investigated. The influence of the changes in particle state on friction coefficient evolution, wear loss evolution, wear morphologies and wear mechanisms were discussed in detail. The results indicate that the presence of abrasive particles dispersed between the sealing interface clearly improves the friction performance of the seal pairs and deteriorates the wear performance of the metal counterpart. The movement and breakage of particles after one single entering into the sealing interface were obtained. And on this basis, the stable wear process can be divided into three stages. In addition, the main causes contributed to this change of wear mechanisms are the random movement and process of continuous breakdown of abrasive particles. Furthermore, the transition of the wear mechanism that clearly describes the wearing behavior of the seal pairs under these abrasive wear conditions was identified. The results of this study enhanced our understanding of the abrasive wear degradation of rubber seal in practical drilling applications.

Introduction

Fluoro rubber (FKM) is widely used as an ideal sealing material in deep hole drilling machinery because of its excellent performance at high temperature, such as incomparable high temperature resistance, excellent resilience, high tensile tear property, corrosion resistance and resistance to wear [1–3]. FKM seals (especially dynamic seals) can operate in hostile environments from fracturing rocks, which prevents the leakage of drilling fluid (the “mud”) from drilling tools and the contamination from the surrounding drilling fluid (mainly the microclastic rock) entering the drilling tools [4, 5]. In the drilling environment, FKM seals will be gradually worn away to failure, eventually leading to eventual seal degradation. Among all the sealing failure mechanisms, abrasive wear resulting from the microclastic rock is considered the primary mode in most cases [6, 7]. Therefore, to effectively improve the sealing ability and the service life, it is essential to understand the abrasive wear process of seals in this particular abrasive environment [5].

A lot of fundamental research efforts have been undertaken on improving the understanding of seal failure owing to abrasive wear. According to the results of these studies, the detritus in the abrasive environment will enter into the sealing interface of the contact pairs during the friction process, which can accelerate the degradation of the seals and the surface damage of hard metals [8–13]. Nevertheless, most of these research results were discussed only by analyzing the final experimental results, including friction coefficient, wear amount and typical wear morphology, etc.. In these analyses, the effect of particles on the friction and wear process was not considered, which is not comprehensive. Our previous research discussed the effect of non-uniform mixed particles with different sizes on the three-body abrasive wear mechanism [14]. In that work, repeated fragmentation phenomenon of particles is discovered, which indicates that under the abrasive wear condition, the existence state of particles will

change constantly during the wear process. Different existence states, such as particle's movement, fragmentation, and embedding, will affect the final wear results, which makes the results appear great random characteristic [15–17]. Therefore, the research results of the current study about the abrasive wear of seals are not yet enough perfect, which limits the progress of rubber seals that provide efficient service properties [5]. To optimize the design of seals for downhole applications, the effects of the changes in particle state on seal failure mechanism during the real abrasive wearing processes must be understood more clearly first, which has been looked at by few current studies.

In addition, due to the actual environment is complex, simulating the downhole abrasive environment accurately will make the analysis complicated. In order to simplify, the current studies usually simulated the abrasive environment by fixing hard particles in one of the contact surfaces or entraining hard particles with single sizes into the contact zone by a rotating rubber wheel according to ASTM standard [18, 19]. In fact, such abrasives are not fixed, but may move freely between the sealing interface [20–23]. Furthermore, in terms of the entry mechanism of particles, for downhole applications in particular, it is generally believed that the particle entering into the sealing interface is related to the violent vibration of downhole tools [24–26]. The drill string vibration is random, so the entry of particles is necessarily not continuous, but random. The size and amount of particles entering the sealing interface are related to the drill string vibration parameters, such as vibration types, amplitude, frequency and so on [27, 28]. The amount and size in each one single entry of the particles are not the same, which is bound to cause significant changes in the final wear results. It can thus be seen, there is still a little bit different between the existence state of particles in existing experimental methods and the actual state of particles. Therefore, in order to more accurately understand this particular abrasive wear process, it is necessary to explore more suitable experimental methods to study this process first.

