
Erosive and Abrasive Wear Resistance of Polyurethane Liners

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Abstract

Material removal caused by the impact and sliding of a stream of particles is a typical wear mode in the oil and gas industry. Protective coatings can be employed to increase the service life of equipment that is exposed to harsh erosive and abrasive environments. Among all the types of protective coatings and liners, polyurethane elastomers have received great attention owing to their excellent wear resistance and comparatively low cost that would allow for large-scale applications. The excellent wear resistance of polyurethane elastomers is a result of their high resilience and propensity to elastic deformation that enables the absorption of impact energy of erodant particles with minimal damage. The relation between the wear resistance of polyurethane and its mechanical properties has been the subject of previous studies. This chapter reviews the research that has been conducted to study the wear resistance of polyurethane elastomers. Testing apparatuses employed, material characterization techniques, evaluations of material removal mechanisms, and parameters with the strongest effect on wear resistance of polyurethane elastomers are herein explored. A review of finite element modelling approaches for in-depth study of the wear phenomenon of polyurethane elastomers is also presented in this chapter.

Keywords: finite element modelling, mechanical properties, polyurethane liner, wear resistance, wear testing

1. Introduction

1.1. Wear and corrosion in oil and gas industry

The advances in technology and higher demand for energy require enhanced rate of extraction and transportation of oil and natural gas fossil fuels. The use of pipelines for

transporting of oil and gas products is a safer method compared to other possible ways of transportation as statistical analysis have shown in Ref. [1]. However, leaks and ruptures can still occur with significant hazard for humans [2]. Beside the life-threatening aspects, failures caused by degradation of pipelines can lead to serious economic losses [3] and environmental disasters such as pollution and contamination of wildlife and sea creatures [4]. Corrosion and wear in components and pipelines can be considered as one of the main causes of failure and leakage in oil and gas industry [5, 6]. All the three major fossil fuels, crude oil, and oil-sand and natural gas are very corrosive. Crude oil contains the corrosive ingredients such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), organic acids, dissolved gases, and salt water [7], while the oil sand comprises of CO_2 and corrosive ions such as Cl^- , HCO_3^- , and SO_4^{2-} [8]. Natural gas is also corrosive due to the presence of CO_2 , H_2S , and some calcium and chlorine compounds [9]. On the other hand, in some sequences of extraction of the petroleum products, erodant particles such as sand may be mixed with the flowing fluid to form multiphase solid-liquid mixtures. The flowing of these mixtures in pipelines and equipment in oil and gas industry may lead to solid particle erosion in addition to corrosion. The combination of wear and corrosion can extensively reduce the lifetime of the equipment due to the higher rate of material loss [10].

Although the corrosion and wear of components exposed to harsh erosive-corrosive environments cannot be thoroughly eliminated, protective coatings can be employed to improve the life time of equipment and prevent early and unpredicted failures. The selection of the proper coating material depends on the service condition, financial aspects, and fabrication processes. In large-scale applications, such as transportation pipelines, polymer-based protective liners are preferred owing to their relatively low cost and ease in fabrication. Among the polymeric protective liners, polyurethane (PU) elastomers have received great attention due to their ease in processability, excellent resistance to corrosion, erosive and abrasive wear, and comparatively low cost that allows for large-scale applications [11, 12]. PUs are organic polymers with the urethane group in their chemical structure that can be synthesized by the reaction of a diisocyanate and a polyol [13]. Although the PU fabrication process is similar to the methods typically used for polymers, its mechanical properties such as high elongation at break and minimal plastic deformation are comparable to that of vulcanized rubber that has a more complicated production process [14]. PU has better wear resistance than most polymers [15], rubbers [16], stainless steels [15], and even some hard-faced tungsten carbide-cobalt (WC-Co) coatings [17]. Excellent resistance to wear and corrosion together with ease in fabrication process and low cost has made PU an excellent option for use as protective liners in large-scale applications such as oil and gas pipelines [18].

1.2. Abrasive and erosive wear

Abrasive and erosive wear are the two major wear mechanisms in conditions where the relative motion between the surface and hard erodant particles is responsible for damage

and wear of the target material. In abrasive wear, the erodant particles are forced against the surface while moving along [13]. The erodant particles may slide or experience a combined sliding-rotating motion [19]. On the other hand, in erosive wear, the progressive loss of material occurs by the impact of hard particles that are moving in a gas or a liquid stream [13, 19]. The wear mechanisms of abrasive and erosive wear are discussed in the following.

In abrasive wear, the erodant particles are forced toward the target while sliding along the surface. As a result of this relative motion, small fragments can be detached from the surface by the cutting action of the sliding hard particles [20]. This wear mode that is one of the major types of abrasion is entitled as microcutting. The microcutting is usually the dominant mechanism of material removal in circumstances where the erodant particles are angular and harder than the target surface. Alongside with microcutting of the surface, the erodant particles may plough the surface by a combined action of cutting and plastic deformation to form groove shaped defects on the surface. The two wear modes of microcutting and ploughing are categorized as cutting mechanisms. On the other hand, in conditions where the grit media are blunt, the accumulation of residual strains together with fatigue mechanism caused by the repeated deformation of the surface is the major mechanism of material removal from the surface. The cracks formed from material defects will propagate by the repeated loading-unloading, leading to reduced strength of surface and loss of material. **Figure 1** shows a schematic of the material removal from a ductile surface caused by cutting and plastic deformation in abrasive wear. In hard brittle surfaces such as ceramics, the fracture of the surface, crack formation, and detachment of small pieces as a result of crack intersections is considered as the major abrasive wear mechanism.

The mechanism of material removal in erosive wear is not only a function of the properties of the target surface but also a function of the testing condition such as velocity and impact angle

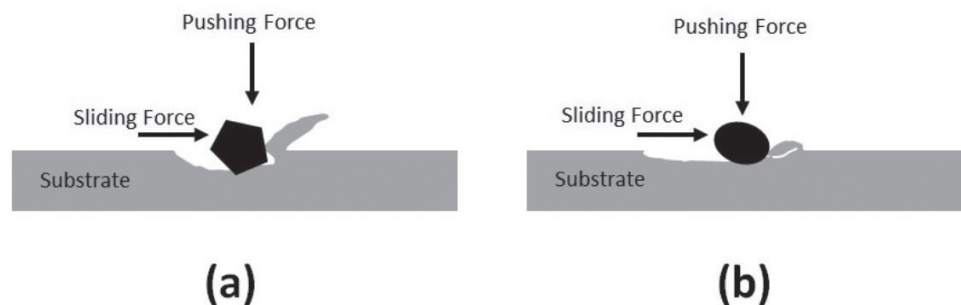


Figure 1. Abrasive wear of ductile substrates: (a) cutting mechanism and (b) plastic deformation together with fatigue mechanism.

