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Thinking outside the circle: Applying tribology to improve system performance

When engineers are faced with a mechanical design challenge, there is no right or wrong way to approach it. Some methods, however, are smarter than others.

For the long-term, trouble-free operation of a mechanical assembly, it is essential to consider all impact factors in the design process. Only when everything in a mechanically engineered aggregate fits and operates well together will it have good operating efficiency and an optimal life cycle.

Most engineers typically follow the process learned during university lectures. They gather the specifications and physical parameters, such as speed, accuracy requirements and space limitations. The engineer needs to understand the acceptance criteria, design limitations and allowable project costs before deciding on a course of action. Just as falling short of performance specifications can doom a project, so can over-designing and cost overruns. Once these parameters have been gathered, engineers lay out their assembly and select components based on space and performance requirements.

Bearings are among the most critical components in a rotary or linear mechanical assembly. The engineer must consider factors such as bearing type, size, speed and load. Usually, bearings are chosen when the designer must incorporate one into their design and are often one of the last design components. However, one important aspect is frequently not considered — tribology. Tribological aspects should be factored into the design at the outset. This can improve the efficiency and life-cycle of tribological contacts, thus improving high-level application.

Tribology

Tribology is the science of wear, friction and lubrication, and encompasses how interacting surfaces and other tribo-elements behave in relative motion in natural and artificial systems (see Figure 1). Tribology is not an isolated practice, but rather a complex, interdisciplinary science where advances are made by collaborative efforts of researchers from fields including mechanical engineering, manufacturing, materials science and engineering, chemistry and chemical engineering, physics, mathematics, biomedical science and engineering, computer science and more [MANG2015, HABI2015].

The tribological system analysis is necessary to understanding tribological impact factors [GFT2002].

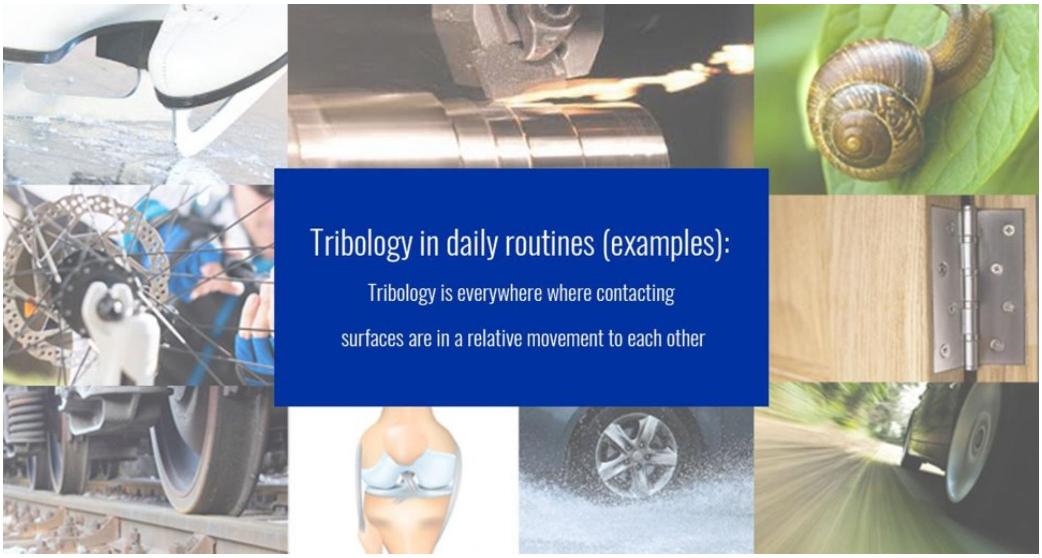

Figure 1: Tribology in daily routines. Source: GGB

> **When applying tribology, it helps to identify critical factors of an application including all tribological sub-systems, and solutions to improve the system and application.**

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Dry-running bearing contact

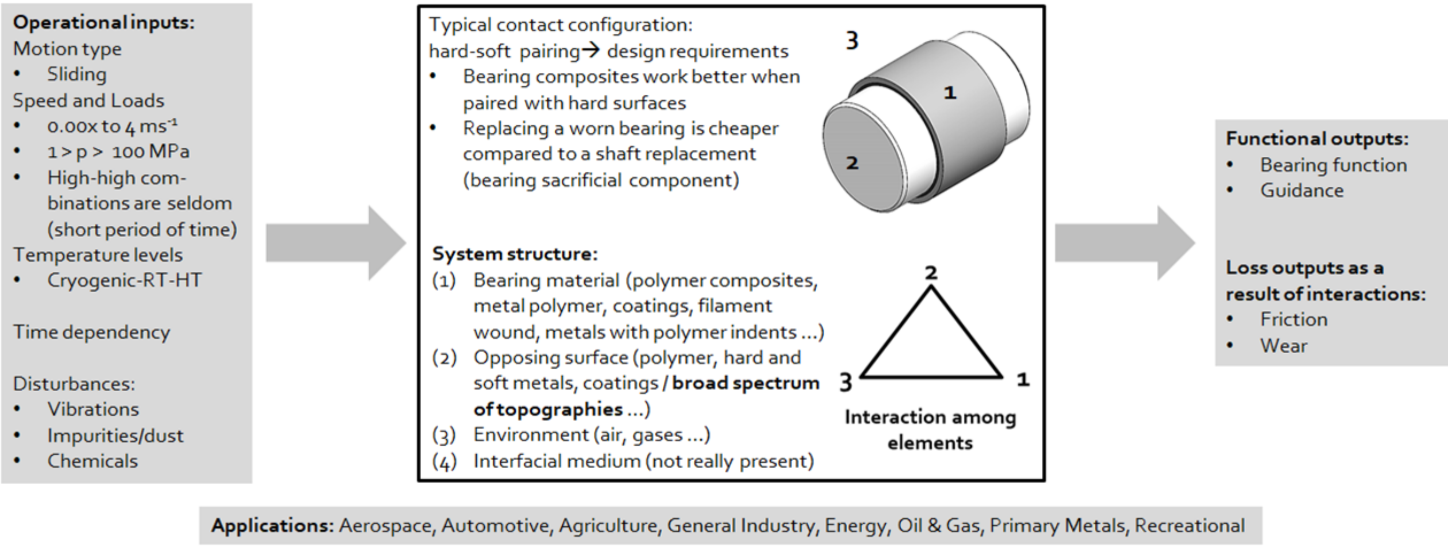
The goal of the system-technical method is to describe a scientific field in its entireness. Entireness means it cannot be described by the intrinsic properties of the individual system elements but rather by the relationships among them [HABI2015]. The tribological system analysis [GFT2002] is used to describe and compile all impact factors and how they affect the functional and loss outputs (friction and wear). Tribological systems consist of the collective stress (operational inputs), the functional and loss outputs as well as the system-structure.

