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Friction and wear mechanism of short-cut aramid fiber and silica reinforced elastomers

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ABSTRACT

Important phenomena during sliding contact of elastomeric materials are friction and wear. Wear reduction of elastomers can be achieved by minimizing the propagation of cracks in the elastomer during sliding contact. Adding fillers like silica and fibers is a way to reduce the propagation of cracks and as a result reduction of wear. In the present study, the wear processes of short-cut aramid fiber reinforced elastomers as a function of sliding distance and their relation to friction are investigated. Two different types of systems are considered, i.e. (1) elastomers reinforced by solely short-cut aramid fibers and (2) elastomers reinforced by short-cut aramid fibers and silica. A pin-on-disc tribometer and a microscope are used to analyze the friction and wear mechanisms of the elastomeric composites in sliding contact with a granite counter surface. The results show that the coefficient of friction of the composites consists of different stages, these stages are influenced by the wear processes during sliding. For elastomers which are reinforced by short-cut aramid fibers and silica, a higher energy input is needed to achieve all stages since the presence of silica in the elastomer matrix increases the resistance of matrix particle detachment. A general friction behavior of short-cut aramid fiber and silica reinforced elastomers is proposed.

1. Introduction

Elastomers are polymers which have both viscous and elastic behavior at room temperature. Generally, they have very weak intermolecular forces, resulting in a low Young's modulus compared to other materials. Elastomeric materials are used in daily applications, such as tires [1] and wiper blades [2]. The capability to withstand large deformations without permanent loss of shape and mechanical properties is one of the reasons for their use. However, a single elastomer usually cannot fulfill all of the required properties which are needed in the applications. Adding reinforcing material, such as silica and fibers, is a way to improve the mechanical and tribological properties of elastomers.

Several possible mechanisms of the initiation of elastomer wear have been proposed [3–8]. Schallamach [3] suggested that the initiation of elastomer wear is caused by stick-slip. The stress concentration at the rear of the contact area between an elastomer and a counter surface results in crack formation in the elastomer surface. Gent et al. [4] suggested that the elastomer wear is caused by the detachment of small particles which are the results of small surface cracks. These cracks are developed by the unbounded elastic expansion of voids when they open the cracks under large internal pressure. Later, Fukahori et al. [5–7] concluded that the initial cracks are formed due to micro-vibration of the elastomer and the stick-slip oscillation will propagate the cracks. Another study concluded that the intrinsic defects on the elastomer surface are the initiation points for the wear of the elastomer [8].

Carbon black and silica have been used as the main reinforcing materials for elastomeric composites in the past few decades. It is caused by their ability to improve the tribological behavior, such as reduce abrasion wear [4]. Studies regarding wear and friction of carbon black/silica reinforced elastomers have been intensively conducted [9–11]. Later, fibers became popular to be used as a reinforcing filler of elastomers because of the processing advantages and increase in strength, stiffness, modulus and damping [12].

The study of fiber reinforced elastomer composites on the tribological behavior have been conducted by using several types of fibers, such as carbon fiber [13], cellulose fiber [14], polyamide fiber [15] and short-cut aramid fiber [16–18]. Khasani [16] studied the abrasion wear

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of elastomer reinforced with 1 phr (parts per hundred rubber) short-cut aramid fibers and concluded that wear of the reinforced elastomer is slightly lower than that of the unreinforced elastomer. The low amount of short-cut aramid fibers also reduces the hysteresis and the abrasive wear of the truck tread composite in comparison with the unfilled elastomer [17]. Later, Rodriguez [18] showed that by adding short-cut aramid fibers into the elastomers leads to the reduction of the coefficient of friction. In a previous study, the effect of fiber orientation on the tribological behavior of short-cut aramid fiber reinforced elastomers has been reported [19]. It is concluded that the steady-state coefficient of friction are the same for all reinforcement directions due to the presence of fibers on the wear surface. Although several studies of short-cut aramid fiber reinforced elastomers have been conducted, the wear processes of short-cut aramid fiber reinforced elastomers as a function of sliding distance and their relation to friction is still not fully understood. The present study aims to investigate the friction and wear mechanisms of elastomers that are reinforced by solely short-cut aramid fibers and elastomers that are reinforced by short-cut aramid fibers and silica. By employing a sliding contact between an elastomeric composite and a rigid counter surface, the friction behavior and its relation to the wear process are investigated.

