

# Wear Failures of Plastics

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PLASTICS (or polymers\*) are used in a variety of engineering and nonengineering applications where they are subjected to surface damage and wear. Examples of the tribological (involving sliding between two surfaces) use of plastics include gears and cams of various machines, tires, break pads, conveyors, hoppers, automobile body parts, aircraft, spacecrafts, hip/knee joint replacement, roller-skating wheels, and household appliances (washing machine, tubs, etc.). Wear of material parts is a very common cause of failure or low working life of machines, leading to financial loss and life hazards. Therefore, it is important to understand how polymers and other materials wear. Similar to the wear of metal, polymer wear is affected by several factors that may be broadly divided into three groups: mechanical, environmental, and thermal. These three groups of factors largely decide the mechanism of wear of a polymer surface when it comes in contact with another surface.

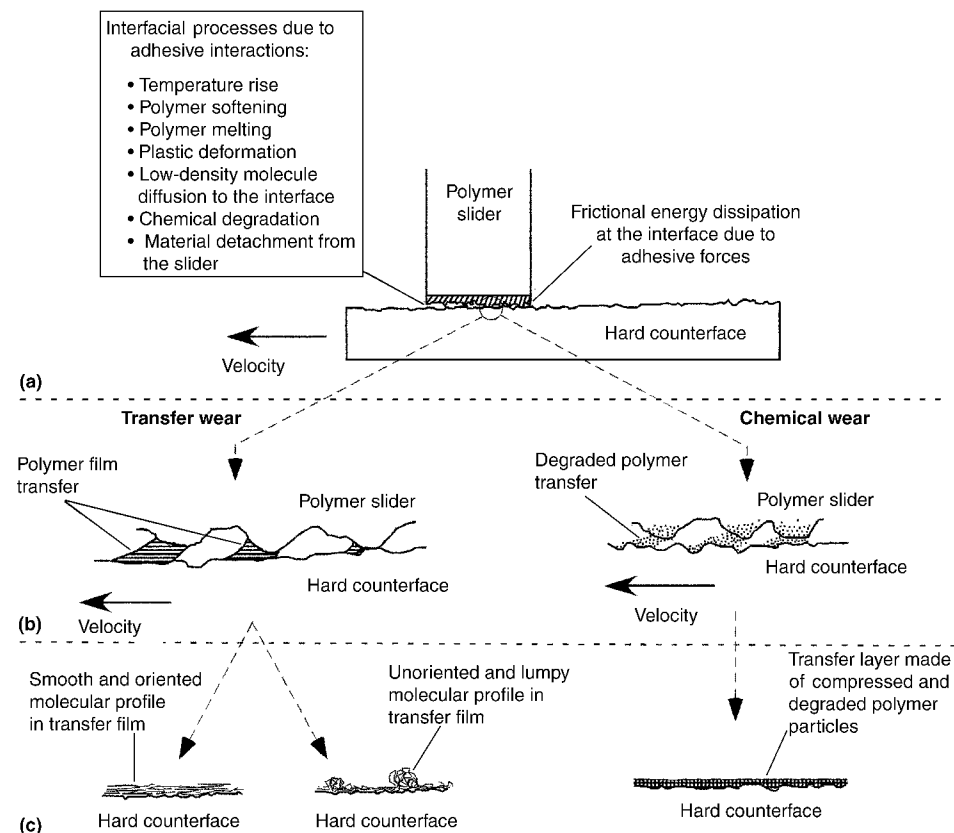
Historically, polymer wear has been studied based on the prevailing wear mechanisms at the contact zone (between the polymer surface and a hard counterface), which led to several methods of classification. The classification of polymer wear mechanisms that has often been followed in the literature is based on three methodologies of defining types of wear (Ref 1). The first classification is based on the two-term model that divides wear mechanisms into two types—interfacial and bulk. The second classification is more phenomenological and is based on the perceived wear mechanism. This classification includes fatigue wear, chemical wear, delamination wear, fretting, erosion, abrasion, and transfer wear. The third classification is specific to polymers and draws the distinction based on mechanical properties of polymers. In the third classification, wear study is separated as “Elastomers,” “Thermosets,” “Glassy Thermoplastics,” and “Semicrystalline Thermoplastics.” These classifications provide a useful basis for understanding wear failures in polymers. More often than not, wear of a polymer is a complex phenomenon that involves several of the wear

mechanisms listed previously in any one wear process. For the purpose of this article, details on several of the aforementioned classifications are expanded, using wear data and micrographs from published works. The primary goals are to present the mechanisms of polymer wear and to quantify wear in terms of wear rate (rate of removal of the material). This analysis is restricted mostly to base polymers (with no fillers). Normally, polymers used in tribological applications are subjected to sliding against hard surfaces such as metals. A polymer-polymer sliding pair, except in few instances, usually produces unde-

sirable high friction and high wear conditions due to enhanced adhesion between the polymer. Also, poor conductivity of the polymers results in elevated temperature at the polymer/polymer interface, leading to melting and rapid wear. Therefore, the focus of this article is on the wear of polymers when slid against metallic surfaces.

## Interfacial Wear

The notion of interfacial wear arises from the popular two-term model of frictional energy dis-



**Fig. 1** Interfacial wear processes. (a) Initial contact of the two surfaces. (b) Running-in process where the soft polymer molecules are gradually transferred to the hard counterface as third-body. (c) Steady-state wear process where the wear and friction phenomena are influenced mainly by the shear and adhesive properties of the transferred film. Reprinted with permission from Ref 1

