Tribological properties of swollen nitrile rubber under dry and wet sliding conditions

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Abstract

When nitrile rubber contacting with water under the external force during the service life, swelling and sliding wear occur. Since nitrile has similar polarity to water, the interaction between water and nitrile rubber and its influence on mechanical and tribological behaviors of the nitrile rubber play an important role in rubber performance, which is extremely necessary to be studied systematically. In this study, immersion experiments were conducted on three nitrile rubber samples which contained different acrylonitrile weight percentages of 18%, 26% and 41% (i.e. N18, N26, and N41) respectively. The hardness, tensile, dry and wet unidirectional sliding wear tests were further conducted. To reveal the mechanisms, the nuclear magnetic resonance (NMR) analysis and scanning electron microscopy (SEM) analysis were performed and interpreted accordingly. The results showed that cross-linking break based structural damage, substance dissolution and surface layer defects occurred after swelling, resulting in decreases in hardness and tensile strength and increases in permanent deformation fracture rates of the nitrile rubbers. The friction coefficient value of the un-swollen NBRs was positively related to the wear loss and decreased with the increase of the acrylonitrile content. During the wear process under dry conditions, the un-swollen rubbers presented hardening in aging while the swollen samples softened along with the deterioration of adhesive wear with higher steady-state friction coefficient value and wear loss. Under wet friction conditions, the susceptible wear behavior of the swollen rubbers induced reductions in friction coefficient and increases in wear loss. The swelling degree and its effects on mechanical and tribological behavior decreased with the increase of the acrylonitrile content. The swelling influences on the tribological behavior of nitrile rubber affected and acted on the entire wear process.

1. Introduction

Nitrile rubber (NBR) is widely applied as a seal or wear-resistant material in many engineering equipment applications with its outstanding properties such as high elasticity, viscoelasticity, solvent resistance and abrasion resistance [1, 2]. The wear behavior of the rubber materials is the key reason for failure problems and it should be considered carefully in design and applications [3]. Recent developments of nitrile-butadiene rubber and NBR-based composites also require the in-depth study of the NBR rubbers [4, 5]. Therefore, many researches have dedicated to the research of the wear mechanisms of nitrile-butadiene rubber materials. Dong et al.[6] experimentally studied the mechanical and tribological properties of the NBRs. The results showed that the mechanical and tribological properties of the NBRs are affected by aging and elevated temperature under dry conditions with the reduction of the tensile strength and tear strength as well as the increase of the wear mass loss. Li et al.[7, 8] adopted molecular dynamics simulations to study the enhancement of the mechanical and tribology properties of the nitrile-butadiene rubber composites. The results showed that by introducing the
carbon nanotubes and graphene, the Young’s and Shear Modulus and hardness can be enhanced while the friction coefficient and abrasive wear can be decreased. Li et al[9] evaluated the tribological properties of the graphene oxide /NBR nanocomposites under dry sliding and water-lubricated conditions. The results showed that the thicker water film caused the decrease of the friction coefficients and specific wear rate.

It is well-known that water lubrication is clean and eco-friendly to enhance the service life of rubber materials. The mechanism of water lubrication has attracted considerable attention from researchers[10]. In some applications, such as mechanical seals, bearings of canned pumps and marine power systems, rubber friction pairs are operated in an aqueous medium, in which water is used as a lubricant directly[11, 12]. When NBR materials are applied in the machinery which operates in the presence of the abrasive slurries, the slurry will lead to the wear of rubbers thereby causing the machine failure[13, 14]. In marine systems such as marine propeller shaft systems, rubbers are commonly used as bearing materials[15]. Wang et al[16] discussed the tribological properties of water-lubricated rubber bearing. The results showed that the friction coefficient and wear are affected by the different rotary speed, load and cooling water temperature, which can further result in the change of the bearing vibration status. Dong et al[17] studied the tribological properties of the rubber under water-lubricated conditions. It was pointed out that the friction coefficient between rubber and the smooth metal surface is related to the velocity, load and hardness of the rubber. However, previous studies mainly focus on the function of water lubrication. The water effects on the physical and structural properties of the rubber itself are rarely discussed.

