Wear behavior of carbon fiber reinforced Poly Phenylene Sulfide

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Abstract:

On a pin-on-disc test rig online measurements of the wear and friction of steel sliding against carbon fiber reinforced PolyPhenylene Sulfide were done. Instead of the standard set-up, a rotating composite disc and steel pin are used. The frictional behavior of this material pair results in a friction coefficient of 0.33, while a carbide film is formed in the wear track. This results in a lowering of the frictional behavior. The wear rate is rather low, but when the wear track is covered with a carbide film suddenly the wear rate raises. This is not due to the wear of the composite material but only as a result of the start of terrible wear of the steel counter face. Moreover, the wear of the pin is strongly related to the wear track. The pin is flattened at the sides of the formed wear track, but in contact with the carbide film there is less wear, resulting in a pin with two flat sides, making contact with the original surface, and a rig in the middle of the pin following the roundness of the wear track. The frictional behavior is strongly dependent on the weft-warp direction.

Keywords: Composites, Wear, Pin-on-disc, carbide film, friction

Introduction

Since poly phenylene sulphide (PPS) (Fig. 1) is a semi-crystalline thermoplastic polymer with high glass transition temperature (90°C) and high melting temperature (280°C) and high mechanical strength, PPS is a promising rubbing material as reported by many authors [1-8]. PPS is also a very well known polymer for its high service temperatures, low creep (even at elevated temperature), fairly low water absorption, quite high chemical resistance, high hardness, flame and thermal resistance, and high rigidity. Unfortunately, PPS is a quite brittle material with low impact strength [9-13].
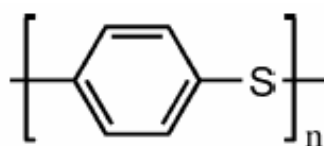
Fig. 1: Poly (*p*-phenylene sulphide)

In the case of pure PPS, the steady state wear rate increased at both low and high sliding speeds. Thermal softening was observed at the sliding speed of 2 m/s thereby resulting in higher wear rate. The coefficient of friction of PPS decreased as the sliding speed was decreased from 1.0 to 0.25 m/s, but the highest sliding speed of 2 m/s showed the lowest coefficient of friction because of thermal softening [14-15]. It was also shown that the development of a transfer film was associated with counter face roughness, and the transfer films were patchy and discontinuous when the counter face roughness was either very low or very high. EDS analysis of the transfer film of PPS composites with CuS as filler material showed that the transfer film consisted of FeS, CuO, Cu, and Fe_xO_y. This indicated tribochemical reaction between Fe in the counter face and S in the filler. The indication of such a reaction was not found from EDS analysis of the transfer film of ZnF_2-PPS composite [4]. In tribological testing the steel counter face does not wear due to the PPS, but as a result of the abrasive action of possible fillers.

To the author's knowledge no literature is found on the wear and frictional behavior of woven plates in relation to the weft-warp directions.

In this paper, it is shown that the wear resistance of the carbon fiber-reinforced PPS, is depending on the behavior of the carbon fibers. The frictional behavior is strongly dependent on the weft-warp direction.

Test rig:

A new pin-on-disc test rig (Fig. 2) was built in order to be able to monitor the tribological behavior of composite materials as bearing material. The materials on the most common pin-on-disc set-up [15-18] (composite pin/steel disc) were switched, namely a composite disc and a steel pin were used. This yields the possibility that in one test the influence of the fiber orientation on wear and friction can be investigated by choosing a unidirectional fiber reinforced composite.
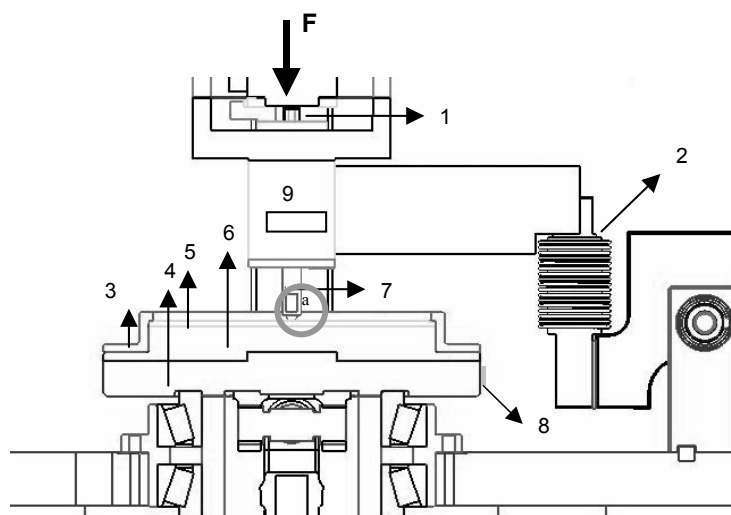
Fig. 2: Pin-on-disc test rig, with (1) normal load cell, (2) friction load cell, (3) ring for keeping the composite disc fixed and in the centre, (4) fixed disc on the test rig, (5) composite disc, (6) removable disc where the composite test specimen is glued on, (7) pin, (8) magnets for triggering, (9) contactless proximitor counter face

