Self-Lubricating Polymer Composites: Mechanisms, Properties, and Applications

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Abstract

The tribological parameters in sliding/rolling mechanism have significant role in overall performance of the materials. To design a material that offers low friction and wear, the material must have specific mechanical and physical properties. In this context the lubrication has important role and it is known that lubrication can reduce the undesired parameters during sliding/rolling. There are certain limitations in the usages of liquid lubricants such as high and low temperatures, extreme load, and speed environments. This raised the requirement of a lubricant in a solid form and coined as solid lubricant. In a situation where no external lubrication is possible, there is a need of lubricant that performs by itself which is called as self-lubricant, and the widely used self-lubricants are polymer based. This chapter provides insight into self-lubricating polymer composites, structural features, mechanisms, factors influencing tribological properties, and applications of polymer composites.

4.1 Introduction

Liquid lubricants cannot be utilized for specific applications like very low, severe temperatures and liquid contaminations. In these cases, solid lubricants are a good candidate in its performances. There are various usage routes that are available such as vapor deposition, applied as film on substrates and also by surface burnish. Over the years, it is witnessed that the solid lubricants with various reinforcements, recent emerging material, carbonous materials, can act as self-lubricating composites. These composite materials offer superior thermal, mechanical, and self-lubricating properties [1, 2]. In the past decades, the research world witnessed significant improvements in the development of reinforcement in aluminum alloys along with the development of polymer composites, typically with graphite in the matrix, and these composites exhibited superior self-lubricant properties for a wide range of materials [3–8]. Furthermore, the significant tribological improvements are observed for the composites which are reinforced with solid lubricant rather than the composites reinforced with ceramic. The micron ranged graphite particles are considered for the fabrication of composites which exhibit better tribological, mechanical, and self-lubricating properties [9–17].

The natural fiber reinforcement in a polymer matrix demonstrated superior tribological performance, greater economic viability, and greater adaptability toward specific environments [18]. The graphene nanoplatelets reinforced nanocomposites exhibited superior tribological and self-lubricating properties [19]. The self-lubricating composites can be used as alternatives for toxic petroleum-based lubricants. Furthermore, these offer greater impact in the reduction of emissions to the environment and also in the reduction of energy dissipations which improve the energy efficiencies [14, 20].

Self-lubricating composites consist of a reinforced matrix of solid lubricant additives and various other constituents and are well suitable for rolling element bearing. Furthermore, commonly used solid lubricant materials are graphite, molybdenum disulfide, layer lattice compounds, and polytetrafluoroethylene (PTFE). The performances of graphite in space applications are dormant since it requires humid/ absorbed vapor environment to exhibit good performance. On the other hand, molybdenum disulfide exhibits greater performance for these applications. Some of the disadvantages of molybdenum disulfide are: (1) shortened life when long sliding in air environment, and (2) the formation of molybdenum oxide can the performance.

PTFE exhibits significant performance in both vapor and vacuum environments. The cold flow under loading conditions is one of the disadvantages of the PTFE. To eliminate this, one has to add suitable binding material. The past research indicates that very limited polymer-based self-lubricants were fabricated. Recent studies revealed that some of the polyimide polymers are capable for superior performance in vacuum environments [21]. A rigorous research is required in these areas since polymer-based lubricants have vast potential. This chapter is intended to understand the tribological properties and environmental influences on the properties of these polymer-based solid lubricants for various applications. Furthermore, various polymers, its fillers, and routes for polymer composites especially for a sliding environment will be discussed. The usages and challenges of polymers and polymer-based composites for space applications as a solid lubricant will also be discussed.

4.2 Structural Features of Polymer

The polymer molecular studies are important to understand the mechanisms involved in the physical properties, and in current scenario most of the polymer-based lubricants are organic based. Very large molecules with carbon atoms are the main component in the organic polymers. The formation of the polymer is by recurring of monomer units and the polymerization conditions influence the growth of the polymer which can be achieved to a molecular weight of several millions. The length of the chain influences the mechanical behavior of the polymers.

Polymers can be classified as thermoplastics and thermosets. The cross-linking capabilities are dormant to the thermoplastics while thermosets are highly cross-linked. In addition, another classification can be noted as amorphous or crystalline. Even in well-crystallized polymers, existence of amorphous regions is existed and vice versa and may affect physical properties. For instance the physical properties of polymer some models are required to demonstrate and presented here. Random coil, fringed micelle, folded or extended chain, and molecular domain are significant models to understand the mechanisms of physical properties. The folded chain model is considered as the much appreciated model than the others. In addition, the existence of complex aggregates of molecules, called spherulites, is the base for folded chain model. XRD studies revealed that the spherulites are comprised of plate like uniform thick lamellae. Further, the SEM and XRD studies also confirmed that

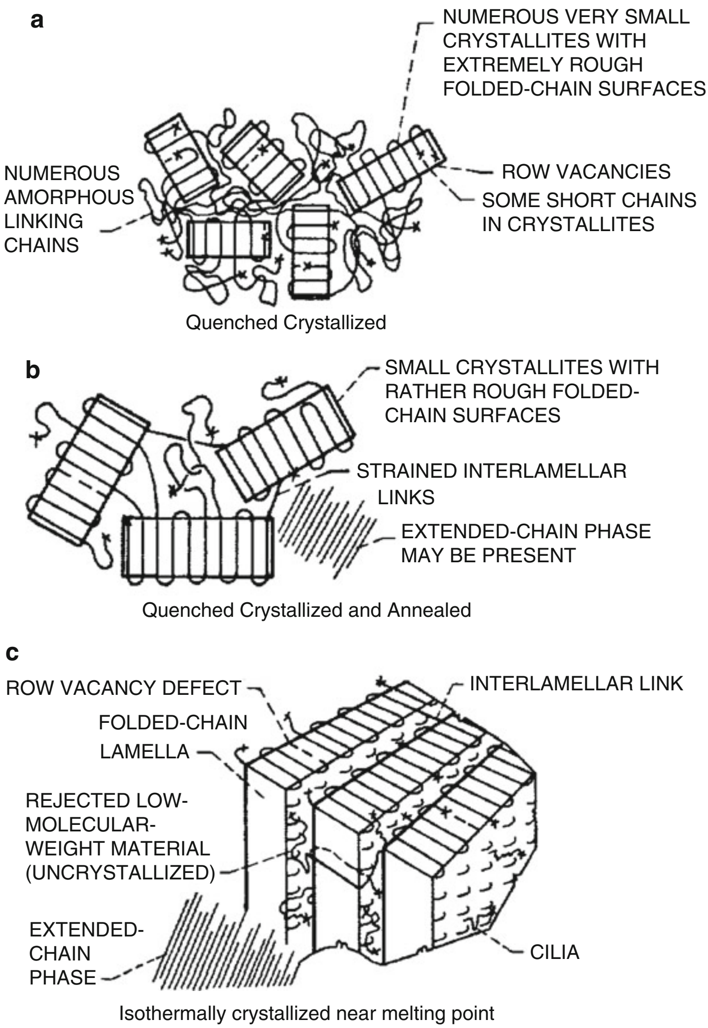


Fig. 4.1 (**a**–**c**) Shows fine structure of a polymer prepared under various conditions [22]. (**a**) Quenched crystallized. (**b**) Quenched crystallized and annealed. (**c**) Isothermally crystallized near melting point

lamellae consist of folded chains which are perpendicular to lamellae surface and are thus called as folded chain. Figure 4.1 illustrates a crystallized polymer for various crystallization conditions. Furthermore, all models also exhibited [22]. The distance between the folds determines extended (>200 nm) or fully extended (no presents of folds) chain crystal.

