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Modern Polymer Composites for Friction and Wear Applications

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In numerous friction and wear applications, the use of polymers and polymer composites has become state of the art. Nevertheless, further developments are still under way to explore new fields of application for these materials and to tailor their properties for more extreme loading conditions. It is the objective of this paper to describe how to design polymeric composites in order to operate under low friction and low wear against various counterparts. Particular emphasis is focused on special fillers (including spherical nanoparticles), often in combination with classical tribo-fillers (such as carbon fibers, graphite flakes, polytetrafluoroethylene particles), for the tribological improvement of thermoplastics and thermosets. A set of practical examples demonstrates how these different fillers act in concert.

Key Words: Friction, Wear, Polymers, Composites, Nanoparticles, Applications

1. Introduction

In the past, many research papers on polymer composites have concentrated on their mechanical property profile, i.e. their strength, stiffness and toughness characteristics [1,2], or their long term behavior, such as fatigue crack propagation or creep resistance [3,4]. Little has yet been published, however, on how the various types of reinforcements influence secondary properties, as for example the composites' friction and wear behavior, although it has been shown that fiber reinforced thermoplastics and thermosets are often used as gears, rollers, and dry slide bearings (Figure 1).

Thermosetting resin based composites, and especially those with continuous carbon fibers, can give better service (e.g. lower wear rates, higher strength) than those with thermoplastic matrices and short-fiber reinforcements when sliding against metals under severe conditions [5,6]. This is because the high fiber contents attainable with thermosetting composites and the preferential load-bearing by the fibers ensures that their tribological properties are mainly determined by those of the reinforcements. However, the majority of friction and wear loaded components are made of discontinuous reinforced polymer systems [7], since they allow more complex geometries and a better tailoring of their tribological characteristics for a particular application (Figure 2).

The requirement profile of the particular application determines how the materials must exactly be designed. That means coefficient of friction and wear resistance are no real material properties, but system properties, i.e. they depend on the system in which these materials have to function. Quite often sliding is the dominant wear mode, and the materials must be designed for low friction and low wear against smooth metallic counterparts (e.g. as gears or bearings), but sometimes also a high coefficient of friction, coupled with low wear, is required (e.g. for brake pads or clutches).

Fig. 1. Polymer coatings and composite parts used in sliding wear applications; the circled components are discussed in more detail later

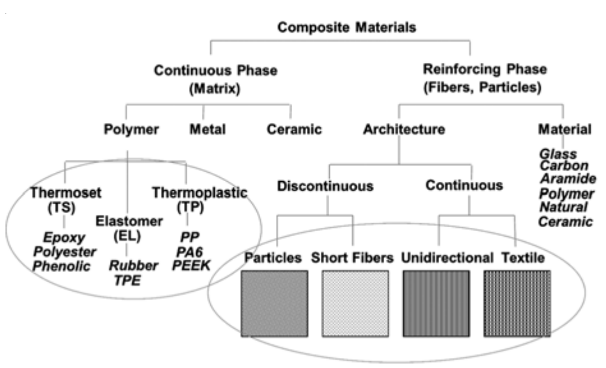

Fig. 2. Systematic illustration of polymer composites used in tribology (circles).

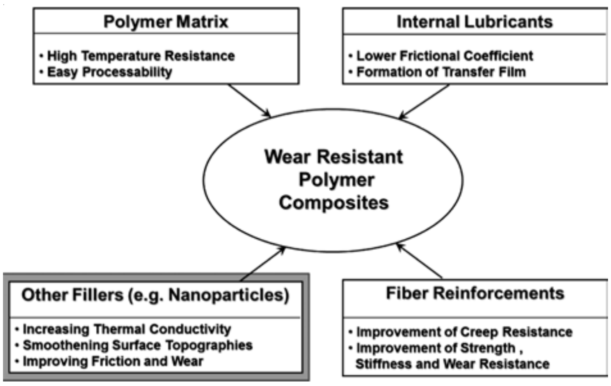

Fig. 3. How to design polymer composite for high sliding wear resistance

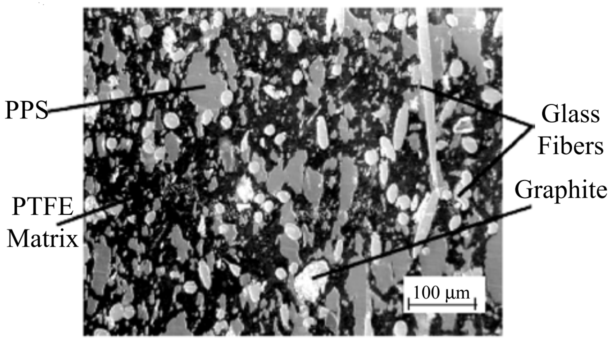

Fig. 4. Typical microstructure of a high temperature resistant polytetrafluoroethylene (PTFE), filled with polyphenylenesulfide (PPS) particles, graphite flakes, and reinforced with short glass fibers [15]

The present paper has the objective to illustrate how polymer based composites can be tailored for friction and wear loading situations, and to show that for future applications the combined interaction between classical tribo-fillers and newly developed nano-reinforcements can provide promising solutions.

2. Basic Components for Wear Resistant Polymer Composites

It is well known that the friction and wear behavior of polymeric materials can be improved by a lower adhesion and a higher stiffness and strength [7-9]. This can be achieved quite successfully by using special fillers. To reduce the adhesion, e.g., internal lubricants, such as PTFE or graphite are frequently incorporated. They also allow the formation of a friction reducing transfer film on the surface of the counterpart material [10]. Continuous or short aramid, carbon or glass fibers are used to increase the stiffness and strength of the polymer system. Since friction between two mating surfaces in sliding contact generates heat, which in turn enhances the temperature in the contact area (associated with a reduction in the mechanical properties of the polymer), from the matrix point of view, a high temperature resistant polymer should be used. In addition, the tribological properties of polymers and polymer composites can be changed by the use of other thermally conductive fillers, including nano-sized particles or carbon nanotubes (dark surrounded field in Figure 3). This has been demonstrated by many authors, of which only a few can be listed here (e.g. [11-14]). However, often the optimum effects for reducing both, the coefficient of friction and the wear rate, can only be achieved if the nano-fillers are used in combination with some of the traditional tribo-fillers mentioned above .This finally leads to a complex microstructure of the composite materials, as for example illustrated in Figure 4 [15].