The pin (7), made of steel, with a length of 35 mm is hollow at the top, because measuring bending of the pin with strain gauges requires a sufficient strain in the steel pin. Two flat parallel faces close to the contacting surface are places for an accelerometer (see Fig. 2,a) and an acoustic emission sensor. Thermocouples can be placed all over the pin geometry. A ball from a deep groove ball bearing forms the mating surface, or the top of the pin. Thus the pin can be reused, while only the ball has to be replaced.

Characteristics of this test rig are: relative velocities from 10 up to 100 mm/s, a possible normal load up to 1000 N, and the possibility to place additional sensors on the pin (2) for further research.

For the measurement of the wear depth of the wear track, a contactless proximitor (9) is used, providing an estimate of the evolution of the wear depth with time.
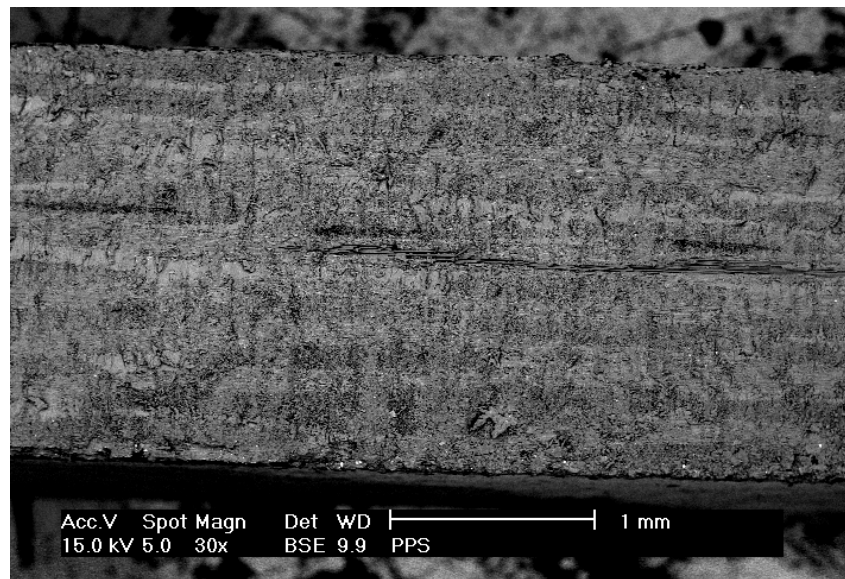
For measuring the normal force on the pin a load cell is placed above the pin (1). This load cell is protected by a spring mechanism, which allows pressing directly on the load cell, without damaging this load cell. Another method to measure the normal force on the pin is by measuring the air pressure in the cylinder used as supplier for the normal force. This cylinder is connected via valves to the compressor. The friction force is measured with a load cell (2).

On the rotating disc, magnets (8) are placed, which are not only used as trigger for the various signals, but are also used to synchronize measured friction and wear signals with the fiber orientation. This type of indication is very reliable, and gives the possibility to calculate the values of the friction force related to a specific orientation (0°, 90°, 180°, 270°).

On a steel disc (6), the composite disc (5) is fixed with bee wax. Due to high frictional loads this might not prevent rotation of the disc, therefore the disc is kept in place with an external ring (3). This ring not only presses slightly the composite disc onto the steel disc at the edge, but also makes sure that the composite disc stays centered to the rotation, yielding a perfectly circular wear pattern on the disc. This replaceable disc construction is then placed on a fixed disc (4). The whole disc construction rests on two bearings, and is driven by the axis of a reduction unit, which itself is driven by an asynchronous motor through a speed reducer and a timing belt.

