Abrasion Resistance Handbook
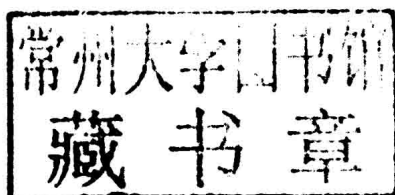
Adam Garcia

Abrasion Resistance Handbook

Edited by **Adam Garcia**

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P R E S S

New York

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Preface

This book provides a descriptive account based on the abrasion resistance of materials and educates the readers with up-to-date in-depth information. Researchers and scientists from across the planet have contributed valuable data and information in this all-inclusive book. It elucidates the abrasion resistance of polymer nanocomposites, high performance fabrics, cement-based composites, rubber, etc. It also discusses the numerical simulation of abrasion of particles. The aim of this book is to serve as a valuable source of reference for readers including researchers, students and even scientists.

This book unites the global concepts and researches in an organized manner for a comprehensive understanding of the subject. It is a ripe text for all researchers, students, scientists or anyone else who is interested in acquiring a better knowledge of this dynamic field.

I extend my sincere thanks to the contributors for such eloquent research chapters. Finally, I thank my family for being a source of support and help.

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Editor

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Abrasion Resistance of Polymer Nanocomposites – A Review

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1. Introduction

In order to be suitable for tribological applications, polymeric materials, which can usually exhibit mechanical strength, lightness, ease of processing, versatility and low cost, together with acceptable thermal and environmental resistances, have to show good abrasion and wear resistance. This target is not easy to achieve, since the viscoelasticity of polymeric materials makes the analysis of the tribological features and the processes involved in such phenomena quite complicated.

Indeed, it is well-known that an improvement of the mechanical properties can be effectively achieved by including "small" inorganic particles in the polymer matrices (Dasari et al., 2009).

For applications taking place in hard working conditions, such as slide bearings, the development of composite materials, which possess a high stiffness, toughness and wear resistance, becomes crucial. On the one hand, the extent of the reinforcing effect depends on the properties of composite components, and on the other hand it is strongly affected by the microstructure represented by the filler size, shape, homogeneity of distribution/dispersion of the particles within the polymer, and filler/matrix interface extension. This latter plays a critical role, since the composite material derives from a combination of properties, which cannot be achieved by either the components alone.

Thus it is generally expected that the characteristics of a polymer, added of a certain volume fraction of particles having a certain specific surface area, are more strongly influenced when very small particles (*nanofillers*), promoting an increased interface within the bulk polymer, are used (Bahadur, 2000; Chen et al., 2003; Karger-Kocsis & Zhang, 2005; Li et al., 2001; Sawyer et al., 2003). However, this happens only when a high dispersion efficiency of the nanoparticles within the polymer matrix is assessed: indeed, nanoparticles usually tend to agglomerate because of their high specific surface area, due the adhesive interactions derived from the surface energy of the material. In particular, the smaller the size of the nanoparticles, the more difficult the breaking down of such agglomerates appears, so that their homogeneous distribution within the polymer matrix is compromised.

As a consequence, the development of nanocomposites showing high tribological features requires a deep investigation on their micro-to-nanostructure, aiming to find synergistic mechanisms and reinforcement effects exerted by the nanofillers (Burris et al., 2007).

In addition, the way in which nanofillers can improve the tribological properties of polymers depends on the requirement profile of the particular application, i.e. the friction coefficient and the wear resistance cannot be considered as real material properties, since they depend on the systems in which these materials have to function.

In particular, such applications as brake pads or clutches usually require a high friction coefficient and, at the same time, a low wear resistance; however, in other circumstances (like in the case of gears or bearings, acting as smooth metallic counterparts under dry sliding conditions) the development of polymer composites having low friction and wear properties is strongly needed.

The abrasion performances of polymeric materials depend on several factors, such as the wear mechanisms involved, the abrasive test method used, the bulk and surface properties of the tested specimens, ...