Laboratory sliding wear tests of these materials are usually carried out (without any external lubrication) on different testing machines, e.g. pin-on-disc [16]. The measured data allow to determine the coefficient of friction μ and the specific wear rate w_s by the following equations:

$$\mu = F_R / F_N, \quad (1)$$

where: F_R = friction force; F_N = normal load.

$$w_s = \Delta m/(d\, F_N\, L) = \Delta V/(F_N L), \quad (2)$$

usually in the dimensions {$mm^3/(Nm)$}, where: Δm = mass loss; d = density of the composite material; ΔV = volume loss; L = sliding distance.

The specific wear rate, mentioned above (also called "wear factor" of the material, k*), can be considered as a kind of "material property", which allows to compare different materials with each other (when tested under equivalent system conditions).

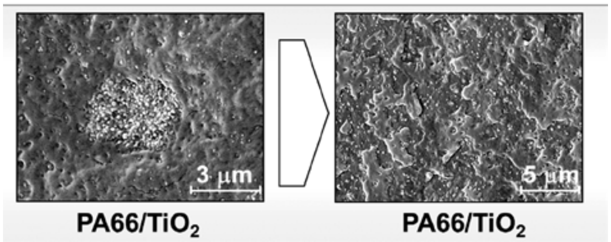

Fig. 5. Objective: transfer of a TiO_2 agglomerate (left) into well dispersed TiO_2- nanoparticles (right)

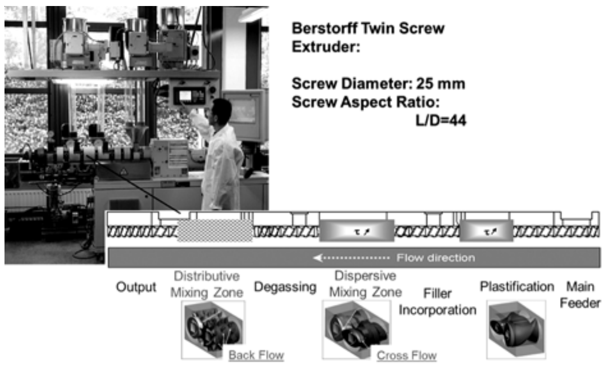

Fig. 6. Various zones and screw elements for breaking-up nano-particle agglomerates in a twin –screw extruder and for distributing them uniformly in a thermoplastic matrix [17]

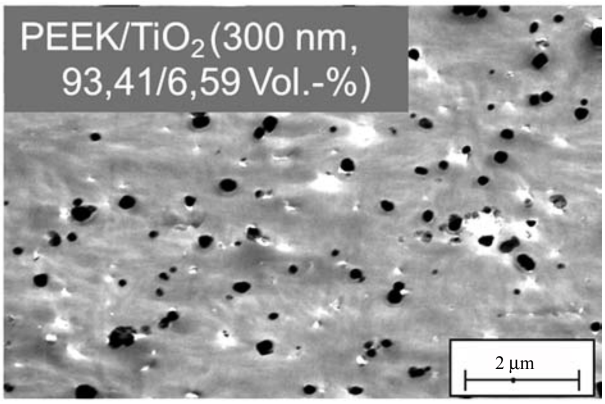

Fig. 7. Homogeneous and agglomerate-free distribution of 7 vol.% TiO_2- nanoparticles (300 nm diameter) in PEEK [17]

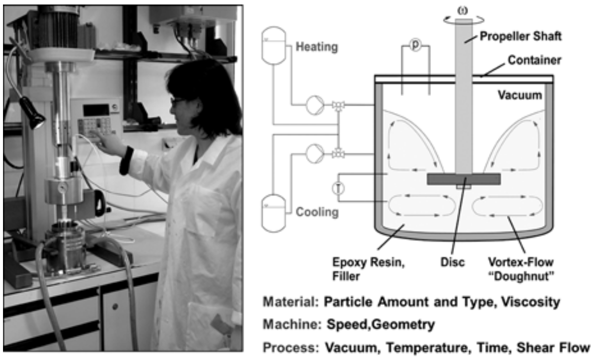

Fig. 8. Mechanical dispersion method of nano-particles in a thermosetting matrix (dissolver technology) [19, 20]

Hardened (HRC 62) and polished carbon steel discs (100 Cr6; AISI 52 100) with an initial surface roughness of *Ra* =200 nm serves often as a counterpart. It is the most frequently used steel for bearing applications, exhibiting numerous advantages: high purity and strength, suitability for hardening without carburizing, and flexibility in the heat treatment.