Materials and method:

The fiber-reinforced composite (Fig. 3) disc under study was a 5-harness satin (see Fig. 4) weave carbon/PPS composite. Poly Phenylene Sulphide (PPS) is a commonly used thermoplastic matrix in aeronautical applications. Eight layers of fabric were stacked in sequence $[0°/90°]_{2s}$, the angle indicates the warp direction of the reinforcement layer. This results in a carbon content of $50 \pm 3\%$. Discs were cut out by water jet process, and a cross section of the material is shown in fig 3. The white zones constitute pure PPS, while the dark zones represent carbon fibers. The thickness of the discs is about 2.5mm; while the discs have a diameter of 160mm.

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Fig. 3: Scanning electron microscopic image of the cross section of the carbon-fibre reinforced PPS
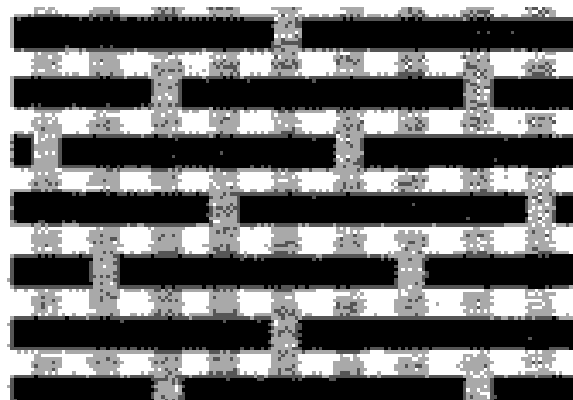
Fig. 4: Schematic diagram of 5-harness satin weave

The EDX-spectrum of this cross section (Fig. 5), shows high peaks of C (Carbon) and S (Sulphur). Also Au (gold) is found in minor amounts. This is due to the fact that the sample was pre-treated with a minor amount of gold for higher contrast SEM images. The peaks of Si (Silicon) and K (Potassium) originate from the abrasives used in water jet cutting.
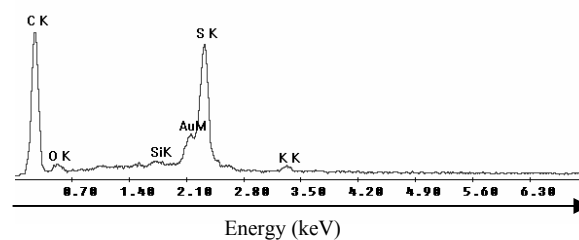
Fig. 5: EDX spectra of the area in fig 3.

Carbon fiber reinforced PPS-discs were mounted on the removable disc (Fig. 2, 6). A closer look on the test set up is given in Fig. 6. The test parameters were 250N normal load and a relative velocity of 20 mm/s. A test consisted of 10.000 revolutions with a sliding distance of 400 mm per revolution, yielding a total sliding distance of 4 km.
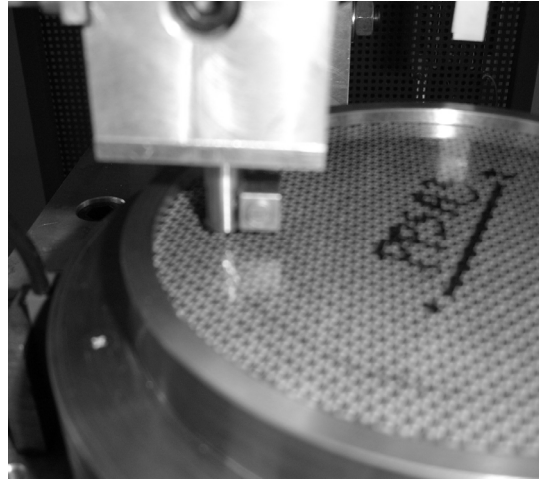

Fig. 6: Pin-disc configuration, closer look at contact zone

Results:

WEAR:

Results of the tests performed at 250 N and 20mm/s are presented in figs. 7 and 8. In these graphs, the wear and frictional behavior of the pin-disc material combination is plotted as a function of the time. Each point of the curvature is obtained by averaging 250 points, measured at 50Hz of each round, so each curve in the graphs of Fig. 7 and Fig. 8 consists of 10,000 points being one average value for each round.
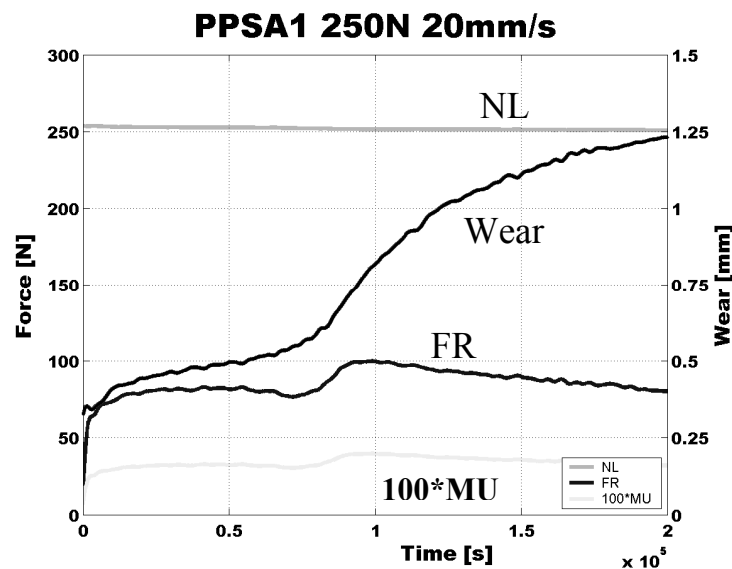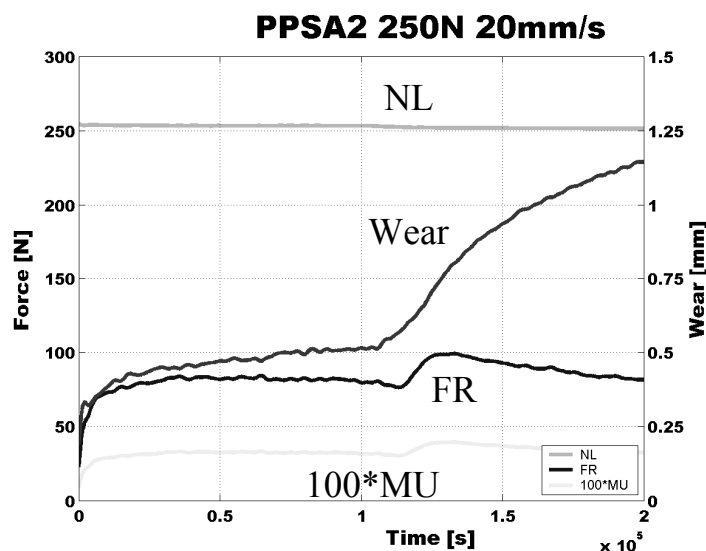

Fig. 7: Test results at 250N, 20mm/s (Disc PPSA1) with the upper line the normal load (NL, left axis), the 2 lowest lines are the friction force (FR, left axis) and the coefficient of friction multiplied by 100 (100*MU, left axis), also indicated on the left, while the second line from above is the evolution of the wear depth (right axis)

