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CHARACTERIZATION OF THE FRICTION BEHAVIOR OF TABLE TENNIS RUBBERS

Abstract

Recently, novel polymeric materials (bulk elastomers, elastomer foams, fibers and fiber reinforced composites) were developed and are frequently used for racket sport equipments. These materials reveal highly non-linear, time and temperature dependent mechanical behaviour and the material performance is highly influenced by the environmental conditions (temperature, humidity, pollution). Hence, to support both material development efforts and novel design procedures for high performance racket sport equipments, novel tests methods and procedures to characterize the bulk and surface mechanical behaviour were developed, implemented and applied.

The main objective of this paper is the characterization of the surface behaviour of both pimple in and pimple-out table tennis rubbers. Hence, the friction between table tennis ball and rubber surfaces was measured under various sliding motion conditions and the results are described and discussed in the paper. Special emphasis was devoted to the proper definition of the friction and the determination of the main influence parameters on the friction.

The rubber friction is widely investigated over a wide range of test conditions and is described and the results discussed in many scientific papers. The main driving force of these investigations was the characterization of tire rubber friction/traction under dry and especially wet conditions. The friction force for rubber is a sum of the contribution of two essentially different physical processes; the adhesion between rubber and solid counterpart and the deformation of the elastomers which is described as the hysteretic deformation of the rubber

$$F_r = F_{adh} + F_{hyst} \tag{1}$$

Where F_r is the friction force, F_{adh} the adhesion force component and F_{hyst} is the hysteretic deformation force component. While the hysteretic component can be derived from the dynamic mechanical test performed and described in the previous paper, the determination of the adhesion component remains a challenging task.

To gain more insight into the complex surface behaviour of rubbers friction tests were performed using a universal microtribometer (UMT, CETR, Campbell, CA, USA). The table tennis ball was glued into a fixture and this was positioned in the upper moving part of the UMT. The test specimen was the rest of the cut table tennis rubber sponge and was glued to a steel plate fixed in the lower stationary drive of the UMT. The table tennis ball was first pressed with a controlled normal force (F_z) into the rubber surface and subsequently a linear sliding motion with controlled rate was applied. The normal force was varied as 1, 2, 5 and 10 N and the sliding rate was 0.1 and 1 mm/s in the experiments.

Both the normal (F_z) and the friction force (F_x) was continuously measured and recorded during the test. The coefficient of friction (COF) was then calculated in the test software.

The results of these investigations are described and discussed as:

- *Influence of the normal load and sliding rate on the friction behaviour of table tennis rubbers,*
- *Effect of the surface cleanness on the friction behaviour,*
- *Recognition of the modification of the surface by additional treatment and*
- *Comparison of the friction characteristic of various commercial table tennis rubber sponges.*

Key words: *table tennis, pimple-in and pimple out table tennis rubbers, friction behaviour, sliding rate and load dependence, cleanness, material comparison*

In addition to the bulk elasticity, the surface friction plays an extraordinary important role in the behavior of table tennis rubbers. Hence, the friction between table tennis ball and rubber surfaces was measured under various sliding motion conditions and the results are described and discussed in the paper. Special emphasis was devoted to the proper definition of the friction and the determination of the main influence parameters on the friction. Furthermore, dynamic mechanical analysis (DMA) tests were also performed to estimate the hysteretic contribution to the friction and compare various rubber types. Finally, instrumented rebound tests were performed and the time dependent change of the advancing and receding angle (rebound) was measured and compared for various rubber types for clean and for dirty surface conditions.

