# FRICTION AND WEAR STUDIES OF SOME PEEK MATERIALS

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## ABSTRACT

The friction and wear behavior of several types of PEEK polymers and composites were studied. The influence of carbon fiber, lubricant and thermally conductive fillers were evaluated, as well as the effects of contact load and temperature. The tests were done using a reciprocating ball-on-disc set-up. The materials were tested under the load of 5 N and 15 N, at room temperature, 80°C, 120°C and 150°C. The difference between the materials was substantial, with a friction coefficient varying between 0.03 and 0.3 for the different materials at 120°C. PEEK with carbon fiber filler showed an improvement in both friction and wear compared to unfilled PEEK. When adding lubricant, PTFE, to the composite the friction and wear were improved even more. PEEK with thermally conductive filler on the other hand had both highest friction and wear. Increasing the temperature slightly decreased both friction and wear for most of the PEEK materials. At 150°C, only the composite with PTFE lubricant had a low friction and wear.

Keywords: PEEK, carbon fiber, friction, wear.

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## INTRODUCTION

Polymers as construction materials are more and more common in industrial applications [1,2,3]. The benefits of self-lubrication and low weight make them desirable materials. Mechanical strength and thermal properties are two major criteria for the application and selection of polymers in high performance industrial systems. Often, a compromise between mechanical and thermal properties needs to be considered in order to obtain optimized results. The development of polymers has gone towards higher strength and improved resistance to severe environments.

Poly-ether-ether-ketone (PEEK) shows big potential as a construction material, and is already used as that today. It is most often filled with some kind of reinforcement, e.g. glass fiber (GF), carbon fiber (CF), metallic particles etc. For some applications, i.e. gears, reinforcement is necessary to prevent the teeth from breaking. Fibers contribute to higher strength and allow it to be used as a construction material. In tribological context the fibers can improve the formation of transfer films on the counter surface. But they might also act abrasive, causing wear [4,5,6]. So improved mechanical properties might not improve the tribological ones. PEEK composites perform better than pure PEEK in tribological test [7]. Besides reinforcement, better lubrication is often needed and therefore some PEEK materials also have a solid lubricant as filler, poly-tetra-fluoro-ethylene (PTFE) for example. PTFE is known for creating a tribofilm, and therefore lowering the friction and wear [6,8].

One challenge in industrial applications is that the materials often become exposed to elevated temperatures. This is a limitation for polymers. Lower strength at higher temperatures, often at a level around and above the glass transition temperature ($T_g$), increases the risk of plastic flow and failure [5]. For PEEK, $T_g$ is 143 °C. There is also a risk for a temperature increase in the tribological contact, which might lead to failure due to the poor thermal conductivity. Thermally conductive fillers are therefore used, which can increase the operational P-V range [9]. But as for the mechanical properties, improving the thermal conductivity might not improve the tribological performance.

This paper aims to investigate the influence of temperature on both friction and wear of five different PEEK materials with different filler content.

## EXPERIMENTS

### Polymers

Five PEEK materials, with different fillers purchased from two manufacturers, were tested, see Table 1. For two of the materials the type and amount of filler were not fully specified. The polymers were injection molded in the shape of plates measuring 100x100 mm or 150x150 mm, with a thickness of 3 mm. They were then cut into plates measuring about 30x60 mm. The appearance of the plates was blotchy, with small and brighter areas.

*Table 1. The materials investigated, filler content and tensile modulus specified. The information comes from the data sheets provided by the manufacturers. (Manufacturers Victrex PLC and Lehmann & Voss & Co. The supplier is MAPE plastics AB, Borås, Sweden).*

| ***Name of PEEK material*** | ***Fillers*** | ***Tensile modulus (MPa)*** |
|---|---|---|
| Victrex 650G | None | 3500 |
| Victrex 650CA30 | 30 wt% CF | 27000 |
| Luvocom 1105/XCF/30 | 30 wt% CF | 32000 |
| Luvocom 1105-8165 | CF, lubricant, thermally conductive modified | 22000 |
| Luvocom 1105-0699 | CF, PTFE lubricant, other lubricant | 24000 |

### Experimental set-up

A reciprocating ball-on-disc test setup was applied, using ball bearing balls of 100Cr6, with a diameter of 10 mm, and polymer plates. The load was 5 N or 15 N. The peak-to-peak sliding distance was 5 mm and the frequency was 2 Hz, giving a mean sliding speed of 20 mm/s. All tests were run for 2000 cycles.