Melt by regulating crystallization, annealing, and mechanical stress are the routes to the formation of extended chain crystals. The mechanical stress method exhibits the chain unfolding features and two models have been proposed [23]. In the first model, plastic deformation influences the chain unfolding in the applied force direction. In second model, shearing deformation influences the chains gradually to become tilted by twisting and slipping in along the direction of force. In general, the low friction and wear properties are exhibited in exteneded chain structure.

4.3 Polymer Composites: Self-Lubricating

The addition of various materials to polymers is carried out to improve the load-carrying capacity, tribological performances, and thermal conductivity. The load-carrying capacities can be improved by adding the fibers as reinforcement materials to the polymer and together they form the polymer composites. Also, additives used to improve the tribological properties may reduce the load-carrying capacities (may have easy slip planes). Thus, thorough considerations and understandings are required to meet both requirements. This can be achieved by reinforcement of fibers and lubricating additives, or combination of non-lubricating and lubricating fibers. Small pieces of fibers can be dispersed in the matrix. Improvement in the thermal conductivity of the polymer composite can be achieved by dispersing thermally conductive materials in the matrix. In general, combinations of polymers and various additives can be used [24]. As discussed in an earlier section, the usage of polymer composites for specific applications requires understanding and the possible polymer composites in space applications are PTFE/glass fiber, PTFE/glass fiber/MoS_2, Polyimide/MoS_2 and PTFE/Woven glass fiber/resin as bearings, gears, and cages.

4.4 Lubrication and Wear Mechanisms of Polymer Composites

The success of the solid lubricant determined by the level of holding the stress formed due to the loading and tangential friction stresses for polymer-based composites. If not, they may experience plastic deformations, brittle fracture evolutions, high wear, and even catastrophic failures. In some cases, it is observed that rapid wear sustains until the polymer supports the progressive increase in the contact area. Also, dynamic stress highly influences the wear mechanisms. A lower dynamic stress is beneficial to exhibit a mild wear behavior. These infer that stress plays vital role in the performance of self-lubricating polymer-based composites. In general, while designing these types of lubricants an account of stress must also be considered with greater attention for better performances.

The synergy between polymer and additives is important in terms of their tribological properties and their working environments even when they are having significant load-bearing capacity [25]. A shear layer development in the mating surfaces will support the improved properties for designing better lubricants. This layer reduces the adhesive and abrasive action in the sliding surfaces and stresses in the polymer surfaces. Also, a thin layer will be adequate to exhibit these improved properties. Some polymer materials have self-forming ability of shear layer.

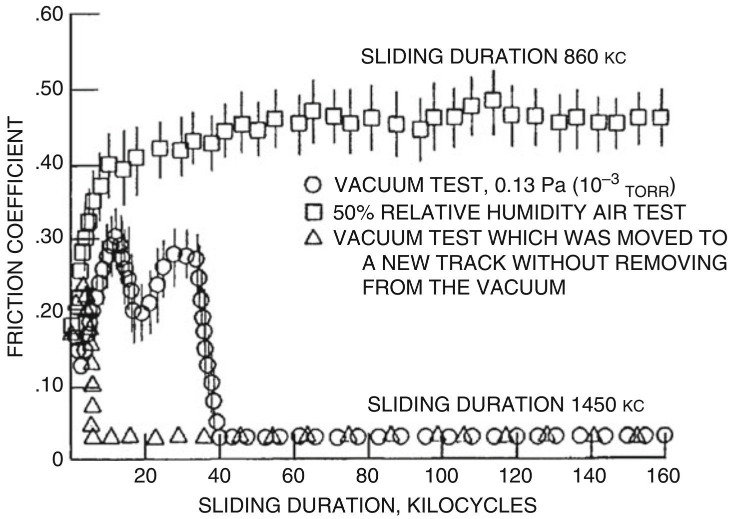


Fig. 4.2 The friction responses of a commercially available polyimide in various environments [27]

The extended chain mode of PTFE chain in the surface reduces shear and results in low friction [26]. Furthermore, bulk PTFE may not have good load-bearing capacity. In these conditions, the usage of PTFE as reinforcement in body and as coatings or films is the preferred way to achieve greater life.

In vacuum and air environments, some polyimides form thin shear layer at the surfaces [21, 27].

The tribological performance (friction and wear) of the polyimides are superior in nature for various environmental conditions like vacuum and high temperature. Furthermore, one of the reasons behind performance is the formation of extended chain molecule [27]. The load-bearing capacities of these polyimides are greater as compared with PTFE and also exhibit low friction. This infers that in some special cases like space applications, the additives are not required to reinforce. On the other hand, the tendency to absorb water and the subsequent increase in the friction are the challenges in the development and applications of polyimides. Thus, removal of water vapor and water vapor layer is important while using polyimides for a specific application.

The friction coefficients of polyimides in various environmental conditions are illustrated in Fig. 4.2; the result shows an increase in the coefficient of friction in air with 50% humidity conditions, whereas the coefficient of friction decreases in the vacuum conditions [27].

Ultra-high-molecular-weight-polyethylene (UHMWPE) polymers offer greater load-bearing capabilities. On the other hand, this polymer has poor temperature withstanding capabilities, and this infers that these polymers may have good performance in low temperature conditions.

The quality of the shear layer formed determines lubrication performance of the composites. This shear layer has significant role in maintaining the performance.

Thus, quality and reliability are important in bonding to the polymer surface and this can be called in a short way as “flowing into itself.” The layer movement without failure during sliding determines the sustainability of the lubrication performance. Furthermore, the factors influencing the layer must be analyzed thoroughly especially the fatigue. The formation and specialties of transfer films are important in the wear behavior. A thin film offers good wear performance, while thick film promotes the adhesive forces, resulting in severe wear.

