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Investigation of abrasive erosion of polymers

S. W. ZHANG, WANG DEGUO, YIN WEIHUA
University of Petroleum, P.O. Box 902, Beijing 100083 People's Republic of China

Mechanisms of abrasive erosion for polymers, including polyurethane, styrene–butadiene rubber, nylon-6 and polytetrafluoroethylene, have been investigated using a special abrasive erosion test machine designed by the authors. Based upon some observations of the abraded surfaces of test samples using scanning electron microscopy (SEM), the mechanisms of abrasive erosion for the polymers examined could be summarized as follows: a microcutting action of the abrasives with a certain kinetic energy; microdelamination of the surface layer of the materials resulting from initiation and propagation of microcracks; mechanochemical and thermal decomposition of materials; and surface peeling, resulting from plastic fracture expanded from local plastic deformation of the material. The influence of these factors on the wear rate of the abrasive erosion has been studied, and the relevant wear-rate equations are presented.

1. Introduction

Abrasive erosion may be defined as the wear process of a solid surface caused by a fluid medium containing particles flowing in a direction approximately parallel to the surface of solid at a certain speed. It is also considered as a type of sliding erosion elsewhere [1, 2]. This wear usually occurs in a number of equipments handling granular materials and in freight pipelines. In recent years, certain polymeric materials with more advantages than metals in many aspects, were considered as suitable materials for an abrasive wet slurry application. Although sliding erosion has been studied extensively [1–12], the mechanisms of abrasive erosion of polymers still remain inadequately investigated. Therefore, the purpose of this study was to reveal the abrasive erosion characteristics of polymers.

2. Experimental procedure

Experiments were conducted using a special testing machine (Fig. 1), which simulates, as close as possible, the wear pattern of abrasive erosion and the operating conditions of hydrocyclone used in an oilfield. The fluid medium (water with viscosifier) containing quartz particles with grade 7 hardness, is pumped from the slurry tank into the test cavity, and then back to the tank. A schematic drawing of the test cavity is shown in Fig. 2. The test conditions are given as follows: velocity of flow 7.2–11.08 $\mathrm{m\,s^{-1}}$; particle concentration 5–30 wt %; particle size 76–450 μm; fluid viscosity 1×10^{-3}–30×10^{-3} $\mathrm{N\,s\,m^{-2}}$ (20 °C); and fluid temperature 63–67 °C.

Four kinds of polymeric material were chosen as test samples. The properties of the materials are given in Table I.

Scanning electron microscopy (SEM) was used to examine the eroded surface. The erosion rates of materials were measured. The worn samples were heated in a thermostatically controlled oven before each measurement in order to eliminate error due to sample swelling.

3. Results and discussion

3.1 Morphological characteristics of the worn surfaces

3.1.1. Polyurethane (PU)

Indentations and scratches were found on the worn surface (Fig. 3a). Obviously, microdeformation and microtearing occurred in the surface layer by the action of microcutting of the flowing abrasive particles. Hence, the generation of tensile, compressive and/or shearing stress in the surface and subsurface of the solid could be deduced. Moreover, it could be considered that the maximum shear stress is always generated at a certain depth beneath the surface of PU material, similar to that in a metal. Consequently, under the action of alternating stress caused by the continuous impacting of the flowing abrasive particles, crack growth could appear and extend gradually into the surface or subsurface layer.

The crack nucleation possibly results from faults in the material (such as voids, impurities, etc.) or from the fracture of molecular bonds and intermolecular chains induced by mechanical or thermal effects. Mostly, crack growth would be initiated at a certain depth in the subsurface, namely the site of maximum shear stress; moreover, the direction of crack propagation would be parallel to the surface. With increase of the tangential force (friction force), the location of the maximum shear stress will gradually move up to the surface. In addition, the deformation hysteresis-induced heat of the subsurface is usually higher than that of the surface, which could change the orientation of the molecular chains and result in rupture of the

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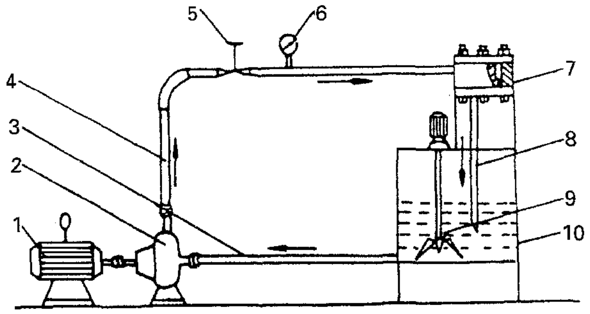

Figure 1 The abrasive erosion test machine. 1, motor; 2, slurry pump; 3, inlet tube; 4, discharge tube; 5, regulating valve; 6, pressure gauge; 7, test cavity; 8, underflow tube; 9, mixer; 10, slurry tank.