Many papers reported in the literature focus on the investigation on the physical processes involved in abrasive wear of a wide variety of polymers; the obtained results demonstrate that two very different mechanisms of wear may occur in polymers, namely cohesive and interfacial wear processes, as schematically shown in Figure 1.
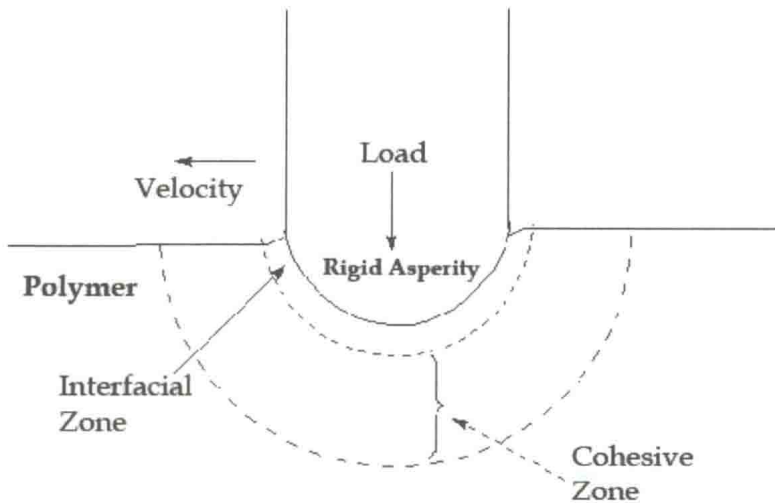
Fig. 1. Schematic representation of cohesive and interfacial wear processes (Adapted from Briscoe & Sinha, 2002)

In the cohesive wear processes, such as abrasion wear, fatigue wear and fretting, which mainly depend on the mechanical properties of the interacting materials, the frictional work involves quite large volumes close to the interface, either exploiting the interaction of surface forces and the consequent traction stresses or through the geometric interlocking exerted by the interpenetrating contacts. Contact stresses and contact geometry represent two key parameters that determine the extent of such surface zone.

On the other hand, the frictional work in interfacial wear processes (like transfer wear, chemical or corrosive wear) is dissipated in much thinner zones and at greater energy

density with respect to cohesive wear processes, so that a significant increase in local temperature occurs. Furthermore, the extent of wear damage can be substantially ascribed to the chemistry of the surfaces involved, rather than to the mechanical properties of the interacting materials.

As far as cohesive processes are concerned, *abrasion wear*, which is the most common type of wear encountered in polymer composites, can be divided into two-body and three-body abrasion wear. The former occurs in the presence of hard asperities that plough and induce plastic deformation or fracture of the softer asperities.

The latter relates to the presence of hard abrasive particles or wear debris in between the sliding bodies: such particles or debris derive from environmental contaminants or can be the consequence of two-body abrasion processes. In general abrasion wear depends on several factors, such as the hardness of the materials in contact, the applied load and sliding distance and the geometry of the abrasive particles as well.

Fatigue wear derives from surface fatigue phenomena, i.e. from the repeated stressing and un-stressing of the contacts, and can lead to fracture through the accumulation of irreversible changes, which determine the generation, growth and propagation of cracks. This kind of wear may also occur together with *delamination wear*, where shear deformations of the softer surface, caused by traction of the harder asperities, promote the nucleation and coalescence of subsurface cracks. As a consequence, the delamination (i.e. detachment) of fragments having larger size occurs.

Fretting wear is caused by relative oscillatory motions of small amplitude taking place between two surfaces in contact. The produced wear fragments can either escape from between the surfaces, thus promoting a fit loss between the surfaces and a decrease of clamping pressure, which may lead to higher vibration effects, or remain within the sliding surfaces, so that pressure increases and seizure eventually occurs.

Transfer wear belongs to interfacial wear processes and involves the formation of a transfer film (solid or liquid, depending on the interfacial temperature) in polymer-metal, polymer-ceramic, polymer-polymer sliding contacts. Such film invariably transfers from polymer to metal or ceramic, whereas the direction of transfer is not obvious in the case of polymer-polymer sliding contacts.