2. Materials and methods

2.1. Materials

The studied materials are elastomers based on a styrene butadiene rubber (SBR) and a butadiene rubber (BR) with two types of reinforcing systems: highly dispersible silica and non-treated short-cut aramid fibers. Non-treated short-cut aramid fibers means that the surface of short-cut aramid fiber does not has any coating, such as epoxy or resorcinol formaldehyde latex (RFL). The initial length of the short-cut aramid fibers is approximately 3 mm, and their diameter is 10–12 µm, supplied by Teijin Aramid B.V, Arnhem, The Netherlands. The friction and wear mechanisms are studied in two different types of systems. The first system; elastomers reinforced by solely short-cut aramid fibers, whereas the second system; elastomers reinforced by short-cut aramid fibers and silica. Details of the formulation in parts per hundred rubber (phr) are given in Table 1. The formulation of the first system is based on the optimum formulation in a previous study [20], whereas the formulation of the second system is based on a silica-reinforced passenger car tire tread, called “Green Tire” [21]. The fiber direction of all composites is randomly oriented. Therefore, the composites can be assumed as isotropic materials. It means that the mechanical properties of the composites are the same in all directions. The composites with a thickness of 2 mm and 5 mm were prepared for tensile and tribometer tests, respectively.

2.2. Experimental method

The mechanical properties of the composites were evaluated using tensile tests. An Instron tensile tester 3343 series was used, according to ISO 37 at a crosshead speed of 500 mm/min. In the present study, the tribological tests are representative of a car tire tread in contact with the road. The elastomeric composites represent the tire tread, while a granite counter surface represents the road. During rolling contact of a car tire, sliding friction occurs at the trailing edge due to deformation of the tire [22]. The sliding friction phenomenon also occurs during strong deceleration. A pin-on-disc tribometer from CSM-instruments was used for investigating the friction behavior of the elastomeric composites. The pin-on-disc tribometer was equipped with a granite sphere with a radius of 17.5 mm, sliding against an elastomeric composite flat disc. The arithmetic average roughness of the granite sphere with a cut-off length of 800 µm is 1.16 ± 0.18 µm. The tribometer tests were performed under dry sliding at room temperature. To investigate the wear mechanism of the elastomeric composites during sliding friction, a Keyence VHX-5000 microscope and a Jeol JSM 6400 Scanning Electron Microscope (SEM) were used to scan the wear surface of the elastomeric composites.

In a previous study, it has been reported that the steady-state coefficients of friction of 15 phr short-cut aramid fiber reinforced elastomer (composite 1) for several reinforcement directions show the same values although the mechanical properties of these composites are different [19]. To gain a better understanding of that findings, the wear processes of composite 1 and its relation to friction during sliding contact is studied. The operating conditions used in the experiments are the same as applied in Ref. [19], i.e. a contact pressure of 0.2 MPa, a velocity of 0.2 m/s, and at ambient temperature. The chosen operating conditions represent sliding friction that occurs in a rolling car tire at a velocity of approximately 60 km/h.

The friction and wear mechanisms of silica and short-cut aramid fiber reinforced elastomers was studied by using composite 2. Two levels of energy input were used, i.e. high energy input (a contact pressure of 2.4 MPa and a velocity of 0.3 m/s) and low energy input (a contact pressure of 0.8 Mpa and a velocity of 0.2 m/s). All the tests were repeated three times to check the repeatability of the experiments.

Table 1
Material formulation of the composites.

