

Wear of polymers

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Abstract: This paper reviews some of the recent progress which has been made in the area of the sliding wear of polymers. Wear mechanisms are classified under three broad approaches which reflect primarily the way this subject has been historically studied. It is demonstrated here that the wear of polymers is influenced by the contact conditions, the bulk mechanical properties of the polymer and the properties of the ‘third body’, which generally appears in the form of transfer film or degraded polymer particles between two sliding surfaces. Further, this paper establishes a link between the different contact and material parameters and shows how they are important in elucidating the generic wear mechanisms for polymers. The effects of environment and lubrication upon polymer wear are briefly explained in terms of the chemical interactions between the liquid phase and the polymer. The capabilities and limitations of current predictive wear models for polymeric contacts are also highlighted.

Keywords: wear, polymers, contact conditions, bulk mechanical properties, ‘third-body’ properties

NOTATION

A	real area of contact
F	friction force
2θ	included angle of a conical indenter
τ	interfacial shear stress

1 INTRODUCTION: SEMANTICS AND RATIONALIZATIONS

The process of ‘wear’ may be variously defined but most generally it is quantitatively measured in terms of the mass, or volume, loss from a sliding or eroding contact. The sequence of events is invariably as follows. Mechanical forces, frictional work, impact forces, contact fatigue stress, cavitation forces and so on induce damage in the contact members. Eventually, or may be also immediately, the surfaces lose mechanical cohesion and debris is produced. Chemical wear has a similar character but on a smaller scale. Subsequently, but

perhaps immediately, this debris is expelled from the contact zone and the process of wear is observed. The pathway is convoluted not least because the damage and wear processes produce, by their action, significant modifications to the properties of the materials in the contact zone; the ‘third body’ evolves [1]. For polymeric systems there is also the very significant prospect of marked environmental influences, which will include the role of lubricants as well as the often-dominant consequences of frictional heating.

There are at least three ways in which the subject may be rationalized by a simple review such as this (see Fig. 1). The choice of approach depends upon the audience; here the three established methodologies are offered together as each has a unique value.

The generic scaling approach may be taken first, which emerges from the accepted value of the two-term non-interacting model of friction [2]. Friction is, as a first approximation, of two kinds: interfacial and bulk (ploughing). As frictional work causes the damage and the subsequent wear, this is a potentially useful means of classifying the wear as ‘cohesive’ and ‘interfacial’ in its nature. This scheme will be explored and discussed in Sections 2 and 3. A more pragmatic approach would follow a more classical line and list ‘wear’ processes by some perceived judgement of the origins and consequences. Thus there may be ‘abrasion’, ‘transfer wear’, ‘fretting’, ‘chemical wear’, ‘erosion’, ‘fatigue wear’, ‘delamination wear’ and so on; this might be described

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Wear classification for Polymers

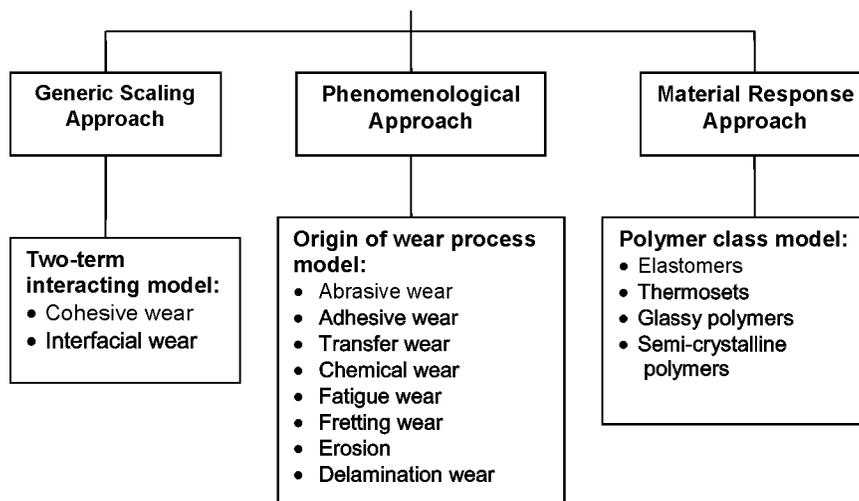


Fig. 1 Simplified approach to classification of the wear of polymers

as a phenomenological and subjective classification. This method of analysis has value for those who practise extensive electron microscopic examination. The third approach recognizes the extremely wide diversity of response of polymeric systems and focuses upon the material response combined with the prevailing contact deformation. Thus, wear can be subdivided according to material response to produce a scheme where each polymer 'class' is dealt with in relative isolation from the rest. In this type of division elastomers, thermosets, glassy polymers and semi-crystalline polymers can be distinguished as having unique attributes in the context of their wear behaviour. This has been historically the way the description of the subject of polymer wear has largely evolved. Sections 4 to 7 follow this theme.

The subsequent sections will deal with two of the three methods of division: generic scaling responses (Sections 2 and 3) and material-based responses (Sections 4 to 7), followed by a section on lubricated wear of polymers (Section 8). A concluding discussion will survey the current wisdom and will discuss further the classes of the generic response.

2 COHESIVE WEAR

The classification of cohesive (bulk, ploughing, subsurface) wear arises from the success of the two-term non-interacting model of friction (see Fig. 2). If there are seen to be, as a first-order approximation, two modes of friction energy dissipation then there ought to be two general modes of damage and the consequent wear. Clearly the same argument will apply to the interfacial component. This is a crude division and has major flaws in its application in certain aspects of process engineering and in the detailed investigation of such areas as the

scratch damage of polymers in lubricated environments. The two-term division has merits in that it makes a clear distinction between mild deformations such as cohesive wears and the more energy intense interfacial wears.