Tests were run at four different temperatures, room temperature (RT), 80°C, 120°C and 150°C. This was achieved using thermo elements mounted inside the disc sample holder. The ball was in contact with the polymer plate to ensure heating before the test was started. The temperature rise from the friction itself is negligible [10].

A pre-study was made to investigate the variation in friction and wear between different parts of the polymer plate. Three tests at RT with the load of 5 N were conducted, showing no significant difference. The reproducibility of the test was good and therefore, it was decided that only one test would be conducted at each temperature and load.

Analysis

The surfaces and wear marks of both the polymer plates and balls were imaged with an optical microscope. The polymers were also investigated using SEM (ZEISS 1550). The samples were cleaned with ethanol and a thin layer of gold had to be evaporated on the surfaces prior to SEM.

RESULTS

A significant influence of the temperature on the friction behavior of the tested materials was observed. The development of the friction coefficient with number of cycles is shown for the 5 N load tests in Figures 1–4. In general, the friction was lowest at 80°C or 120°C and highest at 150°C (which is higher than $T_g$ of PEEK). At RT the friction coefficient varied between about 0.10 and 0.30, with Victrex 650G showing the lowest and Luvocom 1105-8165 the highest levels, see Figure 1. At 80°C all materials showed lower friction than at RT, except for Luvocom 1105/XCF/30 that remained at the same level, see Figure 2. At 120°C Victrex 650CA30 showed the lowest friction, about 0.04, which was lower than the value at 80°C, while Victrex 650G showed high friction, about 0.38, see Figure 3. At 150°C all materials showed relatively high friction, except for Luvocom 1105-0699 that remained at a low level, about 0.05, see Figure 4.

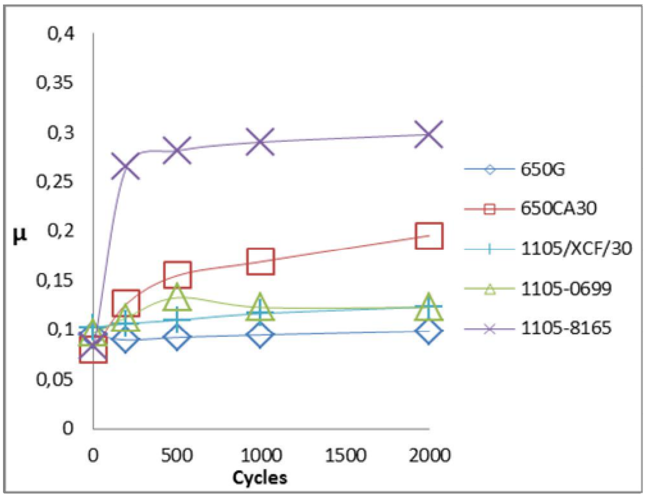


*Figure 1. The friction coefficient behavior at room temperature and under the load of 5 N. Reciprocating ball-on-disk test, steel ball of 10 mm diameter, five different PEEK based materials.*

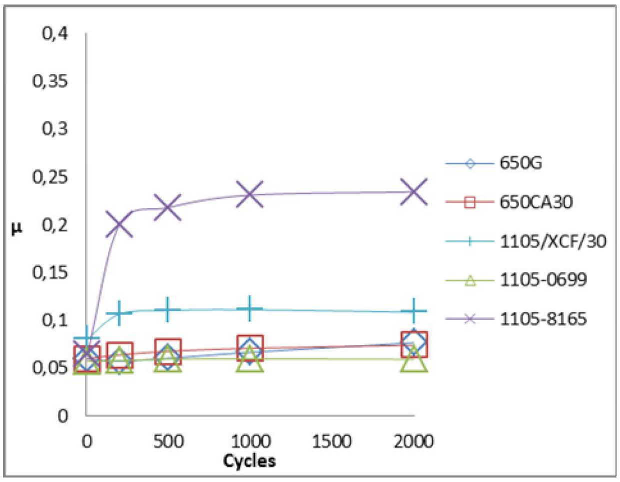


*Figure 2. The friction behavior at 80°C and under the load of 5 N. Reciprocating ball-on-disk test, steel ball of 10 mm diameter, five different PEEK based materials.*

