PolyTrib 2014
1st International Conference on Polymer Tribology
11th – 12th September 2014, Bled, Slovenia

POLYMERS IN TRIBOLOGY: CHALLENGES AND OPPORTUNITIES

[1]P. De Baets*, [2]S. Glavatskih, [1]W. Ost, [1]J. Sukumaran
[1]Ghent University, Department of Mechanical Construction and Production, Ghent, Belgium
[2]KTH Royal Institute of Technology, Machine Design, Stockholm, Sweden

Abstract

Seminal characteristics such as good corrosion resistance, self-lubrication ability and acceptable wear resistance have made polymer based materials to become popular in a wide and diverse range of tribological applications. Despite numerous applications and decades of research in polymer tribology, a considerable number of questions remain unsolved both regarding fundamental understanding and engineering design issues. One of the reasons is the vast number of different polymers and polymer based composites that are in use, but also the diversity in applications and the difficulties to observe the governing tribomechanisms.

Material and component producers are often the only owners of composition and basic material characteristics. Thus, designers and application engineers are obviously forced to rely on catalogue information and scattered literature data. For that reason prior to application of a chosen material/component functional and tribological tests with scale models or laboratory set-ups are performed to obtain better confidence in the proposed design solutions. Each time again the definition of an adequate test program is of major concern.

The present paper discusses some challenges related to the use and testing of polymer based tribocomponents such as bearings, sliders, gears, rollers, etc. Attention is not only given to basic influencing parameters such as contact load, sliding/rolling velocity, environmental conditions, mating surface conditions, etc. Also experimental strategies and advanced measuring techniques that allow to follow the dynamic nature of transfer film formation and wear are considered. Finally, actual trends in reinforcements (e.g. natural fibres) and lubricant additives (nanoparticles) are discussed together with opportunities for improved tribobehaviour.

Keywords:

Polymers, Polymer based composites, Tribotesting

*Corresponding author: Patrick.DeBaets@ugent.be

1. Introduction

Because of some advantageous properties polymers and polymer composites, further called PaPBC's, have found their way in numerous applications in a wide variety of industrial sectors. They are used for machine components such as gears and bearings, as guide ways and sliding systems in civil constructions, biomedical implants etc. Small but also very large size components made of PaPBC's are used in engineering and domestic applications. Since many decades research on their tribological behaviour has been conducted [1][2]. Nevertheless, there are still numerous open questions and unknowns about PaPBC's as a tribological solution, also is due to the continuous development of novel materials and new applications. This paper aims at pointing out some of the problems, challenges and opportunities related to the use of PaPBC's and at giving some direction to future research and development activities in this field.

2. Sources of tribological data

Designers willing to apply PaPBC's generally rely on catalogues and technical and scientific literature as basic information, that they sometimes, mostly in critical situations, complement with an own experimental campaign. As a matter of fact the available catalogue information on PaPBC's has grown a lot in the last years, both in quantity and quality. And some material producers really have metamorphosed into solution providers with comprehensive design guidelines and calculation methods. However, generally spoken catalogue information still suffers lack of clarity and incomplete information. Due to understandable commercial concerns very often material composition, component production and tribotesting conditions are omitted, hindering successful and reliable use of the provided data. The scarcity of information in catalogues may also pertain to lack of understanding on the dynamic tribological behaviour of PaPCBs. If the testing conditions values are not reported, then the friction and wear coefficients may represent a slacked value. In this respect we are not convinced that providing more ample information would harm commercial interests, rather on the contrary. In order to gain some self-confidence designers and constructors try to rely on scientific data produced by academic institutes. Very soon they come to the conclusion that they get lost in a vast amount of disperse and scattered data. For the same PaPBC coefficients of friction and wear coefficients are inhibited with large variations, depending on test conditions (type of test rig, normal load, sliding velocity, counter material properties,…). In addition, contradictory data is found among different laboratories. Another drawback of many of these data is the difficulty to adequately translate or extrapolate them to the real tribo-application of interest. It seems that the time is ripe for performing review research to gather, interpret and comprehensively present numerous but unfortunately highly scattered data on PaPBC tribology. Finally, when not satisfied by literature resources, the end user tends to define his own experimental program to find out or validate friction and wear values with respect to a well-defined application. This also shows that a central repository system is required for gathering the existing data which can be effectively compared with tailor made laboratory experiments.