4.5 Lubricating Mechanisms: Transfer Film of Polymer Composites

The shear layer and its mechanisms play important role in various aspects as stated in the earlier section. It can be noted that the shear emerges within shear layer on the bulk surface, transfer film on counter surface, or it can occur in between the both. The mechanism involved in the performance of ball bearing uses a double transfer lubricating film as shown in Fig. 4.3.

The influence of load in an ambient air environment on the double transfer of PTFE (Rulon-A and 5% MoS_2) composite was studied by [29] on testing apparatus (Fig. 4.4). The result indicated that as increase in load leads to slight decrease in the roughness of the wear track. In addition, at the mean stress level of 1.38 GPa the transfer film was insufficient to prevent roughening of the surfaces (Fig. 4.5). These indicate the importance of the limiting stress for the effective transfer film at ambient air atmosphere. The double transfer lubrication regime can be successfully used in higher load conditions only. Thus, it can be a potential candidate for the various space applications.

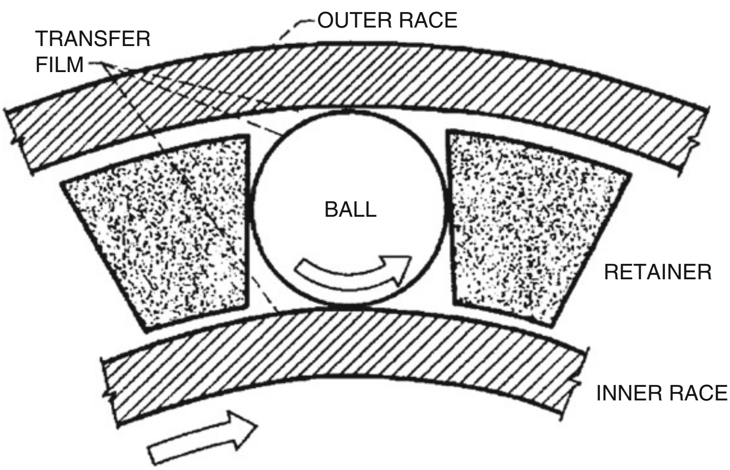
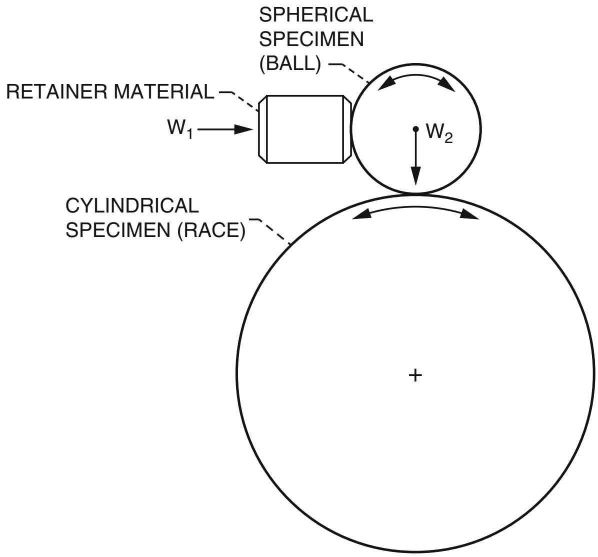


Fig. 4.3 Ball bearing film transfer mechanism [28]

Fig. 4.4 Transfer analysis equipment [29]



4.6 Factors Influencing Polymer Composite Wear and Transfer

This section deals with the factors that affect the performance of polymer composites.

4.6.1 Load/Stress

As stated in an earlier section, it is clear that the polymer film and its wear behaviors are highly influenced by the load and stress [30]. The mild wear was exhibited on low loads and severe wear was exhibited at high loads. The formation of shear layer and its delamination features and thin transfer film results in the mild wear behavior. The formation of brittle fracture or severe plastic deformations results in severe wear. In addition, polyamide-bonded graphite fluoride film of 0.0025 cm thickness exhibits the mild wear and severe wear regime specialties as stated above [31]. A linear progress of wear rate was observed in mild wear regime and an exponential progress was observed in severe wear regime.

4.6.2 Contact Area

The contact stress and its effects in the transfer film are important entities on the performance of polymer-based composites. The contact stress is deducted from the contact area. Thus, in a case where the load cannot be reduced further, another alternative is to increase the contact areas which will helps to reduce the contact