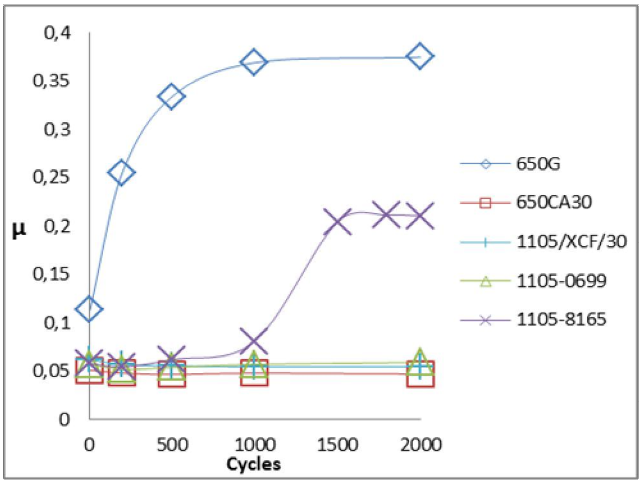


*Figure 3. The friction behavior at 120°C and under the load of 5 N. Reciprocating ball-on-disk test, steel ball of 10 mm diameter, five different PEEK based materials.*

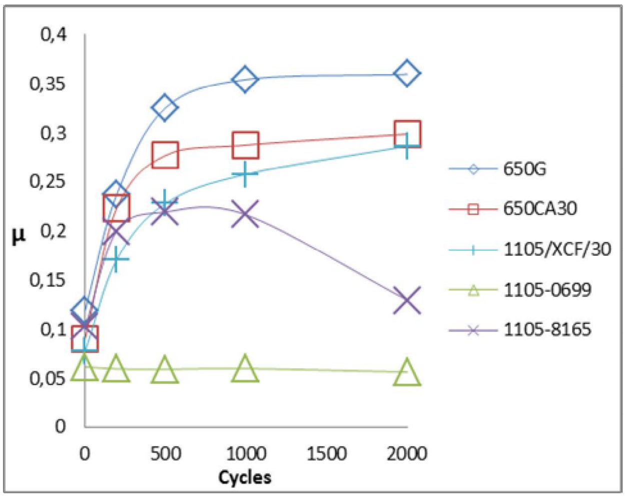


*Figure 4. The friction behavior at 150°C and under the load of 5 N. Reciprocating ball-on-disk test, steel ball of 10 mm diameter, five different PEEK based materials.*

For Victrex 650G the friction coefficient was about 0.10 at RT and about 0.06 at 80°C for both 5 and 15 N contact load. At 120 °C and 150°C the friction coefficient was higher at 5 N than at 15 N, about 0.35 and 0.30 respectively. The appearance of the wear tracks varied depending on the temperature. At RT and 80°C the original surface ridges were only slightly flattened. The wear track from the 120°C test showed more deformation, see Figure 5. The outer sides were smooth, due to plastic plowing, while the middle part was wave-like, due to plastic flow [11], see Figure 6. Interesting to note is that the central part had the same height as the unworn surface. This wavy surface structure covered the entire wear track at 150°C. With increasing temperature the PEEK gets softer and the load then leads to viscoelastic and plastic plowing and deformation, a common behavior of polymers [12]. The steel ball counter surfaces showed clear wear marks, except for the ball from the 120°C test that showed polymer transfer to the ball but no clear wear mark, see Figure 7. The adhesion between the ball and polymer is what caused both friction and wear [13].