When the rubbers contacting with the liquid medium under the external force during the service life, the swelling and wear will be occurred inevitably[18, 19]. At present, the studies of the rubber swelling mainly aim at oil medium[20, 21] and chemical media[22, 23]. Mousa et al[24] studied the effects of the dynamic curing on the oil resistance of the NBRs and discussed the effects on the mass swell and mechanical properties. With the increase of the sulfur loading, the swelling weight is accompanied by a steady reduction. Ping et al[25] studied the thermal aging and scaling of NBR samples under the alkaline condition. They found that a lot of micro-cracks and scales can be observed on the NBR surface, and the oxidation degradation and hydrolysis happen. Loo et al[26] investigated the effects on the fatigue of the swollen elastomers in different solvents. The results showed that the rubber under dry conditions is combined with the longest fatigue life, while the rubber swollen in biodiesel is the least. However, these studies are merely involved in the swelling effect on the tribological properties of NBRs. As the wetting behavior of the oil-water liquid has been emphasized due to the improved oil recovery efficiency of the Oil-water mixed oil recovery technology[27], a few studies considered the swelling effect on the tribological properties under Oil-water conditions. Hu et al[28] investigated the corrosion behavior of the type 1045 (AISI) carbon steel (CS) in oil-water fluids. The results showed that water presence can exacerbate frictional corrosion. Lv et al[29] researched the effect of cyclohexane swelling on the aging, friction and wear characteristics of the NBRs. The results showed that swelling caused by the liquid medium can increase the friction and wear of the rubber materials. In the studies mentioned above, water was mostly used as the comparative solvent materials. However, water is polar similar to the nitrile. Therefore, the interaction between water and rubber, and its influence on the mechanical and wear behavior of the rubber elastomer play an important role in rubber performance, which is extremely necessary to be studied systematically.

To the authors’ knowledge, the study of the water swelling effect on rubber now mainly aims at the swelling applications, such as water-absorbing rubber[30]. However, the tribological properties of the NBRs influenced by swelling behaviors were not investigated completely under water conditions. Hence, in this study, the swelling behavior and mechanism of the NBR were first discussed to evaluate the swelling effects on the rubber physical and structural properties based on the weighting, NMR and SEM analysis. This is followed by the research on the mechanical properties of the NBRs represented in hardness and tensile properties to explore the swelling effects. Finally, the friction coefficient, wear variation and SEM morphologies of the NBR samples were presented to compare the wear mechanism and resistance of the un-swollen and swollen rubbers under dry and wet conditions.

2. Methods and experiments

2.1. Swelling testing

The swelling tests of the NBRs were performed at ambient temperature and pressure in deionized water (industrial grade) by a hanging immersion tester. Three kinds of NBR rubbers with different acrylonitrile weight percentages of 18%, 26% and 41% (N18, N26, and N41, with hardness (Shore A), values 71, 73 and 74) were prepared in this work[31] (supplied by Lanzhou Petroleum and Chemical Company, China.), which were commonly used in engineering. Detail information of the samples is shown in table 1. Every component of the NBR samples can be purchased on the open market. The immersion samples were in the sizes of 40 mm × 25 mm × 6 mm and dumbbell-shaped 1 A (thickness 2 mm and the standard distance 20 mm),

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The MPV-600 ring-on-block tester

2.2. Wear testing

The worn NBR samples were also dried in the thermostat oven at a temperature of 80 °C for 4 h [32]. The NBR samples were dried after immersion using filter paper. The weight of the samples before and after the immersion experiment was measured by the electrical balance with an accuracy of 0.1 mg respectively. The volume was measured by the vernier caliper with an accuracy of 0.01 mm and calculated by the average of the three measurements in the middle of the three directions. The hardness of the samples was finally measured by a Shore durometer with an accuracy of 0.1 Shore A.