Another definition of cohesive wear modes, as opposed to interfacial modes, might be that, in some way to be defined, the wear rate might be related to an accessible bulk mechanical failure property. For example, the Ratner–Lancaster correlation often provides an effective interrelationship between abrasive wear (single pass) and a crude measure of tensile toughness [3, 4]. In the abrasion of elastomers there is evidence of correspondence between fatigue life and wear life [5, 6].

The models thus seek to define the contact stress environment and then relate this to the endurance of the polymer. A damage rate is first predicted and then, by scaling, a wear rate law is predicted. The models may then easily incorporate environmental influences. The central thesis is that a bulk endurance or failure property is accessible by some other means, even if the deformation conditions in the contact zone do not realize those addressed in a 'conventional' mechanical testing; the pressures, strains, strain rates, loading transients are not comparable, for example. Lately, some modifications of the Ratner–Lancaster model have also been presented which do take into account the contact load and the counterface roughness effects [7]. Other notable contributions in modelling wear are those of Kar and Bahadur [8] and Viswanath and Bellow [9]. In both cases, they have applied the principles of dimensional analysis and included factors such as material properties, operational parameters and the counterface roughness.

Sections 4 and 7 will deal with these aspects of cohesive wear in the context of elastomers and semi-crystalline polymers.

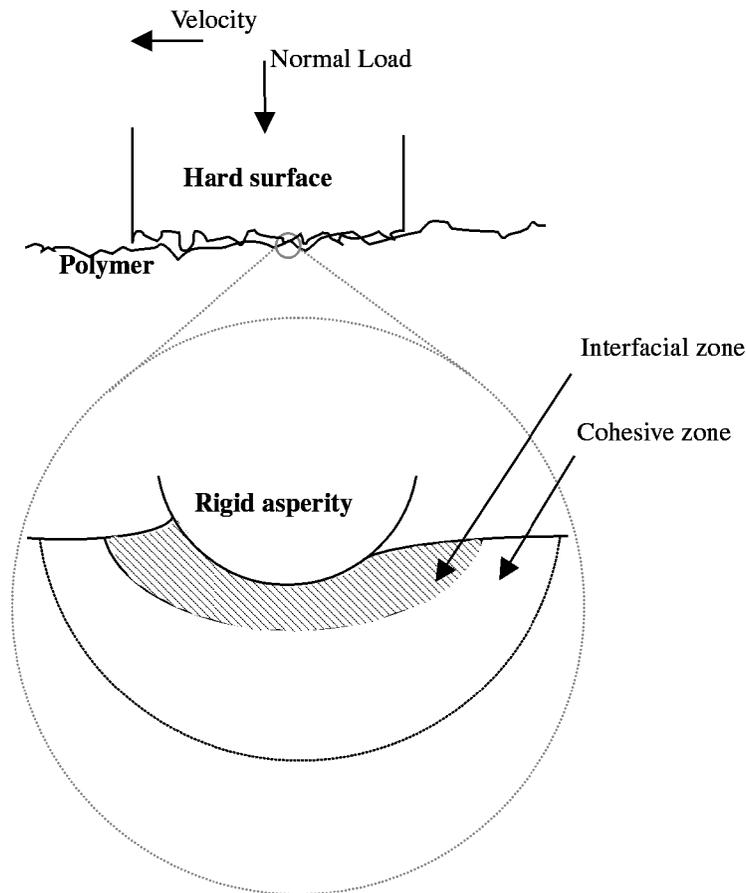


Fig. 2 Two-term model of the wear processes. The distinction between interfacial and cohesive wear processes arises from the extent of deformation in the softer material (usually polymer) by a rigid, non-dissipative, asperity of the counterface. For interfacial wear the frictional energy is dissipated mainly by adhesive interactions while for cohesive wear the energy is dissipated by adhesive and abrasive (subsurface) interactions

3 INTERFACIAL WEAR

The argument for distinguishing this class was mentioned above. It comprises the other part of the two-term model and, more importantly, those modes that do not readily correlate with accessible bulk failure properties.

It is simplest to deal with the so-called transfer damage modes as the first subdivision. The first distinction is that of whether the failure, via transfer, is isothermal or not. Then there is the question of the consequence of quasi-adiabatic interfacial shear behaviour. A scheme is shown in Fig. 3. Some 'special' polymers appear to accommodate near isothermal interface shear-induced softening; basically, the interface zone, as opposed to the actual interface, reorders and as a consequence a highly oriented film and polymeric contact are produced. The friction is often very low and the rate of transfer, and also subsequent wear, may be prolific. PTFE (polytetrafluoroethylene) is the classical example in the unfilled forms [10]. Much

has been published on this topic for a small but uniquely important polymer group of semi-crystalline materials—the 'smooth molecular profile' polymers [11–14].

The 'adiabatic' cases are of two types: the glassy polymers, which are uncrosslinked, and the crosslinked systems, which include the elastomers and the thermoset systems. The thermosets have much importance in brakes [15] and traction couples while the elastomers have much application in automobile tyre applications [16]. In either case there is the prospect of significant chemical degradation and chain scission. The transfer layers, if they occur, are not immediately related to chemical or physical composition of the host polymer. The transfer material does not correspond to what may be described as 'whole' polymer but to a degraded form. In practice this case does not naturally lead to interface shear-induced softening and a reduction in friction. However, the transfer layers will naturally impede the heat transfer processes, which is of significant consequence in brake applications and the phenomenon of brake 'fading'.