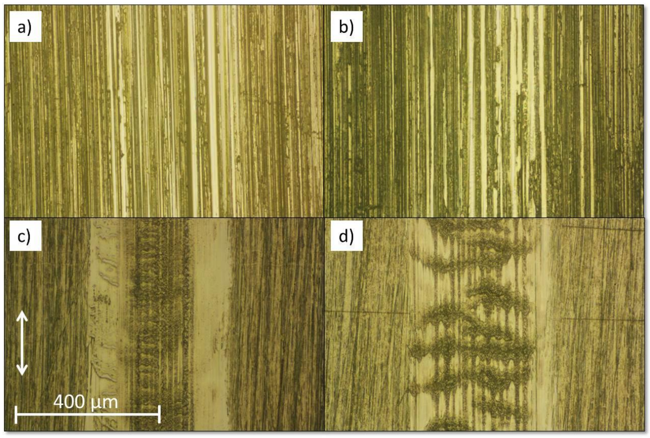


*Figure 5. Optical microscope image of Victrex 650G, under the load of 5 N at a) room temperature, b) 80 °C, c) 120 °C and d) 150 °C. Arrow indicates sliding direction.*

For Victrex 650CA30 the friction coefficient at RT was about 0.20 and 0.14 for 5 and 15 N respectively. At 80°C and 120°C it was lower, about 0.07 and 0.05 at 80°C and 0.05 and 0.03 at 120°C, for 5 and 15 N respectively. At 150°C there was a significant change, the friction coefficients went up to 0.30 for both 5 and 15 N.  At RT, 80°C and 120°C, the wear tracks were very smooth, with some unevenly distributed pits, often around a carbon fiber, see Figure 8. In fact, the wear tracks were smoother and showed fewer pits than the unworn surface. There were some elevations in the smoothened surface, which seemed to be due to carbon fibers underneath the polymer surface. This behavior is previously known [5]. When looking closely at the surfaces there were some parts in the wear track that were still unworn, see Figure 9.

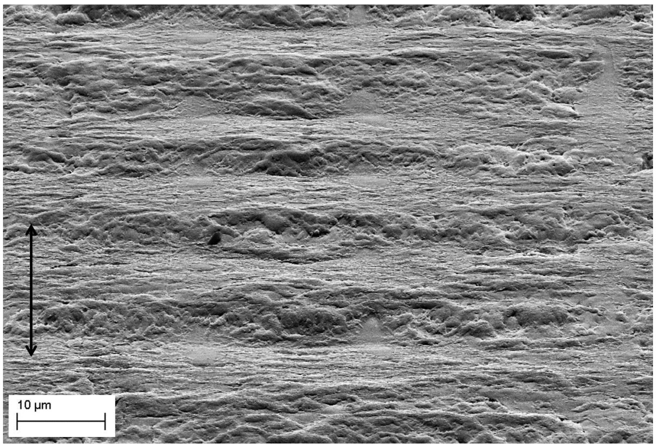


*Figure 6. SEM image of the wear track of Victrex 650G at 120°C and 5 N. The wave-like surface is due to plastic flow. Arrow indicates sliding direction.*

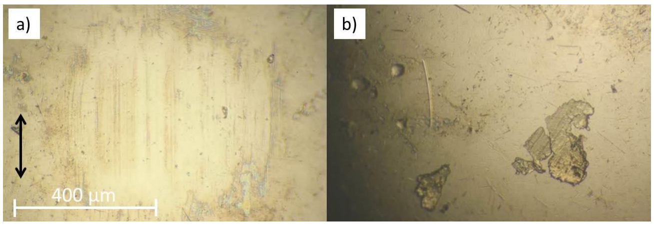


*Figure 7. Optical microscope image of the steel ball counter surface for Victrex 650G, under the load of 5 N at a) 80°C and b) 120°C. Arrow indicates sliding direction.*

At 150°C, on the other hand, the wear tracks looked similar to those of Victrex 650G at the same temperature, showing a wavy structure. The repeated deformations and cyclic stressing that the material undergoes, together with the elevated temperature, lead to fatigue, which means that the material started to crack, see Figure 10. The pits and CFs on the surface contribute to this behavior [13]. The wear marks on the balls were similar to those of Victrex 650G, but at 150°C the central part of the wear mark was covered with a thin film of polymer, see Figure 11. This indicates that there was more material transfer at this temperature than at lower temperatures.