The system-structure is determined by the property profiles of the substantial elements including the base, opposing body and the ambient medium. The typical contact configuration for a bearing contact is a hard-soft pairing where one surface is softer than the other. The softer surface is normally the bearing surface since replacing a worn bearing is less expensive than shaft replacement. Additionally, bearing materials used in dry-running contacts normally perform better when paired with a harder opposing surface. Plain composite bearings are selected for their remarkable sliding performance across large pressure-velocity (PV) ranges and can be used in lubricated or dry-running systems. This makes them ideal for a wide range of applications.

Coatings represent a new material family with high potential for lubricating surfaces in relative motion. Fiber-reinforced materials are also well suited for dry-running tribo-contacts especially at demanding load conditions. The shaft is the second surface involved, referred to as the opposing or counter surface. The material spectrum of the shaft may include polymers, and hard and soft metals as well as coatings. Each of these materials has its own physical and chemical property profile to consider when designing a tribological contact. The topography of the counterface also plays an important role. Each machining process creates a unique topography pattern. The last element involved is the environment. In many applications the surrounding medium is air, but other gases are also possible.

This tribo-structure is stressed with the operational input parameters, referred to as collective stress. It includes the load, sliding speed and duration, and the movement and temperature conditions stressing the system-structure. For most dry-running contact, the motion type is sliding and follows a specific motion sequence that can be continuous, oscillating, intermittent or reversed. The speed can reach high levels in the range of 4 m/s and the load spectrum ranges from very low to demanding loads over 100 MPa. The loads are not static in most applications as the contact must handle dynamic loads. A high-high combination of high loads and high speeds is rare and is normally of short duration. A permanent operation at high-high combinations would destroy the tribological contact due to overheating.

Figure 2 illustrates the impact factors that can alter performance. It also shows that friction and wear characteristics are system-properties and not intrinsic material properties.



Operational inputs:
Motion type
- Sliding

Speed and Loads
- 0.00x to 4 ms^{-1}
- 1 > p > 100 MPa
- High-high combinations are seldom (short period of time)

Temperature levels
- Cryogenic-RT-HT

Time dependency

Disturbances:
- Vibrations
- Impurities/dust
- Chemicals

Typical contact configuration:
hard-soft pairing → design requirements
- Bearing composites work better when paired with hard surfaces
- Replacing a worn bearing is cheaper compared to a shaft replacement (bearing sacrificial component)

System structure:
(1) Bearing material (polymer composites, metal polymer, coatings, filament wound, metals with polymer indents …)
(2) Opposing surface (polymer, hard and soft metals, coatings / **broad spectrum of topographies** …)
(3) Environment (air, gases …)
(4) Interfacial medium (not really present)

Interaction among elements

Functional outputs:
- Bearing function
- Guidance

Loss outputs as a result of interactions:
- Friction
- Wear

Applications: Aerospace, Automotive, Agriculture, General Industry, Energy, Oil & Gas, Primary Metals, Recreational

Figure 2: Dry-running bearing contact. Source: GGB

Technical surfaces

Faces used in dry-running bearings are solid surfaces that contact the bearing and create wear during the relative motion. From an engineering perspective, counterfaces are technical surfaces.

Technical surfaces represent the geometrical limitation of technical components. Many technical surfaces used in tribo-technical systems do not have optimal and homogenous properties (ideal smooth surfaces) as shown in Figure 3. Metallic counterfaces consist of a multi-layer structure including the bulk material, the deformed material area via machining processes, oxide, adsorption layers and potential impurities [HABI2015]. Surface treatments such as hardening or coating are common methods to improve the top surface properties leading to an additional layer. Each individual layer exhibits its unique chemical and physical property profile. In addition to the physical and chemical nature of the surface, the microgeometry (topography) is an essential characteristic of technical surfaces and is mainly determined by the processes used during machining [HABI2015].

Figure 4 and Table 1 show typical surfaces generated using two common surface finishing methods and the resulting surface characteristics.