As is known to all, the real abrasive wear process in the drilling environment is very complicated, which is hard to be simulated accurately [29]. Therefore, it is desirable to choose the appropriate simulation method according to the specific problem being studied. To simplify the analysis, the effect of the particles' entry process can be temporarily ignored first. This paper focuses on what happens after the entry of particles. In view of this, the particles can be pre-spread uniformly on the seal surface first before assembling the test system, which makes the particles exist between the sealing interface at the beginning of the test. This experimental method for simulating the single entry process of particles has been introduced in our previous research, which has been shown to be feasible [14]. The movement and breakage of particles after one single entering into the sealing interface can be effectively observed by using this method. Therefore, this method is particularly suitable for the study of the problems that we concern about. Therefore, in this paper, one kind of abrasive wear environment with single particle size was chose as an example to investigate the influence of the changes in particle state on the abrasive wear process. Compared with the condition without SiO₂ abrasives, the friction and wear process of FKM against 304 stainless steel after one single entry of SiO₂ abrasives were studied. The motivation behind this work is to understand the effect of the changes in particle state on the abrasive wear process of rubber/steel pairs, which will be useful to the optimum design of the seals used in drilling tools.

Experimental Materials And Methods

2.1 Test Rig and Materials

A MMW-1 multi-function tribo tester was used to investigate the abrasive wear process of seal materials, which is shown schematically in Fig. 1. This test rig was manufactured by Jinan OuTuo Test Equipment co. LTD (China), which conformed to the ASTM D3702-94 Standard. As indicated in Fig. 1a-b, a upper metal disk slid against the lower rubber ring sample at a selected rotation speed controlled by an AC motor. As shown in Fig. 1c, the upper metal disk with a diameter of 55mm was made of a stainless steel (SS304) by Tianjin Lurie Stainless Steel Trading Company (China). The counterpart was a O-ring seal with the outer diameter of 47.1 mm and inner diameter of 40mm (Fig. 1e), which was made of FKM by Sannai (Changshu) New Materials Co., LTD. (China). Before each test, the surfaces of the SS304 disk specimens were polished to a surface roughness (Ra) of 0.05-0.1 μm . The FKM specimens were ultrasonically cleaned with ethanol and dried in a drying oven for 30 min to remove moisture. The surface micrographs of the FKM ring and SS304 disk are shown in Fig. 2. The main physical properties and structural parameters of them are listed in Table 1.

As the abrasive wear resulting from the microclastic rock is considered the primary sealing failure mechanisms, the microclastic rock particles were selected as the abrasive particles to imitate the hostile service environment of seals. The main composition of abrasive particles was SiO_2 , which was the main component of rock. In the experiments, SiO_2 particles with 140-160 mesh size were used, which is common between sealed interfaces. The average grain sizes (d) of correspondence were approximately $100 \pm 20 \mu\text{m}$. Fig. 2b shows the SEM morphology of the chosen SiO_2 particles. The chemical compositions of all the test materials are shown in Table 2.

2.2 Test Method and Program

Abrasive wear tests were conducted using MMW-1 multi-function tribo tester in dry sliding conditions. During the tests, the lower ring specimen (FKM) remained stationary and covered with a uniform abrasive medium, whereas the upper disk specimen (SS304) slid against the ring surface of the FKM in a rotating way. In the current study, the abrasive environment was not simulated by fixing particles in one of the contact surfaces or entraining particles into the contact zone sustainably according to ASTM standard. Before assembling the test system, the SiO_2 particles were pre-spread evenly on the lower FKM specimen, as shown in Fig. 1d. At the beginning of the friction process, the SiO_2 particles have already exist between the sealing interface, which can simulate the the state of the homogeneous particles after entering into the sealing interface. In this test, the normal load of 100 N was applied to make the compression rate of FKM seal reach 8%, which is common used for rotating sealing in the drilling condition. The experiments were carried out at a rotation speed of 120 rpm, the corresponding linear velocity of which is 0.26 m/s. All the tests (unless specified otherwise) were conducted at room temperature and for a duration of 90 min. The friction coefficient was recorded continuously by testing the applied normal force and the frictional force real-timely.

In order to obtain the interface state at different times in the abrasive wear process, a series of segmented tests were carried out after 15min. Every segmented test was repeated at least three times to ensure the reliability of test results. Before and after the tests, the masses of specimens were obtained on an electronic balance with up to 0.01 mg of accuracy. The average values of wear volumes were recorded after five repeated measurements under the same conditions. After each test, the surface morphologies of worn tribo-pairs and the particles were analyzed by using scanning electron microscopy (SEM, MERLIN Compact, German Zeiss). And the compositions of samples were analyzed by X-ray energy dispersive spectrometer (EDS).