of the erodant particles [21]. In conditions where the erodant particles impact the surface at low angles with respect to the surface (10 to 30°), the cutting mechanism similar to abrasion will be dominant. At low angles, the particle's normal impact force is high enough to enforce the particle for partial penetration, while the tangential force slides the particle along the surface to microcut small pieces from the target surface. As the impact angle increases, the tangential force produced upon impact will not be high enough to cut pieces from the surface. Alternatively, at higher impact angles of 60–90°, ductile targets will mostly experience plastic deformation, and the material removal occurs due to the microforging and extensive deformation of the target surface. The chips formed will detach from the surface at subsequent impacts due to the further accumulation of the residual strains and final detachment of the formed ridges [20]. Since the chipping mechanism of material removal requires higher number of impacts compared to cutting mechanism at oblique impacts, the ductile substrates present a minimal erosion rate at high impact angles. In contrast, the brittle ceramics have the highest erosion rate at normal impact angles, since the particle's normal force is maximum leading to higher fracture, cracking, and damage of the surface of the brittle substrate.

In many engineering applications, such as slurry motion of particles in a pipe, the material removal mechanism can be considered as a combination of erosive and abrasive wear. The slurry particles flowing in a pipe may slide onto the pipe bottom surface while being pressed toward the pipe surface by gravity and fluid weight. The motion induced by the flowing fluid and the pushing force can lead to abrasive wear of pipe material. On the other hand, the particles that are freely moving along the fluid stream and suddenly impacting the surface due to the flow turbulences within the pipe represent the erosive wear at low impact angles. Slurry flow in an elbow can be mentioned as another example for conditions in which combined abrasive-erosive wear may occur. Some particles are sliding while being pushed toward the surface, whereas some other particles are freely impacting the surface due to their kinetic energy and inertial forces. Consequently, when studying the wear of protective coatings and liners, the resistance of material versus both abrasive and erosive wear should be evaluated.

2. Wear of polyurethane liners

2.1. Material and mechanical characterization methods

The resistance of PU elastomers to abrasive and erosive wear is a function of both the testing condition and the properties of the PU. Ductility or softness, yield stress, elasticity, elastoplastic, and viscoelastic behavior are all parameters that can affect the stresses produced within the PU upon impact of erodant particles and, therefore, its wear resistance. To that end, when studying the wear behavior of PU elastomers, identification of the properties with the most significant effect on wear resistance of PU is of great interest. In this section, common experimental techniques to study the mechanical properties of PU elastomers are discussed. Through different testing techniques available for the characterization of PU, focus will be given to testing procedures for determination of parameters that correlate with the abrasive and erosive wear of PU.

2.1.1. Hardness testing

The hardness testing can be employed as a first-order approximation of ductility of elastomers and plastics [11]. The hardness of elastomers can be measured by a durometer according to the ASTM Standard D2240 testing practice [22]. In this method, the hardness of an elastomer is measured based on the penetration depth of an indenter into the substrate surface. The indentation depth is a function of elastic modulus and viscoelastic behavior of the elastomer [22]. The simplicity of this technique is one of its greatest advantages that allows for quick laboratory testing and in-field evaluations. Although determination of the exact value of elastic modulus is not feasible by this testing technique, the values measured are excellent for comparative evaluation of the elastomer softness. Moreover, monitoring of the indentation depth of the indenter with time can provide data about the viscoelastic response of material and its creep behavior. The hardness testing by durometer according to ASTM Standard D2240 does not provide any information about the elastoplastic behavior.

In a few previous studies [23, 24], it has been shown that the Vickers micro hardness testing that is usually employed for evaluation of the hardness of metals and ceramics [23, 25] can be used as a tool to provide information about the viscoelastic and elastoplastic behavior of polymers. Due to the high elastic deformability of elastomers, the shape of the indent is different from that of metals and a perfect symmetric indentation will not form on the surface. A variation in dwell time of the indenter during the test and also monitoring of the changes in size of the formed indents by time can provide information about the viscoelastic response of elastomers.

2.1.2. Tensile and compressive testing

Data obtained by durometer or Vickers hardness testing do not provide detailed information about the elastomer properties such as the Young's modulus and yield strength. Thorough characterization of PU elastomers can be achieved by testing equipment capable of tensile and/or compression testing at controlled load and displacement. Tensile tests conducted up to failure of the sample can provide information about the elastic modulus, final strength, and elongation at break of the polymer. These are the parameters that can affect the final resistance of a polymeric material to abrasive and erosive wear [21]. The sample size and the applied load and displacement can either be selected from standard testing practices such as ASTM Standard D638 [26] or may be selected similar to the type of loading that occurs in actual erosion or abrasion processes. Tensile testing can also be employed to study the effect of strain rate on the stiffness and strength of materials by testing at different strain rates. This is extremely important when studying the erosive wear of polymeric elastomers since the impact occurs within microseconds at very high strain rates [27]. Beside the tensile testing at different strain rates that can provide information about the viscoelastic response of polymeric materials, relaxation and creep testing can be conducted by this type of testing apparatus either in the form of tensile or compressive stresses. In relaxation tests, the stress relaxation of a material is studied after a sudden displacement at the beginning, while in creep testing, the deformation of the material is monitored upon exposure to a certain stress value [28]. Furthermore, tensile tests can be conducted at controlled temperature to evaluate the effect of temperature on the mechanical response of the studied PU elastomers.

The elastoplastic behavior of PU can be determined by cyclic loading in the form of tensile or compression testing. Cyclic loading-unloading can also provide information about the stress softening (Mullins damage) of elastomers, which is a permanent nonreversible damage to the structure of the material caused by loading [28]. Information about the elastoplastic response of elastomer is essential when studying the wear behavior since in abrasive and erosive wear, the repeated impact of erodant particles produces repeated loading-unloading on the elastomer surface [21].

2.1.3. Rebound resilience

The PU elastomers have better erosion resistance than most metals owing to their softness and high capability for elastic deformation. In fact, the PU elastic deformation enables absorbing the kinetic energy and gradual decelerating of the impacting particles with minimal damage. The kinetic energy absorbed in the form of elastic strain energy will be released later to rebound the erodant particle from the surface. The rebound resilience of PU can be employed as a parameter representing the ability of the elastomer to absorb kinetic energy of the erodant particle upon impact. This property can be measured according to the ASTM Standard D2632 [29]. In this testing practice, a plunger is dropped on the top of the sample surface from certain height. By recoding the rebound height of the plunger, the energy lost during the impact can be calculated. In a fully elastic deformation of the surface upon impact, the plunger would rebound to its initial height. Substrates with higher plastic deformation will restore smaller amounts of plunger energy and the plunger will rebound to a reduced height.