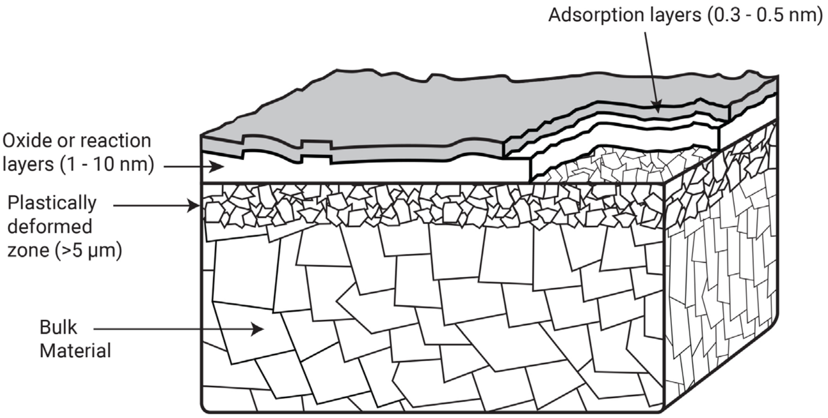


Figure 3: Multi-layer structure of a metallic surface. Source GGB

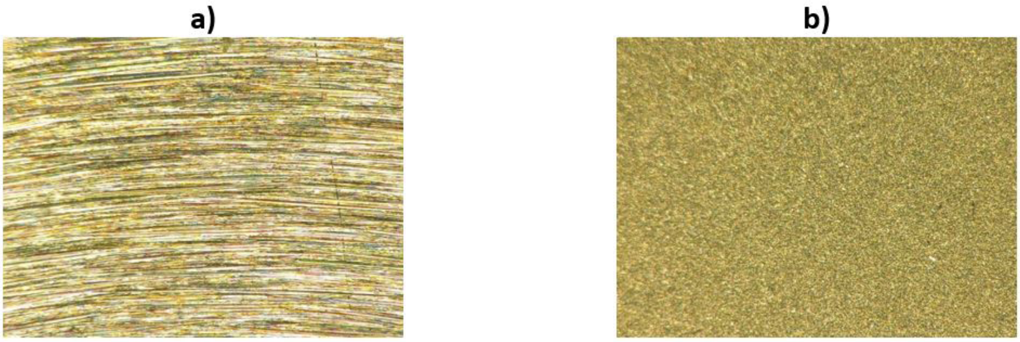


Figure 4: Surface characteristics. Source: GGB

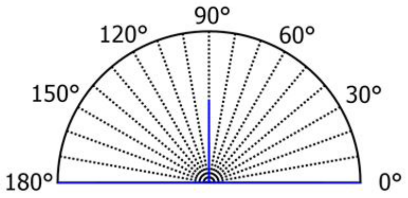
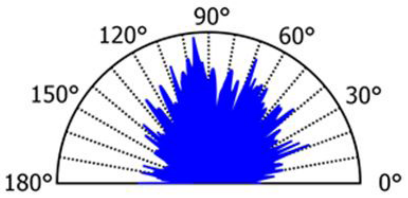
	Str-value **1 = isotropic** **0 = anisotropic**	**Angular spectrum**
grinding	0.109	
lapping	0.958	

Table 1: Surface characteristics. Source: GGB

Wear and friction

Friction is defined as the tangential force resisting the relative motion of two bodies in contact. Wear is the damage to a solid surface, usually involving material loss, caused by relative motion between that surface and a contacting surface or substance [HABI2015].

Protruding asperities cause technical surfaces to contact each other only in small areas. The sum of all micro-contacts is known as the real contact area, which is significantly smaller than the nominal contact area based on the geometrical dimensions. The tribological interactions occur within the real contact area. The tribology community distinguishes four main friction and four main wear mechanisms responsible for friction and wear generation.

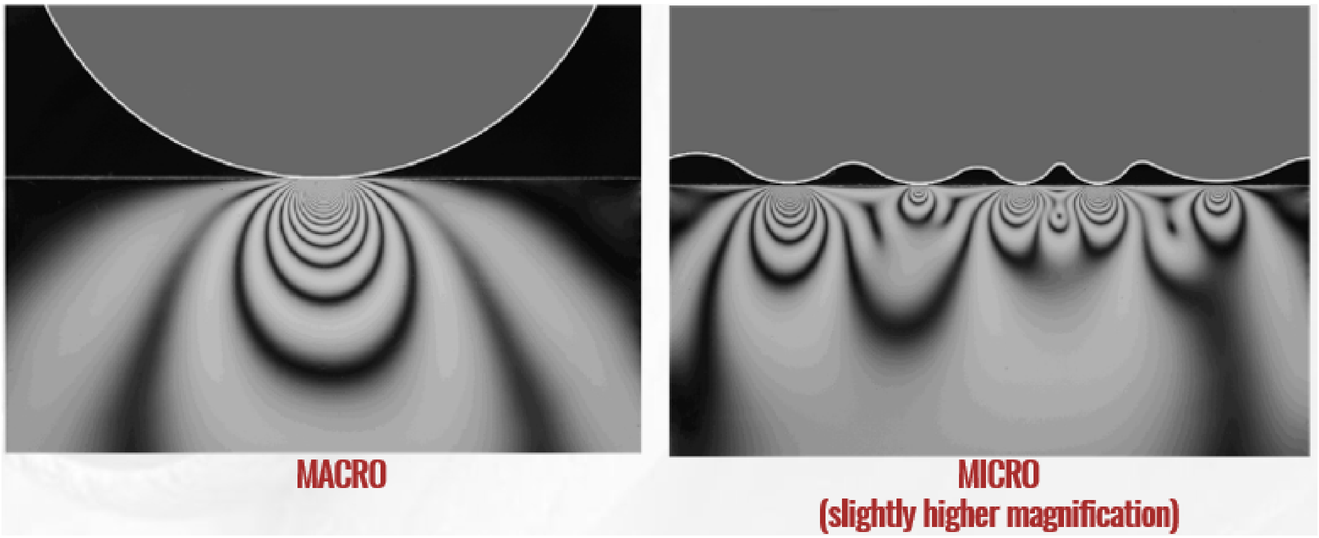


Figure 5: Contact of solids. Source: GGB

The impact of a few micrometers

The shaft surface finishing process is a key factor in the performance of dry-running bearing contacts. Although the magnitude of the topography is only a few micrometers, the impact on bearing performance must be considered.