Several parameters can influence the formation of the transfer film and its role on the subsequent wear processes: thickness and stability of the film, cohesion features between the transfer layers, adhesion forces between the film and the sliding counterpart, chemical reactivity and surface roughness of the counterface slider, polymer structure (crystallinity, flexibility, presence of pendant groups or side chains, ...), adopted sliding conditions (temperature, normal load, velocity, atmosphere, ...) and presence of fillers.

Chemical wear involves a chemical reaction (oxidation, degradation, hydrolysis, ..., which lead to polymer chain scission with the subsequent MW decrease) in between the sliding bodies or a material in itself or a material with the surrounding environment.

A schematic representation of the basic tribological interactions leading to wear particle generation is depicted in Figure 2.
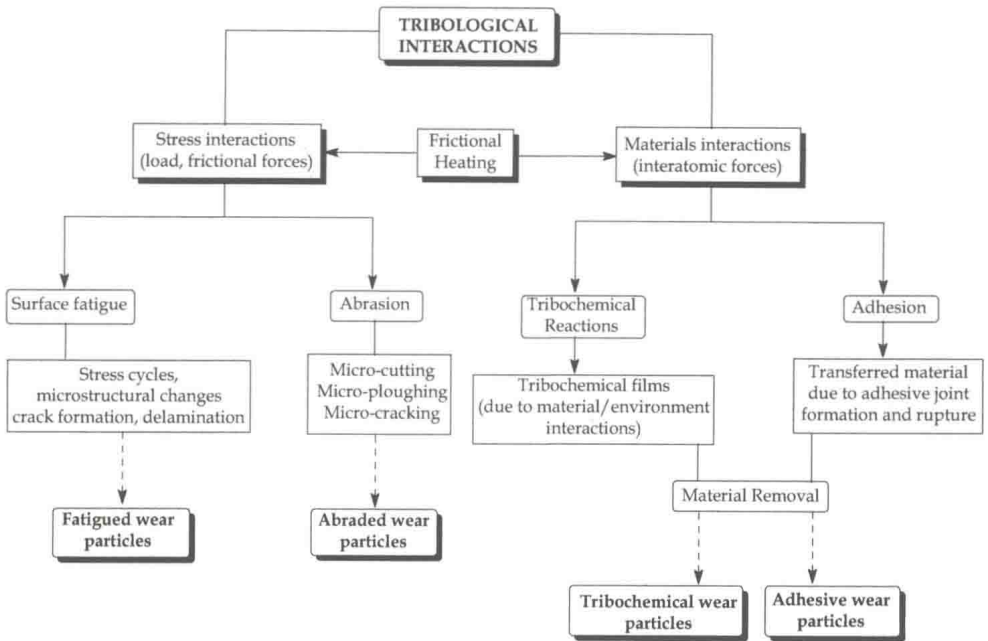
Fig. 2. Different wear processes leading to the formation of material particles (adapted from Czichos, 2001)

It is worthy to note that the wear mechanisms in polymer systems described above for macro- and micro-levels are quite different from those encountered at nano-level.

First of all, nano-level involves very low applied loads (from μN to nN); in addition, the wear particle generation is negligible and the original surface topography is more likely to be preserved for an extended period because of the adopted low wear rate.

Other differences concern the friction forces involved at the nano-level, since the ploughing factor and the inertial effect of the moving components are different, as well as the role exerted by surface forces (adhesion and electrostatic interactions), which become very important.

In the following paragraphs, a review on the recent studies on the tribological behavior of thermoplastic nanocomposites is presented. The role of the structure of the nanofillers and of their morphology (aspect ratio, effectiveness of dispersion within the polymer, ...) and the possible interactions with the environment are widely discussed.

2. Tribology of thermoplastic nanocomposites

2.1 PEEK-based nanocomposites

Poly(ether ether ketone) (PEEK) is a high performance injection mouldable thermoplastic that can be widely used for many applications that require high mechanical strength and an outstanding thermo-mechanical stability.

This polymer has a high glass transition temperature (Tg≈143°C) and a high melting point (Tg≈343°C) and it is also regarded as one of the most promising polymer materials for tribological applications in aqueous environments.