The weight and volume variation between immersed and un-immersed samples are defined as the swelling variation. The weight variation degree ($Q_{sw}$) and volume variation degree ($Q_v$) of the samples before and after the immersion experiments can be calculated by equation (1) and (2).

$$Q_{sw} = \frac{m_n - m_0}{m_0} \times 100\%$$  \hspace{1cm} (1)

$$Q_v = \frac{V_n - V_0}{V_0} \times 100\%$$  \hspace{1cm} (2)

where $m_0$, $V_0$, and $m_n$, $V_n$ are the weight and volume of the sample before and after the swelling test. Then the immersed samples for the swelling tests were dried in the thermostat oven at 80 °C for 4 h [30], which had been checked stable in weight. The drying weight variation degree ($Q_{swb}$) of the immersed samples after drying can be calculated by equation (3).

$$Q_{swb} = \frac{m_d - m_0}{m_0} \times 100\%$$  \hspace{1cm} (3)

where $m_d$ is the weight of the dried sample. The proportion of crosslink chain of the samples before and after the swelling experiment was measured directly by the Hydrogen proton signal of the VTMR20-010V-T nuclear magnetic resonance (NMR) spectrometer with the test parameters of resonance frequency 21.31 MHz, magnet strength 0.5 T, magnet temperature 35 °C and test temperature 90 °C. The proportion variation degree ($Q_p$) of the samples before and after the immersion experiments can be calculated by equation (4).

$$Q_p = \frac{P_n - P_0}{P_0} \times 100\%$$  \hspace{1cm} (4)

where $P_n$ and $P_0$ are the proportion of crosslink chain of the sample before and after the swelling test. XQ-250 rubber strength testing machine (Shanghai non-metallic material testing machine plant) was used to test the tensile properties of the NBR samples after the immersion tests. The NBRs were used for the performance testing with the working condition of 500 ± 5 mm min⁻¹ for the drawing speed. The tensile strength ($TS$) can be measured directly and the tensile permanent deformation fracture rate ($TSF$) can be calculated by equation (5).

$$TS = \frac{L_2 - L_0}{L_4 - L_0} \times 100\%$$  \hspace{1cm} (5)

where $L_0$ is the marking line spacing before the test; $L_1$ is the marking line spacing when the sample was broken, and $L_2$ is the connected marking line spacing by two broken parts measured after 3 min.

2.2. Wear testing

The MPV-600 ring-on-block tester (Jinan Shidai Shijin Testing Machine Group Co. Ltd, China), which could simulate the sliding motion in the applications of NBR rubber, was applied to test the tribology performance of the NBR samples before and after the swelling tests at ambient temperature and pressure under the dry and water condition. The steel friction disc was slid on the rubber samples under dry and water lubrication conditions with the working parameters as follows: load 200 N, rotating speed 150 rpm (around 1.4 m s⁻¹) and test duration 6 min for the dry sliding tests and 2 h for the wet sliding tests. The important properties of the friction disc specimen are shown in table 2 and the sliding wear test composition is shown in figure 1.

The worn NBR samples were also dried in the thermostat oven at a temperature of 80 °C for 4 h. The friction coefficients can be obtained from the wear tester. The wear weight variation degree ($Q_{we}$) of the samples after the wear test can be calculated by equation (6).

$$Q_{we} = \frac{m_{we} - m_0}{m_0} \times 100\%$$  \hspace{1cm} (6)

where $m_{we}$ is the weight of the sample after the wear test. All the above result data were the average of three individual tests, and all the morphologies of the samples were observed by the scanning electron microscopy (FE-SEM, Hitachi JSM-6360, Japan).

| Table 1. Detail information of the NBR rubbers. |
|------------------------------------------------|
| main component | Master-batch | carbon black | vulcanizing agent | activating agent | accelerating agent | anti-aging agent |
| weight fraction | 100 | 70 | 3 | 12 | 4 | 5 |

which were further applied for mechanical tests and wear tests respectively. The volume of the water in the beaker was 1 L and the distance from the liquid surface to the top of the immersion samples was 50 mm. Three samples for each test method of the three materials were tested to obtain the average data of test results. To ensure the rubber samples can be fully swollen, the immersion time was set to 240 h [32].
3. Results and discussion

3.1. Analysis of swelling behavior and the effects on mechanical properties of the NBRs

The effects of water swelling behavior and mechanism on the physical and structural properties of the NBRs were first studied by the immersion experiments. The weight variation degree ($Q_{wa}$), volume variation degree ($Q_v$) and drying weight variation degree ($Q_{wb}$) of the samples after 240 h swelling are plotted in figure 2 respectively.