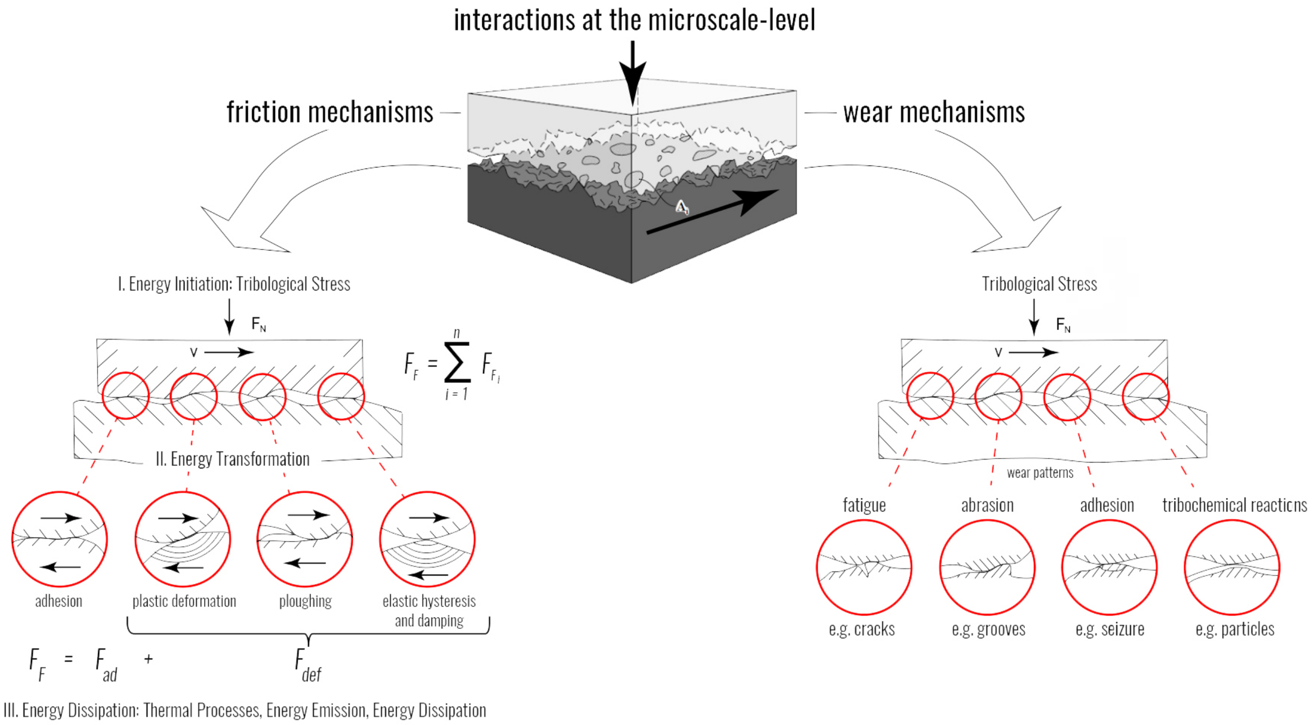


Figure 6: Friction and wear mechanism. Source: GGB

Metal polymer composites and polymer composites are common plain bearing materials.
Metal polymer composite (Figure 7) is a multi-layer structure composed of:

- An impregnated anti-friction overlay enriched with PTFE and fillers (PTFE bearing lining)
- A porous sintered bronze interlayer that provides high wear resistance and serves as a mechanical interlocking system for the PTFE bearing liner
- A steel or bronze backing layer for high mechanical strength

Polymer composites are comprised of a thermoplastic polymer matrix modified with a PTFE filler. Figure 7 represents a micro section of the material showing the slide-active fillers are homogeneously distributed within the matrix.