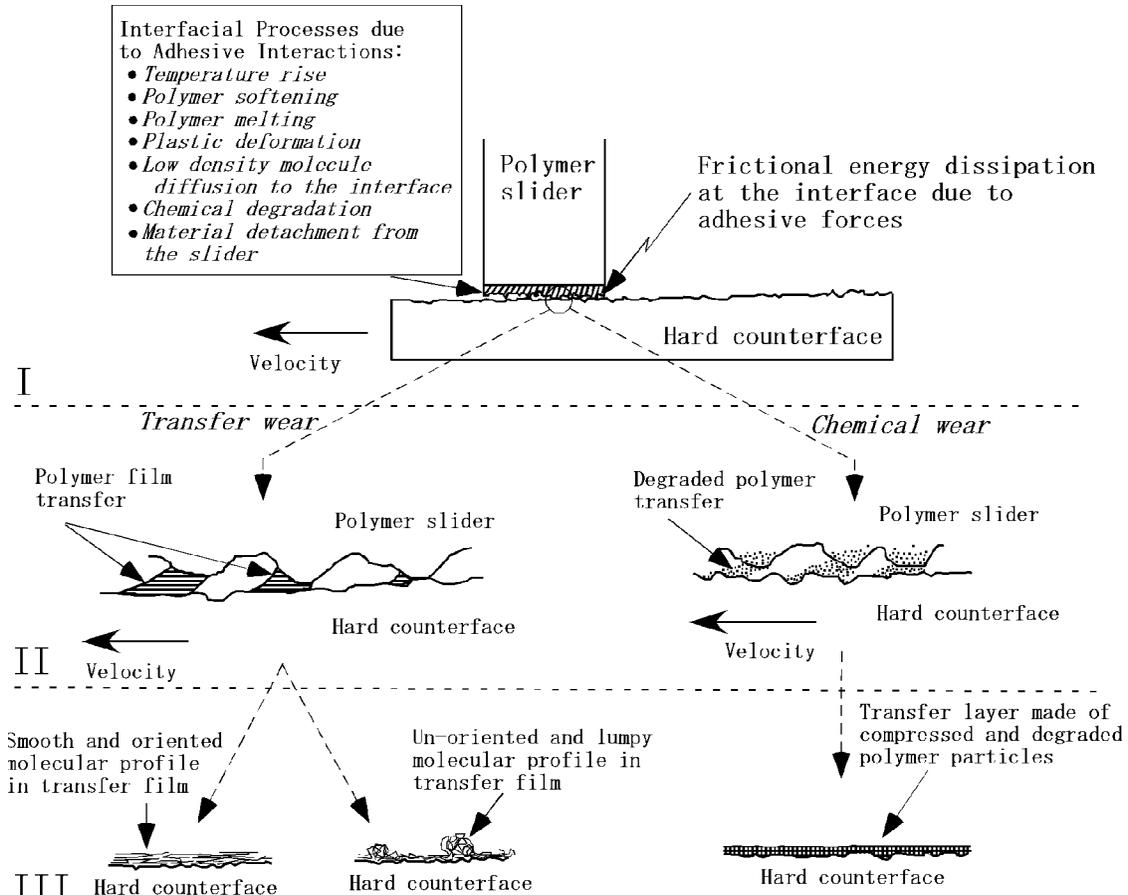


Fig. 3 Schematic description of the interfacial wear processes. I. Initial contact of the two surfaces. II. Running-in process where the deformable polymer molecules are gradually transferred to the hard counterface as a third body. III. Steady state wear process where the wear and friction phenomena are influenced mainly by the shear and adhesive properties of the transferred film

4 ELASTOMERS

The subject of the 'wear of elastomers' has evolved rather separately from that of the wear of other polymers. The main focus here has been devoted to the understanding of the behaviour of semi-crystalline polymers. Thermosets and glassy polymeric systems have not been studied as extensively as these two classes.

To review this area it is consequent to recognize the seminal work of Schallamach [17], although the subject has usefully evolved since then [18, 19]. Schallamach provided very useful precedents, not least the attempt to relate a 'single deformation of events' (he termed these as isolated stress intensifier events) to the prevailing overall wear and contact damage processes.

The work published by Schallamach and his collaborators was of two types: the isolated stress single asperity works and the generic study of wear processes and the subsequent appearance of the worn surfaces (see Fig. 4). The former sets useful precedents for the now-fashionable studies of the scratch deformation of polymers, particularly glassy polymers (see later).

The single-contact deformation studies provided a good picture of the nature of the damage events. The use of sharp needles was a useful illustration of the importance of surface relaxations [20] while the use of 'blunt' indentors provided results comparable to those observed with brittle solids—basically the formation of traction cracks. These studies emphasized the tensile nature of the damage process and also the geometric isotropy of the consequent damage.

Schallamach, his colleagues and indeed others [21] complemented these studies with a series of investigations of wear processes both in the laboratory and on the road; obviously the major driving force of these studies was to elucidate the wear of automobile tyres. Two types of work were reported: unidirectional sliding and random directional sliding. The counterfaces were invariably abrasive bodies or, in some cases, gauzes. Ratner and Lure [22] innovated the use of gauzes to suppress the natural 'clogging' of rough counterfaces caused by wear debris.