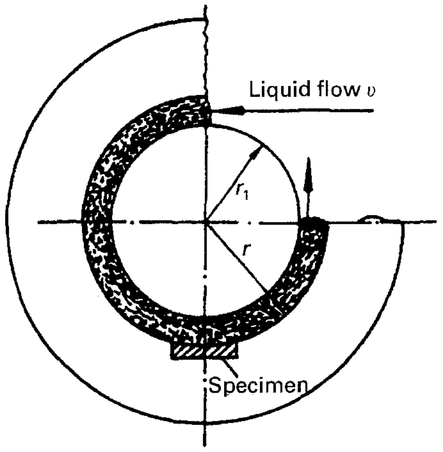

Figure 2 Schematic drawing of the test cavity (cross-section).

molecular bonds or intermolecular chains of the polymer. Consequently, the cohesive energy of the material between the surface layer and substrate will be weakened. At the point of highest temperature, there is possibly the lowest cohesive energy, and that is possibly the location where the crack initiated. Once the cracks are further propagated into the surface layer, fatigue delamination of material occurs (Fig. 3b).

3.1.2. Styrene–butadiene rubber (SBR)

As seen from Fig. 4, the abraded surface is covered with a sticky layer. A number of indentations and

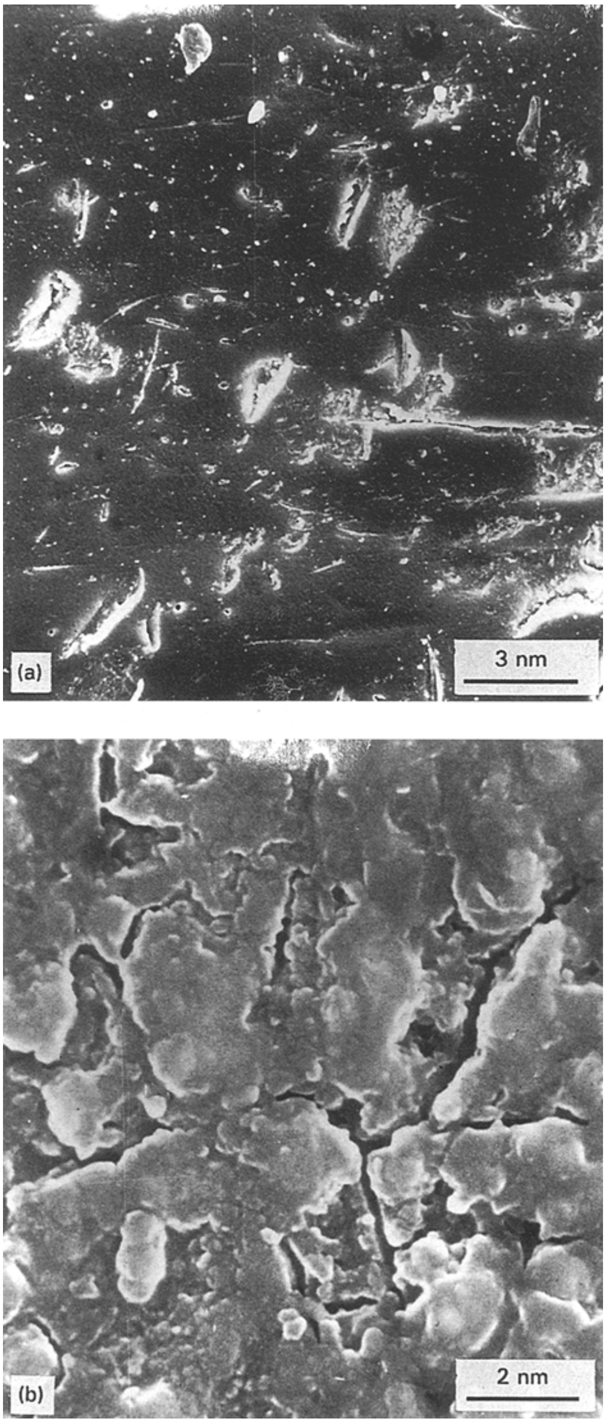

Figure 3 Morphology of the worn surface of polyurethane, showing (a) indentations and scratches, and (b) cracks and delaminations.