2. Tribotesting

Unquestionably small-scale tribotests (pin-on-disc, bloc-on-ring or flat-on-flat) are preferred due to their cost- and/or time-effectiveness and easy handling of test specimens. These tests provide fundamental information and are useful for preliminary material classification, but they often result in important errors when extrapolated towards real working environments [3]. Real criteria for material selection require the tribological characterization under conditions that closely simulate the practical functionality, including the structure of the material sliding couple, the contact geometries, the contact pressures, the type of sliding motion, environmental conditions, mechanical stiffness, energy dissipation, fixation method, etc. As a result, tribological effects are expressed on different geometries and on scales ranging from nanotribology up to teratribology. Some full-scale experiments are reported in literature [4][5][6][7]. While most reliable tribotesting involves the real operating system, it often cannot be tested due to high cost and practical obstructions. Scalability of tribotests has therefore become an important issue, mainly for PaPBC bearing elements. Models should be developed that can relate results of tribotests at different scales. Traditional models with (i) one single mechanical parameter (normal load or contact pressure), (ii) two mechanical parameters (normal load and sliding velocity) and (iii) the contact pressure–sliding velocity model (pv-temperature limit) are only applicable within one testing scale, but not between tests of different scales. Samyn [8] therefore introduced a macroscopic geometry model, considering thermal effects, sample geometry and viscoelastic contact conditions. The base of the model is the definition of a scaling parameter depending on a macroscopic geometry parameter, the Péclet number and the contact pressure. The model seemed to be successful for virgin polymer with respect to friction, but failed in extrapolating wear coefficients. Better models should thus be developed. Lacking appropriate models, tribotesting with large size specimens or components still offers most valuable information. Some features, such as macroscopic reinforcements, fibre reinforcement, debris evacuation groves etc. cannot be scaled down to the size of traditional in lab tribotesters. As an example Figure 1 shows a hybrid sliding pad that is used in a 10 m diameter spherical hinge [9], that has been tested with Soete lab’s 6500 kN flat-on-flat reciprocating tribometer.

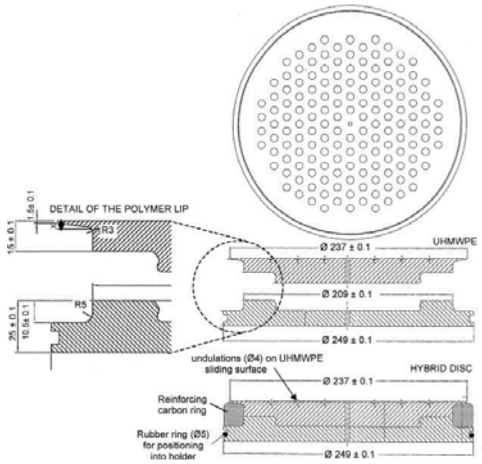

Figure 1: Hybrid UHMWE sliding pad

Figure 2 shows a reciprocating radial bearing tester that is used for experimental research on large fibre reinforced polymers often applied in offshore constructions such as dredging equipment, mooring systems, buoys, etc.

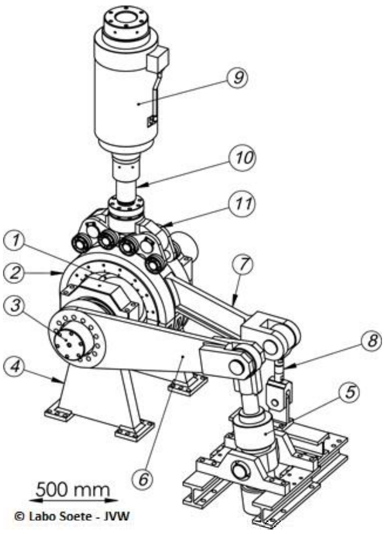

Figure 2: Large scale reciprocating radial bearing tester, max. load 1500 kN [10]

Another problem related to PaPBC tribotesting concerns the impossibility of accelerated testing. Increased sliding velocity and/or normal load often leads to surface temperature increase that results into totally different friction and wear behaviour. Additionally the wear mechanism may differ in the accelerated condition [11]. Even when keeping the contact temperature constant other friction and wear mechanisms come into play with increased velocity or load. Typically high load tests underestimate friction coefficient and wear rate (see Figure 3) and increased velocity tests overestimate friction.