Ingredients	Composite's ID		Supplier
	1 [in phr]	2 [in phr]	
SBR, Buna VSL VP PBR 4045 HM	100	–	Arlanxeo, Leverkusen, Germany
SBR, Buna VSL 5025-2 HM	–	97.3[a]	Arlanxeo, Leverkusen, Germany
BR, KBR 01	–	30.0	Kumho, Seoul, S-Korea
Silica Ultrasil VN3	–	80.0	Evonik Industries AG, Essen, Germany
Zinc oxide (ZnO)	2.5	2.5	Sigma Aldrich, St. Louis, United States
Stearic acid (SA)	1.5	2.5	Sigma Aldrich, St. Louis, United States
TDAE oil	–	6.7	Hansen & Rosenthal, Hamburg, Germany
Twaron aramid fiber	15	20	Teijin Aramid B.V, Arnhem, The Netherlands
Bis-triethoxysilylpropyl-tetrasulfide (TESPT)	–	7.0	Evonik Industries AG, Essen, Germany
S-3-triethoxysilylpropyl-octanethioate (NXT)	6.0	–	Momentive, New York, United States
6PPD stabilizer	–	2.0	Flexsys, Brussels, Belgium
TMQ stabilizer	–	2.0	Flexsys, Brussels, Belgium
Sulfur	2.8	1.4	Sigma Aldrich, St. Louis, United States
N-Cyclohexyl Benzothiazole Sulfenamide (CBS)	3.4	1.7	Flexsys, Brussels, Belgium
Di-Phenyl Guanidine (DPG)	4	2.0	Flexsys, Brussels, Belgium

[a] Containing 37.5 wt% oil.

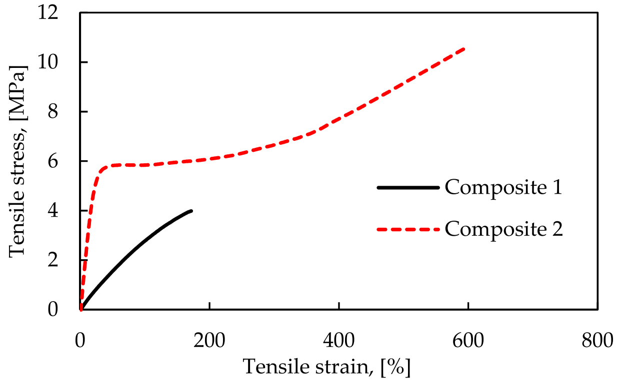

Fig. 1. Stress-strain relations of the composites 1 and 2.

3. Results and discussions

3.1. Mechanical properties of the composites

The stress-strain relations of the composites 1 and 2 are depicted in Fig. 1. As expected, the curve of the elastomer which is reinforced by short-cut aramid fibers and silica is steeper than that of the elastomer which is reinforced by solely short-cut aramid fibers. Elastomer behaves nonlinear at relatively high strains. Mechanical properties of the elastomer at high strain are complex. Therefore, in the present study, the elastic moduli of the composites were defined at a strain of 2%, assuming the material behaves linearly at that strain [23]. The elastic moduli of the composites 1 and 2 are 2.34 MPa and 13.7 MPa, respectively.

3.2. Friction and wear mechanism of short-cut aramid fiber reinforced elastomers

Fig. 2 shows that the coefficient of friction of short-cut aramid fiber reinforced elastomers can be distinguished by 4 stages; (1) the coefficient of friction increases, (2) the coefficient of friction reaches a maximum, (3) the coefficient of friction decreases drastically, and (4) the coefficient of friction reaches a steady-state value. The wear processes of short-cut aramid fiber reinforced elastomer at every stage is studied by using a Keyence VHX-5000 Microscope.

Fig. 3 shows the wear track images of composite 1 during sliding friction. At the first stage of the coefficient of friction curve, initiation of cracks occurs in the elastomer matrix because of its low mechanical properties, see Fig. 3a. Because of wear, the contact area between the composite and the counter surface increases. Therefore, the coefficient of friction increases in this stage, see Fig. 2.