1 Introduction, scope and objectives

In table tennis recently, complex racket designs are used consisting of a wooden or glass or carbon fiber reinforced racket frame with multi-layer rubber/foam covers with special top surface properties. Various rubber compounds and glues (adhesives) are applied in the build up of the multi-layer rubber foam cover to impart greater spin or speed onto the celluloid ball. In terms of material characteristics, important aspects of a successful table tennis racket design are related to the elasticity and damping of the entire sandwich system and the specific surface properties that generate the spin of the celluloid ball upon the impact contact with the rubber surface. Despite the high interest of applying scientific concepts to table tennis, there is currently no widely accepted methodology available to characterize and to determine the performance profile of table tennis rackets as a whole or of individual or combined polymeric material layers in terms of their viscoelastic properties and property functions (Harrison and Gustavsen, 2002). In systematically characterizing table tennis racket materials, various aspects need to be considered. While the monotonic and cyclic small strain bulk deformation behavior of several sandwich rubber types was characterized and the results were presented and discussed in the previous paper (Major, 2005), the surface behavior was characterized in this study.

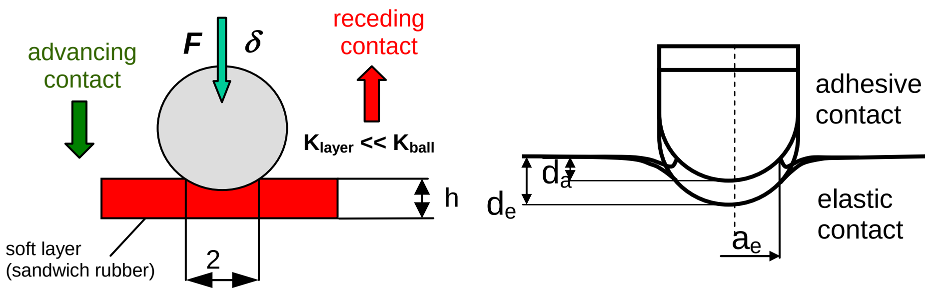
With similar bulk properties of rubber sheets, pimple-in and pimple-out rubbers might reveal significantly different surface properties. Moreover, for pimple-in rubbers the friction properties are of special importance, which are a complex product of the adhesion capability and the surface deformation behavior on a local scale (Charmet et al., 1999).

It is assumed that the dynamic motion performance of the ball after the rubber contact is a complex function of the rubber elasticity (stress-strain curve and hysteretic behavior) and the adhesion behavior of the rubber. The rubber friction is widely investigated over a wide range of test conditions and is described and the results discussed in many scientific papers (Uitz and Wiedermeyer, 1984). The main driving force of these investigations was the characterization of tire rubber friction/traction under dry and especially wet conditions. The friction force for rubber is a sum of the contribution of two essentially different physical processes; the adhesion between rubber and solid counterpart and the deformation of the elastomers which is described as the hysteretic deformation.

$$F_r = F_{adh} + F_{hyst} \quad (1)$$

Where F_r is the friction force, F_{adh} the adhesion force component and F_{hyst} is the hysteretic deformation force component. While the hysteretic component can be derived from the dynamic mechanical test performed and described in the previous paper, the determination of the adhesion component remains a challenging task, especially under highly dynamic conditions.

The dynamic contact (advancing and receding phase) of elastic and viscoelastic bodies with and without adhesion is studied and is described in various papers (i.e., Charmet et al., 1999). The schematic presentation of the contact situation is seen in Fig. 1 where K_{layer} is the stiffness of the viscoelastic layer and K_{ball} is the stiffness of the impactor (ball).



(a) (b)