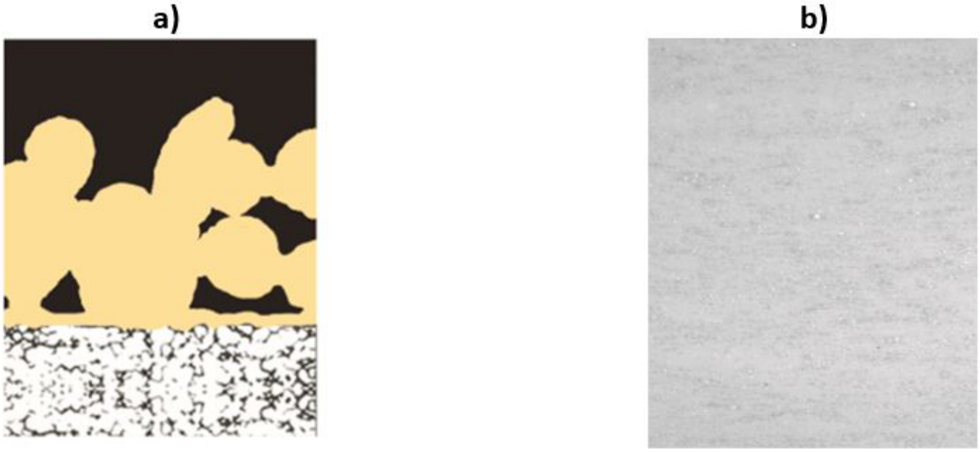


Figure 7: Structural design of the bearing materials. Source: GGB

One important feature of all dry-running bearing materials is to establish a transfer film onto the counter surface. This protective film reduces the wear actions by filling the protruding roughness peaks and valleys. Transfer films are formed by wear debris of the bearing material. They are very thin structures (Figure 8) with a thickness typically smaller than 1 µm, approximately 100 times thinner than a human hair.

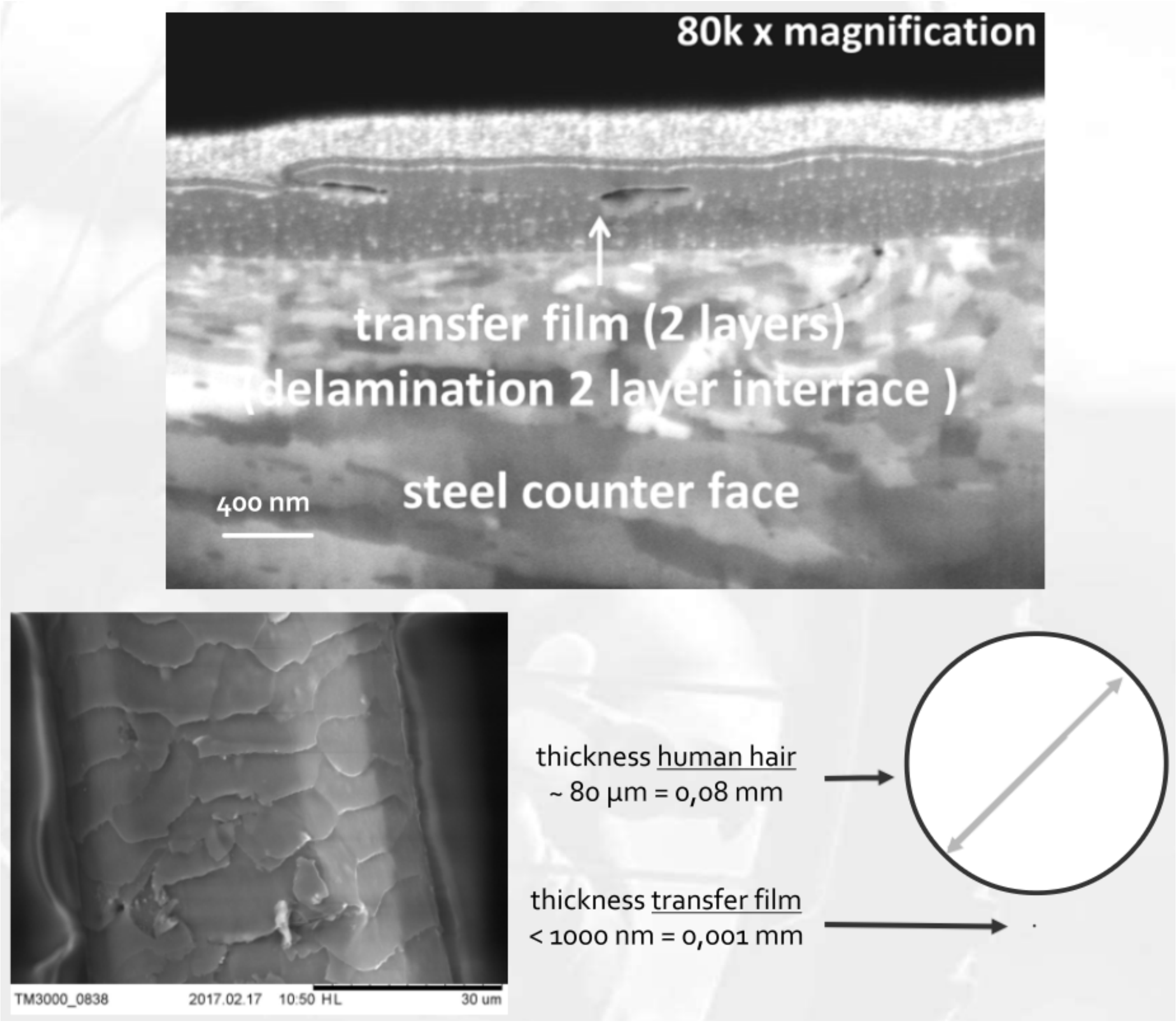


Figure 8: Structural design of the bearing materials. Source: GGB

Performance of a polymer composite

These composite bearing materials were paired with a hardened 42CrMo4 counterface with two different surface topographies used in bearing applications: linear/flat and concentrically ground surfaces. Figure 9 shows the variation in wear performance of the polymer composite when paired with both counter surfaces. This diagram also shows the change in wear performance when modifying the roughness height level. The individual points represent a mean value of a minimum of three measurements. The error bars indicate the maximum and minimum measured value.