Results And Discussion

3.1 Time-Variable Characteristics of Friction Coefficient

Fig. 3 displays the friction process of FKM sliding against 304 stainless steel under different conditions (with and without SiO_2 abrasives). The abrasive particles had a significant effect on the friction coefficients. However, unlike the results obtained by the conventional test method, the friction coefficient under the abrasive wear condition (Condition 2) was much lower than that under the condition without abrasives (Condition 1), which indicated that the addition of particles can improve the friction performance of the seal to some extent. This is similar to the results obtained by Heshmat et al. [5]. At this point, the hard particles could sustain loads to improve lubrication, the properties of which were similar to those of the lubricating film. The presence of particles decreased the factual contact area between the FKM ring and SS304 disk effectively, which could weaken the contribution of the rubber adhesion to tribological behaviors [20, 30]. In addition, under such a condition, the abrasives could move freely between the sealing interface in the form of rolling or sliding, which was bound to weaken the hysteresis effect caused by rubber deformation. The results suggest that the appearance of hard particles is not all bad for FKM seals. To a certain extent, the contact form between the sealing interface was found to be improved, which could enhance the stability of the whole drilling system [31, 32].

Although there was a big difference in the value of friction coefficient, the time-varying curves of the friction coefficients under the abrasive wear environment were similar to those under the abrasive free environment. All the evolution characteristics of the friction coefficient curves could be divided into two stages. First, the friction coefficient decreased after a significant increase as the friction times increased (Stage I), and then the friction coefficient entered the stable stage (Stage II). This phenomenon has been explained in many studies, which will not be repeated here. In addition, some interesting phenomena was found. The peak value at Stage I under the Condition 2 was much lower than that under the Condition 1. This result may be attributed to the weakening of the strong adhesion between FKM seal and metal component [29]. FKM was a viscoelasticity material, the large adhesion area of FKM seal on the SS304 surface was easy to form, which seriously affected the progress of friction. Due to the existence of particles, this large adhesion area was difficult to be formed. Thus, the increase of friction coefficient was not that high at Stage I under the Condition 2.

In addition, a random “wave peak” feature at Stage Ⅱ under the abrasive free environment was not found under the Condition 2. As is known to all, this fluctuation in the coefficient of friction was related to the hysteresis of the rubber friction [20, 21]. When the rubber acted on the metallic counterpart surface under the Condition 1, the hysteresis component of the friction was still an important component. Thus, the coefficient of friction still fluctuated. Due to the existence of particles, the hysteresis of the friction seemed to have waned. This phenomenon will be explained in detail in Section 3.3.

Besides, as shown in Fig. 3, there was a slight steady upward trend in all the friction coefficients at Stage Ⅱ. This may be related to the wear of the friction pair. In order to accurately analyze the friction process, the wear changes of both tribo-pairs in the stable stage were tested and shown in Figs. 4 and 5.

3.2 Wear Volume Analysis

3.2.1 Wear Loss of FKM Ring

The wear losses of FKM rings in the stable stage under different conditions are shown in Fig. 4. As shown in Fig. 4, the wear processes of FKM materials under different conditions were similar. With the Condition 2, for example, in the early stage of Stage Ⅱ, there was little change in wear loss, which demonstrated there were no serious wear and tear at this time. After stable wear was established, the wear effect seemed to decrease. However, with the friction process went on (after 45 min), an increasing trend of the wear loss appeared, which showed that the wear became serious over time. The serious wear made the contact of the friction pair worse to affect the friction process in turn. Therefore, the friction coefficient increased slightly after a period of friction.

Furthermore, there was a difference in the wear loss under different conditions. In the early stage of Stage Ⅱ under the Condition 2, the wear loss showed a trend of negative growth, which should be related to the insertion or attachment of particles. Since the amount of material loss was less than the embedded mass, the weightlessness showed a negative growth trend in the early stage. As the wear progressed, the embedding amount of particles increased, reaching a peak at about 45 minutes. As the wear intensified, the particles attached gradually fall off, making the wear amount under the Condition 2 gradually increase. It could be seen that the existence of particles did change the whole process of friction and wear.