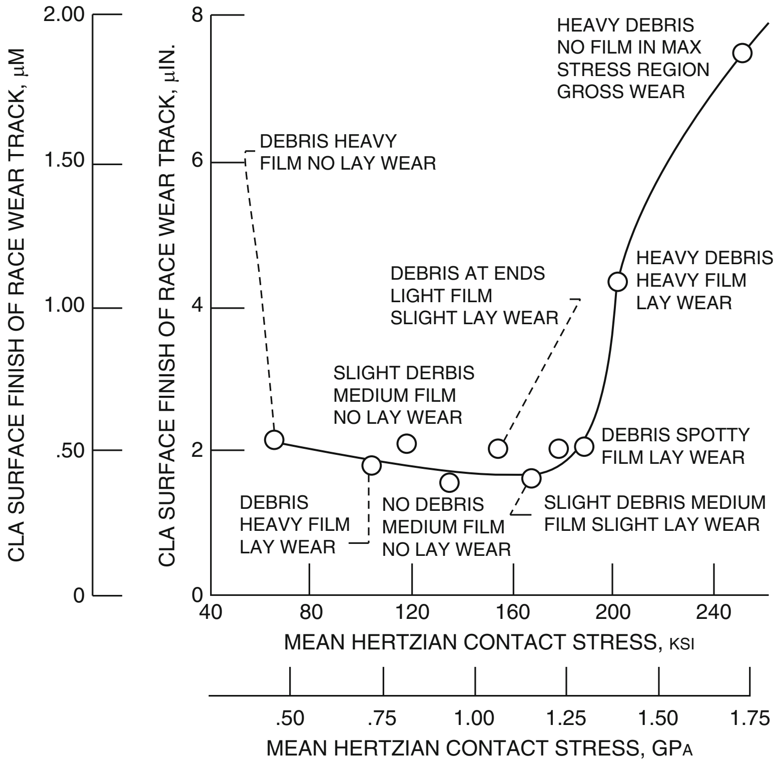


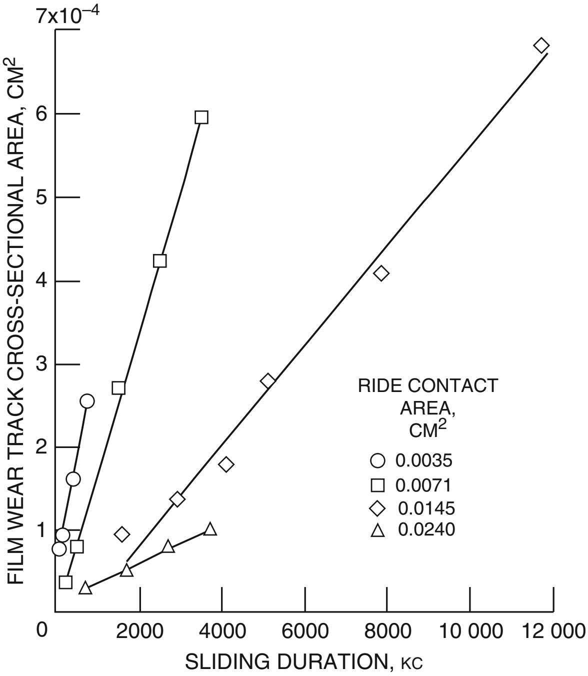
Fig. 4.5 Surface finish of race wear track Vs mean Hertzian contact stress (lubricated with a Rulon-a + 5%MoS_2 transfer film) [29]

stress and the resulting mild wear [30]. Figure 4.6 illustrates the variation of wear rates for polyimide-bonded graphite fluoride film. The formation of transfer film was influenced by the contact areas. The increased contact area and the lower stress lead to poor tribological performance. This is due to the formation of ridges and this increases the localized stress and adhesion. This infers that the contact area plays an important role in the optimum designing of the lubricant.

4.6.3 Sliding Speed

The sliding speed influences the generation of heat due to friction at higher speed. This affects the performance of the additives in the composite matrix. Also, in some cases this frictional heat will help in many ways such as removal of water vapor, influences the molecular relaxation in the polymer molecule, and thus improves its mobility. Furthermore, the sliding speed influences the wear debris size and wear. However, the performance of wear mechanisms is highly influenced by properties of shear film and transfer film. The high sliding speed restricts the reorientation of

Fig. 4.6 Polyimide-bonded graphite fluoride film wear rate Vs sliding duration for a constant load sliding [32]



molecular chains and thus results in the high wear particles and high wear. In addition, the process parameters like sliding speed optimization are important in the design to exhibit superior performances.

4.6.4 Environment

The lubricants like graphite and molybdenum disulfide are highly influenced by the environmental conditions. These lubricants are in two extremes; the graphite exhibits good lubrication performance in absorbed gas or vapor atmosphere, whereas the molybdenum disulfide exhibits better performance in the absence of absorbed gas or vapor atmosphere. In addition, the polymer composites are also highly influenced by the environment during sliding. This phenomenon is due to the additives that are sensitive to the environment. All of these lubricants the PFTE exhibit superior performance in various environmental conditions. The polymer having free hydrogen is highly influenced by the environmental conditions like absorbed vapor and water vapor regimes. The poor mobility of the molecules in the polymer is highly influenced by the presence of water and restricts formation of thin surface layers. In general, polyimides demonstrate better performance in vacuum conditions [27].

4.6.5 Counter Surface Topography

The tribological performance of polymer composites is highly dependent on the counter face material and its specialties. If the counterface is too rough, it restricts the formation of shear and transfer film and thus affects the important tribological properties. Figure 4.7 illustrates the effect of the surface roughness of counter surface for various materials like stainless steel, etc. and Fig. 4.8 illustrates the effect of the surface roughness graphite-fiber-reinforced polyimide composites sliding against different materials. It can be noted that Pyrex glass offers lowest possible frictional coefficient. However, highest frictional coefficient was observed on SS 301 [32]. The results show that at lower roughness counter surfaces exhibit lower wear rates.

Furthermore, the low root mean square (RMS) value and center line average (CLA) value of roughness not always indicates the smoothness of the surface. The over polishing may deteriorate the softer materials and form the hard material in the counterface surface which results in severe abrasion in polymer surface. Especially this behavior can be seen for overpolished 440C HT Stainless Steels against a polymer surface. In initial sliding the surface finish and material type have a dormant influence on the coefficient of friction. As sliding distance progress surface finish and material type influence the coefficient of friction significantly. The Pyrex glass has the smoothest surface and has ability to form extremely thin transfer films for the best performance.

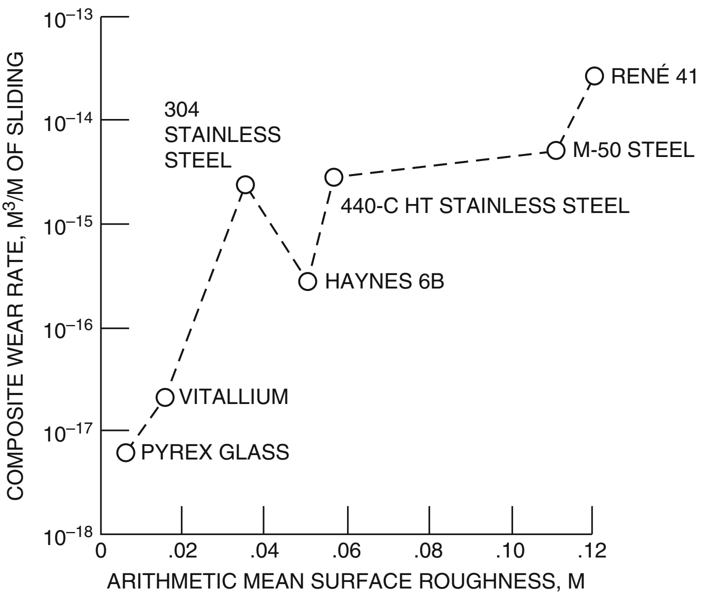
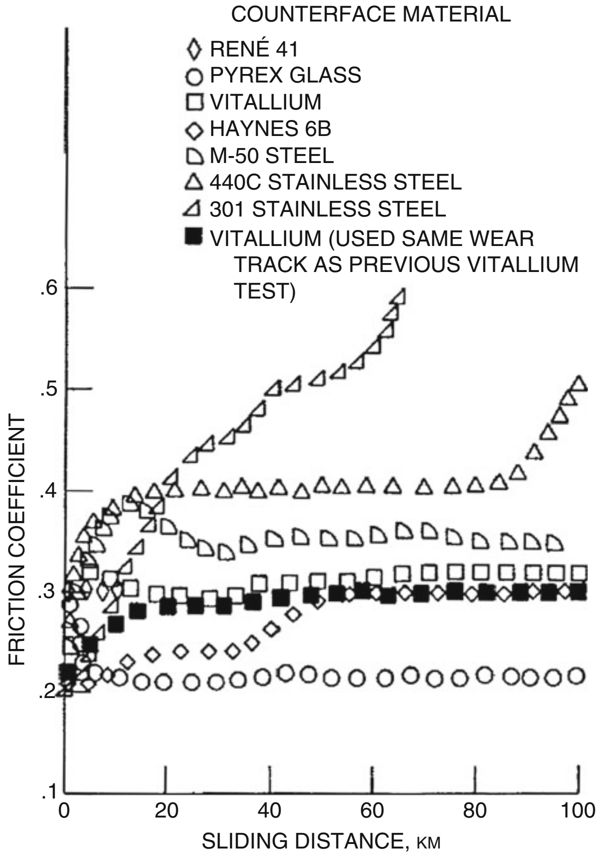