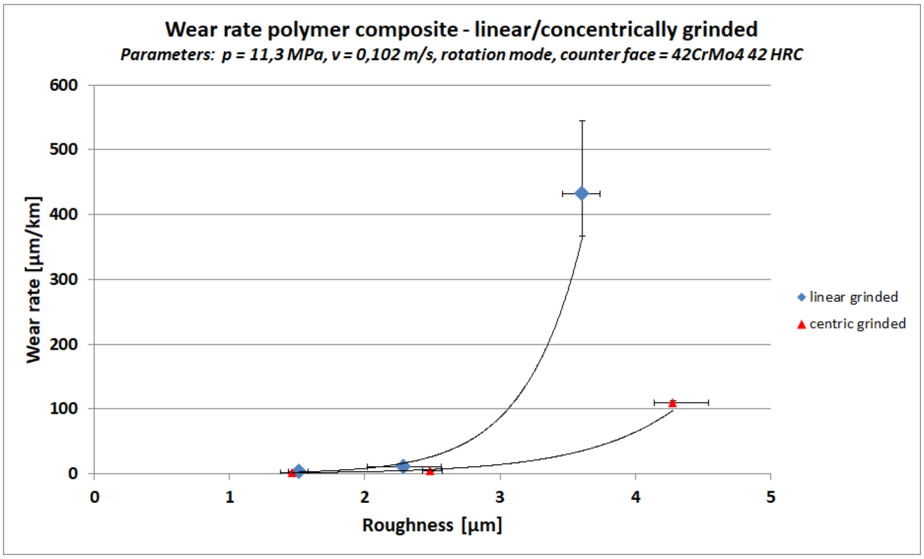


Figure 9: Impact counterface topography — polymer composite. Source: GGB

The results reveal that the counterface topography is a dominating factor when experiencing high polymer wear. Wear rates over two orders of magnitude were measured. The best wear performance was achieved when the composite was paired with the smooth concentrically ground surface. The highest wear values (431 µm/km) were found with a rough linear ground counterface. The results indicate a general trend: greater wear rates at higher roughness levels. This wear is caused by a higher amount of abrasive induced wear, which is considered a critical wear mode for numerous polymeric materials. This effect is well-known in polymer tribology as stated in HABI2015, UETZ1985.

This higher amount of abrasive wear, especially at high roughness levels, may be attributed to an insufficient (or missing) transfer film evolution on rough counterfaces. In this case, the transfer film did not accurately fill the asperity peaks and valleys. A well-developed and well-covering film would effectively protect the polymer surface from further damage by the opposing surface. A scanning electron microscope (SEM) can help visualize and detect differences in transfer film quality.

The linear ground counterface exhibited wear rates two to four times higher than the concentrically ground shaft. Linear grinding creates peaks and valleys with a unidirectional orientation. During continuous rotational sliding, the polymer pin is stressed twice perpendicular and twice parallel to the topography orientation. Stressing against the roughness peaks is considered the origin of higher wear.

This massive change in wear performance directly impacts the life-cycle of the bearing contact, affecting the entire assembly.

Performance of a multi-layer material

The variation in wear performance of the multi-layer material is shown in Figure 10 and indicates the multi-layer material is less sensitive to topography changes than polymer composite.

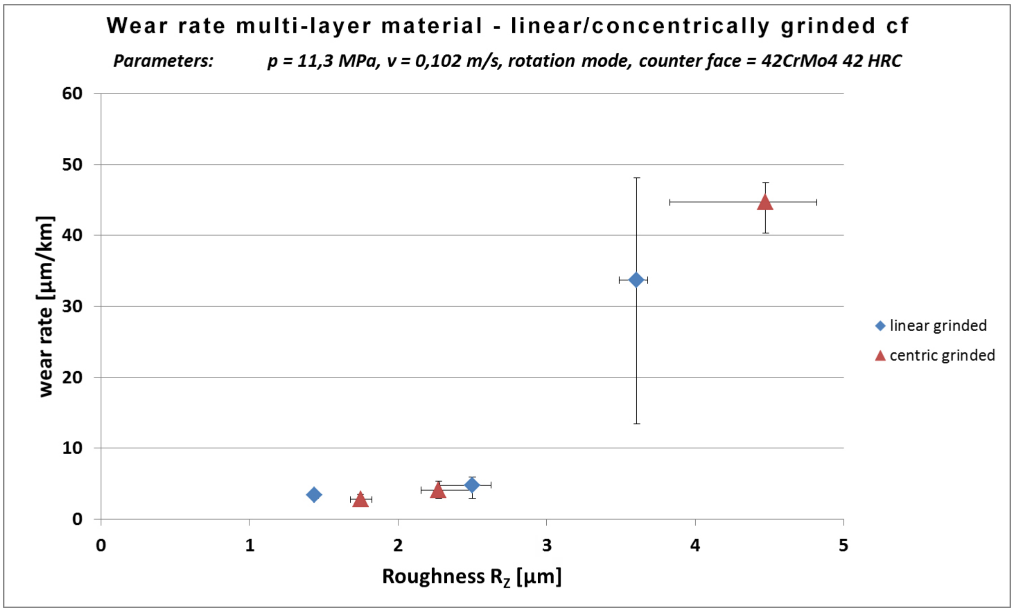


Figure 10: Wear performance of multi-layer material. Source: GGB

Both surface roughness height and topography orientation had minimal impact on the wear performance due to the multi-layer architecture of the material. This robust structure exhibits a higher wear resistance and can smooth the initial steel roughness, making the counterface less aggressive.