The unidirectional sliding produced the familiar 'abrasion patterns' often notable on the surfaces of

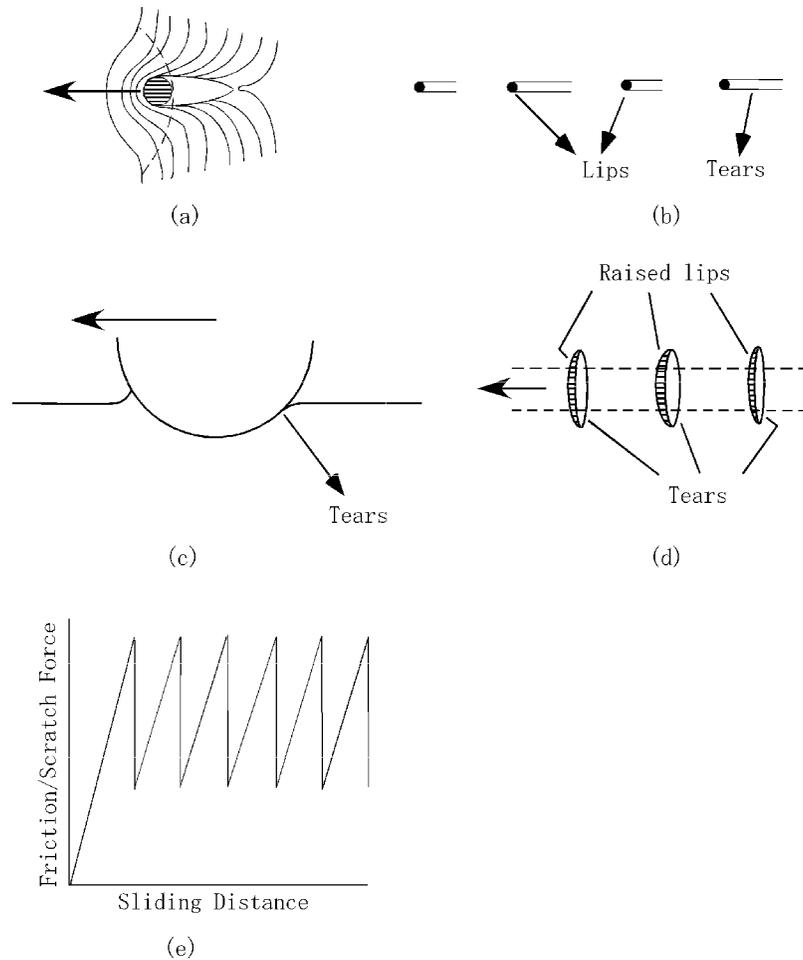


Fig. 4 Damage created on the surface of an elastomer by isolated stress concentration. (a) Surface deformation pattern when a sharp needle or conical indenter with an acute angle is slid on the surface of an elastomer. The elastomer surface is pulled in the direction of motion and fails in tension behind 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

misaligned automobile tyres. The normal section of the worn surfaces has the cuticle structure seen in animal hair which resembles the appearance of the tiling on roofs. Several authors have sought to simulate and model this process often using metal blades contacting rotating rubber discs. Roberts and colleagues [23] related wear to tensile and fatigue properties and Gent and Pulford [24] noted that the high radical concentration, generated by chain scission, could erode metal blades. The picture is fairly well resolved; the damage and corresponding wear is a result of low or high cycle fatigue in tensile fields.

The case of random directional abrasion is less interesting and less studied. The wear rates are generally significantly higher than in the unidirectional case under comparable conditions. The lip, or cuticular structure, is

vulnerable to disruption from non-orthogonal sliding directions.

A few others have since noted other effects. Aharoni [25] mentions scroll formations and Russian work [26] notes the importance of radical scavengers to suppress the propagation of chain scission during low-cycle fatigue-induced abrasive wear.

There was much literature published on the topic of the wear, and tribology, of elastomers in the period up to 1980. The book by Moore [27] was a useful survey and the recent books by Zhang [28] and Denton and Keshavan [29] are very comprehensive. There has also been recent and innovative work produced by Uchiyama and his colleagues [30, 31] on the fundamental basis of the wear processes. It might be reflected, however, that the overall picture has not greatly changed since the

early and seminal work published by Schallamach. The additional parts focus upon fatigue processes and the chemical component of the wear process.

5 THERMOSETS

The main practical area here is associated with the formulation of friction couples such as dry clutches and brake components; there has also been interest in bearing systems. Like the case of elastomers, but more so, this subject has been an academic Cinderella among the various polymer classes. Surprisingly, there has been little published in this area. Rhee and colleagues [32, 33] have produced a range of papers and there are some new contributions [15]. Even here, the focus has been mainly on frictional stability, or 'fade' suppression, rather than wear *per se*. The importance of chemical degradation and degradative transfer is mentioned mainly in the context of thermal stability. The concoctions used in practice do make a fundamental study impracticable.

The subject did take on a renaissance when there was a move to replace asbestos by 'Kevlar', as the use of toxic fillers had to be revisited. This area touches upon the utilization of fibrous composites as bearing materials. There is an interesting literature here [34–37]. The fibre orientation in the matrix is apparently important.

There is a useful literature on the wear behaviours of short and long fibre reinforced thermosets and the influences of fibre content and orientation [38, 39]. Friedrich has edited two books [40, 41] which survey the area and the same author has provided recent research seminars. Naturally, there must be much speculation as to the origins of the wear behaviour of such complex systems. However, some interesting trends emerge. The influence of the principal fibre orientation direction, with respect to the sliding direction, is very interesting if not quite predictable. There is, of course, the nature of the transformed interface to be considered, but the data do fit into the basic geometric models of how contact mechanical stress may propagate and subsequently disrupt the interfacial bonding between the matrix and the reinforcing fibres. The published data note that the strength of the fibre/matrix interface is a crucial factor governing the wear life of the composite.