Fig. 4.7 Composite pin wear rate vs arithmetic mean surface roughness for various materials [32]

Fig. 4.8 Friction coefficient in 50% relative humidity air at 25 °C [32]



4.6.6 Cleanliness

The surface cleanliness is one of the factors to be considered with greater attention. A dirty surface may exhibit an abrasive action and resulting poor tribological performances. Figure 4.9 illustrates the embedded small hard particles into an UHMWPE polymer solid which acts like an abrasive particle and wore a grove in 440C stainless steel counterface [30].

4.6.7 Temperature and Molecular Relaxation

As discussed earlier, the interrelationship between temperature and molecular relaxation is important for the performance of the composite. The movement of chain, or can be called as mobility, depends on certain temperature. This can be above or below the transition temperature which results in high mobility and low mobility,

Fig. 4.9 Surface profile of the sliding contact areas [30]

respectively. In general, the tribological performances of the polymer composites are highly dependent on temperature and subsequent influence on the molecular mobilities. Also, the limited molecular movement will reduce the formation of thin shear layer. Torsional braid analysis (TBA) method is good candidate for analysis of relaxation temperatures [33]. Fusaro [23] conducted studies to understand the synergy of molecular relaxation by TBA method. Polyimide (PI 4701) was considered for the studies and the results demonstrated TBA peaks. The highest peak correlated to glass transition temperature (α-peak). Furthermore, highest peak compared with coefficient of friction shows significant change and another correlated to B-H20 peak (due to absorbed water vapor). From Fig. 4.10, if polyimide is heated to 500 °C in a dry argon environment, it increases the glass transition temperature to 500 °C which offers low coefficient of friction in the range of 300–500 °C. In addition, a low coefficient of friction can be achieved even at 50 °C and the absorbed water vapor should be removed from the polyimide surface as shown in Fig. 4.10a, b.

The molecular relaxation in PTFE-based composite also exhibited couple of relaxations well below the ambient temperatures but not exceptional as they are at or above ambient temperature (~25 °C). Furthermore, the restriction of molecular mobility of PTFE chain for a specific region results in the low coefficient of friction. Also, the additives in the polymer composites influence the lubrication properties. Furthermore, some polymers exhibit an independent behavior to the temperature for their tribological performance.

4.7 Tribological Applications of Polymer Composites

4.7.1 Gears

The gears made of polymer composites are currently being used in light load and space applications which require high precision. These gears run against the SS or Al alloys. The stiffness and hardness with low coefficient of friction are required for these gears. Furthermore, the major challenge in the gear design is the accommodation of physical properties and tribological performance for a specific application. Also, it can be noted that this scenario limits the common polymer usages for various applications. Polyimides, polyamides (nylons), polyamide-imides, and polyacetals

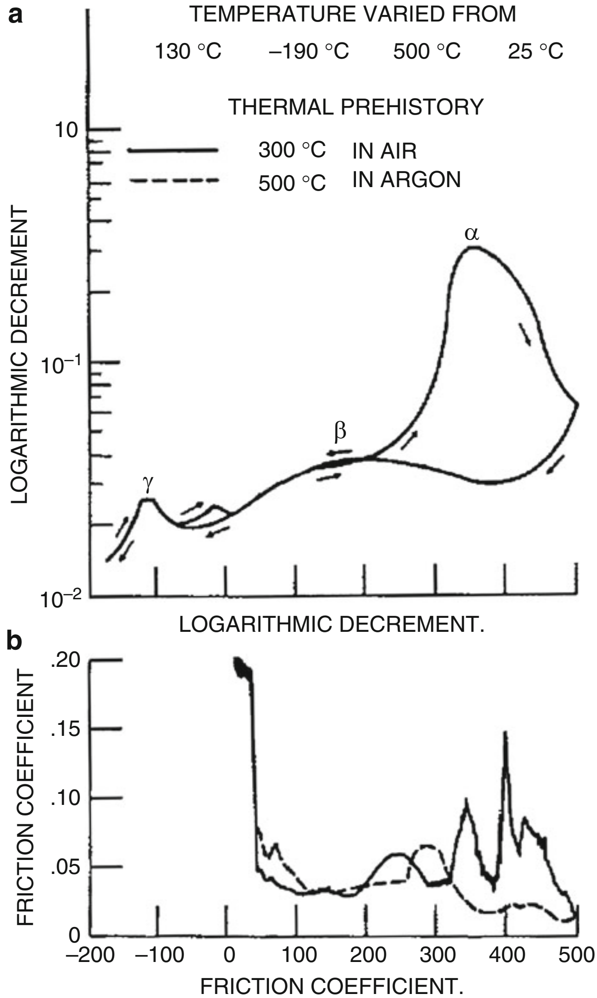


Fig. 4.10 (**a**) Logarithmic decrement comparison and (**b**) the friction coefficient variations for a polyimide film in various temperature regime [23]

are various polymers that can be used for specific applications along with PTFE. In the reinforcement, the fiber glass and MoS_2 are also considered to provide the low coefficient of friction. In addition, in some cases the polyimide with MoS_2 powder additive are being used in the space applications. This offers greater flexibility in the manufacturing and machining regimes to produce fine pitch gears. High-pressure laminate of cotton fabric and a phenolic polymer also can be utilized for the fabrication of gears with greater benefits but offers difficulty in precise manufacturing and machining process [34]. The tribological performance of certain plastic gears was established by Steven [34]. Table 4.1 illustrates the tribological performance of various types of plastic gears.