Nevertheless, it seems that neat PEEK exhibits relatively poor wear resistance with water lubrication in some cases, so that different types of fillers (and nanofillers) have been incorporated into this polymer, aiming to facilitate more applications by enhancing its anti-wear features. In particular, short carbon fibers (SCFs) are currently used in PEEK-based composites for improving its wear resistance, even at elevated temperatures and under aqueous conditions (water lubrication).

Very recently, Zhong investigated the tribological properties of PEEK/SCF/zirconia composites under aqueous conditions, using a three-pin-on-disc configuration (Zhong et al., 2011). A synergistic effect of SCFs with zirconia nanoparticles was assessed: indeed, the composites showed excellent wear resistance under aqueous conditions; SCFs were found to carry the main load between the contact surfaces and to protect the polymer matrix from further severe abrasion of the counterpart. Nano-ZrO_2 efficiently inhibited SCF failure either by reducing the stress concentration on the CF interface through reinforcement of the matrix or by lowering the shear stress between the sliding surfaces via a positive rolling effect of the nanoparticles between the material pairs.

Werner et al. investigated the influence of vapour-grown carbon nanofibres (CNFs) on the wear behaviour of PEEK (Werner et al., 2004). To this aim, unidirectional sliding tests against two different counterpart materials (100Cr6 martensitic bearing steel and X5CrNi18-10 austenitic stainless steel) were performed on injection moulded PEEK-CNF nanocomposites. CNFs were found to reduce the wear rate of PEEK very significantly, as compared to a variety of commercial PEEK grades. This behaviour was attributed to CNFs, which act as solid lubricants; in addition, the roughening effect on the counterpart exerted by CNFs, because of their small size, was minimised with respect to conventional fibre fillers (carbon fibres, PAN-based carbon fibres, glass fibres).

McCook and coworkers investigated the role of different micro and nanofillers on the tribological properties of PEEK in dry sliding tests against 440C stainless steel counterfaces (McCook et al., 2007). To this aim, microcrystalline graphite, carbon nano-onions, single-walled carbon nanotubes, C60 carbon fullerenes, microcrystalline WS_2, WS_2 fullerenes, alumina nanoparticles and PTFE nanoparticles were jet-milled with PEEK and the friction coefficients and wear rates of the obtained composites were measured in open laboratory air (45% R.H.) and in a dry nitrogen environment (less than 0.5% R.H.).

Both wear rate and friction coefficient were reduced in the dry nitrogen environment: in particular, the more wear resistant coatings also had lower friction coefficients. On the contrary, in open air environments the more wear resistant coating exhibited the higher friction coefficients. Furthermore, the polymeric nanocomposites investigated showed similar environmental responses, regardless of the type of micro or nanofillers used.

Hou and coworkers performed tribological ball-on-flat sliding wear tests on PEEK-based nanocomposites incorporating inorganic fullerene-like tungsten disulfide nanoparticles (Hou et al., 2008). The friction coefficient was found to decrease about 3 times in the presence of 2.5 wt.% nanoparticles, with respect to the neat PEEK: this behaviour was attributed to the lubricating capability of the nanofillers.

Zhang et al. investigated the effect of nano-silica particles on the tribological behaviour of PEEK: silica nanoparticles were compounded with the polymer by means of a ball milling technique (Zhang et al., 2008). The wear resistance of PEEK was significantly improved after incorporating nano-SiO_2 and at a rather low filler loading (1 vol.%), the composites showed the optimum wear resistance, which was ascribed to the reduced perpendicular deformation of PEEK matrix and to the decreased tangential plastic flow of the surface layer involved in friction processes. Furthermore, the nanocomposites evidenced much smoother surfaces with respect to neat PEEK.

Pursuing this research, the role of the same nano-silica particles on the tribological behaviour of SCF-reinforced PEEK was also investigated (Zhang et al., 2009). To this aim, 1 vol.% (1.51 wt.%) nano-SiO_2 particles were compounded with SCF/PTFE/graphite filled PEEK in a Brabender mixer; the obtained composite materials were tested using a block-on-ring apparatus at room temperature (counterpart: 100Cr6 steel ring), in extremely wide pressure and sliding velocity ranges. Under all the conditions investigated, nano-SiO_2 particles remarkably reduced the friction coefficients; above 2 MPa pressures, the nanoparticles were found to reduce the wear rate: this behaviour was attributed to a protection effect of SCF/PEEK interface exerted by the nanoparticles, which are able to reduce the stress concentration on SCFs taking place in the surface layer involved into friction.