Luvocom 1105/XCF/30 contained similar components as Victrex 650CA30, but showed a somewhat different friction behavior. The friction coefficient was about the same level, 0.11–0.13, at both RT and 80°C, at both 5 and 15 N. At 120°C the friction coefficient was about 0.05 at 5 N, while it was about 0.27 at 15 N. At 150°C, the friction coefficient was about 0.27 at both 5 N and 15 N. The wear tracks showed similar appearance as those of Victrex 650CA30, except for the one from the test at 120°C and 15 N, which had the same appearance as those from the 150°C tests. At 150°C Luvocom 1105/XCF/30 showed clear signs of viscous plowing, see Figure 12. The ball surfaces had the same appearances as those for Victrex 650CA30, se Figure 13.

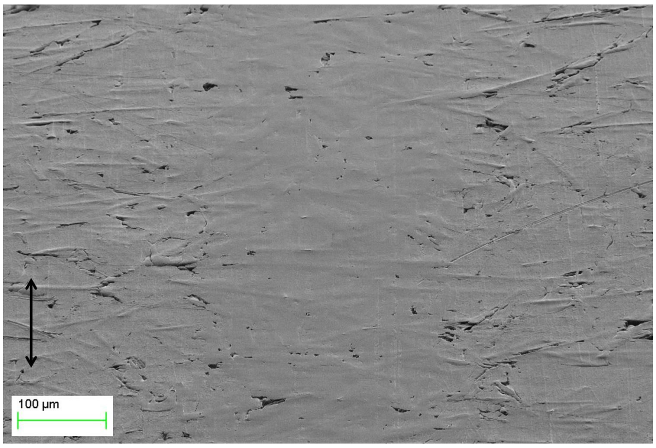


*Figure 8. SEM image of the wear track of Victrex 650CA30 at room temperature and 5 N. Both CF and pits show clearly. Arrow indicates sliding direction.*

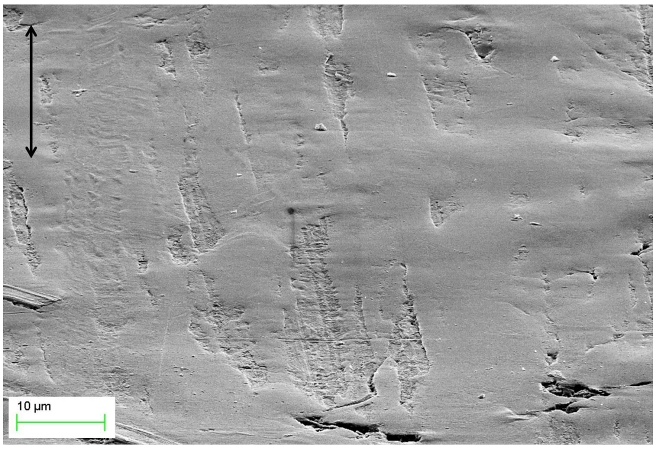


*Figure 9. SEM image of the wear track of Victrex 650CA30 at 80°C and 5 N. Some unworn polymer surface in the wear track. Arrow indicates sliding direction.*

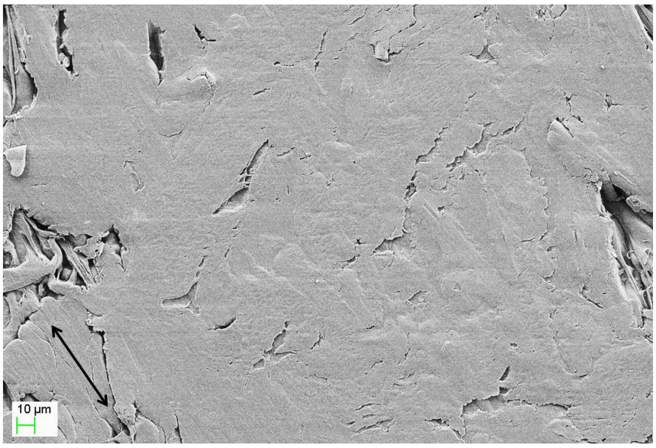


*Figure 10. SEM image of the wear track of Victrex 650CA30 at 150°C and 5 N. The polymer film has cracked due to repeated deformation. Arrow indicates sliding direction.*