6 GLASSY POLYMERS

The common glassy polymers, such as poly(methyl methacrylate), poly(carbonate), poly(styrene) have not been used as bearings but rather as optical windows. The Achilles' heel of polymeric materials, in the context of bearing applications, is their inability to dissipate frictional heat. The rather abrupt thermal softening of glassy polymers leads to uncontrolled thermally induced

failure akin to scuffing in metals; a similar technical problem exists with some other non-crosslinked systems such as the poly(etheretherketones).

Uniquely, polymeric bearing contacts have the propensity to 'scuff'; this is a very notable feature of the behaviour of the non-crosslinked systems where molecular mobility and flow are not constrained by the crosslinking process or by crystalline phases. When a polymeric contact reaches a temperature near to the glass transition or crystalline melting temperature there is naturally a pronounced decrease in the Young's modulus and the hardness.

It is a simple matter to examine the consequences of such an event by considering the rate of energy dissipation in the contact. The basic premise is that there will be, at the transition, a loss of 'asperity persistence'. The model [42] is simple and predicts that the friction is

$$F = \tau A$$

where τ is the interfacial shear stress and A , which is roughly inversely proportional to the hardness, is the contact area; the material properties are decreasing functions of temperature. When the frictional heating is localized at the interface, τ decreases, but the hardness, and hence the contact area, remains largely unchanged; the friction decreases. As the thermal front propagates into the polymer the hardness decreases and the contact area correspondingly increases. The frictional work increases as a result and at some stage a catastrophic failure mode is instituted; there is a complete loss of asperity persistence and the contact area approaches the apparent contact area. The process has many features which are similar to the 'junction growth' models developed for metals in the early literature. The overall consequence is a massive and highly damaging contact failure. The phenomenon is well exemplified by the behaviour of virgin PEEK (polyetheretherketone) against metal counterfaces and in lubricated media [43]. Certain additives in conventional lubricating fluids have the capacity to induce plasticization, at elevated temperatures, in such engineering polymers [44]. The combination of frictional heating and ambient plasticization leads to high contact areas and scuffing failures (a Rubenstein effect [45]). The same problem is not seen with modified materials (PEEK combined with PTFE [46], for example), as the self-lubrication additive is capable, because of third-body formation, of producing a low friction counterface. 'Self lubricating' polymers such as PTFE and linear poly(ethylene)s have the capacity to form oriented layers that are 'weak' in shear and hence do not generate the same degree of adiabatic shear heating at the interface (see the next section [10]).

Other parts of this review will deal with the subtle effects induced by special contact displacement modes—linear motion combined with load axis spin for example.

One of the interesting features of the overall wear response is the influence of the kinematics of the contact configuration. The process of fretting is a good example of the importance of debris accumulation and debris expulsion from a contact zone. Again, the problem revolves around the imposed complexity of the sliding motions and the details of the specific actions of the interface shear fields. Chateauinois and colleagues [47, 48] have recently encountered this problem in the context of a glassy polymer, PMMA (polymethylmethacrylate). The imposed sliding kinematics have a major influence upon the overall rate of fretting wear.

It is unlikely that polymers of this class would be used for advanced tribological service. More likely is the prospect that, because of their cost and utility, they may have a tribological function as part of an overall design requirement. The most obvious examples currently are the use of poly(acrylate) in 'bathware' and 'domestic' surfaces and the various usages of poly(carbonates) in optical windows. A noticeable interest in the marring or scratching of such polymers is apparent in recent literature [49, 50]. This would not, by conventional definition, be regarded as 'wear'; the parallel with the Schallamach precedents is of interest and better wear models may accrue because of this focus upon perceived surface damage.

The scratch work, mainly for PMMA, leads to several general conclusions. The damage evolves through a range of severity as the contact strain is increased: viscoelastic smoothing or 'ironing', plastic or viscoplastic grooving, extensive plastic flow and tearing, pronounced fracture or tearing and finally cutting or chip formation. The contact strain may be loosely defined as being proportional to the tangent of the included semi-angle of the indenter.

There is an expanding literature on the topic of the scratching of polymers which provides a refreshing and exciting addition to the understanding of damage processes [48–53]. A typical damage map is shown in Fig. 5 [53]. A combination of frictional force measurements, atomic force microscopy (AFM) and topographic studies, scanning electron microscopy (SEM) images, nano hardness and modelling have shed much light on the processes involved.

7 SEMI-CRYSTALLINE POLYMERS

For a very large variety of reasons these systems have been very extensively studied, not least because of the historically practical and academic interest in the wear of the poly(tetrafluoroethylene)s, PTFE, and the sister polymers such as the linear poly(ethylene)s, in particular the high molecular weight poly(ethylene)s; the latter have found great favour in orthopaedic replacement components. The class is also one that sees a wide range

of applications—PTFE and high-temperature polymer composites for bearings and compressor piston seals [54], nylons as common automobile bearings [55], poly(ethylene)s in marine environments and poly(vinylidene fluoride) in electrical shielding.

