SLOVAK UNIVERSITY OF
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Fretting wear tests on tribometers - basics, industrial relevance and test realisation

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Introduction

This work on the topic of experimental fretting wear focuses on a systematic and novel approach to design and evaluate a tribometer, these are apparatus to test simplified tribological systems. A general description on the fretting wear basics and examples of typical fretting wear occurrences of various applications are shown. The state of the art on fretting wear test is represented and also considers standards regarding fretting wear tests since these are possible the most important and generally accepted tests. The industrial relevance for experimental testing as a background topic considering the understanding on how fretting wear occurs and on how material, coating and lubrication solutions can be found with experimental means.

A novel fretting wear tribometer is developed based on state of the art measurement techniques and to achieve a reasonable experimental setup with planar contacts. Three novel concepts, a rigid planar contact alignment, a dual eccentric drive mechanism for small displacement and an quasi insitu image acquisition system to better understand fretting wear mechanisms are experimentally validated. The evaluation of this tribometer concludes with through different test series. These also show established and new solutions to avoid or reduce fretting wear by the means of polymer coatings and solid lubricant pastes. Polymer coatings are chosen from the state of the art of coating supplies and comparably tested as well as some types of solid lubricants.

Basics

Terminology

Technical and geometrical description of fretting conditions: The geometrical description of the conditions where fretting wear can be observed, related to [Hei89] and [CH10], can be described with an oscillating relative displacement $\triangle x$, which is shorter than the possible macroscopic contacting area lengths of each body, L_{C1} respectively L_{C2}. The macroscopic contact area length is determined on the contacting bodies in direction of the displacement. A quick estimation for the minimal contact length can be done with the Hertzian Theory [Her81]. Additionally, to the Hertzian analytical calculation the contact area length for the reference system body includes the displacement amplitude. In cases where fretting wear occurs, the relative displacement is much smaller than the contact area length.

$$\frac{L_{C1}}{L_{C2} + \triangle x} \approx 1 \tag{1}$$

In most cases of fretting wear the contact ratio equation (1) gives a ratio value of around 0.9 to 1 from observed practice cases. This can be estimated through measurements of the worn areas on the contacting bodies. Later described special cases in partial slip regimes have a ratio of nearly 1. Graphically the geometrical description of fretting wear conditions can be seen in fig. 1 on an normal and tangential loaded contact. The tangential load is changing directions repetitively.

Oscillation amplitudes greater than the contact length lead to reversing sliding wear. For example, in a conformal shaft-bore system, with an oscillating rotating shaft, depending on fit or manufacturing tolerance, with the same deflection angles, fretting wear or reversing sliding wear can be established. This is influenced by the contact length of the shaft and bore, which changes significantly with the tolerances in the conformal contact. The same applies to the approximation of the bodies in which the contact width increases. The boundary between fretting and reversing sliding wear can therefore be fluent in the test and in practice.

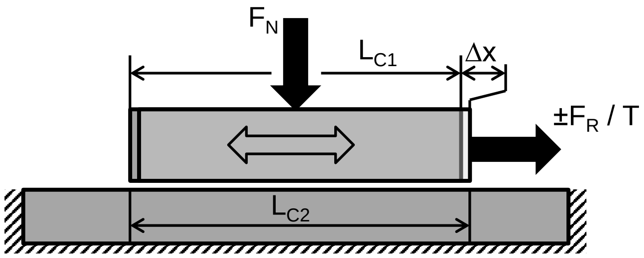

Figure 1: Schematic for the definition of fretting wear

The terminology in English international literature divides the term directly into observable phenomena with causal fretting wear. The worksheet 7 of the German Society of Tribology [GfT09] list fretting and fretting wear as the general term, fretting corrosion as fretting with visible corroded surfaces and fretting fatigue as crack initiation, crack growth and crack failure induced by fretting wear friction stresses. The classification into system classes of HEINZ in [SHS10] and [Hei89] gives an assignment to technical systems.

Fretting wear examples from applications

The problems that occur in practice, which are caused by fretting, can both lead to spontaneous failures, as well as creeping loss of function. Spontaneous failures are therefore more likely to be associated with fretting fatigue fracture phenomena, where crack initialization can be found in fretting wear areas (greatly increased notch effect due to dimples or grooves). Dimensional decrease by fretting leads to steadily increasing clearance or a decrease in a defined preload or the like. In this case, the system function changes at the contact and the consequences can lead to a machine damage far outside the contact itself. Heinz [Hei89], names the component as a stopping tappet, which is installed in a mechanical combustion engine control actuator, the component undergoes not only the tension in stop position but also a shock load due to engine vibrations (from the internal combustion engine, crank mechanism). The load leads to a scarred surface, which is pronounced depending on the preferred direction of the vibrational motion. With lubricated system and impact load, a steady discharge of wear particles can lead to a noticeable decrease in size and the failure of the system function. Components where comparable damage occurs, can also have equivalent functions. In the reports of the alliance insurance, BARTEL in [Bar65], practical cases of damage are described on the basis of the influences that lead to their emergence. In general, machine elements or component connections are here called, which are either rather loose (with clearance) or allow relative movements by elastic deformation. Below are the categories (sorted by influences) with examples from BARTEL [Bar65] listed and described.