Table 4.1 Tribological response of plastic gears [34]

Test	Materials		Tooth load, N/mm	Pinion speed, rpm	Lubricant	Total pinion revs	Tooth flank wear rate, mm depth per encounter	
	Pinion	Wheels					Pinion	Wheels
1	Carbon fibre inpoly-acetal	Stain-less steel	[a]21 (60)	50	Dry	5×10^{4}	1×10^{-7}	Zero
2			21	50	Dry	3×10^{5}	7×10^{-8}	
3			21	50		5×10^{5}	7×10^{-8}	
4			21	100		7×10^{5}	2×10^{-8}	
5			21	200		16×10^{5}	5×10^{-9}	
6			21	500		30×10^{5}	5×10^{-9}	
7			21	1000		60×10^{5}	5×10^{-9}	
8			7(35)	1000		30×10^{5}	[b]3.5×10^{-9}	
9			3(23)	1000		30×10^{5}	[b]2×10^{-9}	
10			1(13)	1000		30×10^{5}	[b]1×10^{-9}	
11	Vespel SP31	Stain-less steel	21 (50)	50	Dry	5×10^{4}	1×10^{-8}	Zero
12			21	50		3×10^{5}	7×10^{-9}	
13				50		5×10^{5}	7×10^{-9}	
14				100		7×10^{5}	9×10^{-9}	
15				200		16×10^{5}	6×10^{-9}	
16				500		30×10^{5}	5×10^{-9}	
17				1000		60×10^{5}	4×10^{-9}	
18			7(30)	1000		30×10^{5}	3×10^{-9}	
19			3(20)	1000		30×10^{5}	2×10^{-9}	
20			1(10)	1000		30×10^{5}	1×10^{-9}	
21	Vespel SP8	Stain-less steel	7	200	Dry	1×10^{5}	4×10^{-8}	Zero
22				200	Dry	40×10^{5}	4×10^{-9}	
23				200	BP110	1×10^{5}	8×10^{-8}	
24				200	BP110	40×10^{5}	4×10^{-9}	

[a]Tooth contact stress in N/mm^2
[b]Steady state wear rate after running-in wear completed

Polyimide and polyacetals gears running against materials like SS, Ti, or Al for low loads exhibited superior tribological performance which was studied by European Space Tribology Lab (ESTL). In comparison, with polyimide and polyacetals, the polyimide dominates in the low wear rate even the polyacetals reinforced with carbon fiber with a maximum load of 10 N/mm tooth width.

PTFE + MoS_2 + glass fibers-based polymer composite has been studied by Vest [36] and used as retainer material for oscillating bearings. The results show that the usage of this composite performed in a significant way even after 1×10^6 cycles of testing. In addition, even after 7.6×10^7 cycles at 100 rpm the bearings are in good conditions at 7 N. Furthermore, the loading of the bearing also influences the generation of wear debris. High wear debris is observed in the unidirectional test having loading value of 23 N. This implies the poor performance in the higher loads.

PTFE-MoS_2 polymer composite as a cage material which is used in gimbal ball bearings was studied by Christy [35] who observed the potential usage since they produce uniform transfer films.

The ESA demonstrated potential usage capabilities of PTFE/glass fibers/MoS_2 composite for various bearing applications [37]. They observed that the composite exhibits superior performances, which is limited to maximum Hertzian contact stress of 1200 MN/m^2 at 20 °C. Also, they demonstrated the composite without MoS_2 and claimed that there are a lot of advantages for the usage of MoS_2 as an additive in the matrix. Some of the advantages are prevention of tick transfer which results in better performance.

The torque results of various lubricants like sputtered MoS_2, ion-plated lead, and PTFE composite cage show that the sputtered MoS_2 bearing failed (b/w 0.7 to 3.6×10^6) in certain revolutions with low torque noise. In the case of ion-plated lead and PTFE composite cage, both performed in a similar manner, but greater torque noise was observed in the ion-plated lead cage [37]. A comparison of torque properties was established for above PTFE polymer composites with various cases by Roberts [38] (Fig. 4.11). The results indicate that sputtered MoS_2 film has significant torque performances.

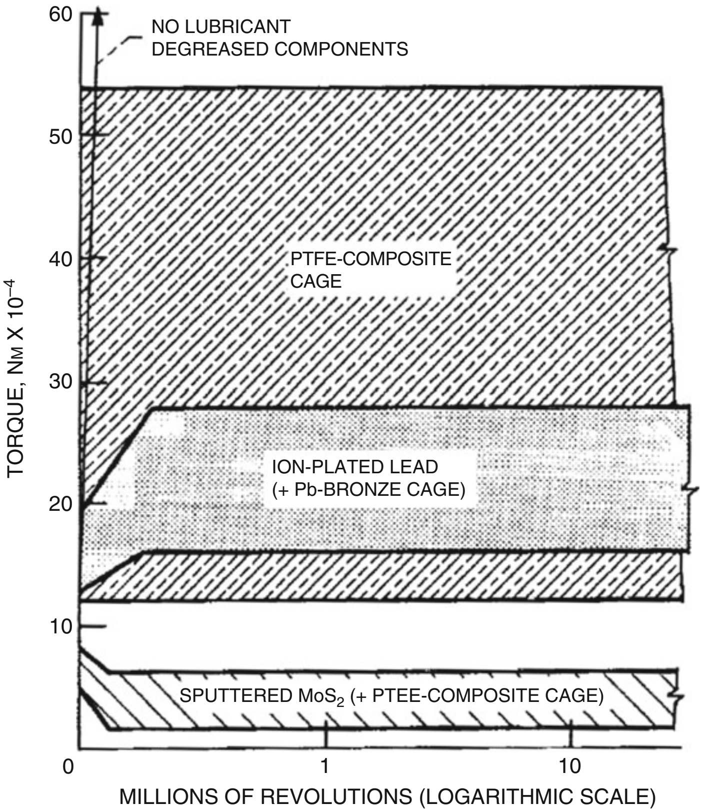


Fig. 4.11 Mean torque bands from repeated tests of solid lubricated ball bearing (ED20: 40 N preload) preload pairs in vacuum conditions [38]

4.7.2 Cryogenic Ball Bearings

The cryogenic technologies are backbone of the space missions. In which contains various electrical instruments, devices which required to be working in a cryogenic temperature [39]. Apart from the instruments and devices, it is quite important to the mechanical components and its performance in the cryogenic temperatures for various space vessels. Some of the examples are high speed turbo pumps and cryogenic engines which require bearings that are capable to produce significant performances in various harsh cryogenic environments where conventional bearings cannot adopt. In this situation the importance of solid lubricants arises.

NASA established notable research works related to the development of the self-lubricating composite materials and its usages are bearings for cryogenic environments [28, 40–45]. The turbopumps consist of several ball bearings which require thorough design considerations for better performance. For this, one has to give importance to ball race material, self-lubricating cage material, cage with superior physical and mechanical properties, and several design factors to reduce the internal heat generation.

PTFE are considered as the best lubricant for these cryogenic applications. On the other hand, PTFE offers poor strength; cold flow and poor thermal conductivity are some of the challenges. In the case of heat generation, the PTFE dominates the performances. This opens up the research opportunities to reinforce the PTFE with other additives to improve the performances in various aspects. In connection to this, an early PTFE composite formulation and its features are illustrated in Table 4.2 as bearings which serve in extreme conditions.