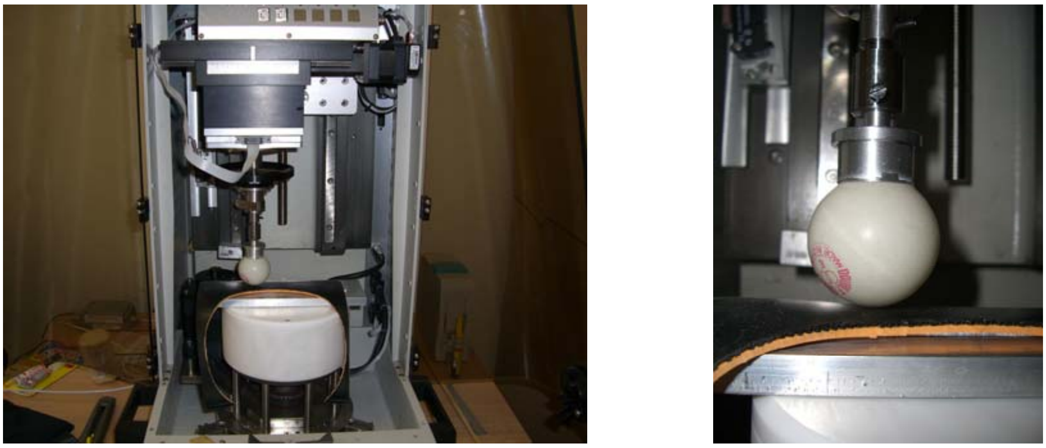
Fig. 1: *Table tennis ball (ideal rigid) and rubber sheet (non-linear elastic) in the contact situation (a) and (b) the surface profile in pure elastic contact compared to adhesive contact.*

The main objective of this study was the characterization of the friction behavior of table tennis sandwich rubbers consisting of specific rubber cover sheets (pimple-in) and sponge (cellular) rubbers under both monotonic and cyclic loading conditions.

2 Experimental

2.1 *Friction test using a tribometer*

Friction tests were performed using a universal microtribometer (UMT, CETR, Campbell, CA, USA). The test set-up is shown in Fig. 2. The counterpart was an unclean table tennis ball. The table tennis ball was glued into a fixture and this was positioned in the upper moving part of the UMT. The local contact situation is seen in Fig. 2b.



(a) (b)

Fig. 2: *Friction tests with table tennis ball and sandwich rubber on a tribometer; (a) tribometer test set-up and (b) local contact.*

The test specimen was the rest of the cut table tennis rubber sponge. The test specimen was glued to a steel plate fixed in the lower stationary drive of the UMT. The table tennis ball was first pressed with a controlled normal force (F_z) into the rubber surface and subsequently a linear sliding motion with controlled rate was applied. The normal force was varied as 1, 2, 5 and 10 N and the sliding rate was 0.1 and 1 mm/s in the experiments. Both the normal (F_z) and the friction force (F_x) was continuously measured and recorded during the test. The coefficient of friction (COF) was than calculated in the test software. The data were transferred into scientific calculation software (OriginPro7, OriginLab Co, MA, USA) and the diagrams were constructed and plotted.

Two different groups of the pimple-in rubbers were investigated. While in the first test series the rubber types provided by the producers without additional cover film were tested, covered with a transparent cover film were applied in the second. In the first case the rubbers were stored in a sport bag about 1 month long before testing. These rubbers were than tested without and with additional surface cleaning. The cleaning was realized using isopropanol alcohol. In the second case the cover film was removed only immediately before the test. This surface was tested only in this state and was assumed as clean. In addition, two pimple-out rubber types were also tested. One of them was tested also after additional manipulation of the pimple surface.

2.2 *Dynamic mechanical analysis*

Monotonic and small scale cyclic compression tests (DMA) were performed using disc shaped specimens with a diameter of 34 mm cut from the original rubber sheet. The tests were performed both between parallel compression platens (uniaxial tests) and using ball shaped indenter (indentation type tests). The experimental work involved various table tennis sandwich rubber types from different producers with different thicknesses.

(a) (b)

Fig. 3: *Monotonic compression and dynamic mechanical analysis test set-up on an electrodynamical test system; test system and (b) compression platens.*

To determine the hysteretic component of the friction the DMA experiments is of special importance. Hence, these tests are described and analyzed briefly in this chapter.

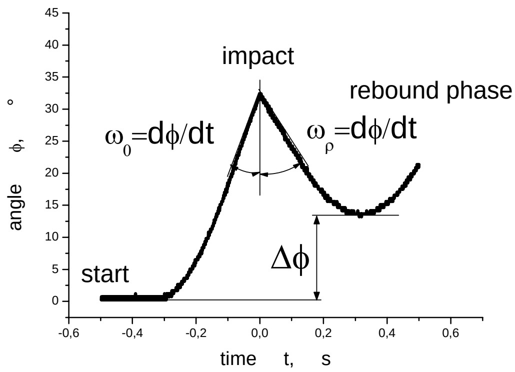
Dynamic characterization tests were performed under cyclic compression over a wide frequency range to determine the frequency dependence of the complex dynamic stiffness, K^*, the visco-elastic damping, $tan\delta$. All of the above tests were performed at room temperature (23 °C) and at 50% relative humidity using either a high rate servohydraulic polymer test system (MTS 831.59 Polymer Test System, MTS Systems Corp., MN, USA) or an electrodynamic test system (BOSE 3200, MN, USA).

During the cyclic experiments the frequency was swept from 1 to 100 Hz, the mean load was force controlled having two values and the dynamic amplitude was displacement controlled also having two selected values (one represents smaller the other larger deformations).

2.3 *Impact rebound tests*

To simulate the real impact contact between ball and rubber sheet, impact rebound tests on various rubber types were also performed. A novel instrumented rebound test system was used in these experiments. This system was developed on the basis of a conventional pendulum (Zwick, Ulm, D) and modified and instrumented for impact rebound tests. The instrumentation involves both the measurement of the angle (advancing and receding) by an inductive RVDT (Positek P500.60DJ, Cheltenham, UK) and contact forces. A 3D piezoelectric load cell (Kistler 9347B, Winthertur, Ch) along with three charge amplifiers (Kistler 5001) is able to simultaneously measure not only the normal load (z) but also the shear component in-plane in both directions (x ynd y). The signals are recorded by a storage oscilloscope (Tektronix TDS2004B, Baeverton, OR USA) and the data transferred via USB to PC and analyzed by scientific data analysis software (Origin 7.5, OriginLab, MA, USA). The test system is shown in Fig. 4a and a typical rebound signal is plotted in Fig. 4b.

(a)



(b)

Fig. 4: *Rebound tests; (a) test system and (b) the angle signal with the various stages of the impact and rebound process.*

Disc shaped specimens with diameters from 32 to 40 mm were cut from the remaining part of the rubber sponges. All types of rubber were tested first in a clean state and the surface was made dirty by fine powder at the second set of the specimens. Furthermore, the rebound was characterized with specimens positioned at 90°, 67 °, 45° and 22° regarding to the horizontal plane. The impact test rate was about 1 m/s, corresponds to a starting angle of 31,2°.

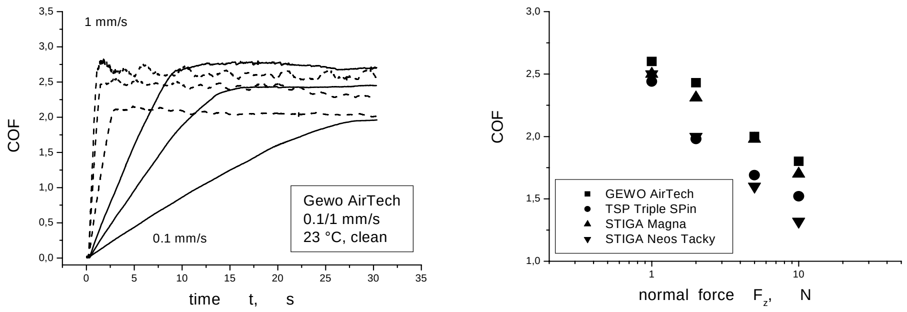
3 Results and Discussion

3.1 *Friction tests*

The results of these investigations are described and discussed in terms of

- Influence of the normal load and sliding rate on the friction behaviour of table tennis rubbers,
- Effect of the surface cleanness on the friction behaviour ,
- Recognition of the modification of the surface by additional treatment and
- Comparison of the friction characteristic of various commercial table tennis rubber sponges.