The intriguing facet of the semi-crystalline polymers is the variety of their 'transfer' wear or damage responses. There are probably three types of behaviour; the classification is an old one and many would cite the work of Tabor and colleagues [10, 56] as being seminal here. Figure 6 illustrates. A distinction is first made between isothermal and adiabatic processes, although this is made more on a judgement of extent rather than kind. This apart, for the isothermal cases, three situations are regarded as being encountered (Fig. 7). Firstly, there is transfer or not; poly(propylene)s are regarded as not forming transferred layers but the situation is unclear. What is clear, however, is that the PTFEs and linear poly(ethylene) do transfer, under a wide range of contact conditions, to many counterfaces [57–59]. There is evidence that ambient temperature and sliding velocity are important variables [56]. This apart, the isothermal condition that gives transfer does so in two ways. There is the case of the so-called 'smooth molecular profile, or special, polymers' which produce, once sliding has commenced, thin highly oriented and weakly adherent layers; this is typical of the PTFE and UHMWPE (ultra-high molecular weight polyethylene) systems. The static friction is high but the dynamic friction is low and the resulting wear (see later) may be very high. Technically, the prospect of low friction motivated the great interest in these materials.

The seminal work was probably that by Pooley and Tabor [10] but Tanaka and colleagues [31, 57] have made useful contributions. The basic idea was that certain polymers, under the action of interface shear gradients, would produce reoriented interface zones and indeed transferred layers [60]. Stolarski and colleagues [61, 62] demonstrated this point nicely by undertaking studies of the friction and wear of a range of polymers, including the 'special' polymers under the action of combined linear and rotational sliding. Linear sliding produces oriented interfaces with low friction and high wear. The addition of the rotation disrupts the natural orientation process. As a result the frictional forces increase towards the static (un-oriented) values. Wang *et al.* [63] have recently revisited this problem in the context of the wear of UHMWPEs. The evidence is persuasive; rotation disrupts highly oriented transfer. The fact that the consequent dry wear is reduced is explained by an argument that high friction and high energy dissipation promotes the formation of more strongly attached transferred layers. Earlier, Briscoe *et al.* [64] had examined the consequences of gamma irradiation for the tribology of these systems. Interestingly, for the PTFE materials gamma irradiation does not produce chain scission but rather a reduction in

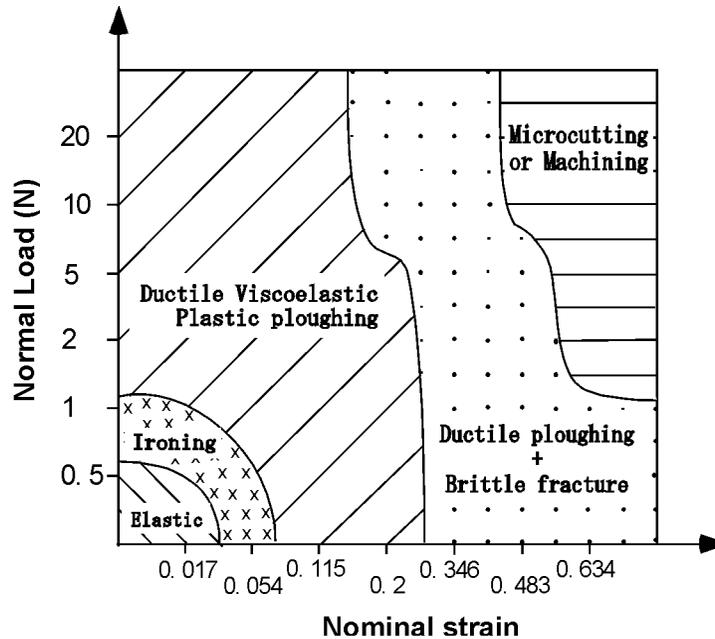


Fig. 5 Scratching mode map for PMMA. The diagram shows the dependence of the observed scratching deformation mode upon the nominal contact strain and the applied load. The nominal contact strain was calculated as $0.2 \tan \theta$, 2θ being the included angle of the indenter with respect to the plane of the polymer surface. The scratches were produced at a constant scratching velocity of 0.004 mm/s, at ambient temperature of 20 °C and under unlubricated contact conditions [53]

molecular weight and a corresponding increase in the crystallinity. It would appear that high degrees of crystallinity inhibit transfer and suppress wear. The action of fillers has a comparable effect. These 'highly structured layers' are capable of producing low friction but high wear; the volume of transfer wear per pass is low but does lead to an accumulated highly net wear rate.

The problem here, for bearing formulations at least, was resolved by the addition of a range of organic and

particularly inorganic fillers: particles, fibres and porous supports. The use of a, say, 10% w/w of a glass particle in a PTFE composite has often been shown to reduce the wear rate by up to at least three orders of magnitude [65]. Many authors [66–68] have speculated upon why this occurs. Polymer blends are another example for the enhanced wear resistance of polymers [8, 69, 70]. Certain transition metal oxide fillers have also been reported to induce mild polymer degradation at the interface and thus create strong valence bonds between the transferred