3. Synergistic Effects of Nanoparticles and Classical Fillers on Friction and Wear

3.1 Preparation of Nano-Particle / Polymer Compounds

Since nano-particles possess a high tendency to stick together, strong shear forces are necessary to break up these agglomerates during their incorporation into the polymer matrix (Figure 5). The whole process can be supported by the use of additional chemical additives, such as surfactants (e.g. stearic acid or polyfunctional alcohols). When using thermoplastics as the matrix for injection moldable tribology components, a twin-screw extruder, equipped with appropriate feeders for the various fillers, is usually the best processing solution (Figure 6) [17]. In case of a high temperature resistant PEEK, filled with titaniumdioxide (TiO_2)- nano-particles of 300 nm in diameter, this resulted in a uniform distribution of the fillers, as shown in Figure 7. A dissolver disc in combination

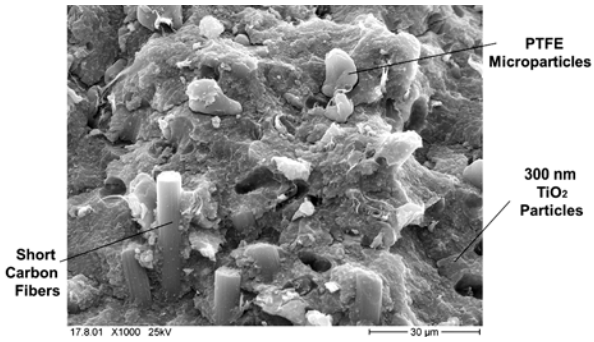

Fig. 9. Combination of micro- and nano-fillers on the fracture surface of an epoxy matrix tribo-compound

with a pearl mill can be applied in order to create the necessary shear and collision effects for destroying the nano-particle agglomerates in thermosetting resins (Figure 8). In combination with other tribo-fillers, this results in a microstructure which is exemplarily illustrated in Figure 9.

3.2 Sliding Friction and Wear of Different Nano-particle Containing Polymer Hybrid Composites

The addition of sub-micron or nano-scale particles to classical tribo-composites can significantly change their friction and wear performance [18]. One reason is that the abrasiveness of

hard nano-particles decreases remarkably as a result of the reduction in angularity in comparison with micro-particles. This can have another advantage, namely that these nano-fillers, once they get freely movable in the contact region between the mating surfaces, can act as distance holders and as nano-polishing agents which smoothen the topographies and reduce the coefficient of friction. This, in turn, can also lead to a reduction in temperature of the contact region [21]. Further, it can be expected that the higher thermal conductivity of ceramic nano-particles, as compared to the polymer matrix, also increases the thermal conductivity of the composite, which can contribute to a reduction in heat development in the sliding contact area. Details about some findings of other researchers in the literature on the effect of nanoparticles in reducing the friction and wear properties of polymer composites can be found in a recently published book chapter [16].

To fully promote the effect of nano-particles, systematic studies of their combinative effect with traditional fillers have been recently carried out by Zhang et al [12, 22-26]. Various polymers were chosen as matrices e.g. epoxy, polyamide 66 (PA 66) and polyetherimide (PEI). Short carbon fiber (SCF) and two solid lubricants, graphite and PTFE, were used as traditional tribo-fillers. The average diameter of the SCF was ~14,5 μm, with an average fiber length of ~90 μm. The graphite flakes and the PTFE powders were ~20 μm and ~4 μm respectively. Nano-sized TiO_2-inorganic particles were applied as additional fillers. The average diameter of these particles

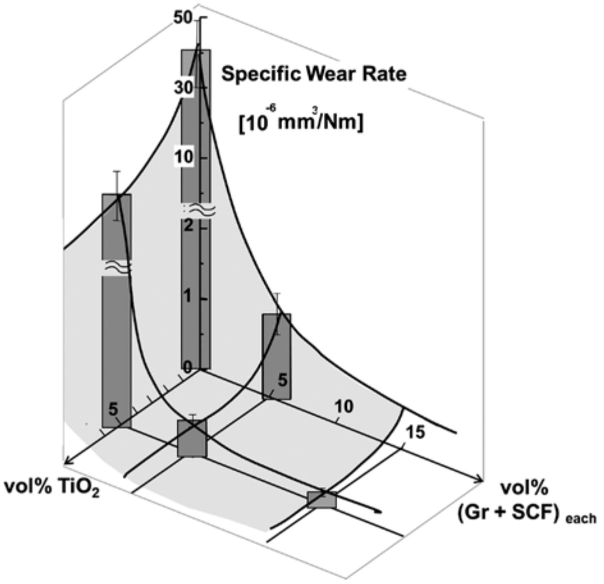

Fig. 10. Various degrees of improvement in wear resistance, depending on micro- and nano-filler combination (nano-TiO_2; Gr.=Graphite; SCF=short carbon fibers)

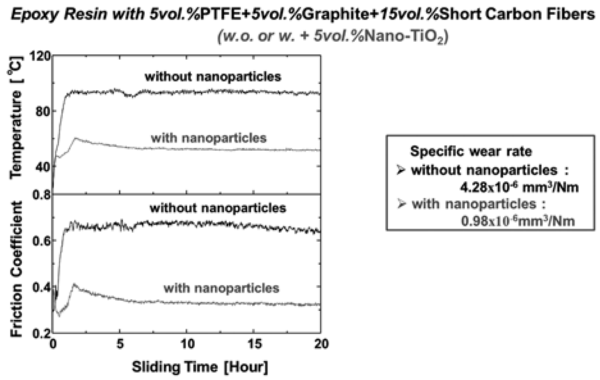

Fig. 11. Comparisons of the sliding process of two EP composites with and without nano-particles tested at 4MPa and 1m/s over a period of 20 hrs [27]

was 300 nm.

The tribological performance of a series of epoxy-based composites was preliminarily investigated at a pressure of 1MPa and a sliding speed of 1 m/s [12, 23]. The results in Figure 10 exhibit the synergistic effect of nano-TiO_2 particles and traditional tribo-filler on the wear resistance of