2.1.4. Dynamic mechanical analysis

The viscoelastic and time-dependent behavior of polymers can be characterized by either tensile/compression testing at controlled strain rates or by dynamic mechanical analysis (DMA). DMA can be conducted with different sample geometries, and since the vibration amplitudes by DMA are usually less than 100 μm , the DMA electronic shaker can vibrate the samples at very high frequencies [30]. Thus, the mechanical response of the studied PU can be categorized at different vibration frequencies or strain rates. Due to the relative small vibration amplitude in DMA, the measured properties are usually within the elastic region of the elastomer response. The data obtained from DMA are reported in the format of storage and loss modulus [30].

2.1.5. Thermal properties

The thermal properties of PU elastomers can also affect their resistance to erosive and abrasive wear. Heat can be generated during abrasion and erosion of PU elastomers by two mechanisms of (a) hysteresis and repeated deformation of PU and (b) the friction forces between the erodant particles and the target surface. The thermal properties of PU elastomers such as thermal conductivity and heat capacity can affect the temperature distribution below the impacted surface and, therefore, the wear resistance of the elastomer. Thermal conductivity of polymers can be measured by thermal constant analyzers [31]. Furthermore, the heat- and thermal-based test procedures such as differential scanning calorimetry (DSC) can provide

information about the chemical structure of the elastomer such as glass transition temperature and melting points of the elastomer [28]. This information enables the selection of protective liners to ensure that the elastomer will remain within its rubbery phase in operation.

2.1.6. Testing procedures for evaluating abrasive and erosive wear resistance

The resistance to abrasive and erosive wear can be determined by conducting standard wear testing procedures. In most of the wear testing practices, the volume loss for a specific period of time will be employed as the parameter representing the wear resistance of the material. The volume loss can be measured either by optical techniques or simply by measuring the mass loss and further calculating the volume loss according to the density of the tested material. Clearly, larger volume loss for a given time is representative of lower resistance to wear. From among the different types of available abrasion testing procedures, the ASTM Standard G75, B611, and G65 are the most commonly employed testing procedures to study the abrasive wear of materials [32–34]. The ASTM G75 is the standard testing practice for determination of resistance to abrasion caused by slurry [32]. In this testing condition, the samples move in reciprocating motion while being forced toward a surface covered with slurry. While in this testing condition, wear occurs at both forward and backward motion, in ASTM G65 and ASTM B611, a rotating wheel is used to abrade the test coupons in a single direction. ASTM G65 is the standard test method for measuring abrasion resistance using a dry sand/rubber wheel apparatus [34]. **Figure 2** shows a schematic of the ASTM G65 abrasion testing procedure. Although this test has been widely used in previous works for evaluating the abrasion resistance of metals and ceramics, the heat produced in this test caused by friction forces can lead to unreliable results when evaluating the wear resistance of heat-sensitive substrates such as PU. ASTM B611 is very similar to ASTM G65, though the test is conducted in slurry, and the rotating wheel is made of steel rather than rubber [33]. This testing method may be preferable over ASTM G65 since the wet slurry can cool the sample during the test. It should be noted that in abrasion tests a wet area is in contact with the PU, and care should be taken to ensure that the wet environment will not affect the wear resistance by a possible chemical reaction between the PU surface and the wet slurry, and also a change in properties of PU by water absorption.

ASTM Standard G76 can be mentioned as the most commonly used standard test for evaluating the erosion resistance of different target materials [35]. In this testing scheme, the erodant particles are accelerated in a gas jet prior to impacting the surface at a desired angle. **Figure 3** shows a schematic of this testing procedure. This testing technique is advantageous for erosion testing of heat-sensitive substrates such as PU since the high velocity of the impacting jet can mitigate the adverse effects of a temperature rise during testing.

2.2. Relation between mechanical properties and wear resistance of polyurethane

The superior wear resistance of PU is due to its softness and high capacity for elastic deformation. In fact, the PU softness and high elastic deformability allow for gradual deceleration of the erodant particles while absorbing their kinetic energy. The kinetic energy absorbed will be released later to rebound the erodant particle from the surface. Accordingly, a study of the

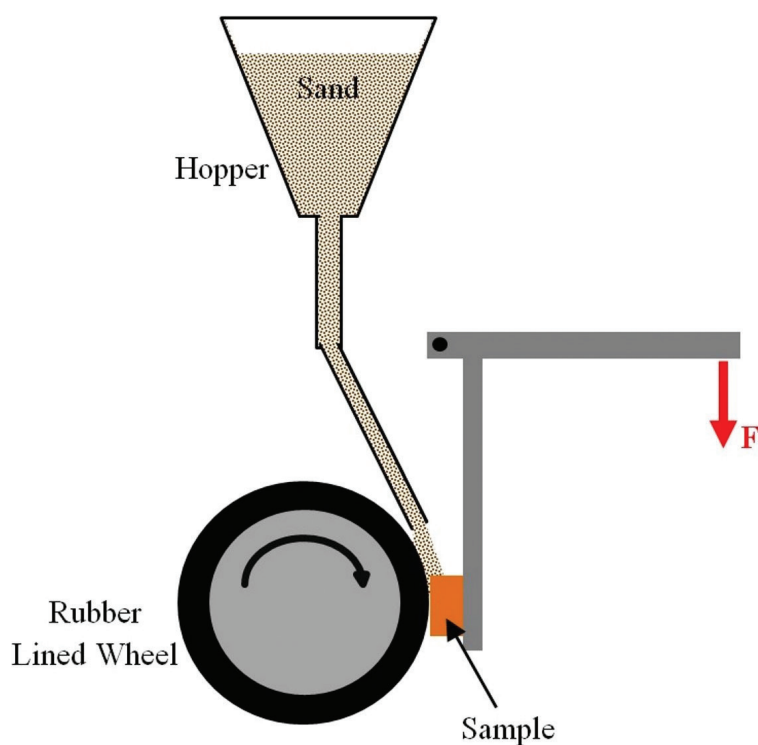


Figure 2. Schematic of standard testing method to measure abrasion resistance by dry sand/rubber wheel apparatus [34].