From figure 2, it can be observed that the weight of the N18, N26 and N41 increased with the $Q_{wa}$ of 0.64%, 0.49% and 0.22% after 240 h immersion respectively. Meanwhile, figure 2 shows a similar pattern of the volume variation rates of the NBR samples with the $Q_v$ of 0.82%, 0.52%, and 0.32% respectively [33]. Since the $Q_v$ of the NBR samples tended to perform a higher variation degree, it can be indicated that the rubber molecular chain expanded after swollen. For the drying tests, it can be seen from figure 2 that the weight of the NBRs was reduced.

Table 2. Important properties of friction disc specimen.

| Size (mm) | Material | Hardness (HRC) | Surface roughness (Ra) |
|-----------|----------|----------------|-----------------------|
| Φ178 × 12 | 40Cr steel | 62             | 0.1 μm                |

Figure 1. Main components of the sliding wear tests.

Figure 2. Variations of $Q_{wa}$, $Q_v$ and $Q_{wb}$ of the NBR samples after 240 h immersion.
after drying with the $Q_{wb}$ of $-0.0442\%$, $-0.0113\%$ and $-0.0089\%$ for the N18, N26 and N41 samples respectively. It can be supposed that some of the rubber additives or small molecules were dissolved during the immersion. According to the data comparison above, it can be clearly seen that the queuing sequence of the swelling variation degree of the NBR samples was $N18 > N26 > N41$, which indicates that with containing the higher acrylonitrile content, the N41 could be influenced at a lower degree by swelling.

To further confirm the essence of the molecular chain variation and the weight reduction, table 3 lists the proportion variation degree ($Q_p$) of crosslink chain of the samples after the 240 h immersion experiments. It can be seen from table 3 that the proportion of crosslink chain of the swollen NBRs decreased (original values 20.82 %, 22.56 %, 27.74 %) and the reduction negatively correlated with the increase of acrylonitrile content. The variation rates of the N18 and N26 samples were about 1.81 and 0.54 times greater than that of the N41 sample respectively.

Figure 3 shows the surface micrographs of the rubber samples after swelling in water for 240 h. Some misty and dot-like precipitates, lamellar perks and holes could be found on the surface of the immersed samples. The number of surface defects of the NBR samples negatively correlated with the increase of the acrylonitrile content, which is consistent with the previous results.

Under the condition of pressure differential, the water molecules could penetrate into the NBR structure, leading to the swelling behavior. After the liquid medium entering the molecular network, the internal structure of the NBRs was expanded, providing more internal spaces for the liquid media. The slightly soluble precipitates tended to gather in the surface layer of the NBR samples, which led to the increased content of the precipitates on the rubber surface. The hardening precipitates and the breakage of the fairly weak Hydrogen bond reduced the

Table 3. Variation percentage (%) of the cross-linking chain in the molecular network of the NBRs before and after immersion experiment.

|         | N18  | N26  | N41  |
|---------|------|------|------|
| Cross-linking chain | $-13.56$ | $-7.45$ | $-4.83$ |
flexibility of the molecular chain resulting in the cross-linked structural damage of the NBR molecular network and the substance dissolution. Thus, surface defects could be observed.

With the increase of the acrylonitrile content, the distance between the molecules could be decreased and the intermolecular force increased which made it difficult for the water molecules to enter the NBRs [34]. N41 behaved a better water resistance performance with its lowest swelling and dissolution rates under the water conditions than that of the N18 and N26.

After the immersion experiments, the swelling effects on the mechanical properties of the NBR samples were investigated by testing the hardness, tensile strength and fracture permanent deformation respectively. Figure 4 shows the hardness values of the NBR samples before and after the water swelling. It can be seen that after 240 h immersion, the hardness of the N18, N26 and N41 declined from 71, 73 and 74 (Shore A) to 67.1, 71.7 and 73.4 (Shore A) respectively. After immersed for 240 h, the hardness variation of the N41 reached the lowest value of 0.6 Shore A. It was 1.17 and 5.5 times lower than that of the N26 and N18.