BARTEL further describes different influences on fretting wear by design, manufacturing, assembly, operation and environment and describes them with the examples machine elements shown in Fig. 2. Despite the sources age, most application examples are still relevant and show the importance of considering fretting wear in the product life cycle. The listed design approaches and design guidelines are fully applicable today, with the use of more modern materials, lubricants and manufacturing methods allows more specific approaches. Likewise, in the development of new applications, there are cases of fretting wear in which the fretting wear inducing facts are not in the consciousness of designers or developers.

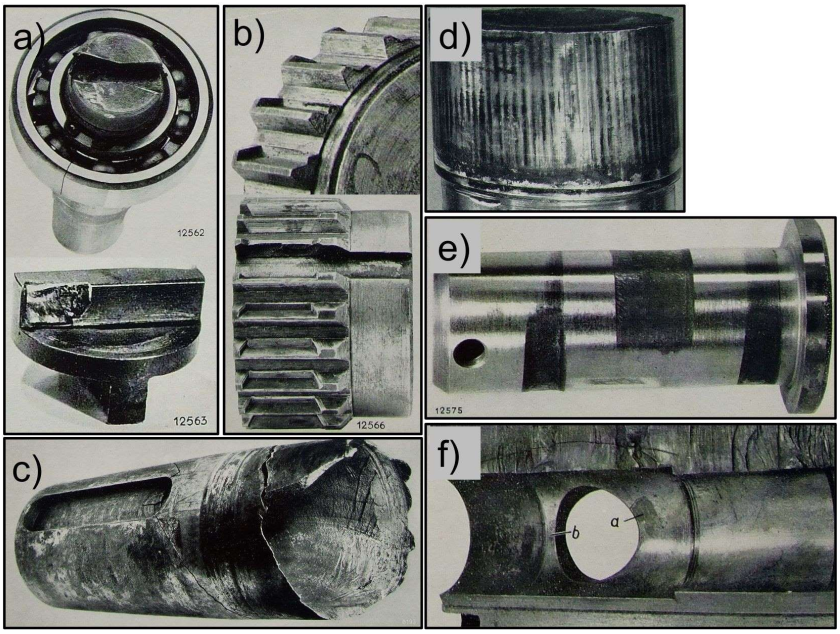

Figure 2: Roundup of machine element fretting wear damages. a) cross ledge coupling, b) tooth coupling, c) shaft seat with key way, d) bearing seat, e) shear bolt, f) cylinder wall of a compressor. Source of image: [Bar65]

Wear mechanisms and failure types

From the detailed treatment and classification in [CH10] the possibilities are selected to describe the fretting wear mechanisms with the combination of different wear and failure types. In principle, the following wear mechanisms are possible:

Adhesion as an initial and recurring manifestation which causes micro welds and particles to be formed by the transfer or termination of roughness peaks. The surface is badly damaged by adhesive wear. This is accompanied by a significant change in the mechanical conditions (contact stiffness / compliance, surface pressure) in the friction contact. Surface topography changes irreversibly. **Pitting** and microcracking due to high shear stresses at the onset of slip in contact and local adhesively formed bridges. Depending on the load, cracking may occur. If the crack growth is faster than the material removal by other mechanisms, a permanent break can occur. **Abrasion** usually as a result of the particles formed in the friction point. Particles with greater hardness compared to the original material and low tendency to adhesion chip, furrow and break the body. This also induces further particle formation. Also, direct abrasion of the base and counter body can ablate the surface of the softer body and cause particles to emerge or agglomerate depending on local contact pressure distribution **Tribochemical reactions** and especially oxidation or corrosion in metallic contacts with friction of surface and particles. The quasi-closed contact and the possible high energy input favor the tribochemical reactions. The reactions allow chemically modified particles of the base material, usually oxides in steel-steel pairings, and coatings to form. Coverings can be of a temporary nature and can also be removed by abrasion and adhesion. Also important is the ratio of surface to volume of the resulting particles. With the ratio increases the reactivity or reduces the time required for a particle to convert to a passive state. Nanoscale effects, such as the agglomeration of polar particles can also be relevant influences.