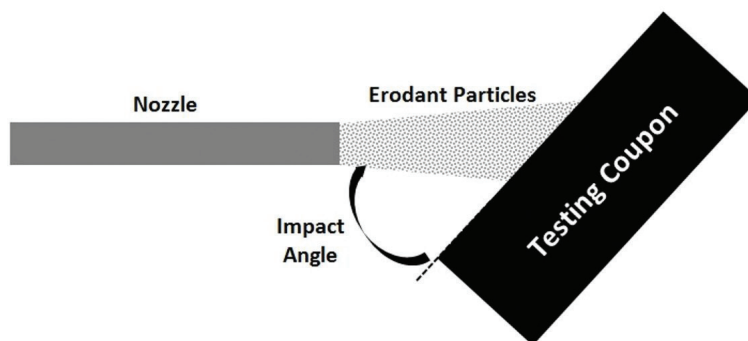


Figure 3. Schematic of erosion testing procedure according to the ASTM Standard G76 [35].

effect of PU softness on the wear resistance of PU has been the subject of a number of previous studies. The PU hardness as measured by durometer or Vickers hardness testing can be a representative of material softness and overall ductility as was discussed in Section 2.1.1 of this chapter. Li et al. [11] studied the erosion resistance of a series of castable PU elastomers with

hardness values ranging from 20 to 90 IRHD. A trend of an increase in erosion rate with increasing hardness was observed. It was further shown in this study that the erosion rate does not correlate with the elongation at break of the studied polymeric elastomers. The effect of softness on the erosion resistance of rubber elastomers has also been the subject of previous studies. In a study by Zuev et al. [36], the effect of slurry temperature on the erosion rate of rubber elastomers was studied. It was found that the erosion rate decreased when the temperature was increased from 20 to 70°C. Since rubber would become softer at elevated temperatures, it can be concluded that the increase in softness at higher temperatures could have been the reason for the reduction in the erosion rate. Similarly, in another study by Marei et al. [37] where the erosion resistance of rubber was evaluated at elevated air temperatures, it was reported that the softer elastomer had lower erosion rate. At elevated temperatures, the rubber became softer due to the greater difference between the testing temperature and the rubber glass transition temperature [37]. Consequently, the softness is certainly a factor affecting the erosion resistance of elastomers, including PU. The softness and high deformability of elastomers enable the deceleration of the impacting particles at a longer time compared to hard surfaces such as metals or ceramics. As the impact time becomes longer, the impact forces and the stresses decrease accordingly due to the impulse formula. The impulse formula states that the force is the time derivative of momentum as:

$$m\vec{v} = \int \vec{F}_{\text{impact}} dt \quad (1)$$

where m is the particle mass, Δv is variation in particle velocity vector, F_{impact} is the impact force, and t represents time. Thus, the impact stresses are smaller in softer materials due to the longer impact duration.

Evaluating the effects of hardness on the resistance of PU to abrasive wear has also been the subject of previous studies. Hill et al. [38] evaluated the wear performance of PU by employing an abrasion testing procedure according to the ASTM Standard G65 [34]. The results from this study supported the validity of the graph of wear rate versus hardness proposed by Pitman [39] as shown in **Figure 4**. As seen in **Figure 4**, the abrasion resistance of PU does not vary significantly with hardness in Region B. The graph in **Figure 4** also shows that reducing the hardness of PU to very low values, Region A, increases the wear rate. This behavior is in contrast with erosion of PU elastomers in which the softer PU elastomer has higher resistance to erosive wear. The graph in **Figure 4** suggests that except for very hard PU elastomers (Region C), the harder PU elastomers have better resistance to abrasive wear, since the harder PU can better resist the penetration of erodant particles during the abrasion testing. The reduced penetration means smaller stress level and, therefore, reduced damage to the substrate caused by repeated deformation of PU.

Although the PU hardness seems to correlate well with the resistance to abrasive and erosive wear, PU elastomers with similar hardness values may have different resistance to abrasive and erosive wear [21, 40]. Ping et al. [17] evaluated the erosion resistance of two PU samples with relatively similar hardness values. In this study, the elongation at break obtained through tensile testing was introduced as a parameter that can affect the wear resistance of PU elastomers. It was shown that PU with higher elongation at break (320%) had higher resistance to erosive wear compared to PU with lower elongation at break (250%). Zhang et al. [16] also showed that

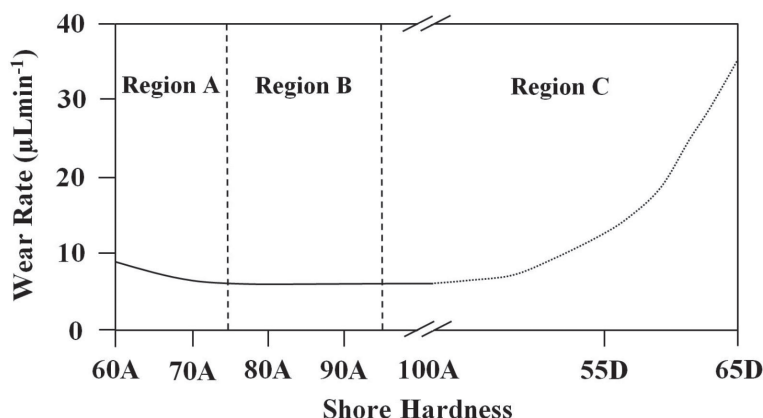


Figure 4. Abrasive wear rate of PU as a function of hardness [38, 39].

PU elastomers with higher elongation at break (520%) had higher resistance to erosive wear compared to other polymers with lower elongation at break such as polytetrafluoroethylene (150%). Similarly, Ashrafizadeh et al. [21] showed that a reduction of the elongation at break of PU at 100°C led to a sudden increase in erosion rate of PU at that temperature. According to the impulse formula, the softer material enables longer impact time and, therefore, reduced stresses and damage. However, the elongation at break of the material should be high enough to enable the deformation of the soft elastomer without failure. In fact, if the deformation strain caused by the impact of the erodant particle exceeds the strain at break, failure of the material will occur leading to detachment of fragments from the surface.

Tensile cyclic loading of PU samples allows for comparing wear resistance, hysteresis and elastoplastic behavior. Hysteresis of a polymer represents the fractional energy lost in a deformation cycle [21]. Beck et al. [41] conducted cyclic loadings to study the effect of PU hysteresis on wear resistance. It was found that PU elastomers with similar hardness values had different wear rates due to the differences in hysteresis of the studied elastomers. PU elastomers with higher hysteresis exhibited higher erosion rate. Larger hysteresis can negatively affect the strength of an elastomer in two ways: (a) higher heat production and temperature rise below the worn surface and (b) greater permanent irreversible damage to the polymer structure upon loading [28]. Thus, a material with a higher hysteresis not only suffers from adverse effects of temperature rise but also experiences a higher damage level upon impact of erodant particles. This can accelerate the progressive damage caused by the repeated impact of particles leading to final removal of material from the surface at a higher rate.