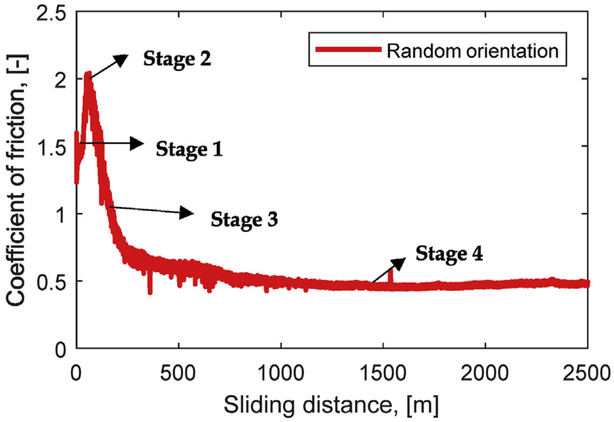

Fig. 2. The coefficient of friction as a function of sliding distance of composite 1 with randomly oriented fibers, a velocity of 0.2 m/s and a contact pressure of 0.2 MPa.

At the second stage of the coefficient of friction curve, the coefficient of friction reaches a maximum value. The wear mechanism in this stage is depicted in Fig. 3b. Some particles of the elastomer matrix detach from the composite and exist on the surface. When many elastomer particles are detached from the matrix, a certain part of the fibers are sticking out from the composite, see Fig. 3c. They are present on the wear surface and align in the direction of sliding. The existence of fibers on the wear surface will result in the increasing surface roughness which leads to the reduction of the real contact area between the elastomer and the counter surface. Hence, the coefficient of friction decreases approximately 4 times lower than that of the maximum value, see the third stage in Fig. 2.

Due to the repeated sliding contact, the processes of initiation and propagation of cracks occur continuously. After a certain sliding distance, many fibers cover the wear surface, see Fig. 3d. They orient in the direction of sliding and prevent the composite from the initiation and the propagation of cracks. As a result, wear of the composite can be reduced. Since the counter surface is mainly in contact with the fibers, the coefficient of friction is controlled by the fibers and reaches a steady-state value.

The specific wear pattern is not visible. This is due to the presence of fibers on the wear surface. It is consistent with the previous research that the specific wear pattern does not develop for the fiber reinforced elastomeric composites [15].

Studying how to minimize the wear of elastomers is of importance because it will increase the lifetime of the components made of an elastomer. Basically, the wear of elastomer can be minimized if the crack mean free path is reduced [24]. Fig. 4 shows the crack propagated of unreinforced elastomer from the cross-section view of the wear track. The wear of the composite can be minimized if this crack is avoided or stopped. Adding fibers is a way to stop this crack. Instead of penetrating further into the composite, the crack will be stopped and it bends to the composite surface when the crack reaches these fibers, see Fig. 5b.

Based on the experimental results, the wear processes of short-cut aramid fiber reinforced elastomers can be explained by Fig. 5. In the initial part of the sliding distance, the cracks are initiated at the trailing edge of the contact because the strain is concentrated at that area [3], see Fig. 5a.

The propagation of crack occurs in the direction of sliding. When the crack reaches the fiber, it will be stopped and it bends to the elastomer surface, instead of penetrating further into the composite, see Fig. 5b. Due to the repeated sliding contact, a part of the elastomer matrix will be detached from the composite, see Fig. 5c. Depending on the orientation of the fibers and the fibers-matrix bonds, some fibers will be detached completely or only a part of the fibers which stick out from the composite will be present on the wear surface and align in the sliding direction, see Fig. 5d.

Persson [24] suggested that there are three possible wear mechanisms that may occur between an elastomer and a counter surface: (1) elastomer wear resulting from the formation and propagation of cracks, (2) elastomer wear due to a very sharp counter surface and (3) the presence of a thin smear layer on the wear surface will reduce the wear rate by protecting the underlying elastomer. For the short-cut aramid fiber reinforced elastomers, mechanism 1 occurs at the beginning of the test, in which the cracks occur in the elastomer matrix due to cyclic loading. After a certain sliding distance, a part of the fibers will be present on the wear surface. The evolution of the wear surface influences friction and wear behavior of the composite. This process corresponds to the third mechanism of wear, in which the modification of the surface is developed. However, in this case, the evolution of the wear surface is influenced by the presence of fibers. Therefore, the wear processes of a short-cut aramid fiber reinforced elastomer appear to be a combination of the mechanisms 1 and 3.