Zhang also investigated the effect of different amounts of nano-silica particles on the tribological behavior of SCF-reinforced PEEK composites. The nanoparticle loading was varied from 1 to 4 vol.% (Zhang et al., 2009).

The variation of nanoparticle content from 1 to 4 vol.% did not significantly affect the friction coefficients of the nanocomposites; in addition, operating with low pressure-sliding velocity (pv) factors, the nanoparticles turned out to worsen the wear rate of the composites, because of the abrasion on SCFs exerted by nanoparticle agglomerates. On the contrary, with a high pv factor, such agglomerates were crushed into tiny ones, so that nano-silica particles were capable to protect SCFs reducing their failures. Similar wear rates were found for the nanocomposites tested at very high pv factors.

2.2 Polyolefin-based nanocomposites

Thermoplastic polyolefins like poly(ethylene)s (PEs) and poly(propylene) (PP) are well-established polymers available at the market, each having a different structure and very different behaviour, performances and applications (Feldman & Barbalata, 1996). Several papers deal with their tribological properties, in the presence of different types of nanofillers.

High density poly(ethylene) (HDPE) was used as matrix for preparing nanosilica coatings, the wear resistance of which was measured using a rotative drum abrader (Barus et al., 2009). It was found that this parameter, despite a significant increase in the mechanical properties of the nanocomposites (stiffness, yield strength and fracture toughness), exhibited lower values with respect to the neat polymer.

Johnson and coworkers manufactured and tested the wear behaviour of HDPE/multi-walled-carbon-nanotubes composites (Johnson et al., 2009). Different weight percentages of

nanotubes (1, 3 and 5%) were used for preparing the samples, which were tested on a block-on-ring apparatus. Wear resistance and frictional properties of HDPE were found to improve in the presence of the nanofillers; furthermore, the addition of multi-walled-carbon-nanotubes to HDPE turned out to bring wear rates down to the level seen in ultra-high molecular weight poly(ethylene) (UHMWPE).

The effect of the presence of Alumina nanoparticles (5 wt.%) was exploited for investigating the abrasion resistance of low-density poly(ethylene) (LDPE)-based nanocomposites (Malucelli et al., 2010). The abrasion resistance of the nanocomposites increased in the presence of the nanofillers, as indicated by the decrease of the Taber Wear Index with respect to the neat polymer.

Very recently, Xiong and coworkers investigated the effect of the presence of nano-hydroxyapatite (nano-HAP) on the tribological properties of non-irradiated and irradiated UHMWPE composites, prepared by using a vacuum hot-pressing method (Xiong et al., 2011). The friction coefficients and wear rates were measured by using a reciprocating tribometer (counterface: CoCr alloy plates). The presence of 7 wt.% nano-HAP in the polymer matrix resulted in lowering both the friction coefficients and wear rate, irrespective of using irradiated or non-irradiated samples, whereas filling 1 wt.% nano-HAP reduced friction coefficients and wear rate of the non-irradiated UHMWPE only.

Misra and coworkers investigated the tribological behaviour of polyhedral oligomeric silsesquioxanes (POSS)/poly(propylene) nanocomposites (Misra et al., 2007). The relative friction coefficient of the samples turned out to strongly decrease from 0.17 for neat PP to 0.07 for the nanocomposite containing 10 wt.% POSS: this behaviour was ascribed to the increase of the surface hardness and of the modulus, due to the presence of the nanofiller.

2.3 Fluorinated-based nanocomposites

Fluorinated polymers usually exhibit many desirable tribological features, including low friction, high melting temperature and chemical inertness. However, their anti-wear applications have been somewhat limited by their poor wear resistance, which has led to the failure of anti-wear components and films.