The relation between the elastoplastic behavior of elastomers and their wear resistance has been the subject of few previous studies. In a recent study by Ashrafizadeh et al. [21, 42], the elastoplastic response of PU elastomers obtained by cyclic tensile loading was compared with the data obtained from erosion testing at controlled temperatures. The results obtained showed that PU elastomers with higher residual strain (permanent set) upon unloading exhibited a higher

erosion rate. This behavior was due to the fact that in PU elastomers with lower residual strain, a higher number of impacts will be needed for progressive damage and final detachment of fragments from the surface. On the other hand, in some studies, the elastoplastic behavior of elastomers has been assessed by evaluating the rebound resilience of the elastomer. For example, in a study by Hutchings et al. [40], rebound resilience was found to be the most dominant factor affecting the wear resistance of rubber elastomers in which the rubber with higher rebound resilience had the highest erosion resistance. It should be noted that measuring the rebound resilience is an approximation of the elastoplastic response behavior since this test only provides information about the elastoplastic response for a single loading condition related to the mass and velocity of a falling plunger [29].

In an assessment of the wear resistance of elastomers, attention should be given to the possible effect of temperature and chemical reactions on the overall wear resistance of PU protective liners. The mechanical properties of PU are sensitive to temperature and may vary significantly even by changing the temperature by around 40°C [21]. Thus, the temperature rise during the wear experiment may affect the erosion resistance of PU [14, 16, 38, 41, 43–46]. This suggests that accurate monitoring of the temperature during wear testing of elastomers is required. A review of the effect of temperature on wear resistance of elastomer is discussed in Section 2.4 of this chapter. On the other hand, the fluid that is in contact with the elastomer surface either as a cooling agent in abrasion testing or as a jet for accelerating the erodant particles in erosion testing can affect the wear resistance of elastomers in two ways. First, a chemical reaction may take place between the flowing fluid and the elastomer surface. For example, it was shown by Zuev et al. [36] that the erosion resistance of rubber is a function of the resistance of the elastomer to chemical reaction with the aggressive media. It was shown that as the concentration of acetic acid increased in the abrasive medium, the wear rate increased. Second, swelling of PU elastomer can affect the resistance to wear. Siegmann et al. [47] showed that for conditions in which the PU was in contact with organic fluid medium, the PU became softer by absorbing the solvent. It was found that higher swelling of the PU led to higher abrasive wear due to the softening of the PU. Thus, testing in dry conditions and controlled temperatures may be ideal when wear testing of PU elastomers to minimize the possibility of swelling and chemical reactions.

2.3. Mechanism of material removal

The mechanism of material removal in abrasion and erosion of PU elastomers by solid particles is a function of the wear testing procedure, properties of abrasive media, and mechanical properties of the target material. The wear mechanisms that have been suggested for PU elastomers can be divided into three categories of (a) cracking below the worn surface, (b) formation and detachment of ridges and (c) random scratches and gouges.

2.3.1. Cracking below the worn surface

In erosive and abrasive wear, compressive and shear stresses are produced by the impact or sliding of the erodant particle [48]. Due to the deformation of the elastomer in front of the

surface, the produced stresses in that area are compressive. On the other hand, the stresses formed by friction forces and dragging of the elastomer are mostly shear as demonstrated schematically in **Figure 5**. The shear stresses generated by the friction forces have a maximum value at a certain depth below the surface (see **Figure 5**) [48]. The elastomer will be retrained from cracking near the surface since the compressive stress has the maximum value. However, as the distance from the surface increases, the compressive stress decays faster than strain does and, thus, depending on the wear process parameters and the fatigue properties of the elastomer, at some depth below the worn surface layer, the shear stresses produced by the repeated impact of particles will lead to crack formation and further propagation onto the PU [48]. The typical cracks formed at a certain depth below the surface have been observed in images taken by scanning electron microscopy (SEM) from the cross sections of a worn PU as shown in **Figure 6**. The existence of a maximum value for the shear stress at a certain depth from the surface has been also shown quantitatively in previous studies by finite element modelling [14]. Detachment of fragments and, therefore, wear of the target material occur as a result of the intersection and extension of cracks formed below the worn surface [14, 16, 43, 48]. The surface of PU samples worn by this mechanism does not have regular patterns. Cracks and detached pieces are scattered throughout the worn surface.

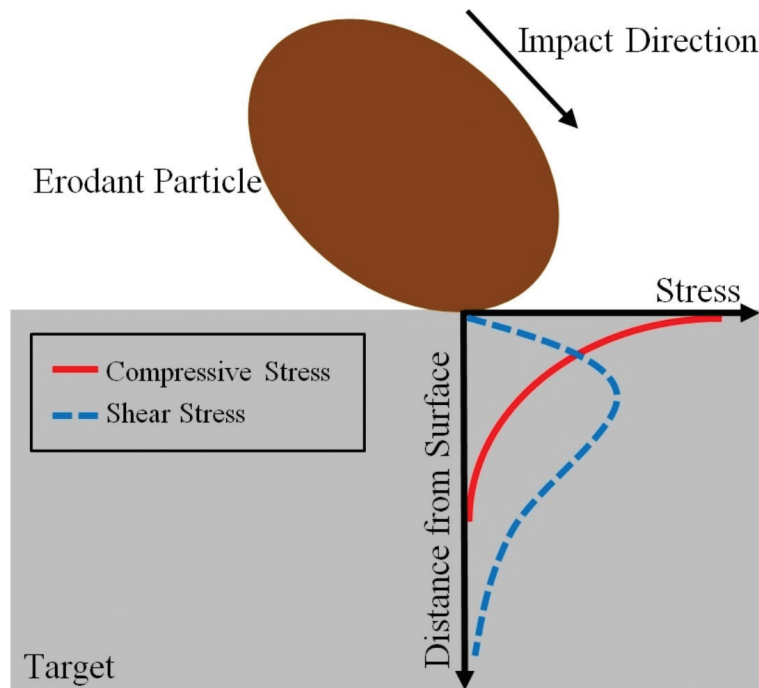


Figure 5. Schematic of stress distribution during abrasion of polymeric elastomers [48].

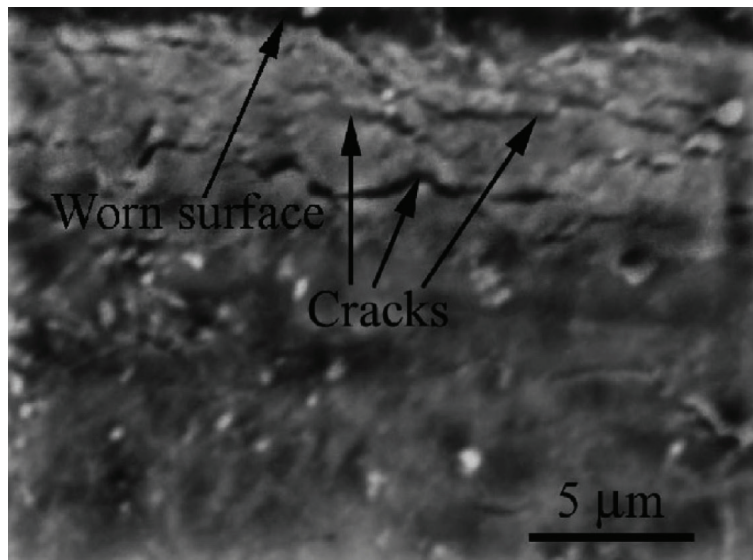


Figure 6. Cracks formed below the surface during abrasion of PU elastomer [48].