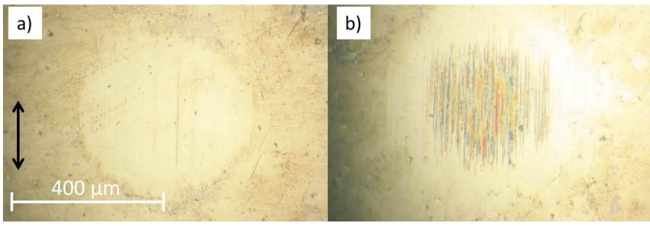


*Figure 11. Optical microscope image of the steel ball counter surface for Victrex 650CA30, under the load of 5 N at a) 80°C and b) 150°C. Arrow indicates sliding direction.*

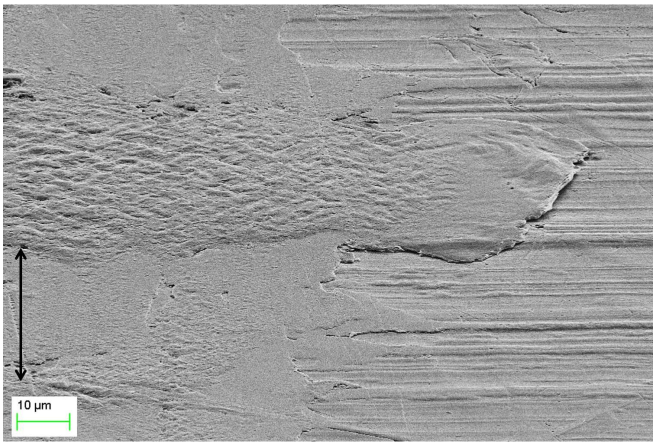


*Figure 12. SEM image of the wear track of Luvocom 1105/XCF/30 at 150°C and 5 N. The material shows signs of viscous plowing. Arrow indicates sliding direction.*

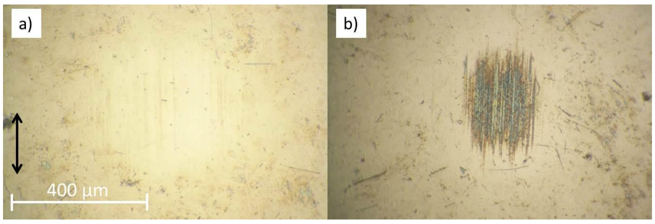


*Figure 13. Optical microscope image of the steel ball counter surface for Luvocom 1105/XCF/30, under the load of 5 N at a) 80 °C and b) 150°C. Arrow indicates sliding direction.*

Luvocom 1105-0699, which contains lubricating additives, always showed low and stable friction. At RT the friction was 0.12 and 0.09 for 5 and 15 N respectively. At 80°C and 120°C it was even lower, between 0.05–0.10. At 150°C it was slightly higher than at 120°C, about 0.06 and 0.12 for 5 and 15 N respectively, but still much lower than for the other materials. The wear tracks were smooth and just mildly worn, at 80°C the wear track was barely visible, and some elevations due to the CF were clearly visible. The low friction and mild wear were thanks to the formation of a tribofilm [6,8]. In SEM the areas with PTFE area clearly shown, see Figure 14. A thin film seems to have been smeared out across the wear track and flakes of polymer covers the pits. The flaky and fibrillar appearance was due to the presence of PTFE, see Figure 15, which has this typical look after deformation [7]. The counter ball surfaces showed similar appearance as for Victrex 650CA30, but no prominent polymer transfer was found at 150°C, see Figure 16.

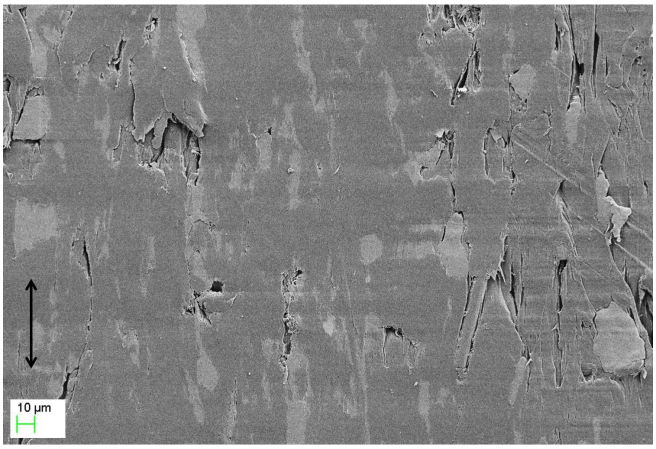


*Figure 14. SEM image of the wear track of Luvocom 1105-0699 at room temperature and 5 N. The lighter areas are PTFE particles. Arrow indicates sliding direction.*