3.2.2 Wear Loss of SS304 Disk

There was little variation on the wear loss of the SS304 disk during the wearing process under the Condition 1. Thus, only the wear losses of SS304 disks under the Condition 2 were shown in Fig. 5. Unlike Condition 1, the SS304 disk showed a relatively severe wear under the Condition 2. The wear process of the SS304 disk could be divided into 3 phases: rapidly rising (Stage Ⅱa), slowly rising (Stage Ⅱb) and final steady phase (Stage Ⅱc). There was a correlation on the the wear loss between the FKM ring and the SS304 disk. At Stage Ⅱa, the SS304 disk was damaged significantly. The presence of particles caused the severe wear of SS304 disks, but reduces the wear loss of the FKM ring. After Stage Ⅱb, the wear of the

FKM ring began to increase, and the wear of the SS304 disk became slower. This also indicates that the wear mechanism changed constantly during the whole abrasive wear process. In addition, the wear amount under the Condition 2 was obviously lower than that under the Condition 1, which could also support our analysis of the changes on the hysteresis component. However, due to the presence of the embedding particles, it was difficult to accurately reflect the real wear process and wear state of the rubber by only analyzing the difference of wear mass loss. Hence, the wear morphologies of materials during the friction process were analyzed.

3.3 Wear Morphology Analysis

3.3.1 Surface morphology of SS304 Disk

The worn surface features of the SS304 tribo-pairs at different time nodes are shown in Fig. 6. As shown in Fig. 6a, at about 15min, there were a large number of ploughing marking paralleled to the sliding direction on the surface of SS304 tribo-pairs. At about 45min, some micro-cutting pits started to appear on the surface, and the ploughing gradually deepened (plough width were usually 5-10 μ m). The deeper ploughing and pits scattered and spread out over the surface. In addition, some small scratches were also discovered (Fig. 6b). After 53min, the number of pits increased (average diameter ranges were 5-20 μ m, irregularly shaped) and more ploughing began to appear (Fig. 6c). At 90min, some wide range of ploughing were destroyed by pits (Fig. 6d), and the special morphology (micro-cutting pits combination furrows) appeared on the surface.

3.3.2 Surface Morphology of FKM Ring

Figs. 7d and 7e show the final worn surface features of the FKM rings under different conditions (with and without SiO₂ abrasives). Under the Condition 1, the typical “Schallamach waves” pattern, a series of periodic parallel ridges perpendicular to the sliding direction, appeared on the wear surface of the FKM rings, which is consistent with the findings of many researchers [33–35]. Under the abrasive wear condition, the “Schallamach waves” pattern was also found on the worn surface of the FKM ring. But they were smaller and denser than that generated under the Condition 1. To further explore the reasons for this change, the worn surface features of the FKM rings at different time nodes were tested and shown in Figs. 7a-d. It can be seen that the wear morphology had great difference in different stages. At 15 min, there were some pits on the surface of the FKM ring, which showed the markings of particles being embedded (Fig. 7a). At 45 min, the scratches parallel to the sliding direction started to become the main form of damage on the FKM surface. Those scratches were approximately 1-2 μ m wide. At this point, a few of pits with the diameter of approximately 10 μ m were also discovered (Fig. 7b). It can be seen that the FKM wear was exacerbated not as the wear results indicated in Fig. 4. As the friction progressed, these scratches were gradually removed and new wear morphologies were found. At 53 min, plenty of micro-cutting pits (marked by a circle, Fig. 7c) and degraded ploughs (marked by a rectangle, Fig. 7c) could be found on the majority of the surface of the FKM ring. It can be seen that before 53 min, there were no distinct “Schallamach waves” patterns on the worn surface. After that, “Schallamach

waves” patterns gradually appeared as the wear progressed further. At the final stage (at 90 min), there were also some smaller and denser “Schallamach waves” on the surface of FKM ring. It followed that the effect of the particles gradually weakened, and the typical two-body wear characteristics began to appear. These changes of wear characteristics should be related to the changes of particles state between the sealing interface. To further investigate the effect of the changes on the wear mechanism, the particles embedded in the ring and debris were analyzed.