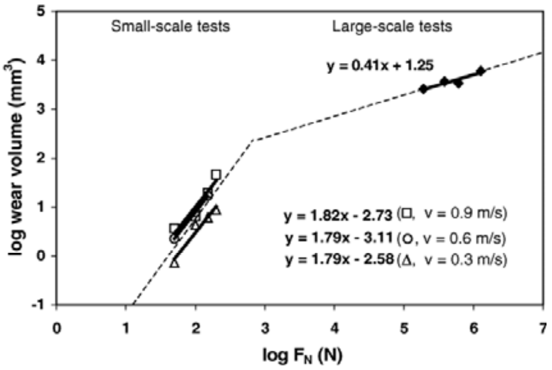

Figure 3: Wear testing of Polyacetal (POM) at two different scales [11]

As PaPBC's can often give rise to stick-slip slip movement, which is particularly harmful for larger constructions, one can be interested in stick-slip tendency. The best method for investigating stick-slip is running a numerical model taking into account the mechanical properties of the real application (mass, stiffness and possible damping) in relation with the friction characteristics (coefficient of friction as a function of sliding velocity) of the material. Generally part of the required data are not known and thus tailor made experiments for understating the stick-slip behaviour are proposed by the end users. One should bear in mind that a reliable stick-slip test is hard to define. Moreover friction testing with small size contact specimens generally underestimates stick-slip possibility, because the mechanical stiffness of such small size test is generally factors higher than in a larger scale test or in a real application.

Finally it should be emphasized that enough attention should be paid to the applied testing parameters. Generally contact pressure and sliding velocity are well controlled. Much less attention is given to environmental conditions and properties of the counter surface. As number of polymers to a certain extent have mechanical properties varying with ambient humidity, this last one should be properly monitored and - even better – controlled. Also in case of lubricated contact the properties of the lubricant should be taken into account. As an example Figure 4 shows the coefficient of friction of a radial PETP bearing in water lubricated conditions. Four different types of water have been used (river, tap demineralised and distilled) resulting into different friction behaviour, mainly in the lower velocity range for which a (semi-) hydrodynamic film could not be developed [12]. For the same bearing the steel counter face roughness has also been examined. It was observed that increasing the shaft roughness form Ra 0.02 µm (ground surface) to 0.4 µm (finely turned) resulted into an increase of the coefficient of friction by a factor 2.5 [13]

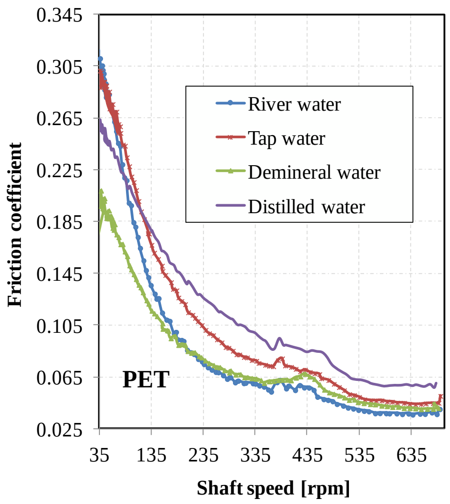

Figure 4: Friction of water lubricated PETP radial bearing (inner diameter: 30.1 mm, width 15 mm, radial load 16 N)

Furthermore, very local surface imperfections, such as scratches in the counter surface, can have detrimental effects on tribological performance. Figure 5 gives the results of reciprocating wear test of a polymer cylinder (diameter 6 mm, width 12 mm, load 50 N, sliding velocity 50 mm/s, ambient temperature 37 °C, 1,000,000 cycles, stroke 15 mm) running against a steel surface with one or one and a half scratches (10 µm deep and 10 µm wide) oriented parallel, under 45° and 90° with respect to the sliding direction. A factor 30 in wear volume has been observed [14].