TABLE I Performance and mechanical behaviour of the four kinds of polymeric materials tested (65 °C)

Properties	Polyurethane	Styrene–butadiene rubber	Nylon-6	Polytetrafluoroethylene
Breaking strength (MPa)	43.3	> 13.7	44.1	15.0
Tearing strength (MPa)	10.8	2.0–6.0	–	–
Shore-hardness	38	13	57	50
Elongation at break (%)	520	500	300	150
Elastic modulus (MPa)	0.7–7	0.7–2	248	38.4
Glassy transition temperature (°C)	– 64	– 60	50–57	115
Coefficient of friction (room temperature) [13]	0.2–0.5	0.48–1	0.16–0.37	0.09–0.11
Mechanical behaviour	Rubbery state	Rubbery state	Soft glassy state	Glassy state

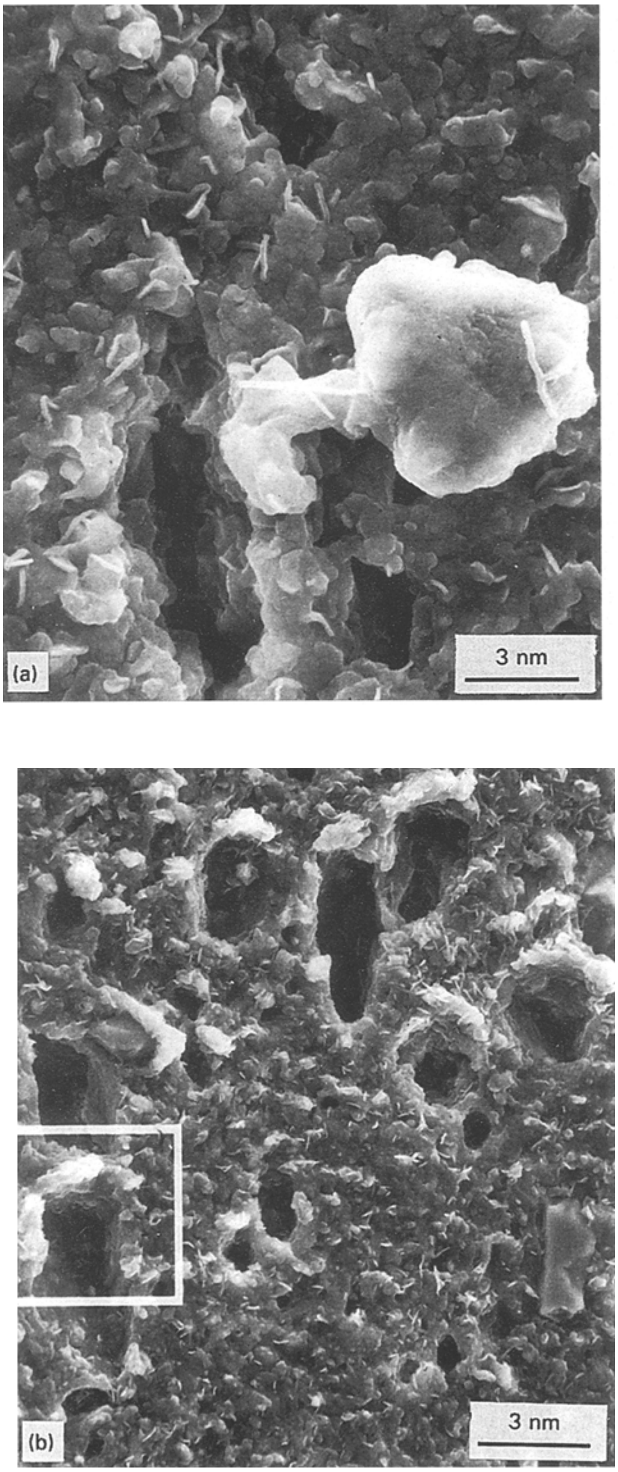

Figure 4 Morphology of the worn surface of styrene-butadiene rubber, showing (a) the sticky layer, and (b) indentations and ridges.

ridges may also be found on the surface layer. In front of indentations, some accumulations, such as lips and torn tongues of material, are formed.