PPSA2 250N 20mm/s

Fig. 8: Test results at 250N, 20mm/s (Disc PPSA2) with the upper line the normal load (NL, left axis), the 2 lowest lines are the friction force (FR, left axis) and the coefficient of friction multiplied by 100 (100*MU, left axis), also indicated on the left, while the second line from above is the evolution of the wear depth (right axis)
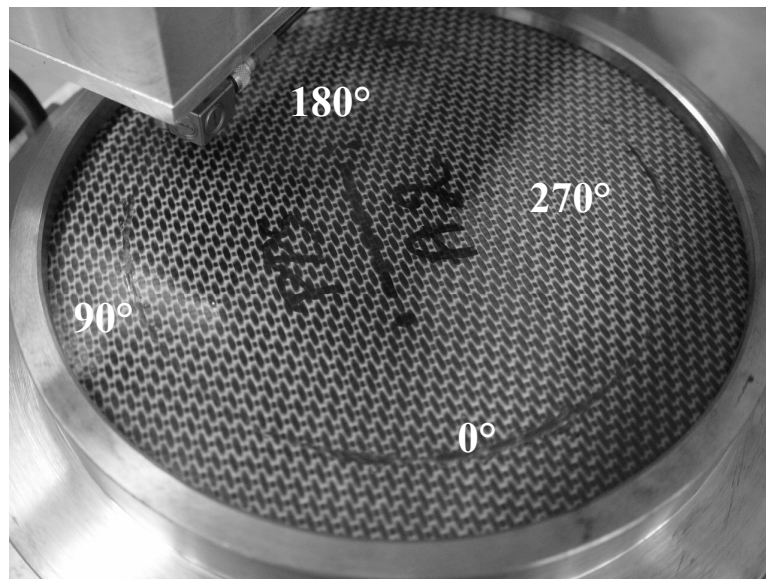
At a constant normal load (250N) the evolution of wear is rather exceptional. After a small running in period, the composite wears very slowly, until, at a certain moment (75.000 s), the wear depth increases very strongly. Just before the rise in wear rate, the friction force decreases, then rises when the wear rate rises, and lowers again linearly after 100,000 s. The total wear depth after testing is 0.95mm.

A second test (Fig. 8) performed under the same conditions shows an identical phenomenon, albeit somewhat later on in the test.

While in Fig. 7 the wear rate increases after 75.000 s, in Fig. 8 the increase of the wear rate starts after 115,000 s. The rest of the graph is exactly the same, as well in evolution in time as in magnitude.

Images of the disc were taken during testing and provide an overview of the worn disc (see Figs. 9 – 10).

Fig. 9 shows the wear track of the disc after 450 rounds. As fig 9 shows, the width of the wear track on the disc correlates with the fiber orientation. The 90° disc position (parallel fiber orientation with the weft direction) and the 0° disc position (indicated via the line in the middle of the disc) orientation have an earlier wear through the top layer of PPS than the 45°, and perpendicular to the weft direction (0° disc position) has an earlier wear through than the parallel (90° disc position) as shown by the larger wear track at the 0° disc position.

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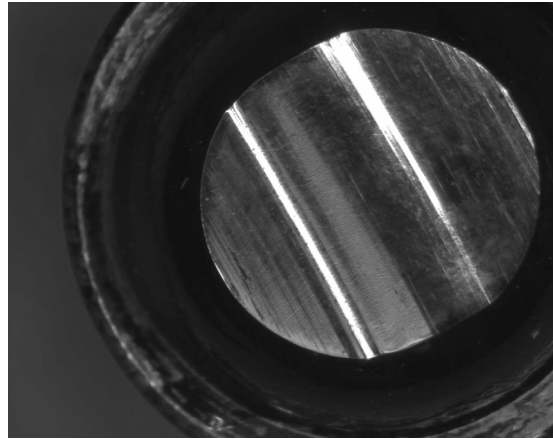
Fig. 9: Image of the wear state of disc PPSA2 after 450 rounds

At the end of the test (Fig. 10) wear debris can be seen next to the wear track, almost equally divided between the inner diameter and the outer diameter of the wear track. Interesting to note is that between the two edges with wear debris, two flat zones are visible where carbon fibers and PPS (as in the original top view of the disc) can be seen, while in the middle the wear track can be seen. These two flat zones does not seem to have suffered from any wear (original surface), while in the middle of the wear track, a carbon (black) film is visible.
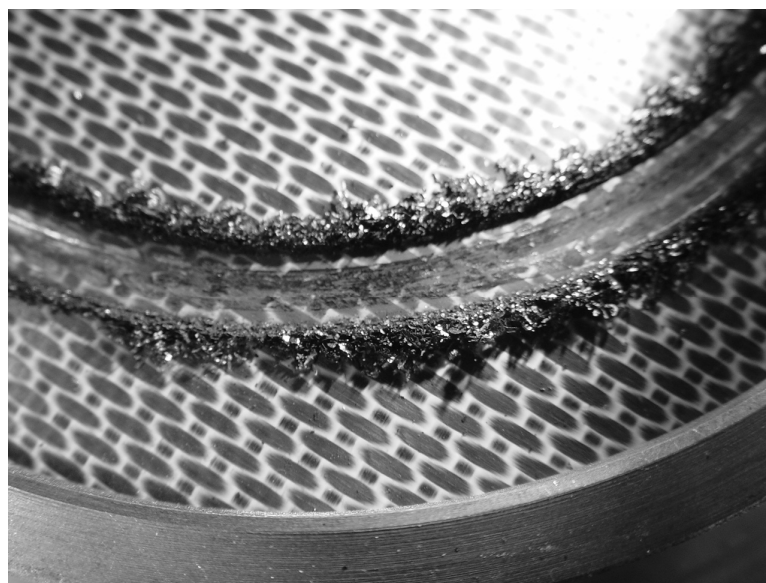
Fig. 10: Wear track of disc PPSA2, after 9000 rounds.