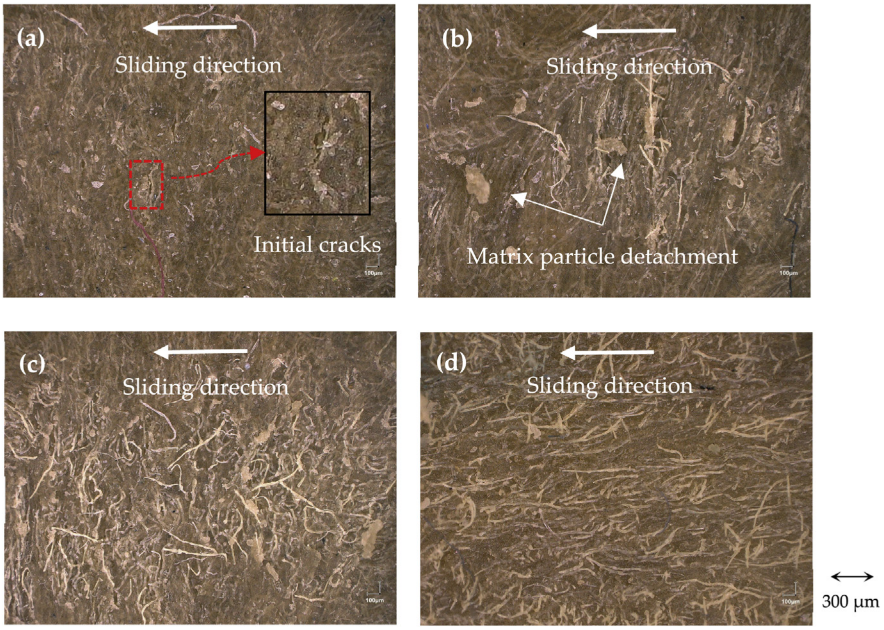

Fig. 3. Optical microscope images of wear processes of short-cut aramid fiber reinforced elastomers: a) the first stage; b) the second stage; c) the third stage; and d) the fourth stage of the coefficient of friction curve (see Fig. 2).

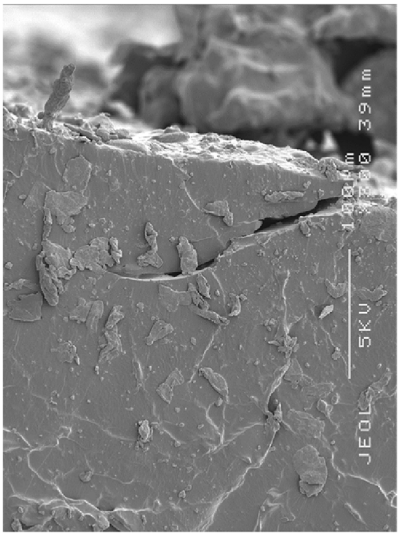

Fig. 4. Crack of an unreinforced elastomer, cross-section view of the wear track.

3.3. Friction and wear mechanism of silica and short-cut aramid fiber reinforced elastomers

Adding silica into a short-cut aramid fiber reinforced elastomer increases the mechanical properties of the composite drastically, see Fig. 1. It may also change the tribological behavior of the composite. Fig. 6 shows the tribometer results of composite 2 with two sets of operating conditions, i.e. low energy input and high energy input. The results show that at low energy input, the coefficient of friction increases at the beginning of the test. After a certain sliding distance, the coefficient of friction shows a constant value once reached a maximum coefficient of friction. Regarding the stage of the coefficient of friction curve in Fig. 2, the result of low energy input indicated that only the second stage is reached. The decreasing coefficient of friction is not found in this case. For high energy input, the coefficient of friction increases at a short sliding distance (first stage). Then, it reaches a maximum coefficient of friction (second stage). After a sliding distance of approximately 1250 m, the coefficient of friction decreases until the end of the test (third stage). For a very long test duration, the coefficient of friction may reach the fourth stage once the rigid counter surface is mainly in contact with the short-cut aramid fibers.