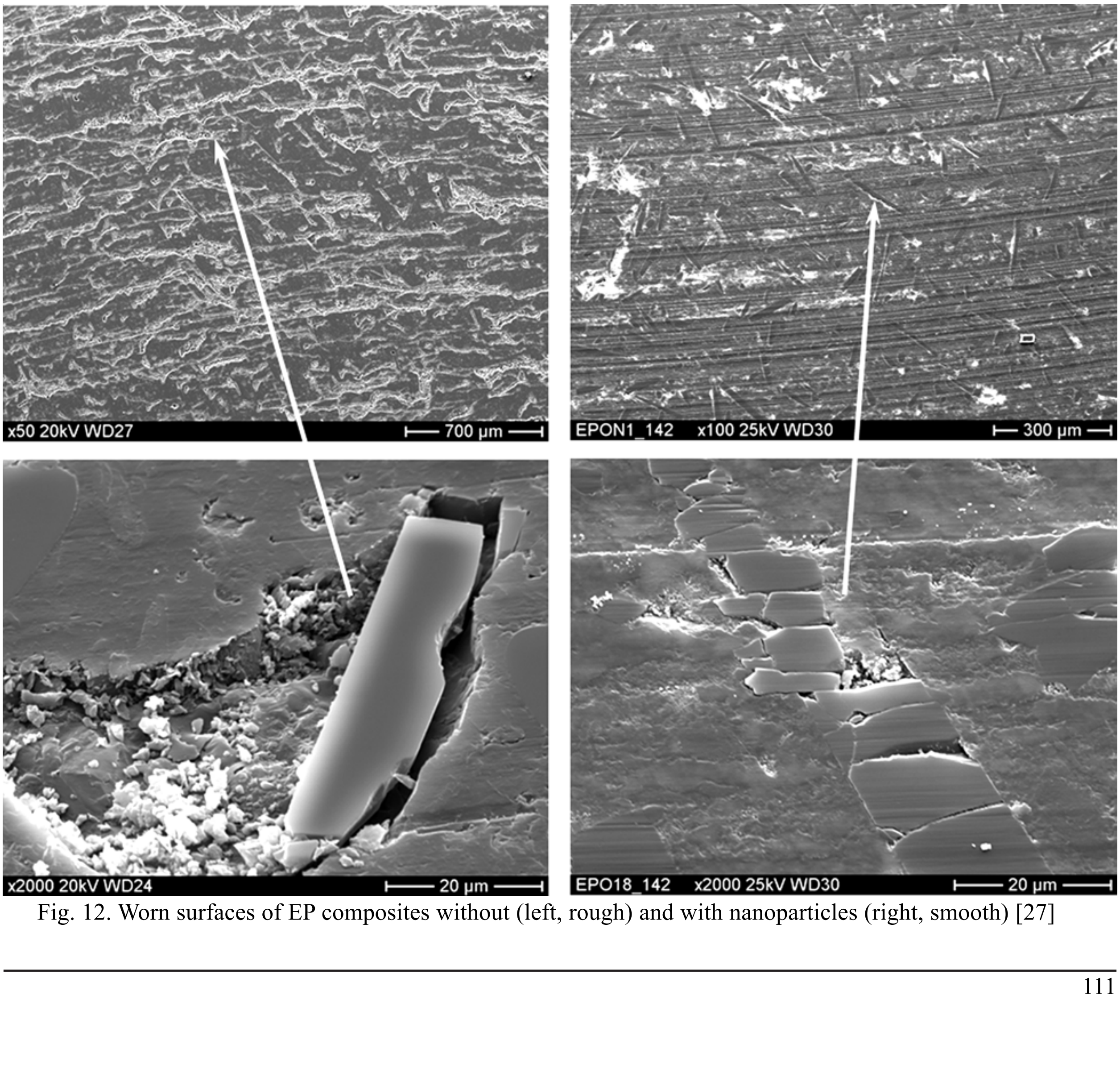

Fig. 12. Worn surfaces of EP composites without (left, rough) and with nanoparticles (right, smooth) [27]

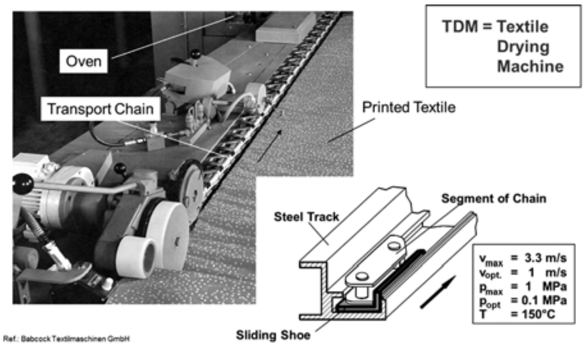

Fig. 13. Principle structure of a textile drying machine (left) and schematic position of a polymer composite sliding shoe in the chain system of a textile drying machine, with the range of operating parameters (right)

PEEK Composites vs. Steel	RT		150 °C	
	w_s [mm³/Nm]	μ [1]	w_s [mm³/Nm]	μ [1]
PEEK	8×10^{-6}	0.45	1.9×10^{-5}	0.46
PEEK + TF + Gr	9×10^{-7}	0.21	2.5×10^{-6}	0.18
PEEK + CF	2.5×10^{-7}	0.29	8.5×10^{-7}	0.35
PEEK + CF + TF + Gr	3.5×10^{-7}	0.17	8.7×10^{-7}	0.13

CF mainly reduce wear rate, while TF and Gr mainly reduce μ !

(TF = PTFE particles ; Gr = Graphite flakes)

Fig. 14. Specific wear rate (w_s) and coefficient of friction (μ) of various PEEK-compounds at room temperature (RT) and at T=150 °C; p = 1 MPa, v = 1 m/s [29]

epoxy-based composites. The wear rate of the hybrid composites filled with both nano-particles and traditional fillers was significantly lower than the values linearly interpolated between those of the composites filled only with nano-TiO_2 or traditional fillers. Moreover, the addition of nano-particles could further reduce the coefficient of friction and the wear rate of the epoxy composites filled with traditional fillers, especially under extreme sliding conditions.