There are two approaches for the initial cause of the formation of oxide particles in steel-steel pairings. One approach describes BARTEL [Bar65], that particles are removed adhesively or abrasive from the base material and then oxidized by the high local friction energies. Decisive is a fine metallic abrasion, which attracts the molecular oxygen and oxidizes immediately. Another approach also described by [Bar65] is that the surfaces are oxidized by the locally high frictional energies and are broken by the changing load. Decisive are the high temperatures at the real friction point and the finding that the number of oxidation products under vacuum or inert gases is significantly lower. In the context of fretting wear, the mass transport of wear particles (and lubricants) in the tribosystem is of particular importance. HEINZ describes in [Hei89] the importance of mass transport in the tribosystem not only for the clarification of wear mechanisms, but also for the selection of test systems in tribometry as well as for the development of solutions for different problems. In [Har05], there is a exemplary developed approach of material flows (or as particle flows) from contact regions in shaft-hub connections. In order to interpret the wear mechanisms and failure modes as findings after a test, HEINZ distinguished in [Hei89] according to the basic parameters. Each can be sorted by oscillation direction with amplitude, frequency, and a formula for the linear fretting and assigned wear mechanism phenomena.

Wear mechanisms as a process of fretting wear as conception of a nonlinear wear process, which can be assumed for cases where fretting wear occurs. The process can be seen as HARTMANN [Har05] describes particle processes as an effect of causal stress. These include particle formation and their transport. Processes of shape and property change as an effect of the causative particle processes. These include the change in shape due to wear and removal of the particles and change in shape due to wear and particle accumulation or increase in particle volume (e.g. lower oxide densities). Change in stress as an effect of the causal processes of shape and property change. The processes are partly interdependent. For example, the change in shape can be the reason for a changing particle transport. This fact is described by linking the changed stress as the causal stress for a new process iteration. In the representation in [Har05] after [Pay00] relationships of the wear process in a friction point are shown in the context of fretting fatigue. Particle transport due to pressure gradients is also described in this work. Particles move over the oscillating movement, always in the direction towards lower pressure in contact.

Influencing factors in metallic material combinations: In [JB75], Johnson and Bill list the influencing factors in the material properties of metallic materials. These are the ratio of metal to metal oxide hardness, the metal structure and structure, the mechanical properties such as elongation at break and modulus of elasticity, the oxidation rates and oxide layer formation as well as the coating hardness and elasticity in coated soft metallic base materials. The authors in [JB75] explain in the context of material and contact pairings that are common and varied in the aviation industry, the difficulties with components that are endangered by vibration wear. In [Bar65], with reference to further literature, additional influencing factors are described. The structural structures of cast iron are e.g. different in their resistance to vibration wear. Accordingly, pearlitic cast iron with a is more resistant than with a ferritic structure. High phosphorus content also has a positive effect. **Oxide forms in steel-steel systems** with iron oxide particles from metallic material combinations under fretting wear can be found with different structural molecules. Figure 3 gives a impression on how iron oxides can be found inside and outside of contacting surfaces under fretting. Their color can leave a hint on which type of iron oxide is present but this is not fully conclusive. The oxides formed are depending on the environmental conditions like temperature and humidity.

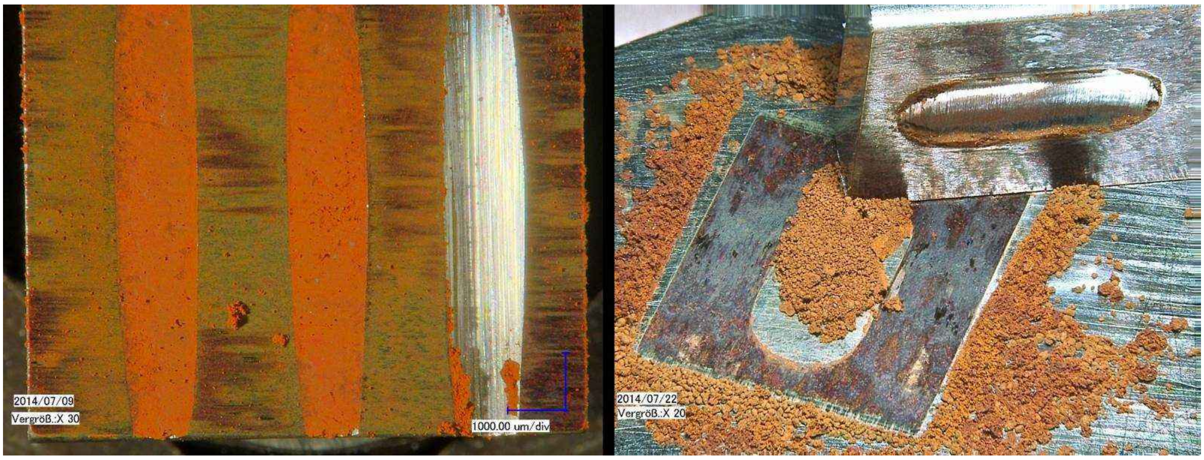

Figure 3: Macroscopic images, left: Red iron oxide particles agglomerated within a slot. