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Self-lubricating polymer composites

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Summary and Outlook

8.1 Summary

This PhD project was initiated with the idea that the tribological performance and service life of the SKF phenolic composite liner could be improved via sliding against a coating, such as TiC/a-C:H, alumina and Ti(Al)N coatings. The TiC/a-C:H coating was the most promising one amongst them, since it is well known for its self-lubricating and anti-wear properties. However, results laid down in Chapter 3 showed that the wear rate of the composite liner is comparable in the cases of sliding against thin TiC/a-C:H coated steel surface and the uncoated steel. The wear mechanism of the composite liner is determined by subsequent processes. First, smearing and transferring of PTFE; Second, de-bonding and fragmentation of glass fibers as well as PTFE fibers, followed by cracking and fracture of resin matrix; third, generations of substantial wear debris and third-body that consist of smeared PTFE and short glass fiber fragments, fine glass particles, and fractured resin. An accelerated wear is found in the phenolic composite liner. These results point at an improvement of the mechanical properties of the self-lubricating composites.

Because of easy processing conditions, Epomet-PTFE particulate composites with a high concentration of SiO₂ particles were produced and presented in Chapter 4. The tribo-results show that within 1000 m sliding distance the Epomet-PTFE composites with optimum contents of PTFE exhibit a good tribological performance and a high load bearing capacity. A low CoF in combination with a low wear rate is achieved for the Epomet-PTFE-12.5 within 1000 m, but a significant increase of CoF is observed when sliding more than 2000 m. The increase of CoF is attributed to the

gradual accumulation of the fractured SiO₂ and back-transferred steel on the worn surface of the composite, which is due to a too high concentration of SiO₂ particles in the composite. This indicates that a tradeoff has to be made between improving mechanical properties (more fillers) and lowering the abrasiveness of the composite (less fillers), to achieve a stable sliding system.

Thereafter, we started to optimize the curing process of two epoxy composites, and the size and concentration of glass fillers in the composites. It is found that with smaller sizes of glass particles (than those in Epomet-PTFE composites) at a lower concentration, the epoxy 6078 composite and the epoxy 25036-25-3 composite [both discussed in Chapter 4] yield a low CoF and lower wear for at least 10000 m stable sliding. On the other hand, the wear on the counterpart steel ball is greatly reduced. In comparison with other commercial self-lubricating materials, they showed promising applications in the field of self-lubricating polymer composite based bearings.

Because the abrasiveness of the composites is essential for attaining a stable sliding system, it triggered our interests to study the abrasiveness of various fillers in the epoxy composites. The results in Chapter 5 revealed that epoxy composites with a larger size of glass spheres give rise to a higher abrasive wear on the steel ball, while the difference is not significant between composites with the average size of glass spheres below 50 μm. Irregular glass particles are found to be more abrasive than the glass spheres in the epoxy composites. The abrasiveness of short carbon fibers filled composites is higher than about 50 μm (average size) glass particles filled composites. For a further improvement of the mechanical properties of the epoxy composites without causing an increase of abrasiveness, nano-fillers were introduced into the composites. Better mechanical properties and a lower wear rate of the composite are obtained with the addition of only 1 wt.% nano-fillers. The reinforcing effects among various nano-fillers are not significantly different, but they can be enhanced by adding more nano-fillers up to 5 wt.%.

Chapter 6 & 7 present findings which are in particular of scientific interests. In Chapter 3, reoriented “micro-fibrils” in some parts of PTFE upon sliding were found in the SEM micrographs. It was found in Chapter 6 that crystallinity of PTFE wear debris is higher than that in the original PTFE sample. The main reason that accounts for the higher crystallinity in the wear debris is the shear-induced long-range ordering of the PTFE

during sliding. SEM images indicated that the long-range ordering of the PTFE in the transfer film has been partly destroyed. ATR FT-IR results suggested a conformational change of the PTFE chains. In this particular case, the local shear needed to increase the long-range ordering was found to be lower than that to cause the conformational change of the PTFE chains.

Chapter 7 shows that the formation of PTFE transfer films and metal-F bonding on the counterpart surface is crucial to the friction and wear performance. The better tribo-performance of the Epomet-PTFE composites when sliding against the Al_2O_3 ball than the Si_3N_4 ball is attributed to the formation of *Al-F* bonding, while hardly any trace of chemical bonding between Si_3N_4 and PTFE is found. It is experimentally confirmed that friction can be greatly reduced by two *F*-terminated surfaces sliding over each other. The formation of *Al-F* bonding is considered as the primary reason of the reduction in friction in the case where PTFE transfer films are insufficient to cover the whole wear scar of the ball. With sufficient PTFE transfer films, the role of *Al-F* bonding is not significant.

The effect of water lubrication and normal load on the formation of PTFE transfer films and metal-F bonding on the counterpart surface is addressed in Chapter 7. In water boundary lubrication, the formation of PTFE transfer films and *Al-F* bonding is inhibited, resulting in a detrimental effect of liquid water on the tribo-performance. A hydrofluoric-acid treatment of the Al_2O_3 ball enhances considerably its tribo-performance in water-lubricated sliding, which again confirms the important role of *Al-F* formation.

Under various loading conditions, an decrease in CoF with increasing load is observed. This is attributed to that a higher load leads to more deformation of the Epomet-PTFE composite and facilitates smearing of PTFE onto the wear surface of the composite and the transfer of PTFE onto the steel surface. The role of *Fe-F* bonding is not as important as the role of PTFE transfer films when sliding under different loads. During sliding, there is a minimum apparent contact pressure required to form detectable amount *Fe-F* bonding on the wear surface of steel.

8.2 Outlook

The outcome of this work is positive and exciting. We improved, not only the tribological performance of the self-lubricating composites, but also

offered an in-depth understandings of certain scientific phenomena that occur at the sliding interface. Nonetheless, research is still needed along the following lines:

1. *Reducing the porosity of the Epoxy 25036 composites:*

It was found in this PhD project that there are quite a few micro-sized pores in the cured Epoxy 25036 composites, which could become detrimental to their mechanical and tribological performance. The origin of the problem lies in the curing process itself. It is possible to reduce the porosity by changing the curing pressure, temperature and time. A proper degassing apparatus could help to reduce the porosity as well.

2. *New epoxy system and cost reduction:*

The load bearing capacity may be further improved via selecting a proper epoxy resin, hardener and accelerator. Another practical issue is to reduce cost of materials. Graphite is much cheaper than PTFE, which could be a good alternative for PTFE. Although the frictional behaviors may get slightly worse, adding more graphite into composites can a good solution.

3. *Challenge on finding the origin of metal-F bonding:*

In this research formation of metal-F bonding was detected, but the mechanisms or the chemical reactions are not well understood up to each detail. A new technology that combines X-ray absorption spectroscopy and electron microscopy was developed at the U.S. Department of Energy's Brookhaven National Laboratory [1]. This could be a promising tool and offer a new pathway to study the dynamic chemical reactions between PTFE nano-particles and metal nano-particles, under a certain contact pressure or under an elevated temperature.

4. *The continuation of this research with SKF:*

As a continuation of this research with our industrial partner SKF should be a test of the performance of the Epoxy 25036 and Epoxy 6078 composites with various thicknesses and shapes, which will fit the dry sliding bearings. Further research could be on small scale tests of dry sliding bearings that use the Epoxy 25036 and Epoxy 6078 composites as the self-lubricating layer, so as to find out the frictional and wear performance, as well as the fatigue wear performance under different contact pressures or at different working environments. The advantage of these

composites, in comparison with other commercial ones, is an excellent performance combined with a low cost and an easy production.

References

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