Figure 5 shows the variation of the tensile strength (TS) and the permanent deformation of the tensile fracture (TSF) of the rubber samples before and after the immersion test. As is shown in figure 5, the TS of the N18, N26, and N41 decreased under the water conditions from around 14.8 MPa, 15.4 MPa and 16.7 MPa to 11.2 MPa, 13.7 MPa, and 14.6 MPa respectively. The TS of the N41 after immersion for 240 h was about 6.2% and 23.3% higher than that of the N26 and N18. Meanwhile, it can also be seen from figure 5 that, the TSF of the N41 after immersion for 240 h was calculated to be 71.04%. It was 3.1% and 24.6% lower than that of the N26 and N18, which is in good agreement with the TS. It is indicated that the N41 performed better tensile properties than the other two rubber samples after swelling.
The mesh structure of the NBR rubber was deformed after the water-swelling. The continuing function of the longtime swelling caused the structural damage and dissolution of the rubber. The decrease of the internal content and distribution uniformity further led to the internal cavity of the rubber. The tensile strength and the elasticity tended to decrease with the reduction of the molecular force, simultaneously the structural defect and the permanent deformation increased.

In addition, the tensile properties are depended on the forces of the chemical bond between the main chains and the intermolecular non-bond forces. With the increase of the acrylonitrile content, the molecular weight per unit area was increased and the molecular spacing decreased, which was apt to the occurrence of cross-linking reactions. As the difficulty of the slip between the molecular chains gradually increased, the tensile strength increased and the elastic decreased, resulting in the lower fracture permanent deformation rate and the better toughness of the N41.

3.2. Analysis of swelling effects on tribological properties of the NBRs
In this section, the swelling effects on the tribological properties of the NBRs are investigated. To better investigate the swelling effects on the tribological properties of the NBRs, the comprehensive analysis of wear behavior is performed. Figure 6 shows the worn surfaces of the N18, N26, and N41 samples ((a) N18, (b) N26, (c) N41).

![Figure 6. Frictional coefficient, wear variations of Qwc, and wear surface morphologies of the un-swollen (1) and swollen (2) NBR samples ((a) N18, (b) N26, (c) N41).](image-url)
It can be seen from figure 6 that the worn surface of the samples before and after the swelling tests exhibited the adhesive wear form with different manifestations and degrees. As is shown in figure 6(a) (1), with poor shear resistance and low hardness, the tear scratches appeared obviously under the action of cutting and the shear damage occurred in the deep surface of the low acrylonitrile content N18 sample. The cracks expanded from the rubber surface to the inside resulting in rough fracture of the larger wear debris [6]. With the increase of the acrylonitrile content, the shear layer appeared in the surface layer due to the reinforced hardness. As the micro-vibration-based repeated plastic deformation caused the fatigue hardening of the rubber structure, under the action of the high-temperature friction, the adhesive spalling occurred at the junction of the hardened layer and the surface layer of the un-swollen N26 sample as is shown in figure 6(b) (1). It can be seen in figure 6(c) (1) that, the adhesive wear reduced on the worn surface of the un-swollen N41. With the increase of acrylonitrile content, the micro-vibration fatigue and the friction heat aging were concentrated on the shallow surface. The wear scars were shallow and the debris turned easy to peel off due to the conversion from plasticity to brittleness of the NBR surface under the action of dry friction. Due to the higher hardness of the N41, hard protrusions and their peeling pits appeared on the wear surface under the combined effect of the high-frequency repeated normal stress and shear stress.