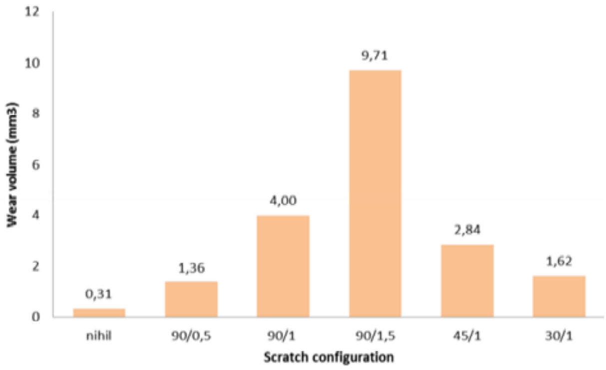

Figure 5: Wear of UHMW-PE (cylinder on plate, load 50 N, sliding velocity 50 mm/s, 1,000,000 cycles, stroke 15 mm) against a scratched counter surface

3. Solid lubricants and strengthening fillers

Although oil and grease can be used as a lubricant in polymer/metal contacts, their use is often restricted due to environmental concerns. Additionally, these lubricants often need adequate and vulnerable sealing systems. Alternatively, solid lubricants can be applied, based on PTFE, MoS_2, graphite or their mixtures. All statements concerning scattered or missing data as already discussed in section 1 are applicable to these solid lubricant filled PaPBC’s, even to a larger extent, and will not further be discussed here.

Practical use, however, has already proved that these lubricants can be beneficial although their lubricating mechanisms are not fully understood. Most researchers hypothetically attribute the favourable tribological characteristics to the mechanism of transfer film formation. A better understanding and possible confirmation of this hypothesis requires observation techniques that are able to observe transfer film dynamics. Its formation and removal during sliding should be observed and quantified. Some potential techniques are discussed in section 4.

The beneficial action of solid lubricants on the other hand results into a diminished wear resistance. It is possible to counteract this effect by strengthening the polymer matrix by means of long or short fibres (polymer fibres, carbon, glass). Today also nanofillers come into play, that are uniformly distributed in the polymer matrix. Examples of such nanofillers are titanium dioxide (TiO_2), silicon dioxide (SiO_2) and zinc sulphide (ZnS). Due to the almost infinite number of combinations of matrix, strengthening agent and lubricant the complexity of such composites rises exponentially. Numerous are the papers describing facts and figures, but scarce are the explanations of the fundamental mechanisms. Figure 6 shows the influence of different filler/lubricant combinations in PEEK with respect to the coefficient of friction obtained by flat-on-flat reciprocating experiments (specimen area 30 x 30 mm, stroke 80 mm, sliding velocity 20 mm/s, load 4/8/10 MPa, test duration 15 hours). As can be seen the same mixtures can result into different results, depending on the sliding direction with respect to the fibre orientation. Indeed, due to the injection moulding process used for specimen production, a certain orientation of microscopic graphite fibres was observed, which also resulted in anisotropic friction behaviour. A load dependency of the lubricant performance is also observed. In this particular situation the friction of PEEK could be halved from 0.4 to 0.2 by addition of a mixture of short carbon fibres (∅7 µm, L = 6mm), TiO_2 (size 340 nm), ZnS (size 300 µm) and SiO_2 (size 12 µm).

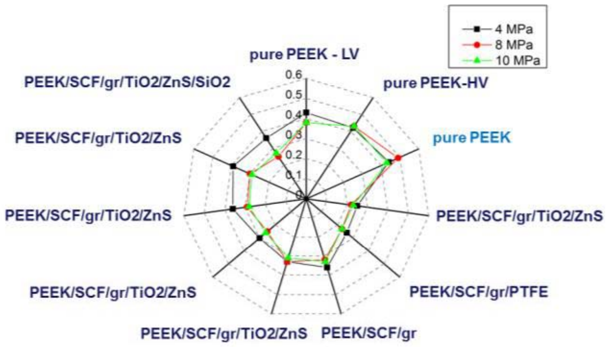

Figure 6: Wear of PEEK against steel (specimen contact area 30 x 30 mm, stroke 80 mm, sliding velocity 20 mm/s, load 4/8/10 MPa, test duration 15 hours)