2.3.2. Formation and detachment of ridges

For conditions in which the stresses produced by the impact or the sliding of hard particles are smaller than the final strength, but higher than the yield strength of the PU elastomer, no loss of material will occur by a single impact. Alternatively, the gradual plastic deformation and formation of ridges on the worn surface are responsible for material loss from the surface. In this mechanism, as a result of repeated impact or sliding of solid particles, the plastic strains will accumulate to generate localized ridges on the PU surface. The ridges formed are perpendicular to the direction of impact or sliding of erodant particles [11]. In other words, the single impact of an erodant particle does not lead to material loss from the surface, and many successive impacts are required prior to damage and material loss from the surface in this mechanism [12]. **Figure 7** shows a typical image of such ridges formed after erosion testing of a PU elastomer, while **Figure 8** shows a side magnified view of one of the ridges. In these figures, the arrow shows the impact direction. The further accumulation of plastic strains will eventually lead to cracking at the bottom of the asperities, followed by the final detachment of the material from the surface. A typical crack produced on the base of one of these ridges is indicated in **Figure 8** by a circle. Consequently, this wear mechanism highly depends on the elastoplastic behavior of PU; PU elastomers with a higher tendency to revert to its initial condition upon loading and minimal plastic deformation have higher resistance to erosive wear since a higher number of impacts will be required to form and detach these ridges from the surface.

The formation of ridges perpendicular to the direction of impact and final fracture of the asperities is the mechanism of material removal in both erosive and abrasive wear of PU elastomers [11, 12, 14, 21, 38, 41, 46, 48]. The morphology and distances of the asperities produced

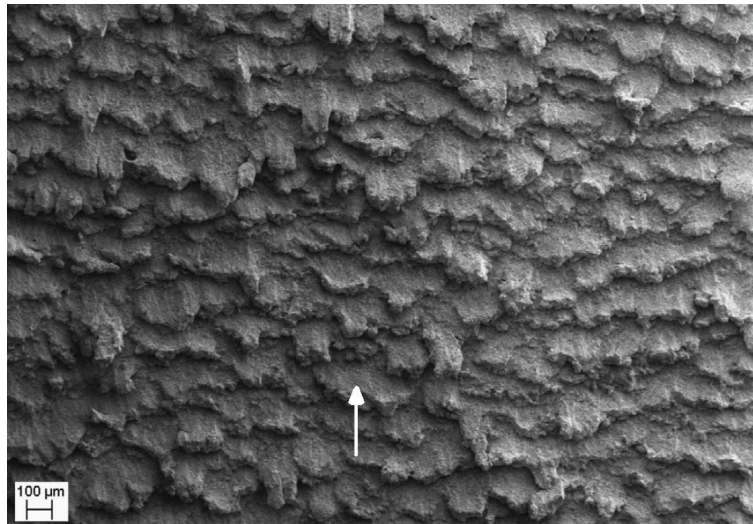


Figure 7. SEM image taken from the top surface of an eroded PU [21].

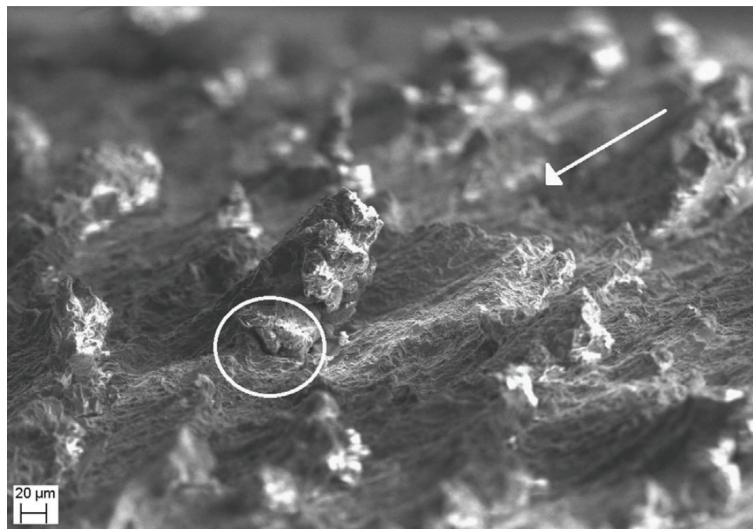


Figure 8. Side SEM image taken from one of the ridges formed on the surface of an eroded PU [21].

on elastomer surfaces are functions of the mechanical properties of the target surface. For example, it has been shown by Hutchings et al. [40] that ridges are more regular in shape and pronounced in rubber with higher resilience. Ashrafizadeh et al. [21] showed that the ridges

formed were smaller for PU elastomers with lower elongation at break. The patterned ridges formed during abrasion of PU elastomers are also a function of the mechanical properties of the elastomer as was shown by Hill et al. [38], that is, asperities were closer in harder PU elastomers. Although a few studies have focused on evaluating the effect of elastomer mechanical properties on the shape of the ridges produced, further research for an in-depth understanding about the relation between the mechanical properties of the tested elastomers, testing condition, and the shape of the asperities formed is required.

2.3.3. Random scratches and gouges

In abrasive and erosive wear of PU elastomers, the material detachment may occur even by the impact of a single erodant particle based on the testing parameters and the properties of the elastomer. This mechanism of material removal is more similar to erosive and abrasive wear of metals in which the primary mechanism of material removal is random scratches and gouges on worn surfaces due to the cutting and gouging action by angular grit media. This type of wear usually occurs when the erodant particles have sharp edges to tear the elastomer surface. In other words, in conditions where sharpness or high velocity of erodant particles lead to production of stresses higher than the final strength of the elastomer, detachment of small fragment from the surface can occur. It should be noted that there is no regular pattern on the surfaces of elastomers worn by this mechanism. The worn surface by this mechanism is covered with cracks and detached fragments similar to the fatigue crack growth mechanism that was explained in Section 2.3.1.