The wear synergy detected in epoxy composites has also been found in further investigations of thermoplastic composites, i.e. with PA6.6 [25] or PEI matrices [26]. The composition of these two polymers filled with only conventional fillers, i.e. 5 vol.% graphite and 15 vol.% SCF, was used as a benchmark. It was selected as the optimum content of conventional fillers, based on work previously carried out for evaluating of the wear performance of a series of epoxy-based composites. Nano-TiO_2 particles served as additional fillers, at a content of 5 vol.%. As expected, the coefficient of friction of both fiber-reinforced thermoplastic composites was remarkably reduced by the addition of nano-TiO_2, associated with a decrease in the contact temperature under all test conditions [27]. This means, the wear resistance of the composites was improved through the incorporation of nano-particles, especially under high contact pressure and high sliding speed conditions. Typical courses of the coefficient of friction and the contact temperature as a function of time are illustrated in Figure 11 for two EP composites, with and without nano-particles, tested at 4 MPa and 1 m/s. It is clear that at the beginning of the running-in stage, sliding performance was similar for the two composites. However, after about an hour the coefficient of friction of the nano-composite was significantly reduced. The surface of the composites with additional nano-particles became much smoother (Figure 12, right) than of the ones without nano-particles (Figure 12, left).

4. Tribological Performance of Polymer Composites in Various Applications

4.1 Sliding Shoes in Textile Drying Machines

Textile drying machines consist of a big oven system, that is designed for drying and thermal treatment of flat textile structures with definite width, e.g. after being printed. For this purpose, the printed textiles are fixed by a number of needle clamps, that are attached to a chain system, which transports the stretched textile through the oven. Due to the fact that no external oil or grease lubrication is acceptable in the oven (fire hazard) and before the textile is entering the oven (contamination of the textiles), the individual elements of the chain need to be equipped with sliding shoes, made of self-lubricating polymer composites (Figure 13) [28].

The classical approach for the development of such materials was partly illustrated in Figure 3, i.e. the use of a high temperature resistant polymer matrix, filled with internal lubricants and reinforced with additional fibers. In particular, polyetherehterketone (PEEK) has two advantages, which are finally determining its selection for being the matrix material for the sliding shoes: a) PEEK is injection mouldable into many of these parts within a very short time, and b) it has a high toughness, which is important for the sliding shoes because they experience a lot of impacts during the movements of the transport chains through the steel tracks [29]. Besides, the tribological behavior of the PEEK can be further improved by the addition of 10 % of each, PTFE particles (TF), graphite flakes (Gr) and short carbon fibers (CF) (Figure 14). It becomes visible, that at both testing temperatures (room temperature RT, and 150 °C) the internal lubricants mainly affect the coefficient of friction, whereas the fibers alone mainly affect the specific wear rate. In combination, however, both tribological characteristics are reduced at the same time in a synergistic fashion.

Assuming that the allowable height reduction of the sliding shoes is 2 mm, their maintenance interval can be calculated as being 6380 hrs (under the standard operating conditions of T = 150 °C, a pressure of p = 0,1 MPa, and a sliding speed of v = 1 m/s), based on the material's specific wear rate of $0{,}87 \cdot 10^{-6}$ mm³/(Nm). If the machine operates ca. 40 hrs per week, this leads to a service life of

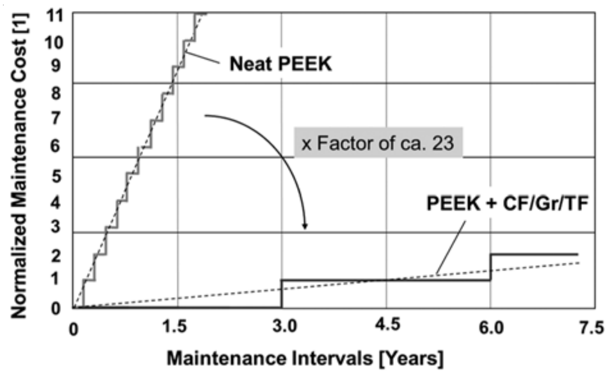

Fig. 15. Improvement in maintenance cost of textile drying machine due to the right choice of fillers in the PEEK matrix of the sliding shoes

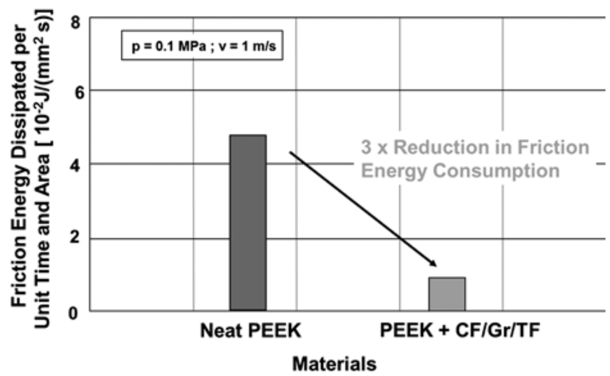

Fig. 16. Reduction in friction energy dissipated per unit area and time due to the additional fillers in PEEK

Fig. 17. Two examples in which filament wound bushings have to operate under harsh environmental conditions (upper pictures) and location of joints in which the bearings are located (lower picture)

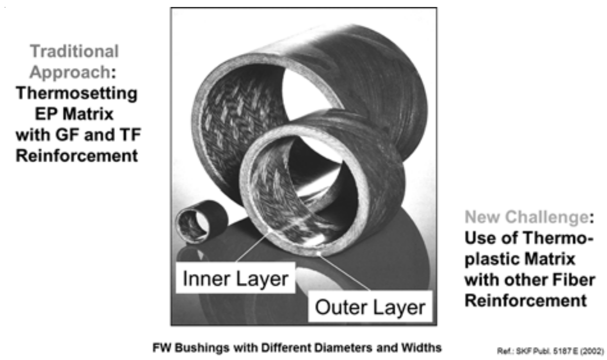

Fig. 18. FW bushings with different diameters and widths

the sliding shoes of ca. 3,3 years. Relative to the neat PEEK, the modification just with CF, TF, and Gr (i.e. without any nanoparticles in this case) results in an elongation of the maintenance intervals, combined with a reduction in normalized maintenance cost (improvement factor of ca. 23 in Figure 15). At the same time, the consumption of friction energy is reduced by a factor of 3, due to the much lower friction coefficient (Figure 16).