Transfer films and wear behavior

For polymer composite materials, abrasive induced wear is a critical wear mode. Increased wear is a result of a missing or insufficiently formed transfer film — roughness peaks are not disguised and remain aggressive. This has been proven with energy-dispersive X-ray (EDX) spectroscopy analysis and SEM on systems with smooth and rough counterfaces (Figure 11a).
Systems with smooth counterfaces produce high wear rates within the first few sliding meters, gradually declining as the system transits into the operational phase (after approximately 400 m). The transfer film masks the counterface and reduces the abrasive aggressiveness of the counterface, leading to an improved wear performance.

Rough counterfaces produce only small wear debris and no transfer film on the steel surface. This proves that a missing transfer film is a key factor when experiencing high wear and that rough counter surfaces can prevent the formation of a transfer film (Figure 11b). They only lead to polymer debris, which escapes the tribo-contact without depositing to the opposing surface.

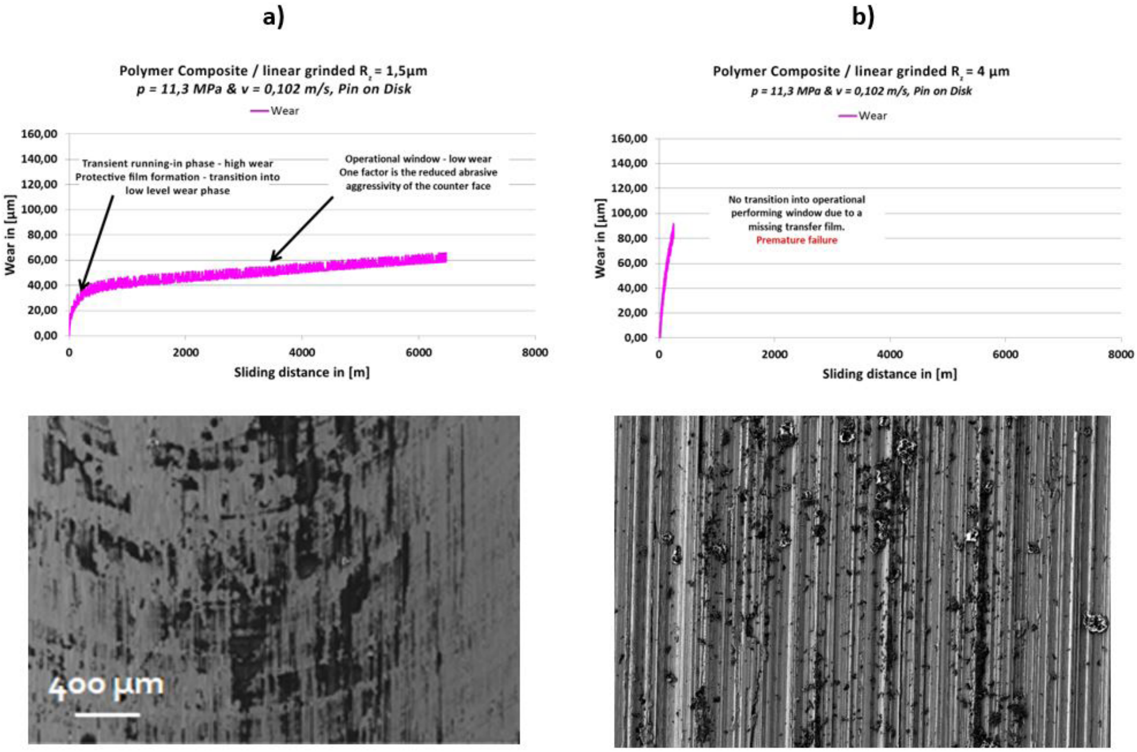


Figure 11: Polymer composite typical wear performances and SEM images of transfer films generated on smooth (a) and rough (b) linear ground counterfaces. Source: GGB

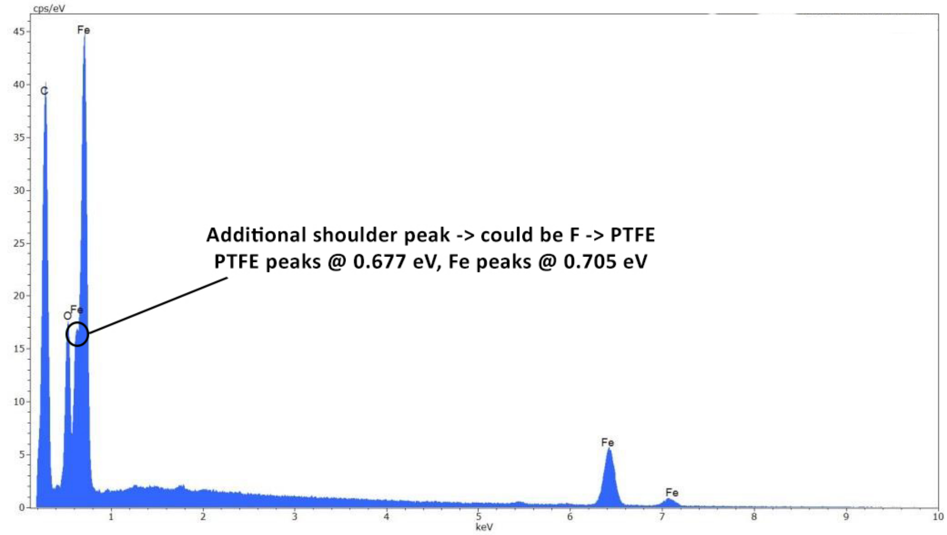


Figure 12: EDX-spectrum. Source: GGB

For multi-layer materials, SEM images reveal a well-developed transfer film on the steel counterface. The transfer film continuously covers the counterface, disguising the initial grinding marks and leaving only small areas of the original metallic surface. This covering of the protruding roughness peaks effectively reduces the abrasive wear actions leading to low wear. The performance of this material can be ascribed to a protective transfer film in synergy with the robust architecture of the material.

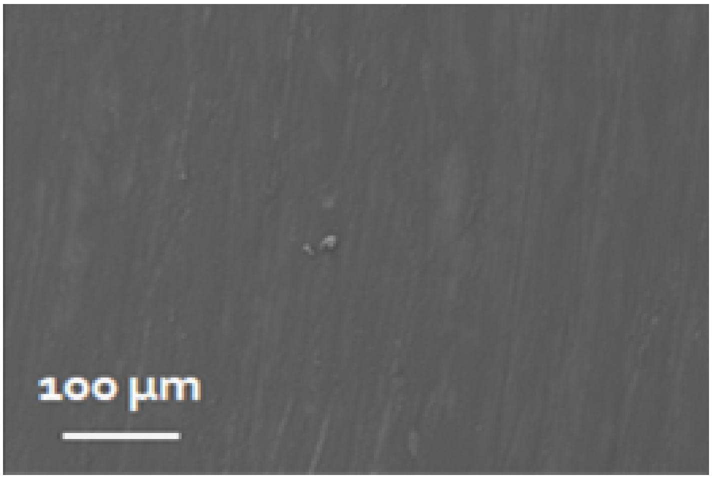


Figure 13: SEM image of the transfer film. Source: GGB

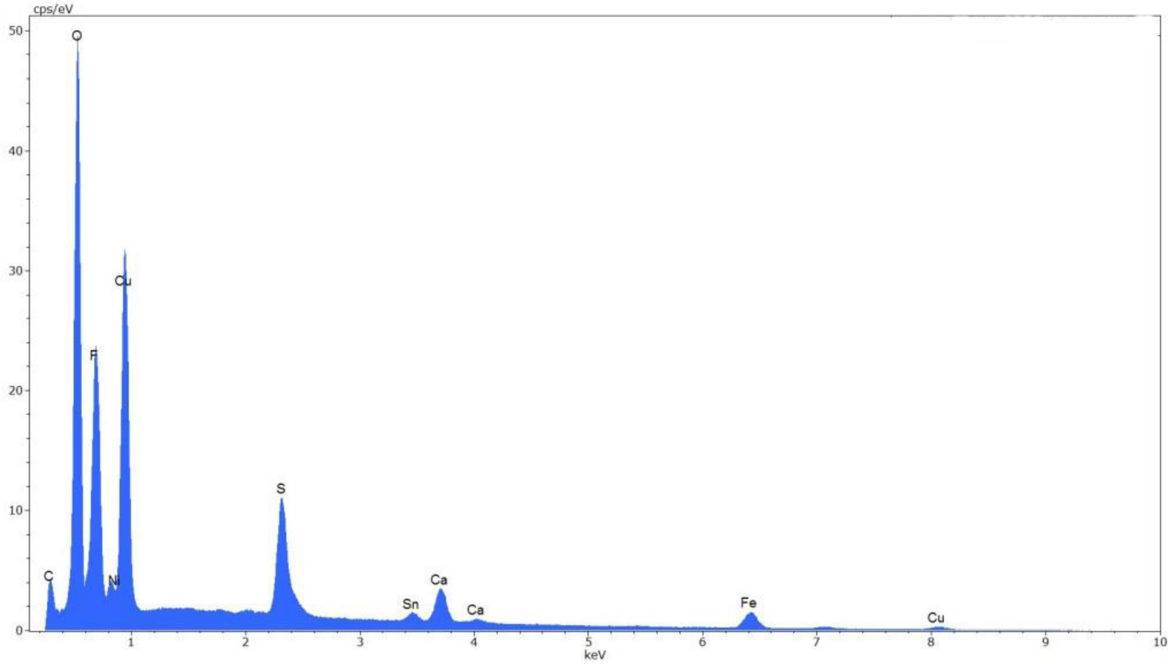


Figure 14: EDX-spectrum. Source: GGB

Conclusion

When applying tribology, it helps to identify critical factors of an application including all tribological sub-systems, and solutions to improve the system and application. When ignored, it can be devastating for the application. Experimental tribological tests and surface analysis demonstrate that the topography of the attacking counterface has a tremendous impact on the wear performance of bearing materials (polymer and multi-layer materials).

GGB

GGB has the expertise to assist design engineers with bearing design and tribological analysis. GGB develops tribologically optimized materials based on tribological results and has a vast knowledge of material science and experience with tribological coatings and bearings.

GGB can also help with other aspects of the tribo-system, including lubrication and shaft material. When operating conditions suggest that dry lubrication is preferred over oil or grease, GGB materials designers can recommend or create materials for these applications. Shaft considerations include material chemical and physical properties as well as surface finish and geometry.

Although they may have a limited understanding of tribology, design engineers should not be deterred from pursuing an optimized tribo-system. Bearing type and material, shaft material and geometry, and lubrication need to be considered.

GGB has the expertise to assist engineers with tribological issues and optimize their bearing designs to reduce friction and wear and maximize efficiency and service life. Contact GGB today.

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GGB, formerly Glacier Garlock Bearings, has the tribological, material science, and applications expertise to provide innovative solutions to even the most challenging requirements, either with standard offerings or with customized products developed in collaboration with its customers. The company also provides local applications engineering and technical support to assure the performance, reliability, and cost-effectiveness of its products.