2.4. Effect of working temperature on wear resistance of PU

The effect of temperature on wear resistance of PU elastomers has been of attention due to the heat sensitivity of PU and the possibility of heat production and, therefore, temperature rise during the abrasion and erosion processes. Unlike metals, the mechanical properties of PU may vary significantly even by temperature variation within the range of $\pm 40^\circ\text{C}$. The fact that the temperature rise of as much as 50°C can occur during the wear process of PU elastomers emphasizes the importance of knowledge about the effect of temperature on the wear resistance of PU [38, 43]. In this section, the effect of temperature on wear resistance of PU and rubber elastomers will be discussed and previous studies related to this topic will be reviewed.

The heat generated during the wear testing of elastomers can be employed as a heat source to evaluate the effect of temperature on the wear resistance of PU elastomers. Hill et al. [38] evaluated the wear performance of PU by employing an abrasion testing procedure based on the ASTM Standard G65 [34]. Two testing procedures were conducted: (a) continuous abrasion testing and (b) abrasion testing with 10 min rest periods every 1.5 min to allow for cooling of the samples. It was found that the samples that were tested with the continuous process (procedure (a)) did not have a constant wear rate due to the uniform temperature within the samples during the test. It was found that the temperature rise affected the wear rate by varying the hardness of the PU. Zhang et al. [43] employed a grit blasting chamber to evaluate the effect of thickness of a PU liner on its erosion performance. It was found that the heat generated

by hysteresis and friction forces increased the temperature of the PU in the layer beneath the surface. The increase in temperature negatively affected the strength of the PU material leading to lower erosion resistance. Even though, the effect of temperature on abrasive and erosive wear of PU elastomers was addressed, in these studies no external heat source for accurate and uniform control of the temperature during wear testing was employed. Accordingly, in some previous studies, testing assemblies capable of erosion testing at controlled temperatures by employing an external heat source has been developed. Zuev et al. [36] conducted erosion testing at elevated temperatures by controlling the slurry temperature. The increase of slurry temperature from 20 to 70°C improved the erosion resistance of the rubber owing to the improvement in elasticity and softness of rubber at the elevated temperature of 70°C. Marei et al. [37] also reported improvement in erosion resistance of rubber at elevated temperatures. In this study, an air blasting test scheme with the controlled temperature on the input gas was developed. It was found that at testing temperatures with greater difference from the glass transition temperature, the erosion rate of rubber was lower. In a more recent study by Ashrafizadeh et al. [21, 42], a test assembly for erosion testing at controlled temperatures was designed and developed. A cold spray system with controlled gas temperature and temperature controller and cartridge heaters were employed to heat the samples from the exposed and unexposed surfaces, respectively. The accurate temperature field within the samples during the erosion testing was further determined by a finite element numerical heat transfer model. In this study, the effect of temperature on strength, elongation at break, and elastoplastic behavior of PU elastomers was also studied and compared with their wear resistance. This comprehensive study showed that the increase in temperature may improve the erosive resistance of PU elastomers in two ways. First, the increase in softness of PU at elevated temperatures would allow for deceleration of the erodant particles at a longer time and, therefore, the stresses generated will be smaller, which means less damage to the substrate. Second, the increase in temperature can affect the elastoplastic response of PU in such a way as to revert to its initial condition with less plastic deformation after the loading caused by the impact force. Thus, a higher number of impacts will be required to deform the PU to the detachment threshold, which means improved resistance to erosive wear. It was further shown that the increase in temperature can negatively affect the wear resistance in conditions where the final strength of PU becomes smaller than the stresses produced by the impact of erodant particles [21].

3. Modelling of wear process of polyurethane liners

3.1. Objectives in modelling of the wear process

Wear caused by impact and sliding of solid particles is a complicated process due to the high number of factors that affect the wear mechanism and final wear rate. Wear resistance is a function of (a) the properties of the erodant particles: shape, density, size, and hardness, (b) the properties of the target material: Young's modulus, plastic behavior, and final strength, and (c) wear testing parameters: velocity of impacting particle, angle of impacts, testing temperature, flow rate, sliding velocity, and pushing force. Accordingly, the experimental investigation of the effect of different parameters on the wear resistance is time consuming and costly. Moreover, wear

caused by impact and sliding of erodant particles occurs within microseconds, and hence, the experimental study of the physics underlying the problem is not a trivial task [27]. The simulation of the wear process by analytical and numerical approaches not only enables the understanding of the fundamental principles of the wear mechanisms; the models developed can be employed after verification as predictive tools to study the effect of different parameters on the wear rate. Through different analytical and numerical models developed to date to simulate the wear of metals, ceramics, and elastomers, the finite element (FE) formulation has received great attention due to the potent formulation of this technique that enables the modelling of complex geometries, material models, and contact algorithms [27, 49, 50]. In the following section, the research works conducted for FE modelling of wear of PU elastomers will be reviewed and discussed.

3.2. Finite element modelling of the wear process

Several studies have focused so far on developing FE models for simulating the erosion caused by solid particle impact of ductile metals such as AISI 4140 steel and nickel (Ni), Al6061-T6, Ti-6Al-4V and brittle ceramics such as tungsten carbide (WC), Cr₃C₂, and SiC [50–53]. The models developed enabled an in-depth study of the stresses and strains produced during the erosion process and also assess the effect of testing factors such as particle size, shape, velocity, and impact angle on the erosion rate. On the other hand, fewer studies have focused on FE modelling of the solid particle erosion of soft elastomeric materials such as PU. In a recent study, Zhang et al. [43] simulated the impact of a single particle on PU liners by a FE modelling approach. In this model, an isotropic hardening elastic-plastic constitutive law was selected for the material formulation, and material removal was modelled by deleting the elements that exceeded the failure strain of the PU. The defined element removal criterion enabled to calculate the wear rate as a result of impact of a single erodant particle. The model developed was employed to study the effect of liner thickness on the erosion resistance of PU. The results obtained by the FE model were in good agreement with experiments only up to the liner thickness in which the effect of temperature was negligible. The model failed to correctly predict the same trend as experiments for the erosion rate versus liner thickness due to the fact that the model did incorporate the temperature rise caused by the repeated impact of particles.

The high elongation at break of PU elastomers can lead to significant deformation and distortion of elements in FE modelling of the wear process. To that end, FE-mesh-free techniques may be employed to eliminate the adverse effects of element distortion while modelling the erosive wear of soft substrates such as elastomers [54]. In mesh-free techniques, there is no connection between the nodes, and the model is discretized with scattered particles. For example, Gong et al. [54] developed a 3D combined FE-mesh-free model with smoothed hydrodynamics (SPH) particles. The viscoplastic material model of Johnson-Cook formulation was selected as for the material model. Even though the elements experienced extensive deformation in the FE model, the results obtained by the combined FE-SPH model predicted similar equivalent stresses at the impact point to that of the FE model with negligible difference [54]. Since the computation time by the FE model was approximately four times shorter than the combined the FE-SPH model, the FE formulation can be considered as the superior technique.