3.3.3 Insertions on FKM Ring

Fig. 8 shows the SEM images of insertions on the worn surfaces of FKM rings during the abrasive wear process (45min as an example). There were some iron filings and particles embedded to the FKM ring surface. From Fig. 8a, the shape of iron filings resembled thin slices (5-20 μ m long) or strips (<5 μ m). The slices were embedded directly into the FKM surface by their sharp ends. Besides these iron filings embedded, particle fragments were also discovered on the surface of the FKM ring, as shown in Fig. 8b. Some notable wear scars could be found under the debris, indicating that those particles generated from the particles crushing and disintegration during the sliding process. Nevertheless, there were large amounts of original filling bodies in FKM rings shown in Fig. 9, which would fall off and enter into the friction interface during the wear process. In order to figure out the source of the particle fragments attached to the FKM surface, a comparative EDS analysis of these particles was analyzed and shown in Fig. 10. The particle fragments in Fig. 8b have the same compositions of Si and O as the SiO₂ particles applied in the experiments, which indicated that these particles were mainly the broken SiO₂ particles. The locations embedded by these particles were also accompanied with the wear scars and ploughs. The abrasive fragments with sharp edges were easily inserted into the FKM ring surfaces, and the iron filings with sharp ends could also easily be embedded into the FKM ring surfaces, which indicated that a slower rate to the mass loss of the ring was caused by more inserts.

3.3.4 Dissociated Particles and Debris Between the Sealing Pairs

The distribution and state of the dissociated particles between the sealing pairs during the stable wear process were tested and shown in Fig. 11. In the stable wear stage, the existence state of particles was similar to some extent. Thus the state at 45 min was chosen as an example for analysis because it was more representative. At this time, both the friction and wear had great changes, which can be seen in Figs. 3-5. As shown in Fig. 11a, there were three different sizes of particles: 1-5 μ m clastic sediments (1P), 10-20 μ m abrasive fragments (2P), and 100 μ m abrasive particles (3P). The most common particles were the 1P particles, which were formed by particles crushing during the wearing process. The 1P particles had a tendency to form small clusters and distribute around a larger abrasive particles. The 2P particles were generated from the original abrasive particles by high contact pressure, whose shapes were like spindles with spikes on one end. The least common particles, largest abrasive particles (3P), scattered evenly on the surface of the FKM ring. It can be seen that it was difficult for larger particles to exist completely between the friction interfaces. The original large particles were more likely to be broken or pushed out of

the interface as the friction went on (Fig.11b). Embedded debris on the FKM ring might form from the larger abrasive particle due to the friction exerted to the ring.

In addition, the appearance of iron filings and the discharge of abrasive fragments could be easily observed on the non-contact area (Fig.11b). The particles and debris embedded on the FKM ring could form a “grinding wheel”, causing severe wear damage to the SS304 pair and generating iron filings in the friction process. Iron filings usually were long strips (50 μ m long and 2 μ m wide) with spikes on the end (like the thorns on the vine). According to Fig. 6, it seemed a reasonable assumption that the abrasive particles were embedded into the rubber ring surface in the early wear stage, applying the sliding wear to the stainless-steel pair. As the wear went on, some abrasive particles were broken into small fragments, and the embedded particles in the rubber ring began to roll in the sealing interface. At the final stage, the abrasive particles became so smaller which almost can't be discharged. Therefore, the main wear mechanism in the sealing pairs seemed to have been changed.

It was absolutely accepted that the abrasive particles played an important role in the wear process. Before 45min, the wearing form changed from uniform wearing to non-uniform wearing because of the transition of the particles states during the wearing process. As the number of abrasive particles increased and the number of large original particles decreased, the partial pressure of the sealing contact interface and the friction coefficient decreased. After 45 min, the friction coefficient started to increase slowly and the wear pattern resembled adhesive wear.