4.2 Continuous Fiber Composite Bearings Used under Severe Conditions

There are many mechanical engineering applications where high loads, strong vibrations and corrosive elements can act on the bushings of movable joints. Such applications include e.g. the lifting devices of refuse trucks, components of agriculture and forestry machines and equipment, packaging machines, or cranes on off-shore platforms. In recent years, it has been found out that under these conditions, filament wound, polymer composite bushings can bring a beneficial solution (Figure 17) [30]. Such bushings, which are commercially available in different diameters and widths, are manufactured using a complex fiber winding technique. Figure 18 indicates that they are composed of two distinct layers. The high strength backing layer consists of a high volume fraction of glass fibers, and the sliding surface is made of PTFE- and other polymer fibers. Both layers are embedded in an epoxy resin matrix. This material selection combines the special mechanical properties of glass fibers with the outstanding tribological properties of PTFE- and high strength polymer fibers. In this way, these bushings bring together also other benefits and features, including: a) good impact resistance, b) insensitivity to edge loading and misalignment, c) good noise and vibration damping, d) excellent resistance to corrosive media, even to salt water, and other chemicals, and e) good insulation preventing passage of electric current. Their load bearing capacity under low sliding speeds (less than 0,01 m/s) can be up to 150 MPa.

A new way to produce such bearings involves a thermoplastic solution. This brings about further benefits, such as higher impact toughness, a greater flexibility in the design of the final components, and faster processing cycles. Figure 19 illustrates schematically the individual processing steps:

a) starting with a pre-designed commingled yarn, consisting of reinforcing fibers (e.g. aramid fibers), self-lubricating PTFE- fibers, and e.g. polyamide (PA) fibers, of which the latter are transferred during the thermoplastic filament winding process into the final matrix of the

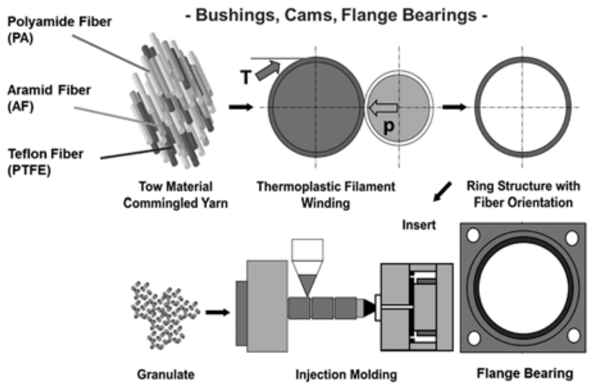

Fig. 19. Principle processing steps for producing filament wound thermoplastic bushings or flange bearings

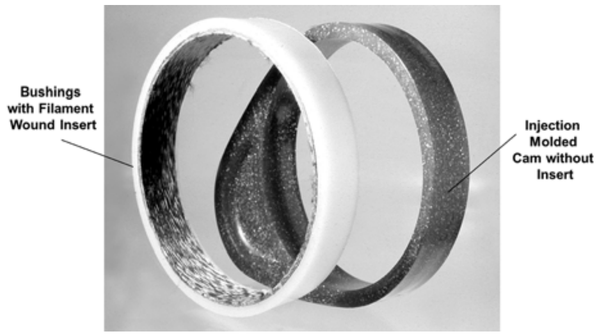

Fig. 20. Real bushings made by thermoplastic filament winding in combination with injection molding (left), and example of complex, injection molded shape (here: cam) without the filament wound insert (right)

composite;

b) filament winding of the tribologically loaded, inner layer of the composite bushing by using a certain steel mandrel, a heating device (e.g. hot air gun; T) and a compaction roller (p) [31];

c) over-winding of the inner layer with a backing layer, using another commingled yarn which consists of the same matrix fibers and a high volume fraction of glass fibers, in order to provide the bushing with a high load bearing capacity;

d) alternatively, the filament wound inner layer can be used as an insert in an injection moulding tool, around which a short glass fiber reinforced thermoplastic (usually being the same as the matrix fibers in the commingled yarn) can be injection moulded in order to create a more complex end-geometry, such as a full flange bearing.

That such products can be produced in this way, is shown in Figure 20. Prior to the injection molding process the insert was preheated in order to guarantee a strong bonding between the wound insert and the surrounding polymer. A very important parameter was the hot air temperature used for preheating. Air temperatures of about 400 °C led to the desired shear strength values of about 18 MPa between the two layers. Testing of this final component in a journal bearing tester indicated its good

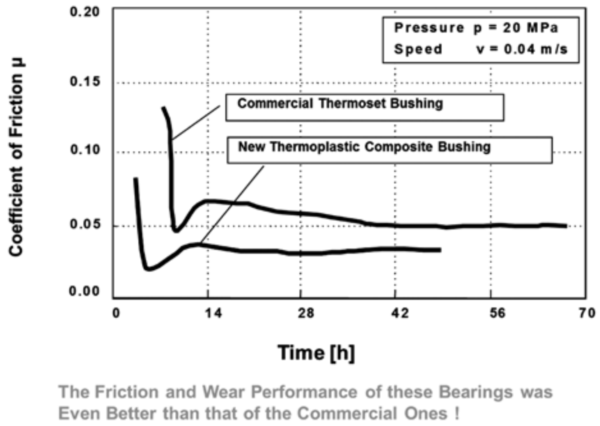

Fig. 21. Coefficient of friction vs. testing time, as determined on real bearings

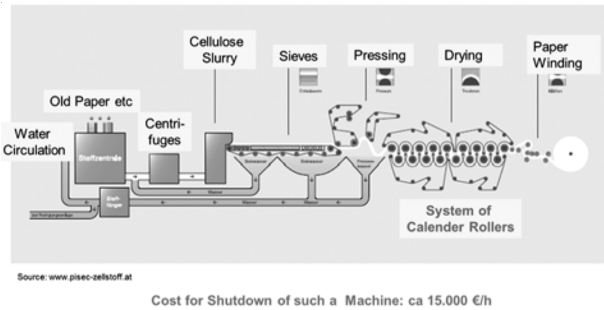

Fig. 22. System of calender rollers in a paper making machine

performance in terms of coefficient of friction, wear resistance and high thermal stability, in relation to a competitive commercial material under comparable pressure, temperature and velocity conditions. In fact, the commercially available thermosetting composite bearing resulted in higher values of the coefficient of friction than the thermoplastic filament wound bearing (Figure 21) [32].