Similar to the erosion of polyurethane, microdeformation and/or microtearing of surface layer occurred obviously under the action of microcutting of the flowing abrasive particles. However, these mechanical effects are more severe than that on polyurethane material, because the strength and hardness of styrene–butadiene rubber is much lower than that of polyurethane. Consequently, mechanical rupture of the macromolecules results, forming reactive radical species. On the other hand, owing to the high elastic hysteresis property of rubber, a large amount of heat might be accumulated in the surface and subsurface layer under the action of intense micordeformation. As a result, both mechanochemical degradation and thermal decomposition of rubber are produced. Because of the degradation of rubber, sticky layer is formed in the surface regions [14]. When the sticky layer is worn down or worn off, microdeformation and/or microtearing of the surface layer will ensue. As the above processes occur repeatedly, the material will be worn off in the way of microcutting and degradation.

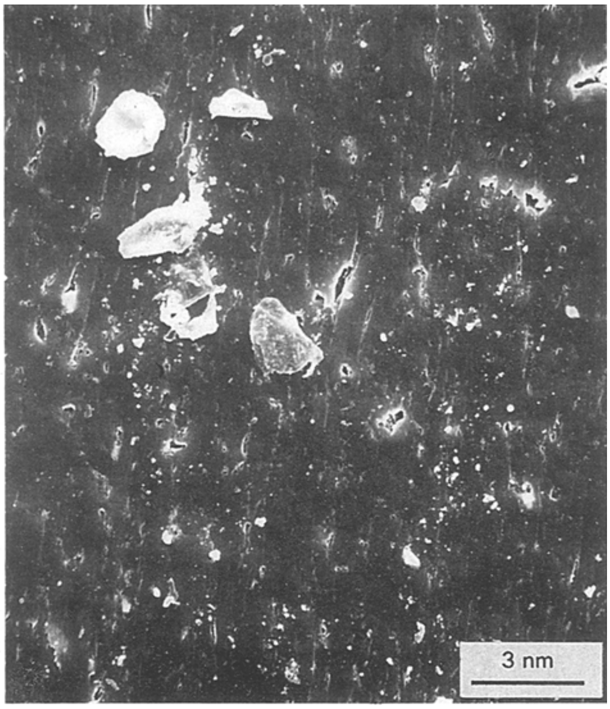

Figure 5 Morphology of the worn surface of Nylon-6.

Both polyurethane and styrene–butadiene rubber are in the rubbery state, but no fatigue delamination occurs in the latter. This could be ascribed to the difference between the properties of both materials. As the friction coefficient of rubber is larger than that of polyurethane, the tangential force (friction force) acting on the surface of the former is larger than that of the latter; therefore, the maximum shear stress of rubber usually occurs on the surface of the material. Moreover, styrene–butadiene rubber is filled with carbon black. One of the effects of carbon black is to improve the thermal conductivity and the heat resistance of a material. These effects will lessen the decrease in cohesive energy between the surface layer and the substrate of rubber caused by the temperature. Therefore, styrene–butadiene rubber does not suffer from fatigue delamination as polyurethane does.

3.1.3. Nylon-6

Scratches and small plastic deformation were found on the eroded surface (Fig. 5). As the crystalline structure of Nylon-6 is a spherulite structure, it could be lengthened and form a fibre structure under the action of applied force. The fibre is not easy to pull out

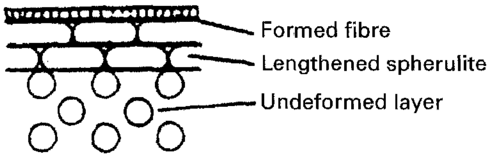

Figure 6 Deformation of the spherulitic structure of Nylon-6.

from the surface layer [15]. Therefore, it could be deduced that the abrasive erosion of Nylon-6 is due to the microcutting of flowing abrasive particles, with the result that the spherulites are lengthened into fibres (Fig. 6), and these fibres are finally cut off or pulled apart.