3.4 Stable Wear Processes Analysis

According to the micro-morphologies of FKM ring/SS304 disk, the stable wear process under the abrasive wear condition could be divided into 3 phases. In the first stable stage (Stage IIa), large amount of trails can be found on the surface of the FKM ring after the particles embedded into the FKM ring. Those embedded abrasive debris and iron filings caused the decrease to the friction coefficient and the mass of the FKM ring increase. Meanwhile, the surface of SS304 pair showed severe wear. Ploughs could be found on majority of the surface area and the mass loss of the stainless-steel was greatly increased. At Stage IIb, large number of ploughs and micro-cutting pits appeared on the surface of the FKM ring, indicating the severe damage. The number of micro-cutting pits increased slowly on the surface of the stainless-steel pair. The wear mass loss of the FKM ring started to increase and the the wear mass loss of the SS304 pair started to slow down. At Stage IIc, the FKM ring wear mass loss still increased slowly, and the wear mass loss of the stainless-steel pair showed less changes.

3.5 Wear Mechanism Analysis

From the experiment results and the wear surface topographies analysis for the FKM ring/SS304 pair, the wear mechanism of the whole friction was constantly changing. For the present work, the schematic sketches of the typical wear mechanisms at different stages, shown in Table 3, were put forward to explain this changing wear mechanism in the abrasive wear condition. In the initial stable phase of the abrasive wear (Stage IIa), the main wear mechanism of the FKM ring was the ploughing effects caused

by the abrasive particles and the iron fillings from the SS304 disk. During this period, the wear amount of the SS304 pair increased sharply and the furrows spreaded on majority of the surface while the surface of the FKM ring showed little wear. In the second stage (Stage Ⅱb), the main form of movement of the abrasive particles was rolling as the third-body in the sealing pair. The mass of FKM began to reduce, and wearing marks, such as micro cutting pits, can be found on the majority of the surface area. In contrast, the SS304 pair also had micro-cutting pits, but the wear on that was much milder. In the later stages (Stage Ⅱc), the wear mechanism of the sealing pairs resembled adhesive wear, and some typical “Schallamach waves” patterns began to appear on the surface of the FKM ring. The SS304 surface showed a special shape of pits combination furrows. Compared with the Condition 2, the FKM ring surfaces showed the typical “Schallamach wavy” pattern under the Condition 1, which was commonly generated by the compression/stretching cycle in the contact area. In the entire process of the two-body wear, the main wear mechanism of FKM ring was adhesive wear and fatigue wear, and little wear and tear was found on the SS304 pair during the whole process.

The results and observations above suggested that particles in the sealing interface played a key role leading to wear mechanism transition. When the particles entered into the sealing pair, some of the particles were compressed between the contact surfaces of the sealing interface, wearing the surface of the SS304 pair through the sliding and cutting. These iron filings were cut from the SS304 surface while the particles were crushed and grinded at the same time. As the particles were crushed and became smaller, some abrasive particles rolled away from the surface of FKM ring under the friction force, and the wear mechanism transitioned into the second stage, a typical three-body wear with non-uniform abrasive particle size. The number of particles was still decreasing as the particles were being ejected and crushed in the sealing pairs. Eventually, the compression and the friction between the sealing pairs wouldn't be strong enough to break these small particles, which led to that these small particles would start rolling between the contact surfaces. This indicated the next stage of wear. In the final stage, the abrasive particles only existed in the partial adhesive region between the FKM ring and SS304 pair, which suggested that it had reached the final stable wearing state. This state was close to the combination of abrasive wear and adhesive wear, which was similar to the two-body wear.

The above discussions could not completely explain the complex interaction between particles and the tribo-pairs. However, the results of this work suggest that the movements and transformations of the particles have a major influence on the transitions of abrasive wearing characteristics for the FKM/SS304 sealing pairs. The wear mechanisms discussed only by analyzing the final experimental results is really not comprehensive. If the seals can be optimized according to the wear characteristics in different wear stages, the wear of mated frictional parts could be reduced significantly to increase sealing life and provide a superior seal. It is hoped that these results will provide experimental support for further systematic studies on the complex interactions of seal materials and particles in drilling environments.