To study the formation and specialties transfer film form cages to bearing inner race was established through profile tracing technique. Figure 4.12 illustrates surface profile for a specific composite cage of inner-race groove of a bearing with a laminated-glass cloth with PTFE binder cage material having shaft speed, 20,000 rpm; thrust load, 200 pounds; coolant, in a hydrogen gas environment [28].

Table 4.2 Properties of PTFE formulated composite bearing cages [28]

Bearing designation	Cage material	Composition, wt%	Cage construction
A B	Laminated-glass cloth with PTFE binder	38% glass cloth laminates with 62% PTFE binder	One-piece body with riveted aluminum side plates
C D	Glass-fiber-molybdenum disulfide filled PTFE	15% glass fibers, 5% molybdenum disulfide, 80% PTFE	One piece body with no external support
E F	Glass-fiber-filled PTFE	15–20% glass fibers, balance PTFE	One-piece body with one-piece riveted aluminum shroud
G H	Bronze-filled PTFE	30% bronze powder, 70% PTFE	One-piece body with no external support

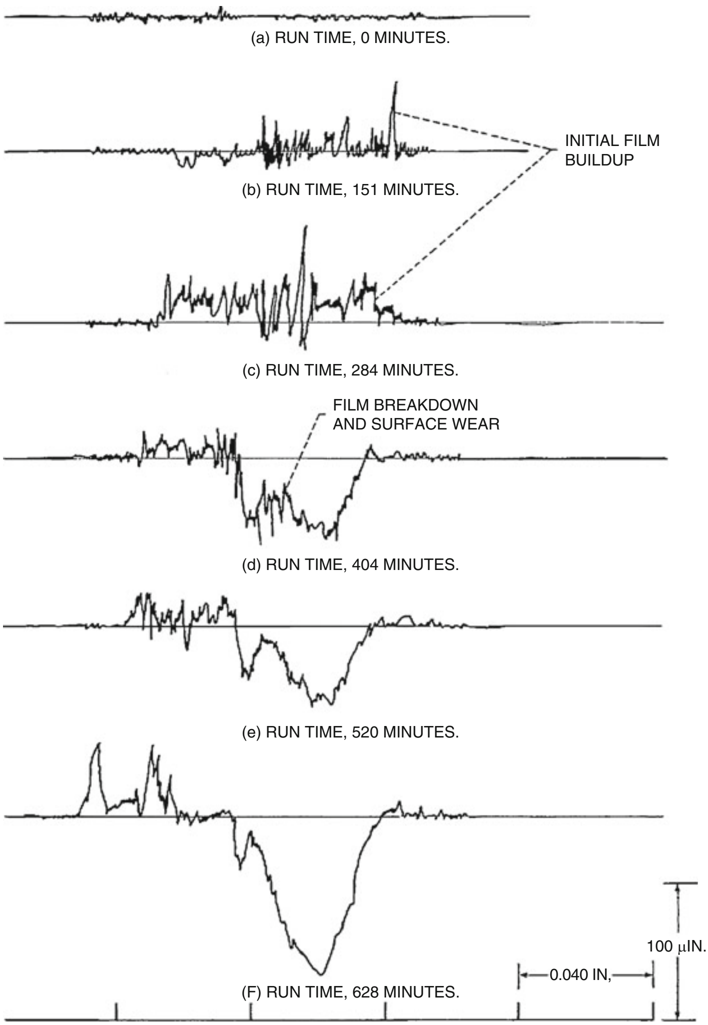


Fig. 4.12 Progressive profile traces of inner-race groove of bearing a with a laminated-glass cloth with PTFE binder cage material [28]

A considerable deposition film was observed after 284 min in the inner race along with scratches formed by abrasive action of glass-fibers in the cage material. This trend breaks down as continuous running progress and finally results in an increase in the wear. After 10 h the bearing progress to a failure. This may be due to the breakdown of the film and subsequent increase in the abrasive action (Fig. 4.13) which indicates alternate layers of glass cloth and PTFE in which soft PTFE worn in a short period of time and then exposed to the glass fiber and eventually fragmented and submerged into the transferred PTFE film. This catalyzed the abrasive action which soon influences the breakdown of the transfer film and increases the wear rates.

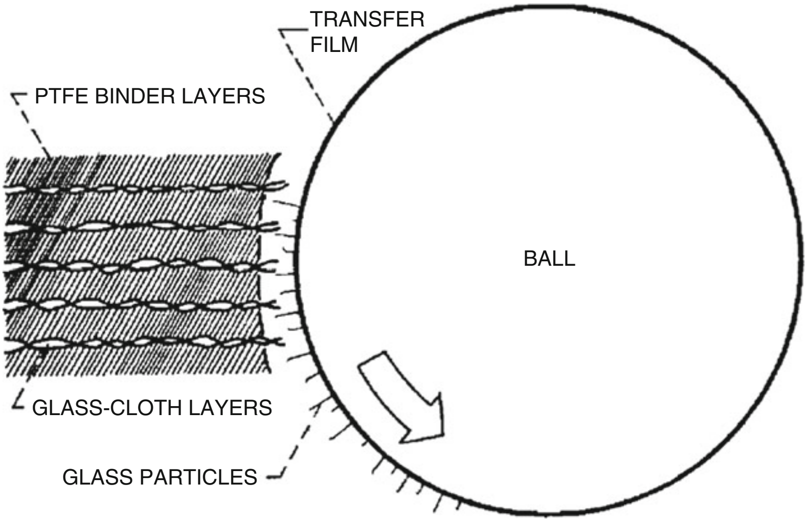


Fig. 4.13 Progress of PTFE binder retainer wear of ball bearing [28]

In general, PTFE composites exhibit better lubrication performance but limited to a period of 10 hrs. Figure 4.14 illustrates the percentage weight loss for all four types of PTFE and the results show that all four have significantly low weight loss. Among those the bronze cage exhibited maximum than the others.

The performance of PTFE composite retainer material was experimentally evaluated by Cunningham and Anderson [43]. The radial load varies from 450 to 2700 N with a speed up to 30,000 rpm. This test has been done in 40-mm-bore ball bearings. The results show that laminated glass cloth-PTFE binder provides better wear resistance among the three PTFE composites (Fig. 4.15). Also, these materials showed better performance in liquid hydrogen pumps rather than in liquid oxygen pumps. In liquid oxygen pumps the laminated glass cloth-PTFE as a cage material exhibits excessive wear and is to be reconsidered for space shuttle main engine applications [46, 47].