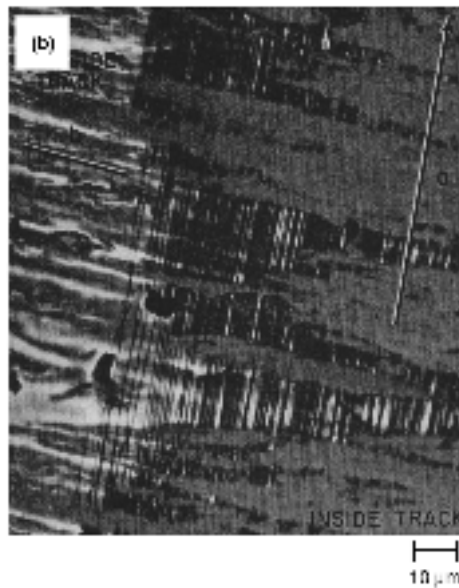
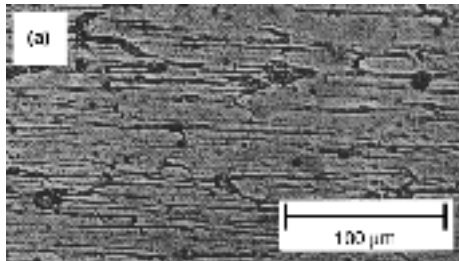
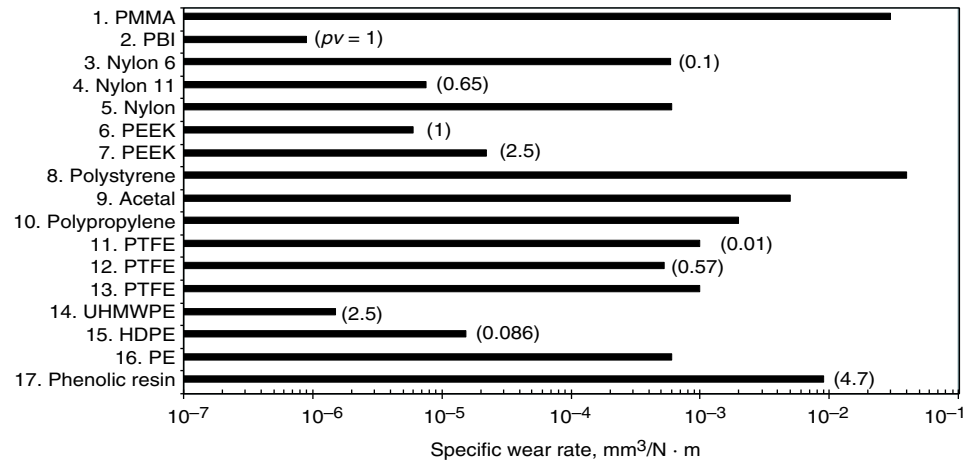
\*The terms “plastic” and “polymers” have some distinctions. However, in this article, the two terms mean engineering plastics. Engineering plastics are polymers that contain very small percentage of additives such as plasticizers and antioxidants in order to enhance their physical and mechanical properties.

sipation (Ref 2). This model states that in any frictional phenomenon, where frictional energy is released at the contact points between two sliding surfaces, there can be two types of energy dissipation—interfacial and bulk. Though subjectively defined, the interface may be considered the region of the material very close (a few microns) to the contact point. This region of the material is almost instantly affected by the stress and thermal conditions arising at the contact points due to sliding. The interfacial wear is defined as the removal of the material due to interfacial friction energy dissipation between asperities leading to events such as material softening, transfer wear, and chemical wear. A schematic of the processes involved in the interfacial wear is shown in Fig. 1.

A distinction within the interfacial wear process may be made based on whether or not the frictional heat dissipation is isothermal or quasi-adiabatic. Isothermal heat dissipation can change the mechanical property of the interface zone as

opposed to the quasi-adiabatic, which affects only the transfer layer normally present at the true interface. The chemical-wear mechanism is initiated if the frictional heat can chemically af-

fect the polymer surface, resulting in the production of degraded polymer molecules. The other important parameter to consider in interfacial wear is the roughness of the counterface.

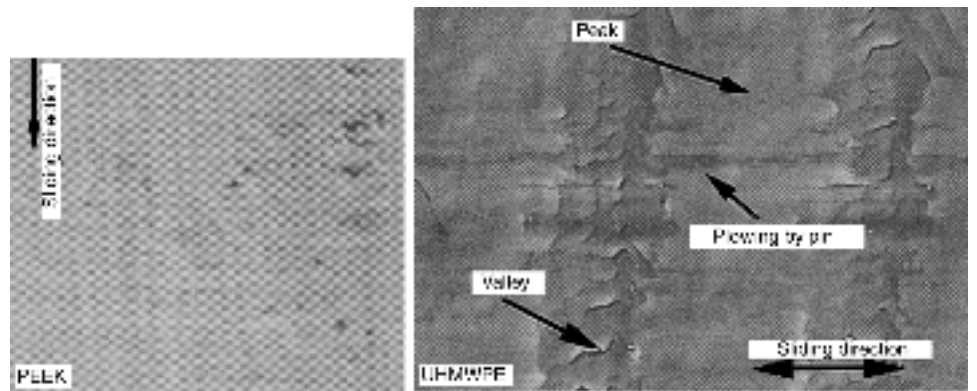


**Fig. 2** Micrographs of oriented PTFE films on the counterface. (a) PTFE transfer film on a glass slide. The film thickness varies between 50 and 500 nm, and sometimes it can show a lumpy feature when the sliding test is carried out at high loads. The film is highly birefringent, indicating that the molecules are oriented parallel to the sliding direction. Reprinted with permission from Ref 3. (b) PTFE transfer film when a PTFE pin is slid over a metallic surface. PTFE covers the counterface, making fibers and layers over one another. The orientation of the fibers in the transfer film can easily change if the sliding direction is changed. Reprinted with permission from Ref 4

Specimen	Material	Counterface roughness ( $R_a$ ), $\mu\text{m}$	Sliding speed ( $v$ ), m/s	$1/S\epsilon(a)$	Normal pressure ( $p$ )		Temperature		Ref
					MPa	ksi	$^{\circ}\text{C}$	$^{\circ}\text{F}$	
1	PMMA	1.2	...	0.09	...	...	...	...	11
2	PBI	...	1	...	1	0.15	20	68	17
3	Nylon 6	...	$5 \times 10^{-3}$	...	20	2.9	...	...	15
4	Nylon 11	0.11	1	...	0.65	0.09	...	...	13
5	Nylon	1.2	...	0.1	...	...	...	...	11
6	PEEK	...	1	...	1	0.15	20	68	17
7	PEEK	0.05	0.5	...	5	0.73	...	...	12
8	Polystyrene	1.2	...	5	...	...	...	...	11
9	Acetal	1.2	...	0.5	...	...	...	...	11
10	Polypropylene	1.2	...	0.1	...	...	...	...	11
11	PTFE	...	0.2	...	0.05	0.007	...	...	16
12	PTFE	...	0.1	...	5.66	0.82	29	84	5
13	PTFE	1.2	...	0.2	...	...	...	...	11
14	UHMWPE	0.05	0.5	...	5	0.73	...	...	12
15	HDPE	0.9	0.03	...	2.8	0.41	...	...	14
16	Polyethylene	1.2	...	0.09	...	...	...	...	11
17	Phenolic resin	0.05	5.6	...	0.84	0.12	...	...	18

PMMA, polymethyl methacrylate; PBI, polybenzimidazole; PEEK, polyetheretherketone; PTFE, polytetrafluoroethylene; UHMWPE, ultrahigh molecular weight polyethylene; HDPE, high-density polyethylene. (a)  $S$ , tensile strength;  $\epsilon$ , elongation to break

**Fig. 3** Specific wear rate for a number of polymers as reported in the literature. The experimental conditions as reported in the literature are given in the table.



**Fig. 4** Micrographs showing surfaces of worn polymers when they were slid against abrasive surfaces. PEEK (left) reprinted with permission from Ref 19. UHMWPE (right) (reprinted with permission from Ref 20) surfaces show scars of abrasive and plowing actions of hard counterfaces.