After testing also post mortem images were taken. For instance the worn pin is shown in Fig. 11.

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Fig. 11: Resulting contact area of pin after 4 km at 20 mm/s and 250N normal load.

The left side on this picture corresponds with the inner diameter of the wear track; right corresponds with the outer diameter of the wear track.

Due to the lighting a curved zone in the middle of the pin can be observed. At the edges of the pin two flat zones are present, with grooves in the direction of motion. The higher middle zone is not flat, but follows a certain curvature.

A 3D scan of the worn pin top was taken. The result (see Fig. 12) reveals a zone, which is higher than the two flat zones at the sides.
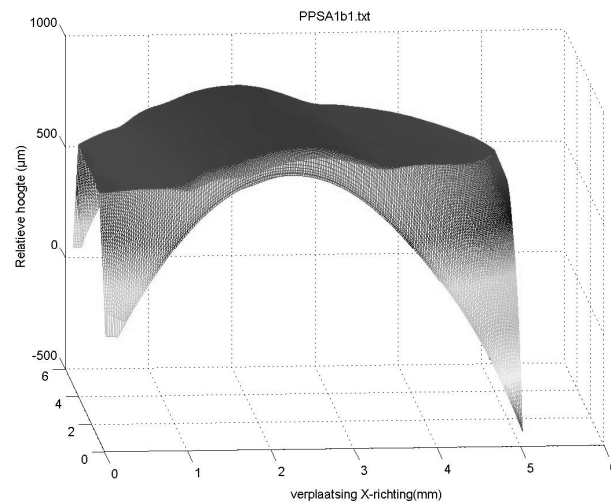

Fig. 12: 3D-scan of final pin top after testing

FRICTION:

The results of the frictional behavior of the pin-disc combination are given in Fig. 13. In this graph two regions can be separated. The first one till half way testing results in a constant coefficient of friction (COF) of 0.33, independent of the orientation of the fibers. Half way the test, when the pin starts wearing a separation dependent on the fiber orientation is reached. The order of friction force, related to the disc position, and therefore also related to the fiber orientation (weft-warp) from lowest value till highest is: 45°, 225°, 90°, 270°, 0°, 135°, 315° and 180°. This is rather strange, and

there is no direct correlation with parallel or perpendicular orientation. Even the 45° orientation behaves not uniform.
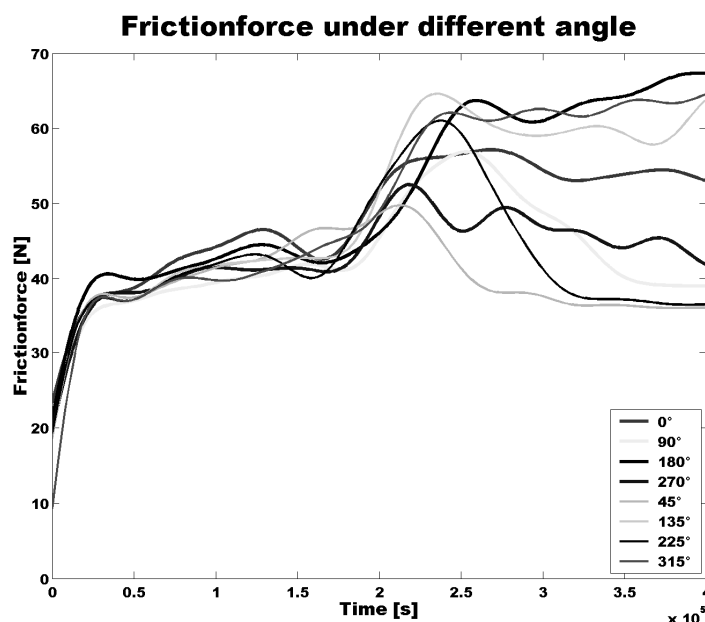
Fig. 13: Test results at 125N, 10mm/s (Disc PPSA4) for the frictional behavior in time, related to the position on the disc

The behavior of the same positions on the disc, but 180° difference acts near the end almost the same. This is completely true for all 45° orientations (45° and 225°) and (135° and 315°). Also the behavior of 90° and 270° seems to yield a comparable value. Strong difference still remains in the 0° and 180°.