4.7.3 Pin Joint Applications

The pin joints are used to establish the articulated motions. The reliability of these joints is to be improved carefully. One such study was conducted by Zhu et al. [48]. The PEEK and its composites (reinforced with 30 wt% carbon fiber, 30 wt% glass fiber, and 10 wt% carbon fiber, 10 wt% graphite and 10 wt% PTFE) were considered for their studies. Figure 4.16 shows the variation of coefficient of friction for different materials. It was observed that for lower and higher loads the composite C (10 wt% carbon fiber, 10 wt% graphite, and 10 wt% PTFE reinforced with PEEK) shows better performance than PEEK and other composites. However, the

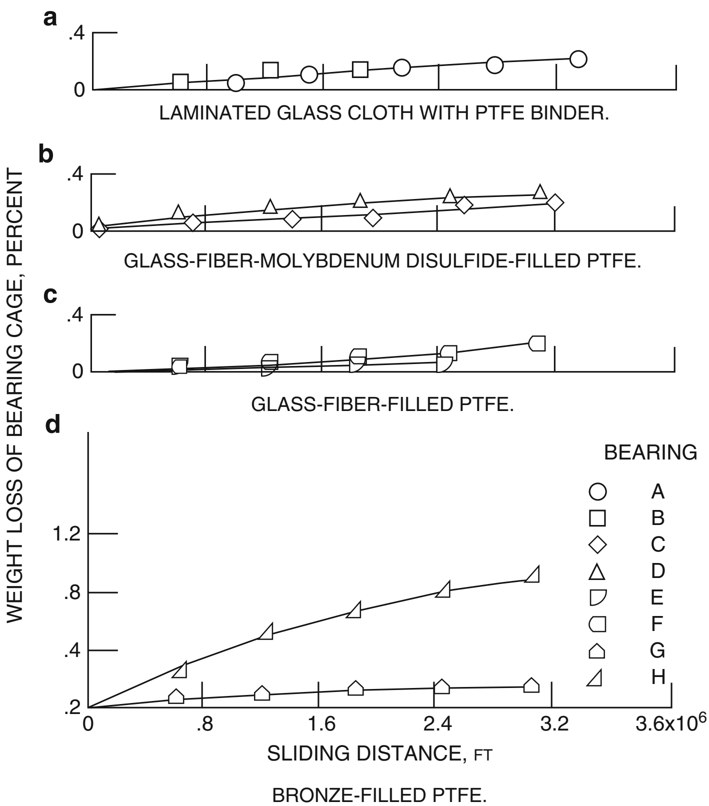


Fig. 4.14 Bearing cage weight loss versus sliding at specific condition for (**a**) laminated glass cloth-PTFE binder, (**b**) glass-fiber-molybdenum disulfide filled PTFE, (**c**) glass-fiber-filled PTFE, and (**d**) bronze-filled PTFE [28]

coefficient of friction for composite B (30 wt% glass fiber) was observed to be increased as the normal load increases.

Recently, PEEK composites utilized as bush materials for articulating revolute pin joints were investigated by Zhu et al. [49]. It was observed that the PEEK-based composite material formulated by PTFE, graphite, and carbon fiber shows better performance than other composites.

4.8 Concluding Remarks

An overview of self-lubricating polymer composites was demonstrated with information related to their influencing factors, tribological properties, and film transfers. Furthermore, environmental conditions also have significant role in tribological properties. Especially a distinct performance was observed in air and vacuum environments. The extreme testing resulted in a good understanding of the influences

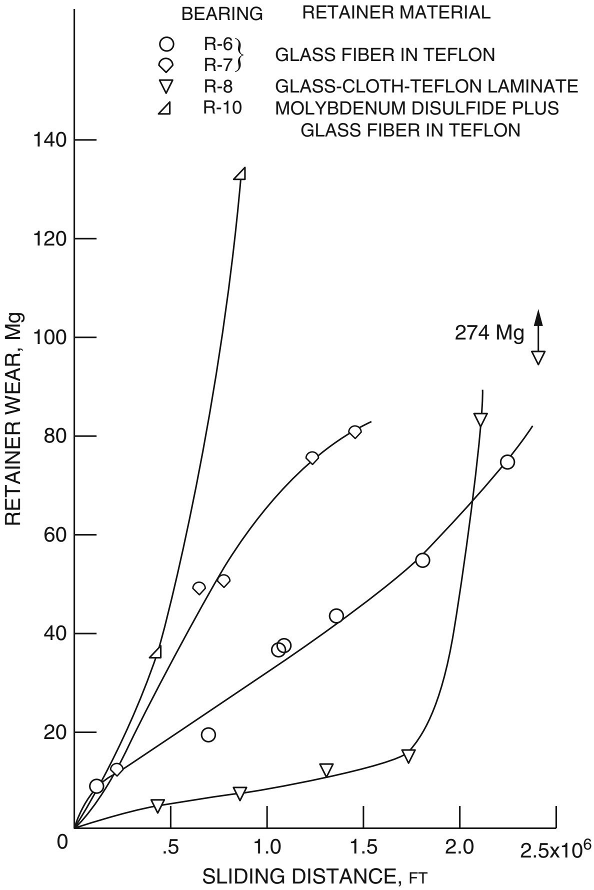


Fig. 4.15 Bearing cage weight loss as a function of sliding distance at specific conditions [45]

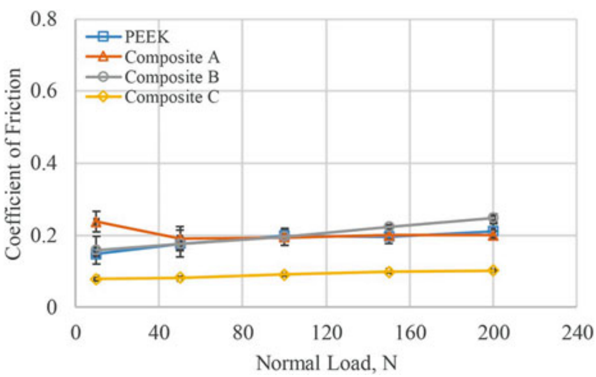


Fig. 4.16 Variation of coefficient of friction vs normal load for various materials [48]

of various parameters. It is noted that the behavior of the solid lubricants may vary for different conditions. The performances of end use devices in real time also may exhibit variable performances as compared with a controlled testing condition. Rigorous and extended research is required to understand the behavior of polymer composites in various environments for a specific application. It is important to extract the superior properties of various polymers and polymer composites for wide range of applications, which are still in a progressive path, and there are special factors that significantly influence the performance of the designed components, especially the transfer film mechanisms and its features, loading, and environmental conditions. A good self-lubricating polymer composite must have significant tribological, mechanical, and thermal properties.

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