In a recent study by Ashrafizadeh [49], a more comprehensive material formulation capable of accounting for hyperelastic, elastoplastic, and stress softening of the elastomer was developed using the FE technique. The material model formulation successfully predicted the elastoplastic and stress softening response of the PU as validated by conducting cyclic deformations of a single element and comparing the stress-strain behavior of the element with that of experiments. This research allowed for an in-depth evaluation of the effect of temperature, material softness, final strength, and elastoplastic behavior on the stresses produced as a result of the impact of erodant particles. The model successfully simulated the cutting mechanism caused by the impact of a single erodant particle (see **Figure 9**). Moreover, the impact of ten solid particles was modelled to study the mechanism of material removal by accumulation of residual strains up to the detachment of material. The model provided support for this mechanism and successfully predicted the shape of the formed asperities (see **Figure 10**) similar to those of the eroded surface of PU as was observed from experiments (see **Figure 8**).

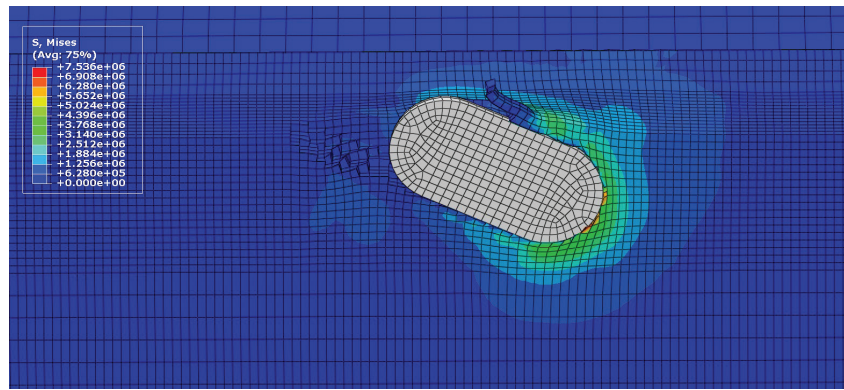


Figure 9. Material removal by cutting mechanism as predicted by the FE model [49].

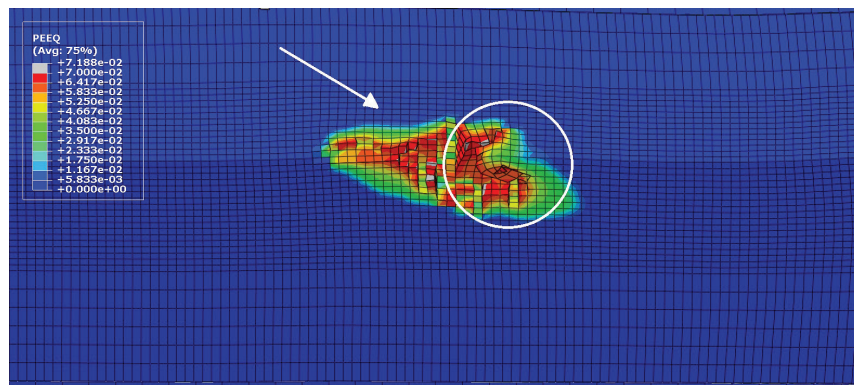


Figure 10. The ridges formed on the surface of an eroded PU as predicted by FE model [49].

4. Future trends

4.1. Wear resistance of filler modified polyurethane liners

Most of polymers including PU elastomers have low thermal conductivity of usually below 0.5 W/mK [31, 55]. Although the low thermal conductivity has made the PU an excellent option for insulation purposes, it can limit the applications of PU as protective wear resistant liners. As was discussed in Section 2.4 of chapter, heat may be produced during wear of PU elastomers by friction forces and hysteresis. The low thermal conductivity of the PU can allow for a localized temperature rise below the worn surface and, therefore, decrease in strength of the material leading to accelerated wear of the surface. On the other hand, fillers can be added to the structure of the polymer to develop multifunctional filler modified polymers with improved mechanical and thermal properties [31, 56].

It has been shown in previous studies that the thermal conductivity of polymers improved by means of addition of highly conductive powder materials such as metallic, ceramic, and carbon-based fillers with high thermal conductivity [57]. The improvement in thermal conductivity of the filler modified polymer is a function of the filler type, shape, size, and distribution within the polymer matrix [31, 58]. In a recent study by Akram et al. [31], nano-graphene fillers were added into an abrasion-resistant PU liner to improve its thermal conductivity. It was found that the addition of 4 wt.% of nanographene filler to the PU structure increased the thermal conductivity of the PU by 164%. Although the possible improvement in thermal conductivity of PU protective liners has been shown in previous studies, the effect of the added fillers on the abrasive and erosive wear resistance of elastomers has been the subject of fewer studies, and future work is required. An investigation on size, shape, concentration, and type of fillers that can simultaneously improve the thermal and mechanical properties of PU elastomers is suggested for future work.

4.2. Relation between wear resistance and viscoelastic response of polyurethane elastomers

In most of the previous studies, the wear resistance of PU elastomers has been compared with the mechanical properties that have been obtained in quasi-static or low strain rate testing conditions. However, the impact and rebounding of the particle occur within a few microseconds with PU deformation at very high strain rates. The mechanical response of PU elastomers at high strain rates can be significantly different from that of loadings at low strain rates [59]. PU may become harder at higher strain rate loading [59]. Thus, knowledge about the mechanical response of PU at high strain rates, and, in general, the viscoelastic response of PU elastomers can provide a deeper understanding of how the time-dependent properties of PU elastomers may affect the mechanism of material removal and the final erosion rate. The viscoelastic properties of PU elastomers can be characterized by hardness, DMA, creep, relaxation, and tensile/compression testing. A study of the relation between the viscoelastic properties and wear resistance of PU is suggested for future research.

4.3. Finite element modelling of the abrasive wear

Even though the successful FE modelling of the erosive wear has allowed for a better understanding of the stresses produced during the erosion process and material removal mechanism of PU elastomers, the number of studies that focused on FE modelling of the abrasive wear of elastomers is limited. Although in some studies such as the research by Martinez et al. [14], the FE technique was employed to analyze the abrasion phenomenon as a result of sliding and contact of PU over rough, rigid surfaces, the modelling of wear caused by abrasive, erodant particles is limited. Such models can allow for a better understanding of the mechanism of a material removal during abrasive wear of PU elastomers and identification of the key parameters affecting the abrasive resistance of PU. A research study to develop FE models to simulate the abrasion caused by sliding of solid particles is suggested for future work.

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