For rough and hard counterfaces, the wear mode is generally that of bulk or cohesive wear. Interfacial wear is initiated only when the counterface is smooth enough to form interfacial junctions between the polymer and the counterface. An excellent example of interfacial wear with isothermal condition is that of polytetrafluoroethylene (PTFE) sliding against a metal surface. When PTFE is slid against a smooth metal surface, friction is high in the beginning but drops to a lower value after some sliding. Because of the presence of frictional stress and heat, the PTFE molecular chains are oriented in the direction of sliding and a transfer film is deposited onto the counterface. The molecular orientation in PTFE is responsible for the drop in friction coefficient. Although the friction coefficient is low, for PTFE wear is

generally high because of the thermal softening of the interface zone and easy removal of the material. This is one of the reasons why PTFE has not been used very widely for tribological applications. Figure 2 shows micrographs of oriented PTFE molecules deposited on the counterface after wear.

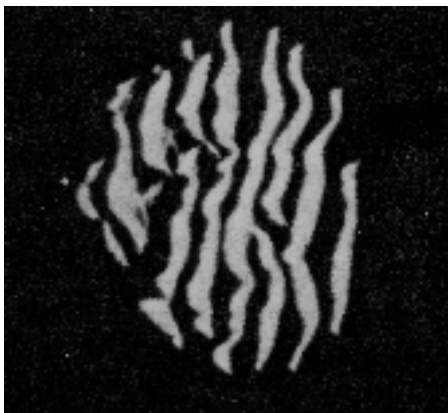
The quasi-adiabatic interfacial wear involves glassy thermoplastics (not cross linked) and cross-linked polymer systems such as elastomers and thermosets. These polymers show a range of wear behavior. For example, thermosets, which do not soften due to thermal energy, undergo chemical degradation at the interface. These degraded products detach themselves from the main body of the polymer and form transfer film and debris at the interface. The wear rate can be very high if the prevailing interface temperature is high. An important application of thermosets in a tribological context is in brake pads where the base polymer is mixed with several additives for optimal friction, wear, and mechanical strength.

Although friction models are available for interfacial sliding, theoretical wear quantification is difficult. This is because wear depends on a

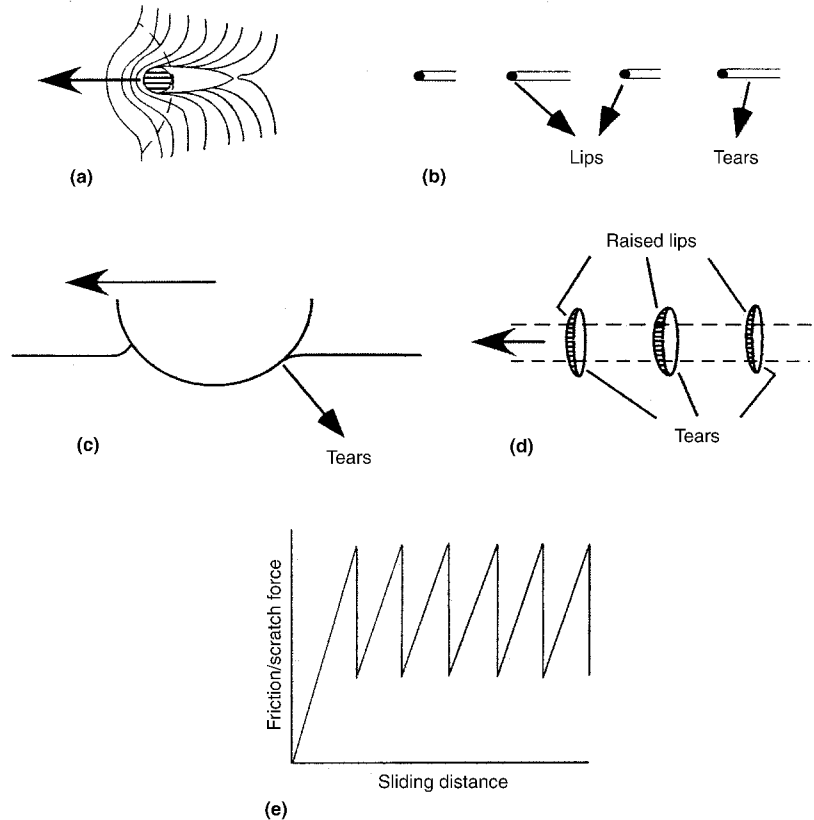
number of parameters other than the mechanical and physical properties of the material. These parameters include temperature, sliding speed, normal pressure, counterface roughness, and the rheological properties of transfer film. The exact influence of each parameter on wear is rarely known. Few attempts have been made to obtain wear laws using empirical means. In one such example involving PTFE, Uchiyama and Tanaka (Ref 5) have rationalized the effects of temperature and normal pressure in relating linear wear (thickness removed per unit sliding distance) with sliding speed. According to their work, if linear wear,  $x$  (length per unit sliding distance), is assumed to be directly proportional to the sliding speed ( $v$ ) at a constant temperature,  $T_o$ , and pressure,  $p_o$ , then linear wear can be expressed by:

$$x = \frac{k_0 (a_T v) (p / p_0)^n}{b_s} \quad (\text{Eq 1})$$

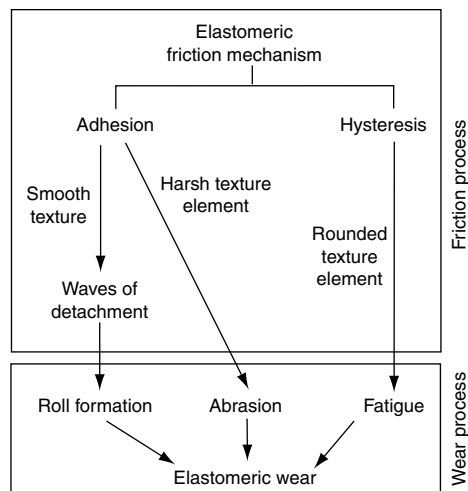
where  $n$  is a constant greater than unity and  $k_0$  is a proportionality constant.  $a_T$  and  $b_s$  are shift factors that depend on the temperature.  $a_T$  and



**Fig. 5** Waves of detachment when an elastomer is slid against a hard and smooth surface. The rubber moves forward in the form of ripples of wave on its contact surface with a smooth and hard counterface. These so-called waves of detachment can produce wear in the form of rolls of detached material or the third body. Reprinted with permission from Ref 22



**Fig. 7** Damage created on the surface of an elastomer by isolated stress concentration. (a) Surface deformation pattern when a sharp needle or conical indenter with acute angle is slid on the surface of an elastomer. The elastomer surface is pulled in the direction of motion and fails in tension behind the contact at  $\pi/2$  to the tensile field. (b) After the needle jumps forward, the surface relaxes and tensile tears are evident on the surface but are now in the direction of motion. (c) Tearing of an elastomer due to tractive stress with a large unlubricated indenter. The tear is generated at the rear of the contact region and is almost at right angles to the sliding motion. (d) A raised lip of elastomer is formed, but no material is actually removed. (e) A typical friction/scratching force profile when a slider is passed over an elastomer. Reprinted with permission from Ref 1



**Fig. 6** Classification of the processes of friction leading to wear for elastomers (adapted after Moore, Ref 23). The diagram clarifies the role of friction in determining the wear mechanism for elastomeric polymers.