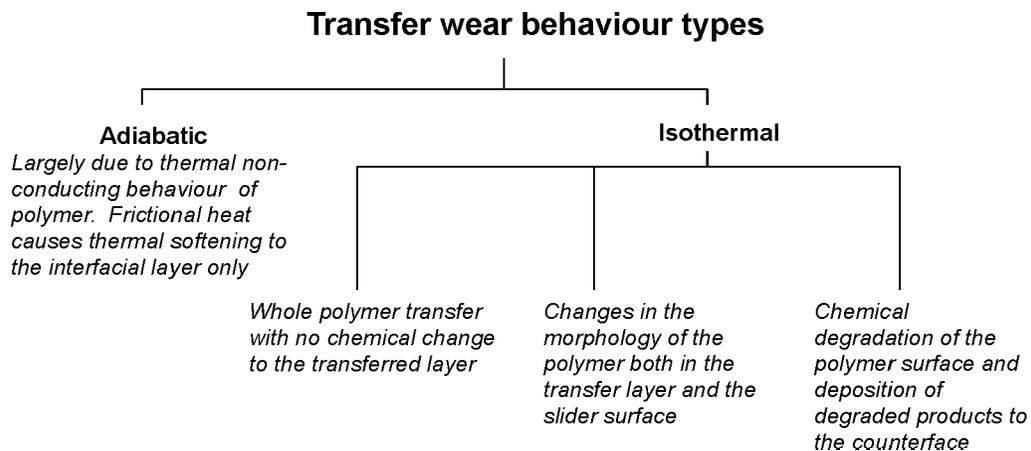


Fig. 6 Generic types of transfer wear behaviour when semi-crystalline polymers are slid on to a hard smooth surface. In every case there is a formation of transfer layer on the counterface though the shear and adhesive properties of the transfer films will vary depending upon the polymer's mechanical properties and the surface topography of the counterface

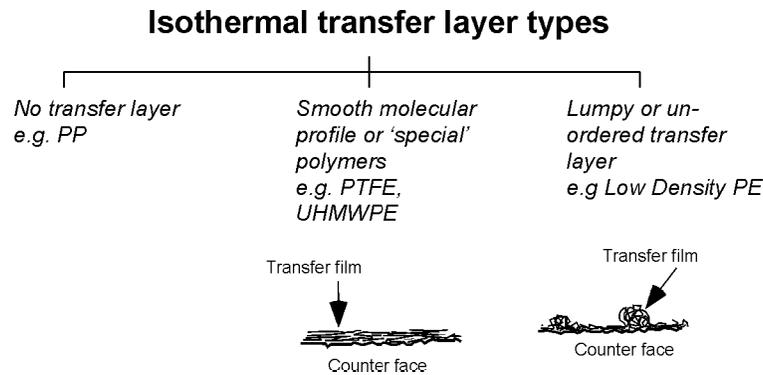


Fig. 7 Types of transfer layers for certain semi-crystalline polymers when slid against a hard smooth surface

layer and the counterface [71, 72]. Similar tribochemical effects leading to stronger bonding of the transferred layer to the counterface have also been tested for polyphenylene sulphide composite filled with 30–35% CuS powder when slid against a steel counterface [73]. Various models are available but basically the fillers are thought to provide a thin, coherent, securely attached transfer layer of the polymer species on the adjacent counterface. A stable transfer layer promotes low friction and low wear. The wear of fibre-filled polymer has been shown to exhibit crack nucleation at the polymer–fibre interface, crack propagation parallel to the surface and crack shearing to the surface, resulting in flakes of polymer debris [74]. Environmental influences, particularly water, may disrupt this process and cause higher rates of wear [13].

Other important parameters that control the wear of semi-crystalline polymers are the initial and steady state counterface roughnesses. This aspect has been dealt with at length in an earlier review [5]. However, it may be appropriate here to mention that for both pure and filled polymers, there seems to be an optimum initial counterface roughness that produces strong adhering transfer layers and consequently low wear [75–77]. For example, PTFE filled with 10% carbon shows a minima in the wear rate at about the initial counterface roughness of $0.4 \mu\text{m}$ (R_a value) [78].

Much less is known regarding the two other cases: no transfer, if it occurs in this class, and the 'lumpy' and un-ordered transfer, which is seen with such polymers as low-density (chain branched) poly(ethylene). Pooley and Tabor [10], for example, reported high friction and relatively thick but un-oriented transfer for this case. Steward and colleagues [78, 79] observed similar behaviours for carbon-filled PTFEs. The general result for those cases is that high friction produces thick un-oriented layers and also relatively low rates of wear.

Central for all of these observations is that nature and adhesive tenacity of the transferred layers is a dominant factor. The abrasion resistance of the class, by and large, may be rationalized using the Ratner–Lancaster corre-

lation for the virgin polymers at least. At a fundamental level there are now issues to be considered regarding the scale of the deformation and the corresponding scale of the homogeneity of the system; for composite materials this is an issue of interest by practitioners but one that is not resolved by those who wish to produce generic models. Friedrich [80] and one of the current authors [5] have commented upon this problem.

8 ENVIRONMENTAL AND LUBRICATION EFFECTS

Though, except for elastomers, polymers are not used in general in the presence of any lubricant, this subject has nevertheless attracted interest from polymer tribologists. One obvious reason is that polymers, intentionally or unintentionally, do become subjected to lubricant contamination, or humidity in the operating environments. Examples are industrial bearings subjected to leaked lubricants or water, household plastics subjected to humidity and polymer human hip/knee joint replacements working in the environment of proteinaceous synovial fluid. One example of elastomer in the lubricating environment is that of the hydraulic seals. Here, the presence of a thin layer of lubricant is essential for the reduction of friction and reduction wear of the seal material. Working fluid film thickness for viscous oils present in seals has often been predicted from hydrodynamic theory [81, 82]. This film generally protects the elastomer surface from coming into direct contact with the solid surface. In the case of a prolonged stationary condition or for very high contact stresses, the lubricating film tends to become squeezed out of the contact region, leading to high start-up frictions and dry sustained contact [83–85]. Such conditions eventually lead to high wear and seal failure. The wear mechanism for such dry conditions can be treated as similar to the case where there is no presence of lubricant (see Section 4).