The wear surfaces of both composites after the tribometer tests are shown in Fig. 7. For the composite at low energy input, a relatively smooth wear track is found on the wear surface, see Fig. 7a. The fibers which align parallel to the sliding surface are pulled out. Some grooves on the wear surface are found due to fiber detachment. While the fibers which are deeply embedded in the matrix show greater resistance to detach, only a small part of the fibers which stick out from the matrix are present on the wear surface. Fig. 7a corresponds with the wear process of Fig. 3b, at which the coefficient of friction reaches a maximum coefficient of friction (second stage).

Fig. 7b shows the wear surface at high energy input after the test. It can be seen that many fibers exist on the wear surface. Since part of the elastomer matrix are detached from the composite, fibers which stick out from the elastomer matrix align to the direction of sliding. A rough surface is found at the high energy input test. Fig. 7b corresponds to the wear process in Fig. 3c. This wear process causes the coefficient of friction to decrease.

For an elastomer which is reinforced by solely short-cut aramid fibers, the propagation of cracks will be stopped after rather long cracks because the distance between those fibers are relatively far, see Fig. 5b. As a result, the composite has a high wear loss. By adding silica to the composite, the cracks can be stopped more effectively. Since the size of silica is very small (order of nanometers) and dispersed in the whole elastomer matrix, they will stop the cracks at short length. A previous study reported that by adding filler particles such as carbon black and silica, the wear resistance will strongly increase because the cracks are stopped by filler clusters at length in the order of a few micrometers [24].

There are two possible wear processes which may occur for an elastomer which is reinforced by short-cut aramid fibers and silica: (1) when a low energy input is applied, the crack reaches the inhomogeneous particle (silica) at a very short propagation length, see Fig. 8b. Therefore, the wear particles of the elastomer matrix are rather small, and the wear track is relatively smooth, see Fig. 7a. Since only a few fibers exist on the wear surface, a decreasing coefficient of friction

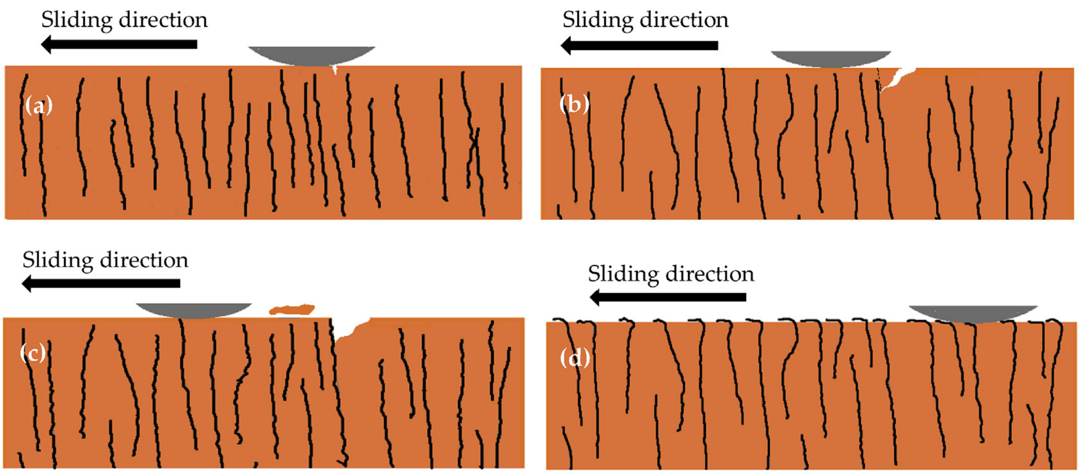

Fig. 5. Wear process of short-cut aramid fiber reinforced elastomers, schematically: (a) initiation of the crack in the elastomer matrix; (b) propagation of the crack; (c) the particle of the elastomer matrix is detached because the crack bends to the elastomer surface; (d) the part of the fibers that protrude above the surface bend and align in the direction of sliding.