$b_s$  are obtained through experimentation by shifting the data on the speed axis and wear rate axis (on a wear rate/sliding speed plot), respectively, such that they coincide with similar data obtained at a temperature of 29 °C (84 °F). The authors claim that the relation can be applied to other polymer systems, too.

## Cohesive Wear

Cohesive wear is defined as subsurface or bulk wear when the interacting surfaces produce damage to the material far deeper into the material than only at the interface. This type of wear is also referred to in the literature as plowing or abrasive wear. Subsurface damage in material can be caused by surface sliding in two ways. First, if a polymer is sliding against a rough and hard surface, the asperities of the hard surface can plow into the bulk of the polymer removing debris. These debris materials generally get transferred to the counterface, forming a transfer film (also known as the “third body”), which eventually makes the counterface appear smoother. The formation of a stable film at the counterface leads to a change in the wear rate of the polymer. The second cause of subsurface damage is through subsurface fatigue cracks, which can lead to the removal of material when these cracks grow to the surface of the polymer. Fatigue wear removes the material in chunks or flakes.

Considerable attention has been given by researchers to the creation of a model for cohesive or abrasive wear of polymers. The most notable model for wear involving bulk properties of the

polymer was given by Ratner-Lancaster (Ref 6). The relation is given as:

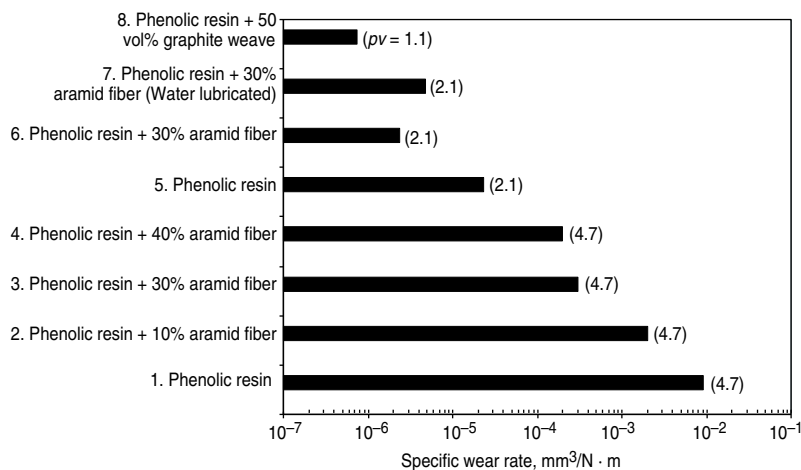
$$V = \frac{K\mu Wv}{HS\epsilon} \quad (\text{Eq 2})$$

where  $V$  is the wear volume,  $K$  is a proportionality constant also termed wear rate,  $v$  is the sliding speed,  $\mu$  is the coefficient of friction,  $H$  is the indentation hardness,  $S$  is the ultimate tensile strength, and  $\epsilon$  is the elongation to break of the polymer. Some evidence of the usefulness of Ratner-Lancaster relation may be found in the work by Briscoe (Ref 7). In this work, the wear rate ( $\text{mm}^3 \text{mm}^{-1} \text{kg}^{-1}$ ) was plotted against the reciprocal of the product of  $S$  and  $\epsilon$ , which furnished, as predicted by the Eq 2, a straight line. In contrast to Eq 2, Rhee has followed a different approach where wear is thought to be nonlinearly proportional to pressure, sliding velocity, and temperature (Ref 8). He proposed an empirical relation of the type:

$$\Delta w = Kp^a v^b T^c$$

where  $\Delta w$  is the weight loss of the polymer, and  $a$ ,  $b$ , and  $c$  are material-dependent variables. Yet another wear model was proposed by Kar and Bahadur (Ref 9) in which they arrived at an empirical relation using the principles of dimensional analysis. Using data obtained for polyoxymethylene (POM) and PTFE-filled POM, Kar and Bahadur obtained a relation given as:

$$V = \frac{1.5 K \gamma^{1.775} p^{1.47} Z^{1.25}}{E^{3.225}} \quad (\text{Eq 3})$$



Specimen	Sliding speed ( $v$ ), m/s	Normal pressure ( $p$ )		Counterface roughness ( $R_a$ ), $\mu\text{m}$	Ref
		MPa	ksi		
1-4	5.6	0.84	0.12	0.5	18
5-7	0.5	4.25	0.62	0.05-0.1	29
8(a)	1.6	0.69	0.10	0.05	27

(a)  $\text{N}_2$  atmosphere at room temperature

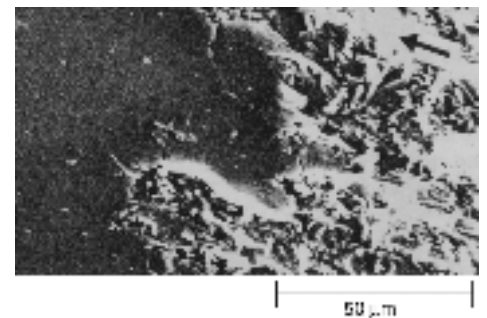
**Fig. 8** Specific wear rates for phenolic resin and its composites. The data are reported for various experimental conditions and  $pv$  (pressure  $\times$  velocity) factors as reported in the literature.

where  $\gamma$  is the surface energy,  $Z$  is the sliding distance, and  $E$  the modulus of elasticity of the polymer. Another variation of Eq 3 may be found in the work by Viswanath and Bellow (Ref 10).

Figure 3 presents specific wear rate (wear volume per unit sliding distance per unit normal load) for a number of polymer systems under abrasive or nonabrasive sliding conditions (Ref 5, 11-18). The data are shown for a variety of experimental conditions as reported in literature. Though the experimental conditions used in these tests were different, some trends may be noticed. Polybenzimidazole (PBI) and ultrahigh molecular weight polyethylene (UHMWPE) show, among all polymers, very high wear resistance. Extremely poor wear resistance is demonstrated by polymethyl methacrylate (PMMA), polystyrene (PS), and phenolic resin. Figure 4 shows worn surfaces of polyetheretherketone (PEEK) (Ref 19) and UHMWPE (Ref 20). These polymer surfaces show scars of wear by plowing and plastic deformation.