Conclusion

This research assessed the influence of the changes in particle state on the abrasive wear process of FKM/SS304 sealing pairs. Resolution of this industrial problem can be useful to the optimum design of the seals used in drilling tools. The main conclusions could be drawn as follows:

1. The presence of abrasive particles dispersed between the sealing interface clearly improves the friction performance of the seal pairs, due to the particles in the sealing interface weaken the contribution of the rubber adhesion to tribological behaviors. Furthermore, they can also deteriorate the wear performance of the metal counterpart, due to the embedded hard debris on the FKM ring contacted directly with the rubbing faces.
2. The movement and breakage of particles after one single entering into the sealing interface were obtained. And on this basis, the stable wear process can be divided into three stages. Moreover, the tribological performance and material removal capacity displayed different evolving characteristics.
3. The transition of the wear mechanism at the stable stage starts from sliding wear, abrasive wear and finally abrasive&adhesion wear. Specifically, the large abrasive particles embedded into the surface of the FKM ring slid and cut the surface of the stainless-steel pair in the initial stage, causing the two-body abrasive wear mainly. As the abrasive particles were gradually crushed and started to roll or slide between the sealing surfaces, the wear mechanisms transformed to the three-body abrasive wear mainly. Finally, the continuous breakage and escape of the particles lead to a state similar to the two-body wear, which was close to the combination of abrasive wear and adhesive wear. Thus, the main causes contributed to this change of wear mechanisms are the random movement and process of continuous breakdown of abrasive particles. This phenomenon can easily cause the serious reduction of the service life of the sealing pairs in engineering and thus should be considered in practical applications.

Declarations

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Tables

Table 1 Mechanical properties and structural parameters of FKM ring and SS304 disk.

	FKM	SS304
Poisson's ratio	0.48	0.33
Elongation at break	300%	-
Modulus of elasticity (MPa)	7.8	2.1×10^5
Hardness	70 Shore A	63 HRC
Roughness (μm)	1	0.1-0.05
Density (g/cm^3)	1.85	7.93
Thickness (mm)	3.55	7
Outer diameter (mm)	43.55	55
Inner diameter (mm)	40	-
Tensile strength (MPa)	16.8	-
Mooney viscosity ($\text{Pa}\cdot\text{s}$)	46	-

Table 2 Compositions of all the test materials.

	C	O	F	Si	Fe	Ca	Mg	Cr	Ni
FKM	39.88	7.5	47.81	3.39	-	0.7	0.71	-	-
SiO ₂	31.41	49.41	-	19.18	-	-	-	-	-
SS304	≤0.08	-	-	≤1.0	≥66.85	-	-	18~20	8~10

Table 3 Schematic sketches of the typical wear mechanisms of FKM ring against stainless steel tribo-pairs with particles

Stage	Tribo-pairs	Initial damage behavior	Wear mechanism
Stage IIa		Ploughing	Sliding wear
Stage IIb		Micro-cutting pits	Abrasive wear
Stage IIc		Small Schallamach waves	Abrasive wear& adhesive wear

Figures

Figure 1

Test rig and photographs of samples: (a) Schematic description of the sliding friction pairs; (b) Test rig; (c) SS304 disk; (d) Sealing clamp after covering SiO₂ particles; (e) FKM ring.

Figure 2

Surface micrographs of the specimens: (a) SS304 disk; (b) SiO₂ particles; (c) FKM ring.

Figure 3

Variation of friction coefficients as a function of time under different conditions (with and without SiO₂ abrasives)

Figure 4

Variation of wear loss of FKM ring with wear time under two test conditions

Figure 5

Variation of wear loss of the SS304 disk with wear time under the abrasive wear condition.

Figure 6

The surface morphology of SS304 tribo-pair under the abrasive condition: (a) after 15min; (b) after 45min; (c) after 53min; (d) after 90min.

Figure 7

SEM micrographs of the worn surfaces of FKM rings under the abrasive wear condition: (a) after 15min; (b) after 45min; (c) after 53min; (d) after 90min; (e) SEM micrographs without abrasive particles.

Figure 8

Insertions on the worn surfaces of FKM rings under the abrasive wear condition: (a) iron filings; (b) abrasive debris.

Figure 9

The original filling body in FKM.

Figure 10

EDS analysis of the particle materials: (#1) original SiO₂ particles, (#2) abrasive debris and (#3) original filling body. (Sampled location #1 in Fig. 2b, #2 in Fig. 8b, #3 in Fig. 9)

Figure 11

Distribution of abrasive particles between the sealing pairs after 45min: (a) 1P(the particle size of 1-5μm) 2P(the particle size of 10-20 μm), 3P(the particle size of 100 μm) (b) particles debris on the non-contact area.

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