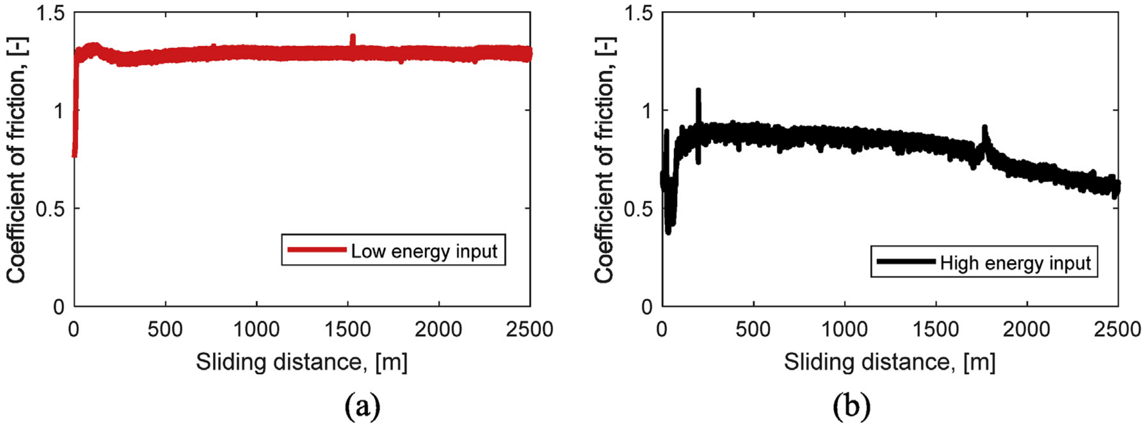

Fig. 6. The coefficient of friction as a function of sliding distance of composite 2: (a) low energy input, $Pv = 0.16$ MPa·m/s; (b) high energy input, $Pv = 0.72$ MPa·m/s.

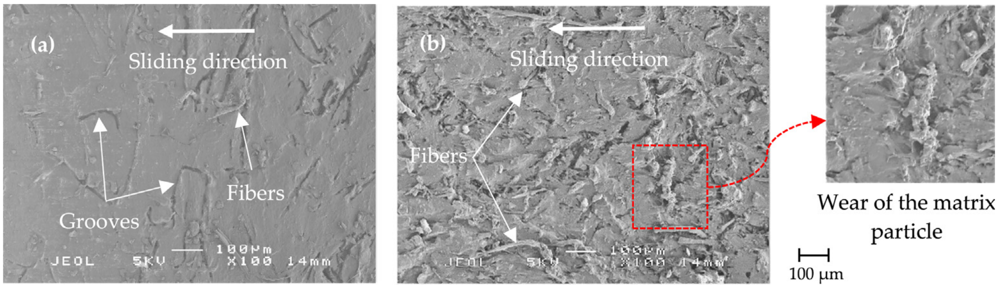

Fig. 7. SEM images of wear surfaces after the tests: (a) low energy input; (b) high energy input.

does not occur for this composite. (2) When a high energy input is used, the silica-matrix bonds will be broken, then the propagation of cracks extends to reach the fiber. As a result, the wear surface becomes rough. Since several fibers are sticking out from the composite and exist on the wear surface, the coefficient of friction reduces, as found in the third stage of the friction curve in Fig. 2. The presence of fibers in the composite increases the wear resistance because the fiber is more difficult to be pulled out compared to the silica. The decreasing coefficient of friction is caused by the reduction of the real contact area between the composite and the counter surface.

A high concentration of fillers, such as silica and fiber, lead to reduction of the distance between these fillers in the composite. Hence, it will increase the wear resistance [25]. However, a too high concentration of fillers will lead to agglomeration of filler networks and reduces the bond between the filler surface and elastomer matrix [26,27]. As a result, the filler-matrix bond may be easy to be broken by propagation of cracks, hence, the wear increases. A strong bond between the matrix and fillers also increases the wear resistance of the composite.

Based on the experimental results, a general frictional behavior of short-cut aramid fiber reinforced elastomers (with and without silica reinforcement) is proposed, see Fig. 9. The coefficient of friction consists of four stages:

1. At the initial part of the sliding distance, the diameter of the contact area increases due to wear. Since the counter surface is mainly in