## Elastomers

The study of wear of elastomers has evolved primarily from the interest in the friction and wear of automobile tires and industrial seals. Schallamach carried out extensive studies on relatively softer rubbers such as polyisoprene, butyl rubber, and natural rubber (Ref 21, 22). Through extensive experimentation on the sliding of rubber against hard surfaces, he found that the process of sliding for rubber takes place through series of detachments at the contact points, giving it the look of a wave (Fig. 5). These waves initiate at the front edge of the slider due to excessive buckling of rubber in the front and runs to the rear of the slider. When a slider in contact with elastomer is pushed forward, the adhesive force (between the slider and the elastomer) generates compressive tensile stress at the front edge leading to buckling and folding of the elastomer in the form of a wave. The detached part further relaxes the material, thus facilitating the movement of the slider. Moore, in a later study of the wear of rubbers and tires (Ref 23), concluded that for elastomeric



**Fig. 9** Micrograph of the worn surface for a phenolic resin-aramid fiber composite (Ref 29) showing partial coverage of the polymer pin by transfer film

materials there are two ways in which the frictional energy is dissipated, leading to wear. The flow chart he produced is redrawn in Fig. 6. In order to model abrasive action of asperities on elastomers, several tests using sharp needles have also been carried out in the past. The process of wear by a sharp needle or an asperity is schematically shown in Fig. 7. Though there are a number of models available that quantify the frictional work done during sliding on rubber, a wear model for elastomers is still unavailable presently except for the abrasive case where the Ratner-Lancaster relation can be applied.

## Thermosets

Thermosets have found applications mainly in automobile brakes, gears, cams, and clutch parts where they are subjected to sliding. Brake pads are one area where thermosets such as phenolic and epoxy resins have been used and studied extensively. These polymers do not soften when the temperature rises at the interface, and thus they prevent the component from yielding or failing in a catastrophic manner during service. However, thermal energy dissipated due to frictional work can induce chemical degradation and wear at the sliding surface. Thermosets have generally been filled with fibers and particles as additives in order to increase the strength and wear resistance of the material (Ref 24–27). Fill-

ers include glass fiber, aramid fiber, and metal oxide particles of various kinds.

The role of aramid fibers, in the context of brake pads, caught special attention from tribologists when there was an effort to replace asbestos used in brake pads with aramid fibers (Ref 18, 28–30). Figure 8 compares the specific wear rate of a few formulations of thermoset composites. The relevant micrograph is given in Fig. 9. It is seen from these results that the wear resistance of phenolic resin increases by almost two orders of magnitude when fillers such as carbon and aramid fibers are added to the phenolic resin matrix. The micrograph (Fig. 9) shows that a transfer layer is formed on the polymer surface in addition to the transfer layer found on the counterface. These strong and highly adhesive transfer layers help improve the wear resistance of the polymer composite.

## Glassy Thermoplastics

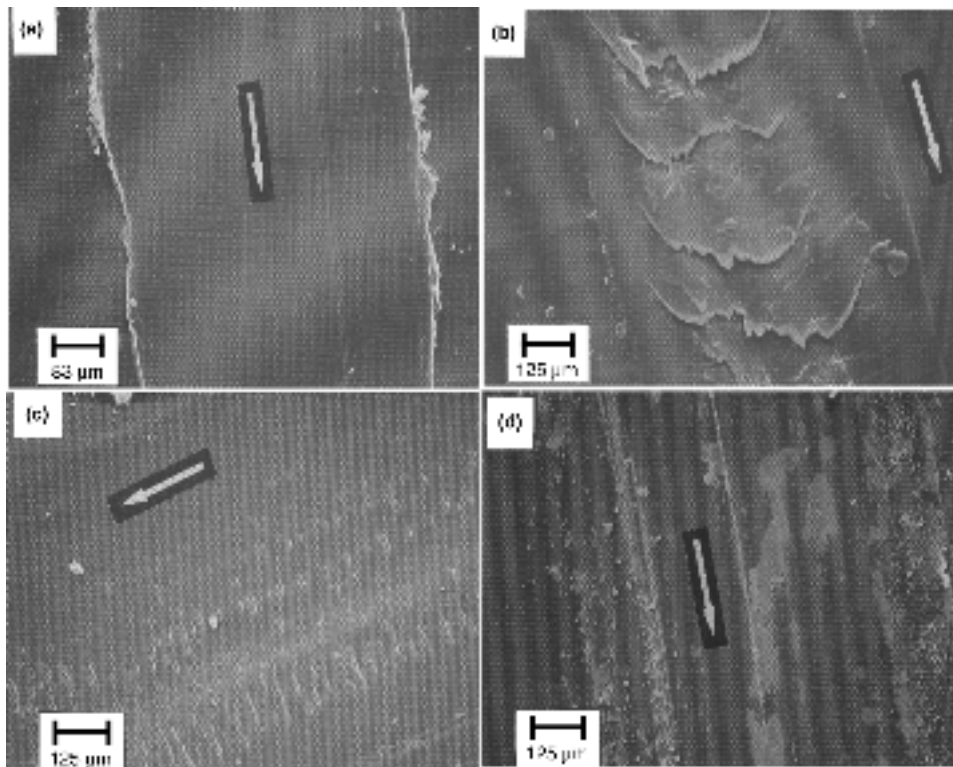
Traditionally, glassy thermoplastics have not been used as typical tribological materials. This is because they show mechanical instability at the glass-transition temperature. However, they are often subjected to sliding, scratching, or abrasion in various working environments. For example, a window pan or automobile body part made of glassy polymer may be subjected to water, dust, and occasional scratching, or a bathtub

may have water plasticization coupled with sliding and compression. Some glassy thermoplastics filled with fibers or particulate fillers have been used for tribological applications. The problem encountered with such polymers is their tendency to fail in a catastrophic manner when the glass-transition temperature is reached. Examples of this class of polymer are PMMA, PS, and polycarbonate (PC). Cross-linked polymer PEEK also behaves in a way similar to glassy polymers (Ref 31). See Fig. 10 for the changes in deformation behavior in sliding of PEEK when the operating temperature is close to the glass-transition temperature for PEEK.