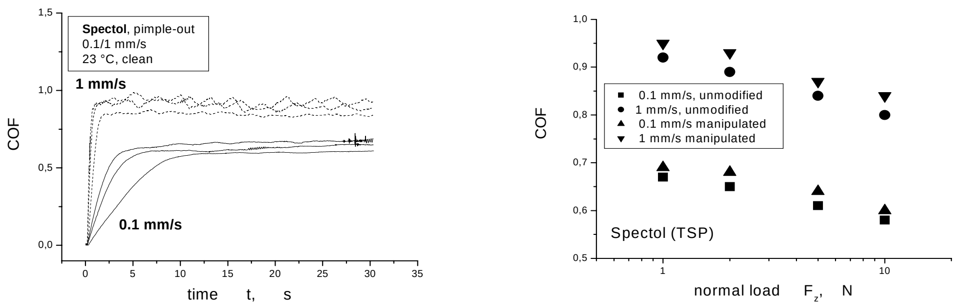
The sliding rate and normal load dependent COF-time curves are plotted in Fig. 5a for a pimple-in rubber type (AirTech^R, GEWO) and a comparison of four rubbers in Fig. 5b. In general, a negligible sliding rate dependence of the COF was observed for all type of rubbers (Airtech^R, TripleSpin^R (TSP), NeosTacky^R and Magna^R (STIGA)) with protecting cover film. The protecting cover film was of course removed immediately before the friction tests.



(a) (b)

Fig. 5: *Sliding rate and normal load dependent COF-time curves for a pimple-in rubbers; (a) Rubber type (AirTech^R, GEWO) and (b) comparison of various rubbers.*

The sliding rate and normal load dependent COF-time curves are plotted in Fig. 6a for a pimple-out rubber type (Spectol^R, TSP). As it was expected the COF values are significantly lower (in the range from 0.6 to 0.9) for pimple-out than for pimple-in rubbers. Furthermore, higher sliding rate dependence and a negligible normal load dependence was observed.



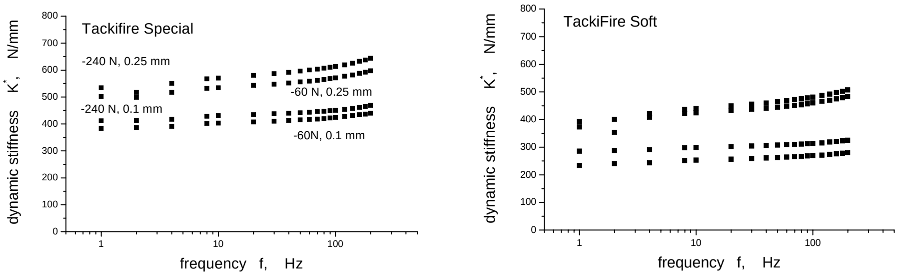
(a) (b)

Fig. 6: *COF functions of a pimple-out rubber for unmodified and for modified state.*

Moreover, as it is clearly seen in Fig. 6b even a small degree of manipulation of the rubber surface can be detected using this method. Finally, the difference between the pimple-out rubbers was also determined, the China pimple-out rubber type revealed slightly (but with clear tendency) higher COF values than Spectol.

3.2 *Dynamic mechanical analysis*

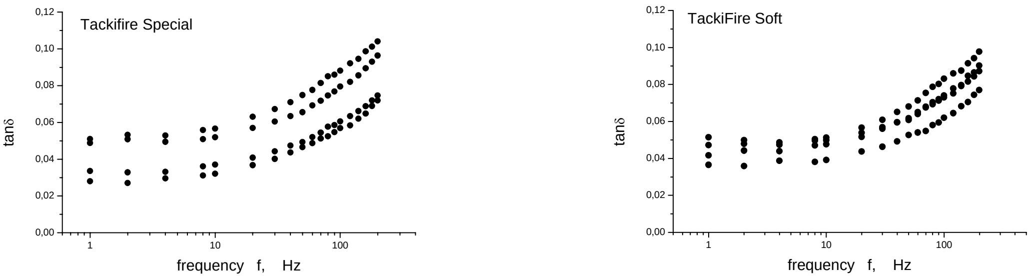
The results of this investigation are discussed in terms of frequency dependent material property functions (K*, tanδ). The frequency and load level dependence of K*, tanδ determined in dynamic experiments are depicted in Figs. 7 and 8 and are subsequently discussed.