Therefore, many researchers have tried to reinforce fluorinated polymers using different fillers, such as glass fibres, carbon fibres, ceramic powders, non-ferrous metallic powders: unfortunately, these fillers induced a large frictional coefficient and abrasion. Quite recently, nanometer size inorganic powders have been chosen as fillers capable to enhance the wear behaviour of fluorinated polymers.

Poly(tetrafluoroethylene), PTFE, is the most common fluorinated polymer used for tribological purposes.

Lee and coworkers added carbon-based nanoparticles, synthesized by heat treatment of nanodiamonds, to PTFE, in order to prepare fluorinated nanocomposites (Lee et al., 2007). The wear resistance, measured through ball-on-plate wear tests, was found to depend on the heat treatment, which nanodiamonds were subjected to: in particular, wear resistance turned out to increase when nanodiamonds were heated at 1000°C. Beyond this temperature, carbon nanoparticles became aggregated and therefore the wear coefficient of

the obtained nanocomposites increased: this failure in the wear behaviour was ascribed to the formation of carbon onions that promoted the aggregation of carbon nanoparticles.

Single-walled carbon nanotubes have been exploited for lowering the wear rates of PTFE (Vail et al., 2009). A linear reciprocating tribometer was exploited for performing the tests (counterface: 304 stainless steel) on nanocomposite samples containing up to 15 wt.% nanotubes. The obtained results clearly indicated that, in the presence of low nanofiller loadings (5 wt.%), PTFE wear resistance is improved by more than 2000% and friction coefficient increased by ≈50%.

Shi and coworkers have studied the effect of various filler loadings (from 0.1 to 3 wt.%) on the tribological properties of carbon-nanofiber (CNF)-filled PTFE composites (Shi et al., 2007). The friction and wear tests were conducted on a ring-on-ring friction and wear tester. The counterface materials was steel 45.

The obtained results showed that the friction coefficients of the PTFE composites decreased initially up to a 0.5 wt.% filler concentration (during sliding, the released CNFs transfer from the composite to the interface between the mating surfaces, acting as spacers and thus preventing direct contact between the two surfaces and lowering the friction coefficient) and then increased, whereas the anti-wear properties of the materials increased by 1-2 orders of magnitude in comparison with those of PTFE. Finally, the composite having 2 wt.% of CNFs exhibited the best anti-wear properties under all the experimental friction conditions.

The tribological investigation on fluorinated polymers has been also extended to PTFE-based blends, as described by Wang and coworkers (Wang et al., 2006). In particular, Xylan 1810/D1864, a commercially available PTFE blend for dry lubricant and corrosion resistant coatings, has been blended with alumina nanoparticles at different loadings (from 5 to 20 wt.%). The wear resistance was measured using a Taber Abrasion Tester and was found to decrease with increasing the content of the embedded alumina nanoparticles in the polymer matrix. The minimum wear rate was achieved when the nanoparticle loading was 20 wt.%.

Another paper from Burris and Sawyer reports on the role of irregular shaped alumina nanoparticles on the wear resistance of Al_2O_3/PTFE nanocomposites (Burris & Sawyer, 2006). A reciprocating pin-on-disc tribometer was used for testing the wear and friction of the samples (counterface: AISI 304 stainless steel plates). It was found that the inclusion of irregular shaped alumina particles is more effective in reducing PTFE wear than spherical shaped particles (the wear resistance of PTFE was increased 3000x in the presence of 1 wt.% former nanofiller), but also determines an increased friction coefficient.

Another fluorinated polymer, namely poly(vinylidene fluoride), was used as matrix for preparing nanocomposites containing a phyllosilicate (organoclay) by Peng and coworkers (Peng et al., 2009). The friction and wear tests were conducted on different loaded nanocomposites (clay content: 1 - 5 wt.%), using a block-on-ring wear tester (mated ring specimen: carbon steel 45, GB 699-88). The nanoclay at 1-2 wt.% turned out to be effective for improving the tribological properties of neat PVDF, since such filler may act as a reinforcement to bore load and thus decrease the plastic deformation.

Tribological studies were also performed on PTFE-based fabric composites (Sun et al., 2008; Zhang et al., 2009). In particular, Sun and coworkers prepared polyester fabric composites, in order to study the influence of alumina nanoparticles and PTFE micro-powders