3.1.4. Polytetrafluoroethylene (PTFE)

Ploughings, scratches and accumulation of plastic deformation were found on the abraded surface (Fig. 7a). Moreover, cracks and wear debris which can be removed, were observed at the base of the accumulation. The debris is mostly in the form of small pieces (Fig. 7b). It can be considered that wear debris is peeling off the solid surface due to microcutting and scratching of particles, and the accumulation of plastic deformation forms on the surface layer under the action of the flowing abrasive particles, because the crystalline structure of polytetrafluoroethylene (PTFE) is a crystal ribbon which is easily slipped [15], and is easily deformed compared to spherulitic structure [16]. The accumulation of plastic deformation is enlarged, lengthened, fragmented and peeled off from the solid surface by continuing action of the following abrasive particles. Hence, it may be concluded that the mechanism of abrasive erosion of PTFE material is primarily plastic fracture.

3.2. Wear rates

3.2.1. Effect of flow velocity

As expected, the wear rates of the four kinds of polymeric material being tested were increased with flow velocity (Fig. 8). In general, as the levels of flow velocity increase, the kinetic energy exerted by the particles during flow on the surface of the samples is enhanced. Consequently, the rates of deformation of the polymers are increased. In other words, the modulus of elasticity of the polymers is enlarged. Obviously, this would decrease the ability to absorb impacts for SBR and PU materials and increase the brittleness of the PTFE and Nylon-6 materials, with the result that the wear rates of the materials rise.

The experimentally determined relationships between wear rates and flow velocity are represented by the four exponential curves, as shown in Fig. 8. These results may be related to the mechanical behaviour of the various materials. Exponents for the PTFE and Nylon-6 materials are larger, because the materials, being in the glassy or soft glassy state, have smaller elasticity or ability to absorb impact energy. In contrast, the SBR and PU materials being in the rubber state, have a larger elasticity and smaller value of exponent, corresponding to a lesser dependence of the wear rate on the flow velocity for these materials.