(a) (b)

Fig. 7: *Frequency dependence of the dynamic stiffness for two rubber types; (a) Tackifire Special and (b) Tackifire Soft.*

The **stiffness** (geometry dependent) is the ratio of change of force to the corresponding change in deformation of an elastic element. The frequency dependence of the complex dynamic stiffness, K* is shown in Fig. 7. Moderate frequency dependence and due to the nonlinearity a more pronounced mean load and dynamic amplitude dependence were obtained. Tackifire Special^R (TF, Butterfly) reveal about 20-25 % higher stiffness in the frequency range than Tackifire Soft^R (TFS, Butterfly). Moreover, TFS reveal more load dependence than TF. The stiffness of the sandwich rubber should be correlated to the speed rating.



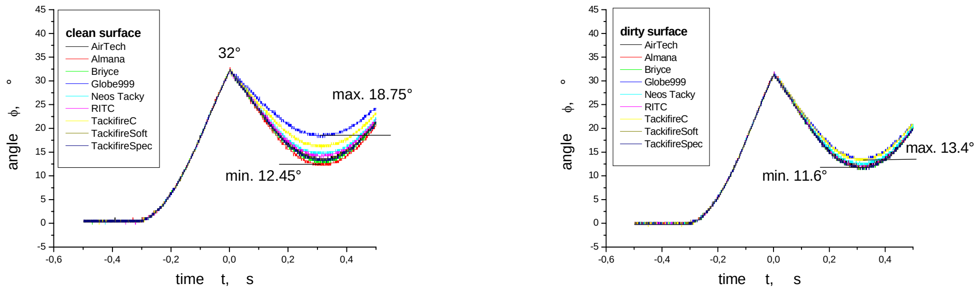
(a) (b)

Fig. 8: *Frequency dependence of tanδ values for two rubber types selected from product group 1; (a) Tackifire Special and (b) Tackifire Soft.*

The **value of tan**δ is the tangent function of the phase angle difference between load/stress and displacement/strain. The value of tanδ is a very important viscoelastic parameter and proportional to the damping properties of a material. It is interesting to note, that TF reveal a more pronounced load level dependence than TFS. Significant frequency dependence of tanδ is observed for both materials (see Fig. 8).The tanδ should be correlated to the control characteristics of the sandwich rubber, in hand due to the bulk damping and due to the contribution of the hysteretic friction on the other.

3.3 *Impact rebound test*

For simplicity, only the change of the angle are plotted and analyzed for various rubber types at 90°.



(a) (b)

Fig. 9: *Change of the rebound angle for various rubber types for; (a) clean and (b) dirty surfaces.*

Based on the angle difference the height difference and thus the energy difference could later be calculated. The change of the rebound angle for various rubber types investigated is shown in Fig. 9. The minimum and maximum values are lower and the $\Delta\phi$ (max-min) significantly higher for the clean surfaces. That is, the rebound behaviour is clearly influenced by the adhesion of the surface and this influence depends on the material grade.

4 Conclusions and Future Work

The results of these characterization methods reveal significant differences in both the bulk mechanical behavior as well as in the surface behavior of the various table tennis rubber types investigated.

Nevertheless, more detailed investigations are needed to characterize the effect of surface properties (wear, reduction of adhesion) and their relationship with the bulk properties on the overall performance of the sandwich rubbers. What is also particularly needed, is a thorough comparison between polymer science based properties and property functions and subjective performance evaluations by top players. In establishing correlations between subjective (player based) and objective (polymer science based) material rankings, a powerful tool may be made available to support future product development efforts.

Acknowledgments

Parts of this project were performed at the Polymer Competence Center Leoben GmbH within the K_{plus}-programme of the Austrian Ministry of Traffic, Innovation and Technology. The funding within this programme by the Governments of Austria, Styria and Upper Austria is gratefully acknowledged.

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