Just after half way of testing (200.000s), for a test at 125 N and 10mm/s, different behavior can be seen for different orientations, but also in the corresponding directions. All the orientations have a rise in friction force, while further on, the 0°, 180° 135° and 315° act almost the same and stay constant after rising. The other directions have or a not so spectacular rise in friction force, and a drop down later on (45° and 270°) or a spectacular rise like 0°, etc. but have a slower drop down in time of their friction force (225° and 90°).

DISCUSSION

The differences between the two tests are due to differences in material structure. Although all the discs had the same stacking sequence ($[0°/90°]_{2s}$), a small difference in thickness of the outer PPS layer is possible. The plates for both tests were cut-out from plates made by compression molding. This technique makes differences in thickness of top layers possible, due to the flow of the thermoplastic polymer, in this case the PPS [19-20]. The difference in thickness of the PPS layer above the first carbon fibers explains the difference in time between Fig. 7 and Fig. 8.

The wear behavior vs. time can be explained as follows. At the beginning of the test the contact between pin and disc is a point contact, resulting in very high contact pressures. As the top layer of the plate is pure PPS this results in a rather large plastic deformation of the PPS layer. As shown in Fig. 9, break through this PPS layer does

not happen at the same time all over the disc. The influence of the orientation of the fibers in the upper fabric, gives an earlier break through for perpendicular orientation to the direction of motion, followed by the parallel orientation, and finally the 45° orientation. This break through could also be visualized when monitoring a full round, where the wear depth changed in relation to the position of the disc. After a completed wear track is formed, carbon starts playing an important role in the friction and wear behavior.

In the wear track a carbon film is formed. This film lowers the coefficient of friction, (around 75.000 s and 115.000s respectively). But also the formation of this carbon film increases the wear rate of the pin.

The worn pin top, with two flat zones, besides a higher zone in the middle, is due to third body abrasion. Carbon particles, and steel particles after initial wearing of the pin, were pressed outside the wear track. These results in wear debris next to the edges and play a role as third body particles.

The final friction coefficient is around 0.33, which is in agreement to the values found in literature [21-22]. The slight decrease of the friction coefficient in the last part of the test is caused by a decrease of contact pressure with increasing wear (and contact zone).

If the complete separation with orientation of fibers is taken into account, a complete different behavior related not only to fiber orientation, but also depending on the weft-warp direction can be noticed. The strange behavior halfway testing can be easily explained by the start in wear of the pin. By that time a wear track has already been formed, and will hardly change later on during the test. Only some metal particles from the pin will get involved in the friction process.

The clear separation 0°, 180° 135° and 315° vs. 45°, 225°, 90°, 270° can be explained by difference in weft-warp direction. While the first group of orientations correspond to a perpendicular movement over the weft the other group corresponds with a perpendicular movement over the warp. The 45° and 225° involves a movement from perpendicular on the weft direction (0°) to perpendicular to the warp direction (90°), the other way around for the orientations 135° and 315°.

CONCLUSIONS

The following conclusions can be drawn from these tests:

1. The new test set-up yields promising results and a high repeatability.
2. The material used in this investigation reveals, in these wear and friction tests, a way to determine differences related to the production process.
3. The measured friction forces are in relation with values found in literature, and the carbon film created in the wear track decreased the overall friction force.
4. The wear of the steel pin was, due to the repeatability of the test results, not related to a possible lower quality of the ball at the pin top.
5. The wear of the pin top is very strongly correlated to the form and the formation of the carbon film into the wear track.
6. The frictional behavior is strongly influenced by the fiber orientation; even the production direction plays an important role. Perpendicular to the warp results in a lower friction if compared with the direction perpendicular to weft direction.

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