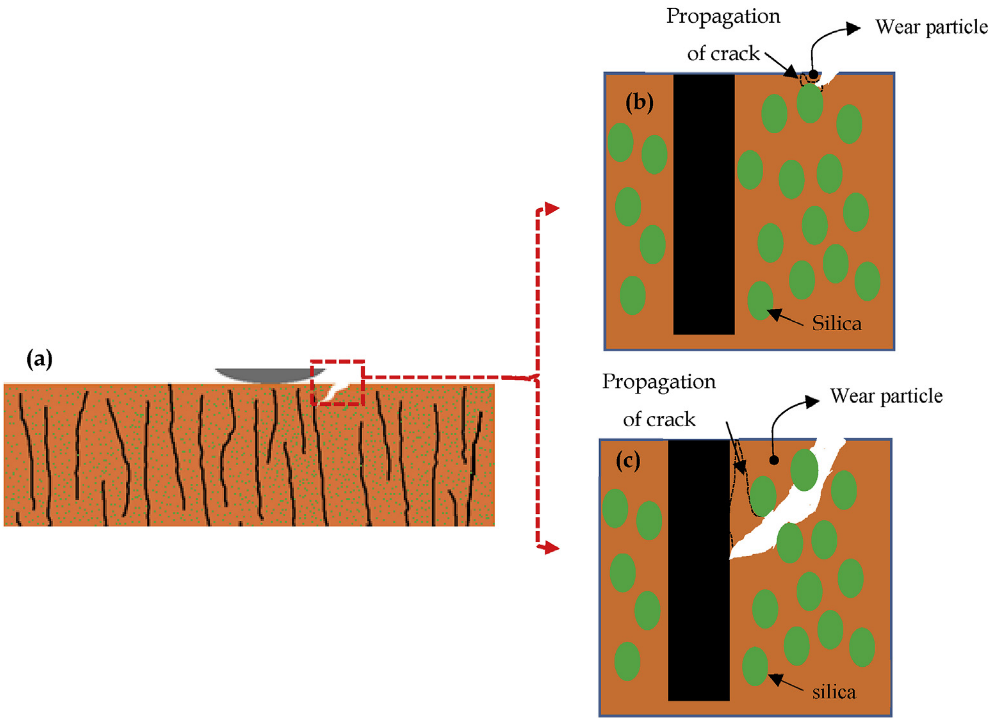

Fig. 8. (a) The crack propagation for silica and short-cut aramid fiber reinforced elastomer, (b) the magnification image of crack propagation at low energy input, and (c) high energy input, schematically.

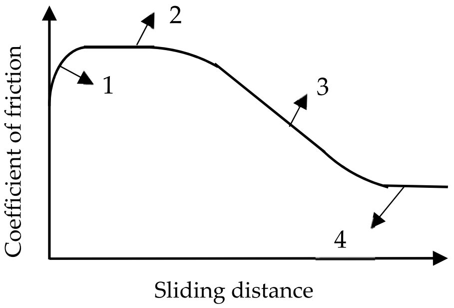

Fig. 9. General friction behavior of short-cut aramid fiber reinforced elastomers (with and without silica reinforcement), schematically.

contact with elastomer matrix, the real contact area is nearly the same as the apparent contact area. As a result, the coefficient of friction increases.

2. The coefficient of friction reaches a maximum value. When the wear loss is low, and only a few fibers exist on the wear surface, the coefficient of friction will be constant.
3. Once many particles of the elastomer matrix detach from the composite and the fibers exist on the wear surface, the counter surface is mainly in contact with the fibers. It leads to the reduction of the real contact area, thus, the coefficient of friction decreases drastically.
4. The coefficient of friction reaches a steady-state value when many fibers cover the wear surface.

4. Conclusions

A mechanism of wear process of short-cut aramid fiber (with and without silica reinforcement) reinforced elastomers and its relation to friction behavior was proposed. The propagation of cracks is an important factor that influences the wear mechanism. The coefficient of friction of short-cut aramid fiber reinforced elastomer can be distinguished by 4 stages. Every stage of the coefficient of friction is influenced by the actual wear process of the composite. The presence of fibers on the wear surface reduces the coefficient of friction drastically. For an elastomer that is reinforced by short-cut aramid fibers and silica, a higher energy input is needed to achieve stages 3 and 4. It is caused by the presence of silica in the elastomer matrix increase the resistance of matrix particle detachment. As a result, only a few amounts of fibers exist on the wear surface.

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