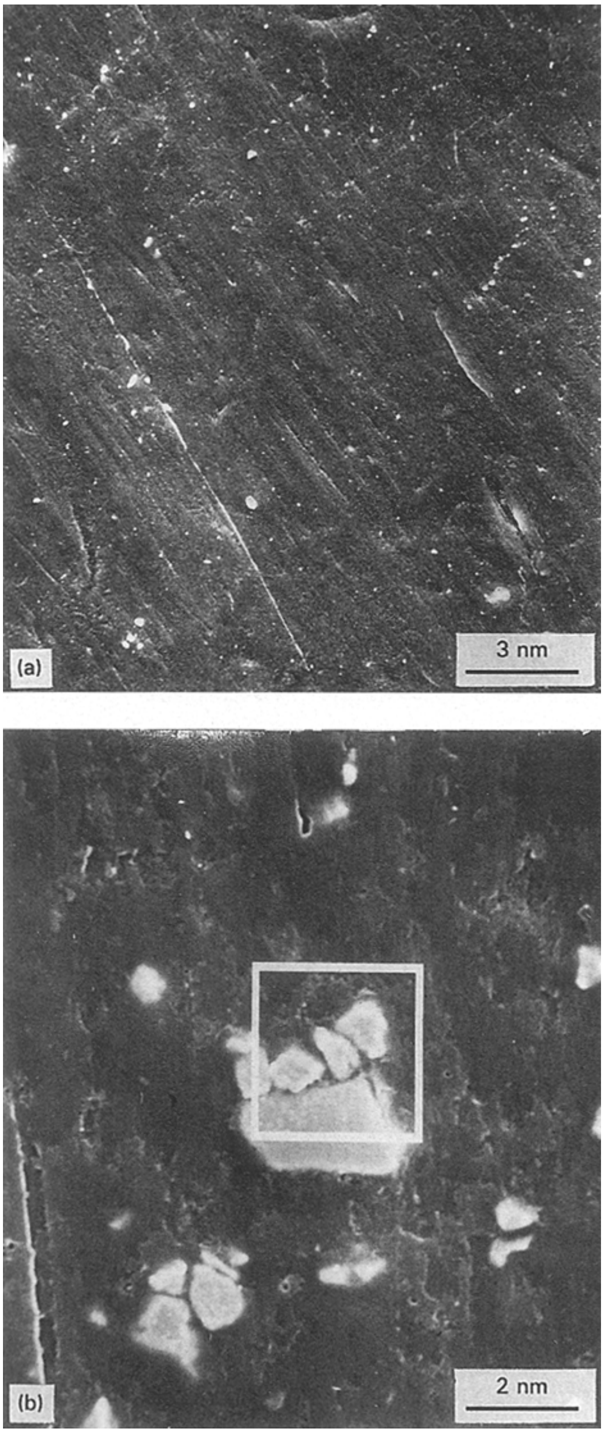

Figure 7 Morphology of the worn surface of polytetrafluoroethylene, showing (a) ploughs and scratches, and (b) cracks and debris.

3.2.2. Effect of particle size

Measurements have been carried out for different particle sizes in order to examine the effect of particle size on the wear rates. These results are shown in Fig. 9, in which the wear rates depend strongly on the particle size in the smaller, particle-size range. Obviously, the larger the particle size, the larger is the

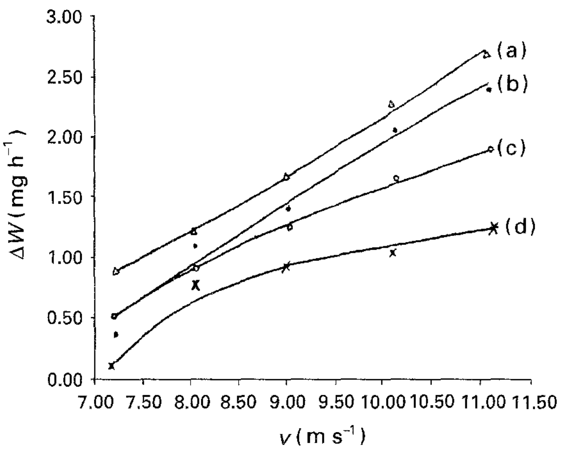

Figure 8 Wear rates, ΔW, plotted against velocity of flow, v, for (a) PTFE, (b) Nylon-6, (c) SBR, (d) PU ($\delta = 0.2$–0.3 mm, $c = 10$ wt %).

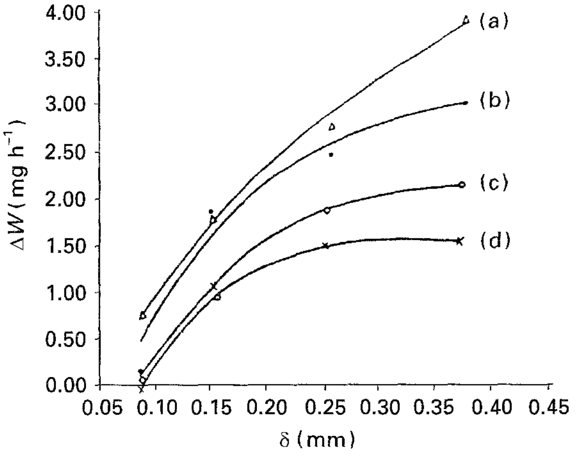

Figure 9 Wear rates, ΔW, plotted against particle size, δ, for (a) PTFE, (b) Nylon-6, (c) SBR, (d) PU ($v = 11.08$ m s^{-1}, $c = 10$ wt %).

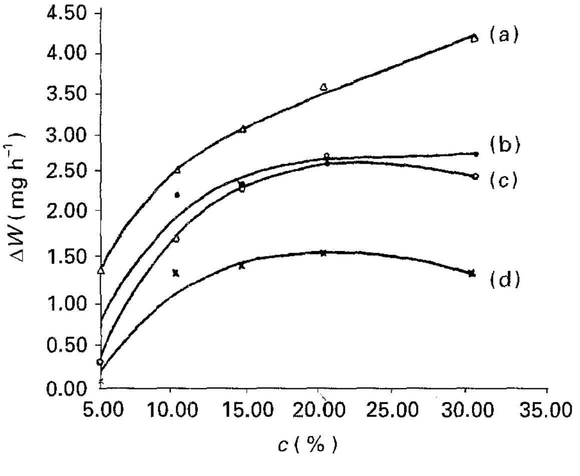

Figure 10 Wear rates, ΔW, plotted against particle concentration, c, for (a) PTFE, (b) Nylon-6, (c) SBR, (d) PU ($v = 11.08$ m s^{-1}, $\delta = 0.2$–0.3 mm).

applied force exerted by the particle on the surface of the sample. However, the number of particles will be reduced with increasing particle size, provided the particle content of the fluid medium is unchanged. Consequently, the probability of interaction between the particles and the surface of materials will be so decreased as to reduce the wear rates of the materials.