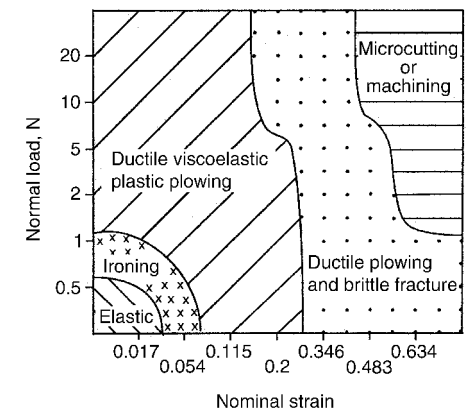
The study of glassy thermoplastic surfaces has mainly focused on understanding the damage processes under a variety of experimental and ambient conditions (Ref 32, 33). For example, damage modes can be studied using the concept of wear maps. Figure 11 gives such a map of PMMA for different normal load and imposed strain conditions. A range of studies have been carried out by Briscoe, Chateauinois, and co-workers (Ref 34, 35) in order to understand the role of the third body in fretting wear of PMMA. Their study with PMMA concluded that the formation of the third body and the wear rate depend on the kinematics of sliding. In linear sliding, as opposed to torsional sliding, the wear rate is low. The worn area showed debris material in rolled and compacted forms. The authors concluded that the energy dissipation in the linear sliding case occurred mainly by the rolling and shearing actions on the rolled debris that reduced the frictional work required for sliding. Therefore, wear in the linear sliding case was low.

## Semicrystalline Thermoplastics

The most versatile use of polymers in tribological application has been for the semicrystalline group of polymers. Semicrystalline thermoplastics include PTFE, polyethylene (PE), UHMWPE, and nylon. These polymers, in ho-



**Fig. 10** Micrographs of worn PEEK surfaces at various operating temperatures. These pictures highlight the changes in the surface deformation behavior of the polymer with temperature. (a) 90 °C (194 °F). (b) 152 °C (306 °F). (c) 180 °C (356 °F). (d) 225 °C (437 °F). Arrows indicate the sliding direction. Glass-transition temperature for PEEK used in the experiment was 148 °C (300 °F). Reprinted with permission from Ref 29



**Fig. 11** Scratching damage maps for PMMA. Scratching velocity = 0.004 mm/s and nominal strain is defined as  $0.2 \times \tan \theta$ ;  $2\theta$  being the included angle of the indenter.

mogeneous or heterogeneous forms, have found applications in gears, bearings, automobile piston seals, knee/hip joint replacement, and so forth. Semicrystalline thermoplastics do soften in the presence of thermal energy; however, the way thermal energy is transmitted from the interface to the bulk depends on the thermal properties of the individual polymer. Based on this behavior, the mode of wear for semicrystalline polymers can be divided into two groups: adiabatic and isothermal. Furthermore, the isothermal type, a common case, is subdivided into three categories based on the way polymer transfer film is deposited onto the hard counterface. Figure 12 delineates these groups of wear processes for semicrystalline thermoplastics in isothermal heat transfer conditions.

Early studies on the friction and wear of thermoplastics was motivated by the prospect of finding an ultralow friction polymer material (Ref 3, 36). Polytetrafluoroethylene provided very low friction coefficient ( $\sim 0.06$ ), though the corresponding wear rate was high. The reason for low friction was found to be highly oriented PTFE molecules that were transferred to the counterface during sliding (Ref 3). The interface of the polymer also showed highly oriented molecules that extended out of the samples showing fibers. In order to reduce the wear rate and utilize the excellent low friction property of PTFE, this polymer has often been used with fillers to form composites. Polytetrafluoroethylene itself has also been used as filler for other polymeric systems such as PE. Figure 13 gives the wear rate of PTFE, and some of its composites when slid against hard metallic surfaces. For surface-treated PTFE (such as  $\gamma$ -irradiation), the situation may be different. Evidence shows that for such a system there may be an increase in the crystallinity of the polymer at the surface and consequently a decrease in the wear rate (Ref 37).

The wear process for semicrystalline thermoplastic polymer may seem to depend very much on the transfer film and its rheological properties, though evidence is also available where it shows that the loading condition can also change the wear mechanism. For UHMWPE, Wang et al. (Ref 38) found that the microscopic surface wear depends on the tensile and elongation properties of the polymer. However, under intense and nonconformal loading conditions the wear mechanism could change to macroscopic sub-surface wear due to fatigue. Thus, the wear mechanism can change if the loading condition is changed. Wang et al. provided a model for the wear of semicrystalline thermoplastics that resembles the Ratner-Lancaster model for abrasive wear of polymers: for microscopic surface wear

$$V \propto \frac{L^{3/2} R_a^{3/2}}{S^{3/2} \epsilon}$$

for macroscopic sub-surface wear,

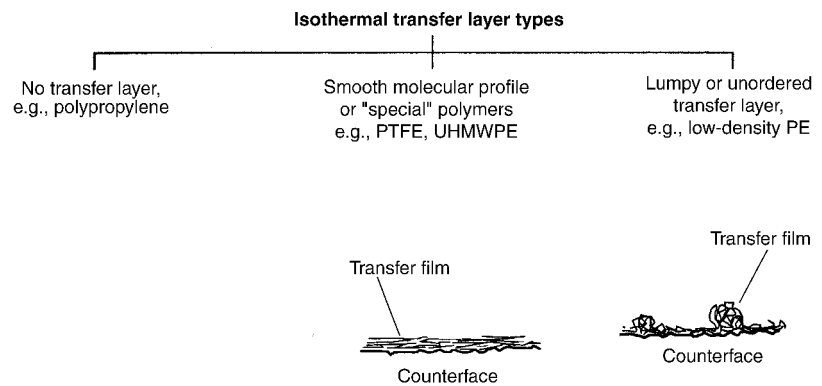
$$V \propto \frac{1}{N} = (\Delta \epsilon_p / \epsilon)^{(1/\alpha)}$$

where  $V$  is the wear volume,  $L$  is the normal load,  $R_a$  is the counterface roughness,  $S$  is the ultimate tensile strength of the polymer,  $\epsilon$  is the elongation at break,  $N$  is the cyclic fatigue life of the polymer,  $\Delta \epsilon_p$  is the inelastic strain amplitude, and  $\alpha$  is a material constant obtained from low-cycle fatigue test using the Coffin-Manson equation (Ref 39).

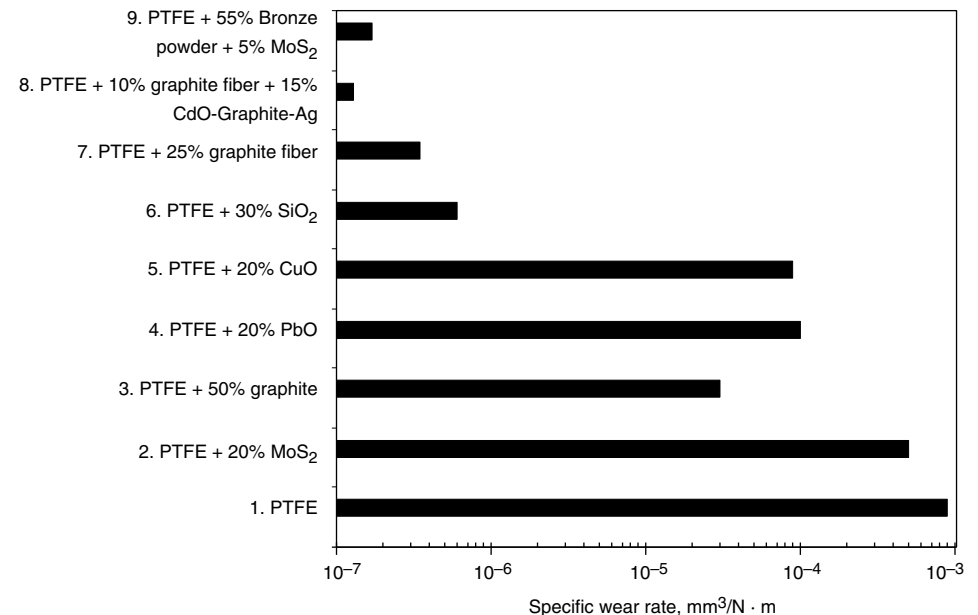
## Environmental and Lubricant Effects on the Wear Failures of Polymers