Different from the aging and wear mechanism of the un-swollen rubber samples, the wear behavior of the swollen rubber exhibited different degrees of softening aging. Compared with the un-swollen samples (1), the swollen samples (2) represented the vacancy and misplacement accumulation and the adhesive phenomenon caused by the shear-based twisted molecular chain mesh structure and the oxidation-based softened surface under friction action and frictional heat. As can be seen in figure 6 (2), affected by swelling and frictional heat, wave-like adhesion wear scar emerged on the N18 wear surface caused by the rubber soften [35]. With the increase of the acrylonitrile content, the high-temperature softening layer formed on the swollen surface. Due to the higher permanent deformation of the tensile fracture after swelling, the rubber molecular chains were elongated when slipped with the adhesive joint under shearing, resulting in the filamentous worn surface of the N26. With thinner swollen surface and higher hardness, the molecular chain got harder to slip which led to the flaky soften adhesion wear debris accumulated on the wear surface of the N41 sample.

It can be seen in figure 6 that, the wear loss of the NBR rubbers decreased with the increase of the acrylonitrile content and increased after swelling. In addition, the $Q_{\infty}$ variations of the N18 and N26 were about 6.5 and 0.5 times higher than that of the N41 after 240 h swollen respectively which is decreased with the increase of the acrylonitrile content and negatively correlated with the swelling weight variation degree. This can be attributed to the frictional thermal softening caused by swelling, which led to the intensified adhesive wear behavior of the NBRs. The friction coefficient value of the un-swollen samples decreased with the increase of acrylonitrile content. Different from the un-swollen friction coefficient curves, the swollen friction coefficient curves show that the wear process after swollen can be divided into four stages. As can be seen in figure 6 for the first stage (a) of the N18 sample, as the water molecules remained in the loose rubber structure after swollen, water film formed and took away most of the friction heat when the water solvent overflowed under the action of the load, which led to a lower friction coefficient. In stage (b), with the loss of moisture, the friction heat accumulation caused the increase of oxidation and the structure softening of the rubber. Meanwhile, the adhesive wear occurred due to the failure of the surface lubrication caused by the high temperature, which led to a sudden increase in the friction coefficient and the intensified wear. In stage (c), the friction coefficient decreased due to the easy cutting [36], which can be attributed to the increase of the swollen layer damage caused by the water loss shock and frictional heat. As the wear process entered the stable stage (d), the friction coefficient tended to be stable and higher than the un-swollen ones, which can be indicated that the swelling effect on the NBR wear behavior could influence and continue to act on the subsequent friction process. The staged behavior of the rubber wear after swelling weakened with the decrease of swelling degree caused by the increase of acrylonitrile content.

Different from the dry conditions, the water film caused a decrease in the friction coefficients as is shown in figure 7 [8]. Since the heat dissipation of water reduced the frictional heat accumulation, the occurrence of adhesive wear was effectively suppressed.

It can be seen from figure 7(a) (1) that, the tear cracks appeared evidently of the un-swollen N18 sample and expanded from the worn surface to the rubber interior in the sliding direction, which indicates that the wear loss was mainly caused by shear tear under the action of cutting. While in figures 7(b) (1) and 7(c) (1), tongue accumulation, micro-adhesion and a few fatigue pits showed up on the un-swollen N26 and N41 samples which indicates that with the increase of the crosslink density and the hardness caused by the acrylonitrile content, the shear mainly occurred in the bonding surface. Under the cyclic contact load and friction heat conditions, micro-adhesive and fatigue occurred simultaneously with the ploughing.

As can be seen in figure 7, the worn surface of the samples (1) exhibited a ridge-like texture in macro-scale obviously, while after 240 h swollen the wear pattern of the samples (2) were reduced to be relatively smooth with swelling-based holes on the worn surface, which corresponded to the smaller friction coefficient values.
based on a smaller fluctuation range of the friction coefficient curves and the greater wear loss of the swollen NBRs. It is indicated that the wear behavior was more likely to occur after swollen. By comparative analyzing these three kinds of NBRs, it can be seen from figure 7 that, the roughness of the ridge-like wear pattern of the un-swollen samples and the number of holes on the swollen samples decreased progressively with the increase of the acrylonitrile content.