A new trend towards the use of natural fibres in PBC's should also be highlighted. Although still not extensively used in industry, natural fibres have some attractive properties related to environmental and energy related issues. The first one is rather obvious, the second one is attributed to the high energy consumption in the production of synthetic fibres and the high cost related to it. Diverse classes of natural fibres can be distinguished (vegetal versus animal fibres, seed hair fibres, bast fibres and leaf fibres). In order to obtain optimal structural and tribological properties natural fibres have to be adequately treated. Figures 7 and 8 show the friction and wear behaviour of unsaturated polyester reinforced with either 48 wt % of glass fibres, or 48 wt % of coconut sheath fibres against steel as a counter face. The results have been obtained with pin-on-disk experiments using hardened alloy steel (64 HRC) with Ra of 0.54 µm, sliding velocity of 3.5 m/s, load 40 N and sliding distance of 2100 m. The figures show that fibre treatment mainly positively influences wear resistance [15].

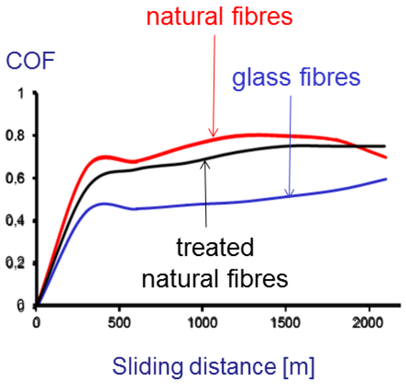

Figure 7: Friction of unsaturated polyester (glass fibre / coconut sheath fibre reinforced) against hardened ally steel (load 40N, sliding velocity 3.5 mm/s)

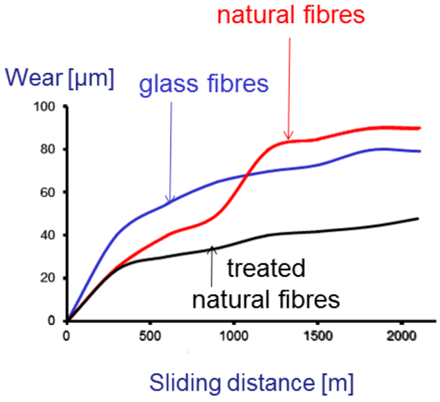

Figure 8: Wear of unsaturated polyester (glass fibre / coconut sheath fibre reinforced) against steel (load 40 N, velocity 3.5 m/s)

Another challenge with natural fibres is the selection of an appropriate fibre. There is lack of knowledge in choosing fibers to match good tribological-mechanical properties [16]. The bonding between fibre and matrix partially helps. Also important improvement could lie in incorporating 3D microstructural characteristics of natural fibres in the wear models.

4. Optical surface observation

As explained earlier some efficient and advanced method of surface observation is an absolute must. Apart from the traditional wear scar investigations, the advanced methodologies should also trace the formation and removal of polymer transfer films. Additionally, it would be of great benefit to be able to quantify this in a more or less semi-automatic way.

There are many analytical techniques which can aid to understand local nature of wear process.

But, a common mistake in wear studies is explaining the tribological influences from the local features observed in the worn surface. Hypotheses based on the local information might be inaccurate if the local information (topographic or morphological) has large scatter [17]. And in most surfaces both the topographic and morphological features are scattered. This problem can be efficiently solved by using reference mapping techniques (relocation profilometry or micrography) [18] [19]. Relocation micrography has been effectively used to track the evolution of surface change in both polymer and counterface material surface. Figure 9 shows the initial and worn contact surface of a commercial (DOCAMID 66-GF30) fibre reinforced composite disk (∅95.22 mm, width 7 mm) tested at 500 rpm (30 % slip ratio) and loaded against a steel disk (∅70.38 mm, width 22 mm) with a mean contact pressure (Hertzian) of 33 MPa.