Except for elastomers, polymers in general are not used in lubricated conditions. However, polymers are often subjected to environmental

conditions that affect their friction and wear performances. For example, polymers used in marine applications get exposed to sea water, and a machine component such as gear or brake pad may come in direct contact with leaking oil or water. For elastomers, their applications in seal rings and automobile tires regularly expose the material to lubricants, chemicals, and water. For industrial seals, the presence of lubricant protects it from dry contact with metal parts and the consequent severe wear. This kind of wear not only lowers the life of the seal, but also affects the metal part. It has been observed that soft elastomer can wear the metal part it comes in contact with (Ref 40). In an effort to increase the life of seals, a number of studies have been carried out to estimate the film thickness of the lubricant for elastomer pressed against a metal (Ref 41–43).



**Fig. 12** Generic types of transfer wear behavior when semicrystalline polymers are slid on a hard smooth surface. In most of the cases there is a formation of transfer layer on the counterface though the shear, and adhesive properties of the transfer films will vary depending upon the mechanical properties of the polymer and the surface topography of the counterface. Reprinted with permission from Ref 1

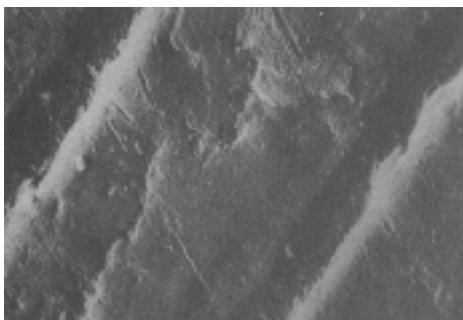


**Fig. 13** Wear rate of PTFE and its composites under different experimental conditions. For specimens 1 to 4: sliding speed ( $v$ ) = 0.2 m/s; normal pressure ( $p$ ) = 0.05 MPa (0.007 ksi). Source: Ref 16. For specimens 7 to 9: sliding speed ( $v$ ) = 1.6 m/s; normal pressure ( $p$ ) = 0.69 MPa (0.10 ksi); counterface roughness ( $R_a$ ) = 0.025  $\mu$ m. Source: Ref 27



The other example of the use of polymers in a lubricating environment is that of the knee/hip joint replacement using UHMWPE (Ref 44, 45). UHMWPE is widely used in making acetabular sockets for hip joints that normally slide against a ceramic ball. The presence of synovial body fluid ensures low friction by lubricating the surfaces. This fluid does not seem to chemically affect the polymer, though it does affect the way transfer film is formed at the counterface. The main problems in the application of UHMWPE for knee/hip joint replacement are the production of wear particles, which tend to become points of bacterial infection growth for the patient, and the wear of the metallic or ceramic counterface leading to increased wear of the polymer.

Environmental fluids and humidity have been found to affect many polymers in two ways. The first is the change in the adhesive and flow properties of the transfer film, and the second effect is that of changing the mechanical properties of the bulk of the polymer due to plasticization. In the presence of a liquid the adhesion of the transfer film is normally decreased, leading to high wear of the polymer (see Fig. 8 for wear data on water-lubricated sliding case). This is because the deposited polymer on the counterface is constantly removed during sliding, requiring further wear of the bulk of the polymer. The effect of liquid on the mechanical properties of the bulk polymer largely depends on the polarities of the polymer and the liquid, as well as on the surface tension of the liquid (thus the surface energy of the polymer) (Ref 46). Many polymers plasticize in the presence of water and some chemical liquids because liquid molecules can easily migrate into the bulk of the polymer. Plasticization of a polymer drastically reduces its mechanical strength and hardness, which gives rise to a substantial reduction in the wear resistance. Briscoe et al. (Ref 47) studied the effect of lubricants on PE. They found that when oleamide and stearamide are applied to the surface of PE, the lubricants interact with polymer molecules and form a chemically bonded monolayer on the outer surface of the polymer. This can drastically reduce the coefficient of friction when the polymer slides against a hard surface.



**Fig. 14** Wear marks on the surface of a nylon/polyethylene antifriction bearing. The bearing was in contact with a rotating steel shaft. 417 $\times$ . Source: Ref 53

## Summary and Case Study

Wear of polymers is an important aspect of their failure analysis and lifetime prediction. Wear failure of polymers is controlled by a number of factors, which include mechanical properties of polymers, such as ultimate tensile strength, elongation to break and hardness, sliding speed, normal load, coefficient of friction, counterface roughness, rheology and adhesive property of the transfer film, and thermal properties of polymers. The adhesive strength of the transfer layer to the counterface has strong influence upon the wear rate. Strong adherent transfer film normally gives low wear rate. Abrasive action of the asperities, adhesive force, thermal softening, chemical degradation and subsurface fatigue are some of the factors that initiate material removal during the process of polymer wear. Effect of lubricants depends upon how lubricant molecules attach themselves to the polymer molecules making bonds between the two molecular entities. Many polymers, in the presence of water or lubricant molecules, plasticize, which reduces friction, but wear can be high because of the decrease in the mechanical strength of the polymer due to plasticization. Lubricants in general reduce the adhesion of the transfer layer to the counterface leading to easy removal of the transfer layer and a high wear situation for the polymer.

**A Case Study: Nylon as a Tribological Material.** First synthesized in 1935 by Carothers (Ref 48), nylon is among few very important semicrystalline industrial thermoplastics. Nylon is the commercial name for those aliphatic polyamides that are made exclusively from  $\omega$ -amino acids (Ref 49). There are several forms of nylon, generally denoted by nylon- $n$  or nylon- $m,n$ , where  $m$  and  $n$  stand for the number of main chain carbon atoms in constituent monomer(s). Among all varieties of nylons, nylon 6 and nylon 6/6 are the most widely produced and used ma-

terials because of their excellent mechanical properties and low cost. Nylon 11 and nylon 12, which show better performance in terms of low moisture absorption when compared to other nylons, are also used extensively; however, they are expensive.