4.3 Thick Coatings on Rollers of Paper Machines

Huge machines with numerous calender rollers are usually used to produce paper from cellulose slurry (Figure 22). In certain sectors of these machines, some calender rollers have a thick polymer composite layer on their surface. These calender roller "covers" must possess a

wide mechanical property profile, i.e. being stiff, strong, and hard, on the one side, and impact resistant, on the other. In addition, their sliding and abrasive wear resistance should be high, in order to prevent short maintenance intervals of the huge production machines (high economical factor). The composition of currently used calender roller covers is based on an epoxy resin matrix, filled with μm-sized ceramic particles. The amount of the compounds used for covering one roller only can range up to 500 kg, depending on the roller's length and diameter (Figure 23) [33].

Recent developments have shown that for the future generation of these covers, the use of additional nano-

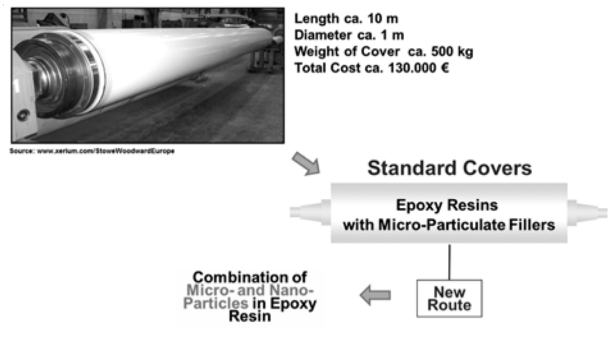

Fig. 23. A large calender roller, freshly covered with a newly designed nano-compound

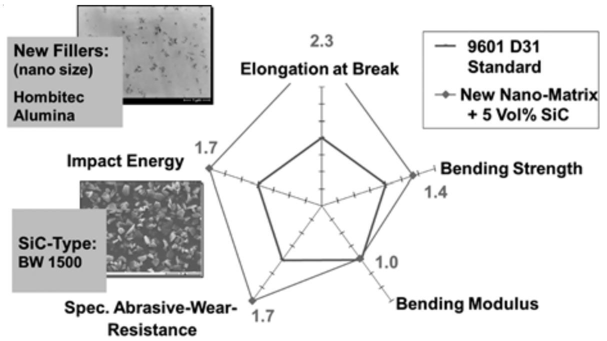

Fig. 24. Comparison of various properties of a standard cover material and a new nano-compound (including micro-SiC and nano-alumina particles)

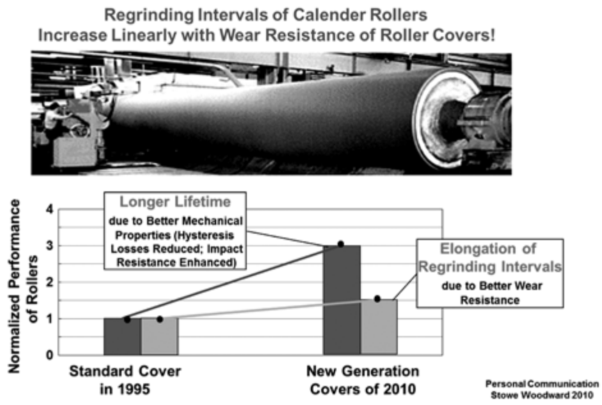

Fig. 25. Improvement in the performance of calendar rollers between 1995 and 2010 due to the additional use of nanoparticles

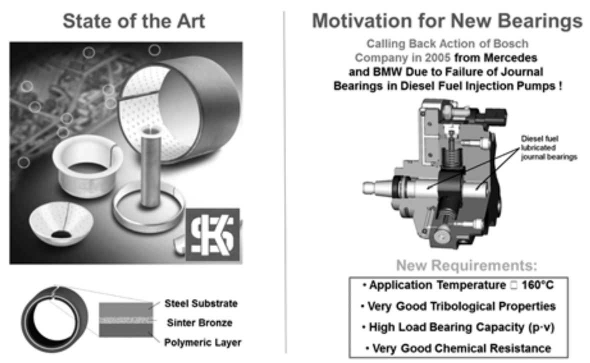

Fig. 26. Schematic structure of hybrid bushings (left) and their requirements in diesel fuel injection pumps (right)

particles can further improve their property profile. In fact, in laboratory experiments it could be verified that the use of nano-sized alumina particles in combination with classical μm- sized silicon carbide particles improves the bending strength, the elongation to break, the impact energy, and the abrasive wear resistance simultaneously, when compared to the standard grade (Figure 24). These improvements are also reflected in the life cycle of the roller covers [34]. Relative to the standard covers of 1995, the new generation of covers has a three times longer life time, due to reduced hysteresis losses, better impact resistance etc. Also the regrinding intervals could be elongated, which leads to longer maintenance intervals and therefore a reduction in shut-down costs of the paper making machine (Figure 25). In the meantime, field tests with real rollers in paper machines have also proved to perform better when the nano-compounds were applied, and also the quality of the paper seemed to be higher.