The corresponding data can be seen from figure 7 that, the fluctuation range of the friction coefficient curves and the variation of the friction coefficients before and after swelling decreased with the increase of the acrylonitrile content. The friction coefficient variations of the N18 and N26 after immersion were about 0.83 and 0.1 times higher than that of the N41. Simultaneously, the $Q_{wc}$ declined with the increase of acrylonitrile content evidently, in which the $Q_{wc}$ variations of the N18 and N26 were about 1.19 and 0.81 times higher than that of the N41 after 240 h swollen respectively. The effects of swelling on the coefficient friction and the wear loss decreased with the increase of the acrylonitrile content, which indicates that the N41 was less affected by swelling than the other two rubber samples with a lower variation.

As the swelling lengthened the rubber molecular chains and decreased the intermolecular force, the mechanical properties of the samples reduced. Under the action of friction and micro-vibration \([37, 38]\), the increased wear surface generated larger contact area between water solvent and rubber, and the water solvent

![Figure 7. Frictional coefficient, wear variations of $Q_{wc}$, and wear surface morphologies of the un-swollen (1) and swollen (2) NBR samples ((a) N18, (b) N26, (c) N41).](image-url)
reciprocated into and out of rubber tissue to accelerate the fatigue fracture of the molecular chain, which made the water molecules more easily to immerse into the rubber tissue and the wear was prone to occur.

With the increase of the acrylonitrile content, the increased crosslink density and the hardness reduced the deformation of the rubber tissue under the same load and further blocked the swelling microcirculation [17], resulting in the reduction in friction coefficient values and fluctuations. Since the swelling behavior was still in progress during the wet sliding wear process, the wear behavior of the NBRs was affected by the interaction and integration of the swelling and pre-wear behavior.

It can be interpreted that the lower friction coefficients were possessed by the lower molecular network structure density and the decrease of the anti-shearing properties of the rubber samples after the swelling tests [29]. Meanwhile, the substance dissolution of the swelling rubber in the water medium inevitably created micro defects on the rubber surface. It can be indicated that the wear behavior was easier to occur after swelling, which led to the wear increase [32, 39]. With higher acrylonitrile content, N41 performed better wear resistance properties than the other two rubber samples.

4. Conclusion

This study has investigated the swelling behavior and the effects on mechanical and tribological properties of the NBR rubbers with three acrylonitrile contents in water media by swelling, tensile and wear experiments respectively. The following conclusions are presented as the outcomes of this study, which could make appropriate reference and guidance for further relevant research.

(a) Affected by swelling, the rubber molecular chain was stretched and the intermolecular force was reduced. The cross-linking structure of the nitrile rubber molecular network was damaged and accompanied by substance dissolution, resulting in the rubber surface layer defects. The swelling degree of the nitrile rubber decreased with the increase of the acrylonitrile content. With the significant effect of swelling on the mechanical properties of the NBRs, the hardness and tensile strength of the swollen rubber decreased, and the permanent deformation of the tensile fracture increased.

(b) During the wear process of the NBRs under dry conditions, the un-swollen rubber fatigue hardened, while the swollen rubbers softened in swelling aging under the action of frictional heat, which further exacerbated the adhesive wear. The friction coefficient value of the un-swollen NBRs was positively related to the wear loss and decreased with the increase of the acrylonitrile content. While for the swollen rubbers, the friction coefficient curves exhibited the characteristics of phase-wise with higher steady-state friction coefficient value and wear loss.

(c) Compared with dry sliding wear, the formation of the water film caused reductions in friction coefficients under wet friction conditions. Similar to the dry sliding wear, the friction coefficient and the wear loss of the un-swollen NBRs were in positive correlation and decreased with the increase of the acrylonitrile content. However, the easier wear of the swollen NBRs led to decreases in friction coefficient and increases in wear loss, with significant swelling-based holes on the relatively smooth wear surface. The fluctuation range of the friction coefficient curve and the variation of the friction coefficient before and after swelling decreased with the increase of the NBR acrylonitrile content.

(d) The early wear surface state of the swollen rubber affected and continued to act on the subsequent wear process under both dry and wet conditions. As swelling behavior was still occurring during the wear process under wet friction conditions, the wet sliding wear was carried out under the interaction of the pre-wear state and the swelling behavior. The swelling affected extent of the NBRs reduced with the increase of the acrylonitrile content.

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