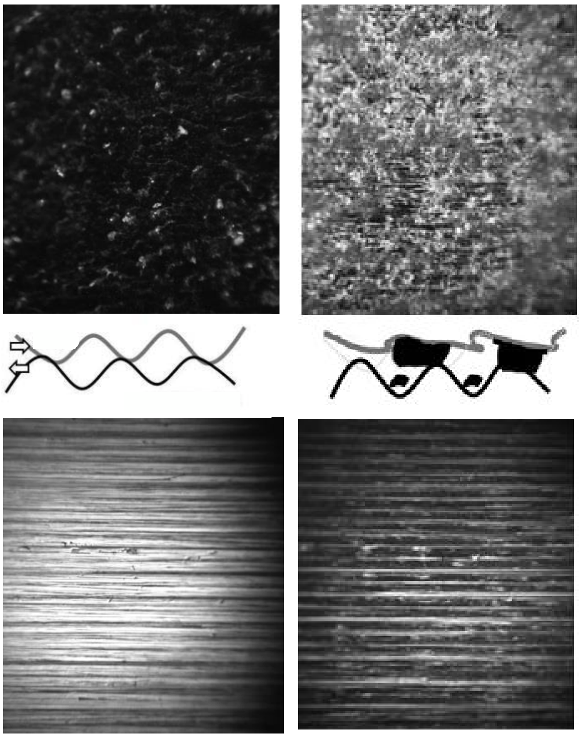

Figure 9: Image of DOCAMID 66-GF30 (top) and steel (bottom) disk surface. Initial contact surface (left) and after 240,000 revolutions (right) in twin disk machine (33 MPa contact pressure, 500 rpm, slip ratio 30 %)

The evolution of the contact surface is understood by comparing micrographs taken at different time periods. This methodology elucidates the formation of a transfer layer on the steel surface and partial removal of this layer and readherance to the original polymer surface. On the polymer surface in Figure 9 the fibre reinforcement is clearly seen, indicating the wearing off of the matrix polymer. These images are valuable for developing image processing algorithms allowing for semi-automated wear assessment [20] which is often followed in bio tribological investigations [21]. It is clear that this technique provides more detailed information but has the draw-back of interrupting the equilibrium of the ongoing wear process because of the repeated stand-still of the tribometer. Hence an advanced technique was developed in Soete lab to monitor moving surfaces at a micron scale resolution.

Though in-situ monitoring technique exists from late ‘70s its usage is rather limited to slow speed applications. The in-situ microscopy developed in Soete lab has the capability of acquiring images at a speed of (35000 fps) in combination with blur estimation techniques. The methodology and the instrumentation allows to observe large wear area, and has been applied to a twin disc set-up.

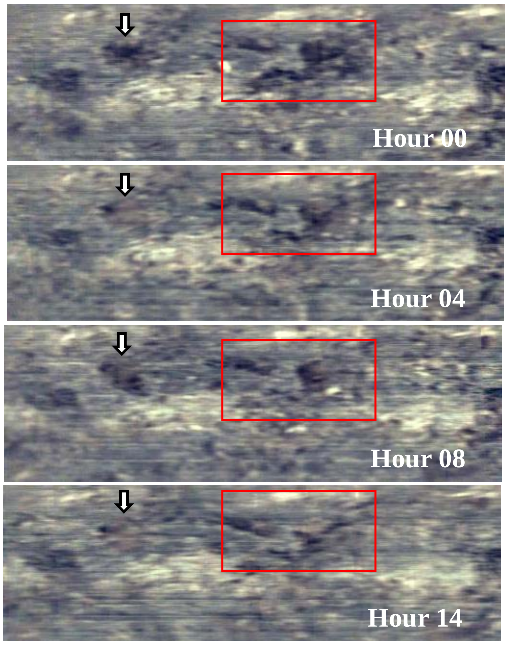

Figure 10: Online images of contact surface acquired at 200 rpm at different instants of time

Figure 10 shows a stitched series of images taken of a disk (∅90.84 mm, width 10 mm) made of phenolic resin, reinforced with polyester fibres and filled with PTFE rotating at 200 rpm and 19% slip ratio against a cylindrical steel (S355-J2, ∅74.95 mm, width 22 mm) counter surface. Careful examination reveals craters and cracks and multiple recurrence of these surface scars as a function of time. Together with transfer film formation and material removal mechanism the dynamic characteristics and the self-healing mechanism of composites are clearly evidenced in *in-situ* studies.

Using recent appropriate optical imaging techniques and taking benefit from the improved computational capabilities, microscopic evaluation can aid better interpretation of wear process. Introducing quantitative micrography in tribological studies can lead to a transformation of the present knowledge base to more sophisticated expert system.

4. Conclusions

This paper showed the inherent richness of polymers as a tribological material. It has also been demonstrated that there is still a need for better understanding. More adequate analysis tools will first have to be developed in order to better follow wear process and wear mechanisms, in real time preferably.