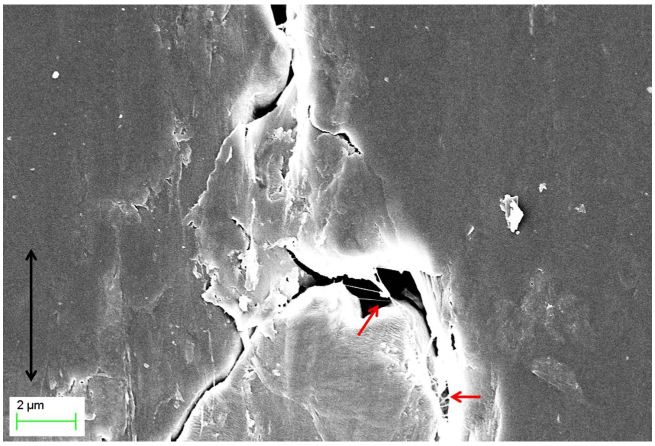


*Figure 15. SEM image of the wear track of Luvocom 1105-0699 at room temperature and 5 N. The PTFE particle in the middle lower part of the image shows sign of threading. Black arrow indicates sliding direction and red arrows highlight threads.*

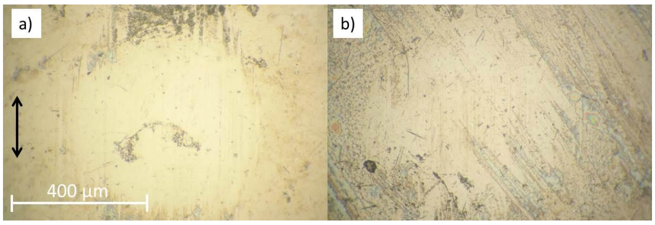


*Figure 16. Optical microscope image of the steel ball counter surface for Luvocom 1105-0699, under the load of 5 N at a) 80°C and b) 150°C. Arrow indicates sliding direction.*

Luvocom 1105-8165 was the worst material when it comes to friction and wear. It showed high friction, and also a different friction behavior, compared to the other materials. At RT the friction coefficient was about 0.30 and 0.24, and at 80 °C about 0.24 and 0.20, for 5 and 15 N respectively. In all these tests the friction increased sharply during the first 100 cycles and then stabilized. At 120°C and 150°C the friction behavior was different. At 120°C and 5 N the friction coefficient was about 0.07 for the first 1000 cycles and then it increased sharply to a stable level of 0.21. At 150°C and 5 N, as well as for 15 N at both 120°C and 150°C, the friction coefficient increased sharply for the first 100 cycles and after some time it decreased to a lower level of about 0.06–0.13. The wear tracks showed significant wear, see Figure 17. Not many carbon fibers were visible, neither in the wear track nor in the unworn surface, but the wear track showed signs of fiber loss. The wear tracks showed areas of smeared material and also areas where big parts of material were missing. The thermally conductive additive apparently changed the mechanical properties as well. It was more easily sheared and the plastic plowing was more prominent. Compared with the others this material seemed to have poorer adhesion between the polymer and CF. There was a lot of grooves that clearly showed that CF was missing. The loose abrasive fibers have probably contributed to the wear. The counter balls showed large amounts of material transferred from the polymer plate, at all temperatures and loads, see Figure 18. Luvocom 1105-8165 also has a lubricant additive but in this case it wasn't enough to prevent adhesion between the bulk polymer and counter surface.