For non-elastomeric polymers, depending upon the polymer and the lubricant's polarity, the presence of lubrication has effects such as polymer plasticisation, reduction of contact area due to fluid film formation at the interface, modification of the shear properties of the interfacial junction and change in the adhesion properties of the transfer film. Briscoe and Kremnitzer [86] have shown that for polyethylene terephthalate fibre/isopropalane–water mixture systems, there are two situations of lubrication depending upon the normal load. At low loads, the lubricating efficiency of the fluid depends upon the surface tension or the wettability of the fluid. Low surface tension generally lowers the coefficient of friction due to the formation of a uniform lubricating layer at the interface. On the contrary, at high load the contact stresses extrude the fluid out of the interface, leading to solid–solid contact and, as a result, a high friction situation is generated. The effect of humidity on HDPE (high density polyethylene), PTFE and Nylon 66 has also been reported [13, 87–89]. In general, these polymers allow limited sorption of water molecules into the amorphous regions of the bulk of the polymer contributing to a decrease in the mechanical properties such as hardness, elastic modulus and shear strength of the polymer. Such sorption is accelerated in the presence of high hydrostatic pressures that are very often present at the polymer/counterface contact regions. The wear rates have been found to increase twofold to threefold under such conditions. The interesting feature of the lubricated sliding of polymers is the presence of very little or no transfer film on the counterface. Probably, this is one of the major factors contributing to high wear as there is continuous removal of the debris from the interface in the absence of a transfer film. For lubricants with larger molecules (fatty acid and paraffins), the plasticisation of the bulk polymer is minimized and thus the friction and wear depends upon the ability of the polymer surface to make a coherent layer of lubricant at the interface. A good lubrication is possible if the contact stress conditions are not too severe. In the case of the UHMWPE used for artificial hip replacement, oxygen–plasma treatment has been used to enhance the adsorption of protein molecules present in the human synovial fluid to the polymer surface due to increased hydrophilicity [90]. Such polymer surface modification can lead to considerable reduction (50 per cent) in friction; however, its effect on wear is still not known. To counter the damaging effects of mixed lubrication and consequent wear of UHMWPE in an artificial hip joint prosthesis [91], different joint designs consisting of a compliant layer such as water swollen hydrogel polymer sliding over hard metal has also been reported to have desirable friction and wear properties [92, 93]. Like other materials, lubrication of polymers, in general, greatly depends upon how the lubricant

molecules attach themselves at the polar sites of the polymer surface and often less upon the viscosity of the lubricant [94].

The available literature on the lubrication and environmental effects on the wear of polymer clearly suggests that polymers differ from metals in at least two aspects. The first is the ability of the fluid phase to penetrate into the bulk of the polymer and thus change the mechanical properties of the polymer. The second effect of the lubricant or the environment is on the change in the adhesive and shear properties of the transfer film. Despite some progress in the understanding of lubricated polymer wear, further research is needed to fully utilise the great potential of using polymers for specific applications in the presence of lubricants. Molecular modification of the polymer surface to effectively accommodate lubricants without affecting the mechanical properties of the bulk of the polymer has some promise.

9 CONCLUDING REMARKS

Wear of polymers is influenced by three major groups of parameters. The first group includes the sliding contact conditions such as surface roughness and contact kinematics. The second group incorporates the bulk mechanical properties of the polymer and how these mechanical properties change with temperature and environmental conditions. The third parameter group, which is in fact defined by the first two groups, involves the role and properties of the 'third body', the transfer film and loose degraded polymer particulates. The wear mechanism, and its magnitude, are defined by the contact conditions, mechanical properties of the bulk polymer and how these parameters lead to the subsequent events of transfer film formation, if it occurs, and debris production. The wear classification based on generic scaling, phenomenological and material response approaches do account for the different parameters in discrete ways and thus make the study of polymer wear more readily explainable.

The wear mechanisms of polymers under known contact conditions and their mechanical properties of the polymers are now fairly well understood. However, the theoretical prediction of polymer wear is still far from being completely resolved. On a limited scale, adhesive interaction (interfacial) can be modelled by the Bowden and Tabor approach, while abrasive (cohesive) interaction is correlated using the Ratner–Lancaster relationship. Major problems in wear prediction are the undefined roles and mechanical properties of the third body and the fact that polymers show a variety of mechanical responses under even a slight variation in the thermal or mechanical stress conditions. Besides, there is always an overlap of different wear mechanisms in any

particular wear process. Therefore, accounting for every wear mechanism without proper knowledge of the extent to which these mechanisms are active in a wear process adds numerous uncertainties to the production of a realistic predictive wear model. For polymer composites, the problem is further complicated by factors such as the filler–matrix bonding properties and the role of the fillers in the third body. Empirical wear relations and wear maps have been successfully developed and used for the practical purpose of material and machine component designs. Despite limited theoretical predictive capabilities for the wear of polymers, this class of materials has been industrially employed in a very large number of tribological applications.

Lubricated wear of polymers is a very complex situation and almost no theoretical models are currently available in the literature for predicting wear. Experiments have shown that polymer wear in the presence of lubricants or any environmental fluid will depend primarily upon the interaction between the fluid phase and the polymer and the counterface. Polymer plasticization, fluid sorption to the polymer surface, alteration of the adhesion properties of the counterface-transfer film and change in the polymer bulk and polymer–counterface junction mechanical properties are the important processes in the lubricated sliding of polymers. Except in cases where there is sorption of the lubricant molecules by the polymer surface, generally polymer wear has been reported to be high in the presence of an external fluid.

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