But besides these scientific need there is a growing demand for review research and comprehensively gathering dispersed scientific and technological data.

References

[1] E. Rabinowicz, K. Shooter, The transfer of metal to plastics during sliding. Proceedings of the Physical Society Section B, 65 (1952), 671.

[2] K.V. Shooter, D. Tabor, The Frictional Properties of Plastics. Proceedings of the Physical Society Section B, 65 (1952), 661.

[3] M. Vermeulen, Wear research on large-scale test specimen, Wear 132 (1989), 287–302.

[4] S. Hayama, Tribology in the large-scale telescope ‘Subaru’, Journal of the Japanese Society of Tribology 51-6 (2006), 426–31.

[5] T. Jendel, Prediction of wheel profile wear – comparisons with field measurements, Wear 253–1/2, (2002), 89–99.

[6] L. Baurle, D. Szabo, M. Fauve, H. Rhyner, N.D. Spencer, Sliding friction of polyethylene on ice: tribometer measurements, Tribology Letters 24–1 (2006), 77–84.

[7] P. De Baets, Comparison of the wear behaviour of six bearing materials for a heavily loaded sliding system in seawater, Wear 180 (1995), 61–72.

[8] P. Samyn, G. Schoukens, Experimental extrapolation model for friction and wear of polymers on different testing scales, International Journal of Mechanical Sciences 50 (2008), 1390–1403.

[9] P. Samyn, L. Van Schepdael, J.S. Leendertz, A. Gerber, W. Van Paepegem, P. De Baets, J. Degrieck, Large-scale friction and wear tests on a hybrid UHMWPE-pad/primer coating combination used as bearing element in an extremely high-loaded ball-joint, Tribology International, 39-8 (2006), 796–811.

[10] J. Van Wittenberghe, W. Ost, A. Rezaei, P. De Baets, L. Zsidai, G. Kalácska. Test setup for friction force measurements of large-scale composite bearings. Experimental Techniques. 33 (2009), 45–50.

[11] P. Samyn, P. De Baets, Friction and wear of acetal: A matter of scale, Wear 259 (2005) 697–702.

[12] T. D. Nguyen, J. Sukumaran, J. De Pauw, P. De Baets. Tribological behaviour of polymer bearings under dry and water lubrication, 5th SCAD conference February 20–21, 2013.

[13] A. Golchin, T. D. Nguyen, P. De Baets, S. Glavatskih, B. Prakash, Effect of shaft roughness and pressure on friction of polymer bearings in water, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 228 (2014), 371.

[14] J. Quintelier, P. Samyn, W. Ost, P. De Baets, T. De Baets, The influence of scratched steel counter face on friction and lifetime of UHMWE-PE, Proc. 8th International Conference on Tribology, Budapest, 2004, 69–76.

[15] S. Irullappasamy, W.J. Jebas Thangiah, S. Bheemappa, Investigation on Mechanical and Tribological Behavior of Naturally Woven Coconut Sheath-Reinforced Polymer Composites, Polymer Composites Volume 33, Issue 5 (2012), 723–732.

[16] J.T.W. Jappes, I. Siva, Studies on the Influence of Silane Treatment on Mechanical Properties of Coconut Sheath-Reinforced Polyester Composite, Polymer-Plastics Technology and Engineering, 50 (2011), 1600–1605.

[17] J. Sukumaran, S. Soleimani, V. Rodriguez Fereira, W. Philips, P. De Baets, An unconventional approach in polymer wear: online vision system, 1th Nordic Symposium on Tribology: Danish technological institute, 2014.

[18] M.J. Edmonds, A.M. Jones, P.W. O'Callaghan, S.D. Probert, A three-dimensional relocation profilometer stage, Wear 43 (1977), 329–340.

[19] J. Sukumaran, Vision assisted tribography of rolling-sliding contact of polymer-steel pairs, PhD-thesis (2014), Ghent University.

[20] S. Soleimani, Computer Vision System for Wear Analysis, PhD-thesis (2014), Ghent University.

[21] S. B. Gunther, J. Graham, T.R. Norri, M.D. Ries, L. Pruitt, Retrieved glenoid components: A

classification system for surface damage analysis, The Journal of Arthroplasty 17 (2002), 95–100.