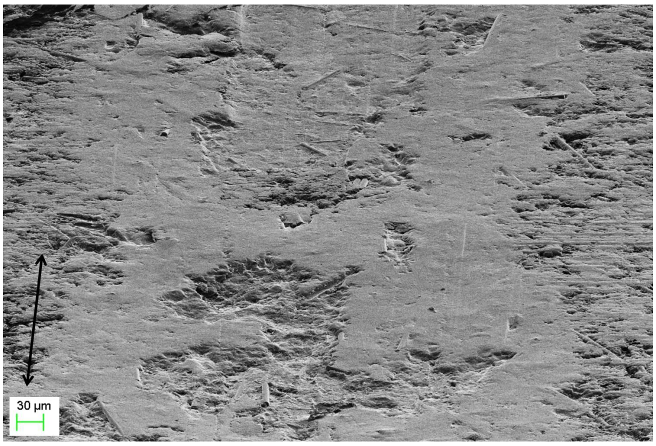


*Figure 17. SEM image of the wear track of Luvocom 1105-8165 at room temperature and 5 N. The material suffers from extensive wear, both polymer and loss of CF. Arrow indicates sliding direction.*

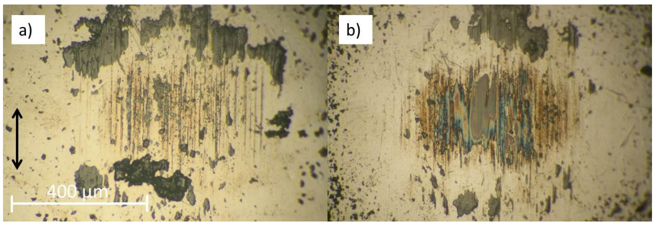


*Figure 18. Optical microscope image of the steel ball counter surface for Luvocom 1105-8165, under the load of 5 N at a) 80°C and b) 150°C. Both show clear sign of material transfer. Arrow indicates sliding direction.*

## DISCUSSION

All materials showed a decrease in friction at slightly elevated temperature, 80°C. Victrex 650CA30, Luvocom 1105/XCF/30 and 1105-0699 showed even lower friction at 120 °C than at 80°C, while the others showed higher friction. At a slightly elevated temperature the material is easier to shear and deform but still has enough stiffness to withstand deformation further down in the material.

The fact that a higher temperature than $T_g$ led to higher friction was expected, since the stiffness decreases drastically. This might lead to an increasing amount of bare CF at the surface, which may act abrasive on the counter surface. And if the fibers come loose, they might cause three body abrasion. The temperature dependence shows that it is an important factor to take into account when choosing a polymer for an application.

Without CF the PEEK material was less durable. Failure occurred earlier, at higher temperatures, than for the composites with CF. But if the tests had been longer, Victrex 650G would probably fail in fewer cycles than Victrex 650CA30 at lower temperatures as well. Apparently, the fibers contribute to a decrease in friction at higher temperatures.

PTFE improved the performance further, owing to the formation of a tribofilm, which reduced both the friction and wear. The low friction at 150°C is probably due to this tribofilm, which protects the surface from wear and higher friction by preventing adhesion between the ball and bulk polymer.

Victrex 650CA30 and Luvocom 1105/XCF/30 have the same declared composition, but the appearance of the surfaces differed slightly. The wear track was in the case of Victrex 650CA30 parallel to the manufacturing marks while they were perpendicular for Luvocom 1105/XCF/30. They had been cut and treated in the same way in order to make the test equal to all materials, but the difference in manufacturing was not taken into account. This is a variable that should not be overlooked.

It was surprising that the thermally conductive composites showed such poor results at elevated temperatures. But studying the surfaces revealed a lot of wear, demonstrating that improving one property might impair another.

Only one test at each temperature and contact load has been performed for all materials. Although the pre-study showed good repeatability, the variation could be higher for some test parameters, e.g. for some of the materials at higher temperatures. However, this study shows obvious trends for the influence of temperature on the friction of different PEEK materials.

## CONCLUSIONS

The following conclusions on friction and wear of different PEEK materials can be drawn from this study:

- Increasing temperature affected both the friction and wear. At slightly elevated temperatures, 80˚C or 120˚C, the friction coefficient was lowest.
- At 150˚C, which is above $T_g$, failure occurs for all materials except for Luvocom 1105-0699, which forms a protective tribofilm.
- The results require further testing in order to better understand the tribological mechanisms and behaviors.

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