4.4 Polymer-Metal Bearings in Diesel Fuel Injection Pumps

There are many applications in the automotive industry where hybrid bushings are needed to guarantee the function of different car components over a long period of time. The components include windshield wiper motors, shock absorbers, steering shaft joints, door hinges etc. (Figure 26, left). By incorporating a plastic material into a porous bronze sinter layer applied to a steel or aluminum back (hybrid structure), a low friction matrix that unites favourable tribological properties with the load carrying properties and thermal conductivity of metals is obtained. The use of solid lubricants in the plastic matrix produces a film between the sliding surfaces and makes it possible to use such bearings in applications without oil- and grease lubrication. It also attributes to low-noise operation at constant speeds and low coefficients of friction throughout the entire service life of the component [35].

In recent years, the requirements on the performance of such bushings have been increased towards higher temperature applications and higher (pressure x velocity) – loading conditions. The new generation of these bushings is supposed to be used as camshaft bearings in high pressure, diesel fuel injection pumps (Figure 26, right), or even in the engine of the cars. One way to fulfil these extremely high requirements, was to formulate and apply a PEEK matrix compounded with special nano-scaled fillers to improve its tribological properties. The motivation for the development of such new hybrid bushings was based on a drawing-back action of Bosch Company in 2005, due to failure of journal bearings in diesel fuel injection pumps [36].

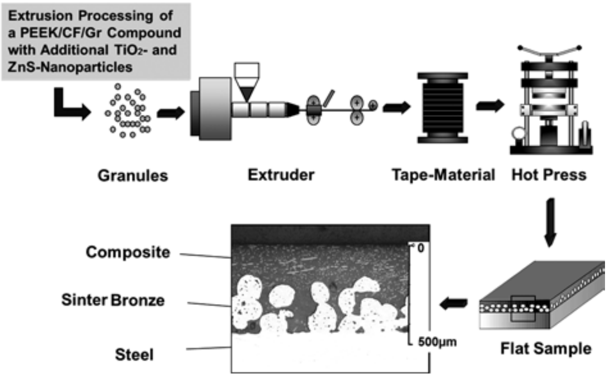

Fig. 27. Laboratory production steps for impregnating a PEEK-composite into the porous bronze layer on top of the steel substrate

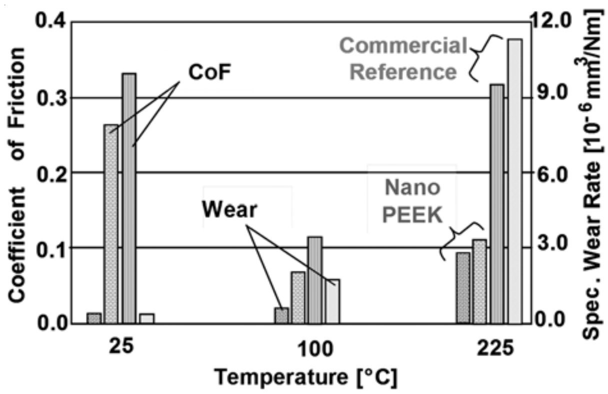

Fig. 28. Specific wear and coefficient of friction of the new (Nano PEEK) -composites in a temperature range between 25 and 225 °C, when compared commercial reference without nanoparticles

During the development phase of this, now commercially available product (Permaglide®, KS Gleitlager, Germany), the compounding of the composites and their extrusion into flat tapes had to be studied on a laboratory scale. The same was true for the incorporation of the tape material into the sinter bronze modified steel substrates, using a laboratory hot press. A good impregnation as well as the achievement of a uniform thickness of the polymer composite layer above the porous sinter bronze scaffold needed to be guaranteed (Figure 27).

In fact, when comparing the two PEEK-compounds with regard to their tribological characteristics (using a ring on flat test configuration), it became evident that, especially at higher loading conditions and elevated temperatures, the nano-modified PEEK was superior to the classical PEEK variant and other, commercially available references. Even at a testing temperature of 250 °C, the new PEEK nano-compound resulted in reliable test data (Figure 28) [37–39].

5. Conclusions

It can be stated that the use of polymer based composites for tribological applications is very widespread, but their structural design depends highly on the engineering system in which these materials have to operate. In most of the cases discussed here, they had to slide against a metallic counterpart, using their self-lubricating function to reduce the coefficient of friction. Special reinforcements helped to make them also quite wear resistant. New developments in this respect use additional nanoparticles that incorporate further, wear reducing mechanisms into the tribo-system. This has not only been shown on a laboratory scale, but also in various applications, such as in paper making machines, automotive components or other mechanical engineering facilities. But there is still enough room for further, future developments. These include also the use of carbon nano-tubes or nano-fibers, as it was highlighted by some recent publications in this field [e.g. 40, 41].

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Сучасні полімерні композити, які використовуються у вузлах тертя та зносу

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Використання полімерних композитів, які використовуються у вузлахтертя та зносу, досягло досить високого технічного рівня. В огляді описані можливості конструювання полімерних композитів, що працюють за умов низького тертя та зносу, порівняно з існуючими аналогами. Особлива увага приділена спеціальним наповнювачам (включаючи сферичні наночастки), часто в поєднанні з класичними трибо-наповнювачами, такими як вуглецеві волокна, графітова луска та частинки політетрафторетилену для покращення трибологічних характеристик термопластичних і термореактивних полімерів.

Ключові слова: тертя, знос, полімери, композиції, наночастки, використання.

Современные полимерные композиты, применяемые в узлах трения и износа

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Использование полимерных композитов, применяемых в узлах трения и износа, достигло достаточно высокого технического уровня. В обзоре описаны возможности конструирования полимерных композитов, работающих в условиях низкого трения и низкого износа, по сравнению с существующими аналогами. Особое внимание сфокусировано на специальных наполнителях (включая сферические наночастицы), часто в комбинации с классическими трибо-наполнителями, такими как углеродные волокна, графитовые чешуйки и частицы политетрафторэтилена для улучшения трибологических характеристик термопластичных и термореактивных полимеров.

Ключевые слова: трение, износ, полимеры, композиции, наночастицы, применение.