TABLE II Wear rates of the four kinds of polymeric material tested[a]

Polymeric materials	Weight wear rates (mg h^{-1})	Volume wear rates (mm h^{-1})
Polyurethane	1.5456	0.9914
Styrene-butadiene rubber	2.4650	1.4709
Nylon-6	2.5050	1.9122
Polytetrafluoroethylene	3.2000	1.5094

[a] Experimental conditions: $v = 11.08$ m s^{-1}, $\delta = 0.2$–0.3 mm, $c = 15$ wt %, fluid temperature 63–67 °C.

Thus, the wear rate of the materials is governed by the competition between two factors: the magnitude of the applied force exerted by the particles, and the probability of the particle acting on the surface of the materials. As shown in Fig. 9, the increment of wear rates for Nylon-6, SBR and PU materials gradually approaches a stable value, once the particle size rises to a certain extent. This may be ascribed to one factor being in competition with the other for all three of these materials. For the PTFE material, the wear rate continuously increases with particle size (Fig. 9a). This could be accounted for by the dominant factor governing wear being the applied force of the particles because the breaking strength and elongation at break of the PTFE material are lower.

3.2.3. Effect of particle concentration

The wear rates shown in Fig. 10 are very different for various materials. In general, the wear rate of materials is increased with an increase in particle concentration, namely the number of particles. However, the greater the number of particles, the larger is the interference effect among the particles or the smaller the impact angles of the particle will be. Thus, the wear rate of materials is also governed by the competition between two effects: impact action and interference effect of the particles. Hence, the difference in the wear rates of various materials under the same testing conditions can be ascribed to the differences in the competition. The degree to which this competition for various materials depends mainly upon the difference in properties of the materials, is based upon the theory of impact erosion, as the wear rate of a plastic material is increased at low impact angle of particles. Because the PTFE material has better plasticity, its wear rate, as given in Fig. 10, shows the expected increment with increase in particle content of the fluid medium.

Values of the wear rates given in Table II show the resistance to abrasive erosion. Apparently, the PU material is much better. For the Nylon-6 and PTFE materials, higher rates of wear would be accounted for by the surface texture of the materials being somewhat changed due to the effect of water in the fluid medium [17].

3.2.4. Wear equations

Based upon the pluralistic linear regression analysis of a great number of experimental data, the wear-rate

TABLE III Values of coefficient, k, and exponents a, b and c for various materials

Polymeric materials	$k(\times 100)$	a	b	c
Polyurethane	45.18	2.7985	0.9963	2.0843
Styrene–butadiene rubber	772.8	1.6768	0.8725	2.1219
Nylon-6	6.18	3.0537	0.5036	1.6377
Polytetrafluoroethylene	12.64	2.5246	0.5070	1.0278

equations of the four kinds of polymer being examined can be represented by the general result

$$\Delta W = kv^a c^b \delta^c \quad (1)$$

The values of the coefficient, k, and exponents a, b and c, which characterize the particular material being examined, are given in Table III.

4. Conclusions

The mechanisms of abrasive erosion of the polymers examined may be summarized as follows.

1. Microcutting action of the flowing abrasives.
2. Surface microdelamination of the material resulting from microcrack growth.
3. Mechanochemical decomposition and thermal degradation of materials.
4. Surface peeling, resulting from plastic fracture expended from local plastic deformation of the material. This conclusion remains to be further verified by investigation of the surfacial chemical effect of abrasive erosion of polymers.

Ranking the polymers being examined for resistance to abrasive erosion, PU and SBR materials are the best and the next best, respectively, both Nylon-6 and PTFE materials are the worst.

The influential factors on the abrasive erosion of polymers are mainly flow velocity, particle size and particle concentration.

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