Historically, nylons have been very popular materials for many tribological applications such as sliding fittings, bearings, and gears. Possibly the greatest advantage of using nylon as tribological material over metals is that no external lubricant is needed and the vibration noise is far less for nylon than for metals. Nylon parts can be extrusion molded with superior strength properties and low overall production cost.

Nylon sliding against nylon is a poor tribological pair due to high friction and high thermal effects (Ref 50). Even pure nylon sliding against metal surfaces does not perform well. However, nylon is an excellent low-friction and wear-resistant material if used in the form of plastic composite sliding against metal surfaces. This can be observed from the few studies that are available in the literature on nylon. Table 1 provides friction and wear results on a few types of nylon and its composites.

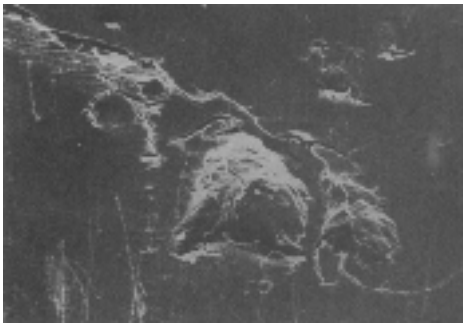
Similar to the case of many other plastics, the tribological performance of nylon greatly depends on its ability to form adherent and stable transfer film on the hard metal counterface. Several studies have shown that if pure nylon is used in sliding, the transfer film is weak and patchy. This kind of transfer film can be easily removed from the counterface due to dynamic actions of sliding. Interfacial temperature also plays its role in making the transfer layer soft and weak. With certain types of fillers in nylon it has been found that the composite makes a very thin but adherent transfer layer. This transfer layer protects the bulk of the polymer from further wear. Common fillers with advantageous effects on the wear resistance of nylon are glass fiber (Ref 50), CuS, CuO, CuF<sub>2</sub> (Ref 51), and PTFE (Ref 13). In the study by Hooke et al. (Ref 50), aramid and car-

**Table 1** Friction and Wear for Nylons

Nylon type	Friction coefficient	Specific wear rate, $\times 10^{-6}$ mm <sup>3</sup> /N · m	Test conditions	Ref
Nylon 11	0.31	7.48	Normal pressure = 0.65 MPa; sliding speed = 1 m/s; quench-hardened AISI steel counterface ( $R_a = 0.11 \mu\text{m}$ )	13, 51
Nylon 11 + 35% CuS	0.42	1.8	Normal pressure = 0.65 MPa; sliding speed = 1 m/s; quench-hardened AISI steel counterface ( $R_a = 0.11 \mu\text{m}$ )	13, 51
Nylon 11 + 5.6% glass fiber	0.38–0.5	2.97	Normal pressure = 0.65 MPa; sliding speed = 1 m/s; quench-hardened AISI steel counterface ( $R_a = 0.11 \mu\text{m}$ )	13
Nylon 11 + 20.7% glass fiber	0.38–0.5	1.66	Normal pressure = 0.65 MPa; sliding speed = 1 m/s; quench-hardened AISI steel counterface ( $R_a = 0.11 \mu\text{m}$ )	13
Nylon 6/6	0.62	...	Normal load = 200 N; sliding against nylon 6/6	50
Nylon 6/6 + 30% glass fiber	0.1–0.3	...	Normal load = 200 N; sliding against nylon 6/6	50
Nylon 6/6 + 30% glass fiber + 15% PTFE	0.05–0.1	...	Normal load = 200 N; sliding against nylon 6/6	...
Nylon 6	0.3	589	Normal load = 825 kN (pressure = 20 MPa); sliding velocity = 5 mm/s; steel counterface ( $R_a \approx 5 \mu\text{m}$ ), extremely high pressure	15

bon fibers were also used as fillers for nylon. However, the authors found high friction for these two fillers and concluded that interfacial heating due to high friction could damage the nylon matrix leading to accelerated wear, especially in the high load and speed conditions.

The main disadvantage with the use of nylons is their water-absorbent characteristics. Mechanical properties such as elastic modulus and hardness as well as physical properties such as glass-transition temperature of nylon drastically reduce with the increase in the absorbed water content in nylon. In this respect nylon 11 and nylon 12 are superior to nylon 6 and nylon 6/6. The percentage water absorption at saturation and 20 °C temperature for nylon 11 and nylon 12 is 1.6% each (Ref 48), while this value for nylon 6 is 10.9% (Ref 48). The percentage of water absorption depends on the amount of crystallinity in the polymer—the higher the crystal-



**Fig. 15** Pitting and surface microcracks on the tooth flank of an oil-lubricated nylon driving gear. 37×. Source: Ref 53



**Fig. 16** Failed polyoxymethylene gear wheel that had been in operation in a boiler-room environment. 305×. Source: Ref 53

linity, the lower the water absorption. A loss of mechanical strength for nylon results in increased wear rate.

One can conclude from this case study that for nylon, the wear resistance characteristics can be enhanced if low water absorbing forms (such as nylon 11 or nylon 12) of nylon reinforced with fillers such as glass fiber, CuS, CuO, or PTFE, are used. To author's knowledge, so far there is no available published work on the friction and wear characteristics of nylon 12.

## Failure Examples (Ref 52)

**Example 1: Wear Failure of an Antifriction Bearing.** Shown in Fig. 14 is the worn surface of an antifriction bearing made from a nylon/polyethylene blend. The bearing was worn in contact with a steel shaft. Movement of the shaft against the bearing caused abrasive marks (Fig. 14). Fine iron oxide particles acted as an abrasive, producing the failure mechanism observed.

**Example 2: Failure of a Nylon Driving Gear.** Figure 15 shows pitting on the tooth flank of a nylon oil-lubricated driving gear. The pitting produced numerous surface microcracks in association with large-scale fragmentation (frictional wear). The stress-cracking effect of the lubricating oil is believed to have played a role in initiating the observed microcracks.

**Example 3: Failure of a Polyoxymethylene Gear Wheel.** A polyoxymethylene gear wheel (Fig. 16) exhibits a different failure mechanism. This component had been in operation in a boiler room and is believed to have failed because of considerable shrinkage. The oriented crystalline superstructures and the microporosity are reported to be due to postcrystallization. The porosity is attributed to the difference in densities between the amorphous (1.05 g/cm<sup>3</sup>, or 0.04 lb/in.<sup>3</sup>) and the semicrystalline (1.45 g/cm<sup>3</sup>, or 0.05 lb/in.<sup>3</sup>) states (Ref 53). Breakdown along the crystalline superstructure started mainly at the mechanically stressed tooth flanks. In addition, oil vapors, humidity, and other degradative agents could also have contributed to the observed failure.

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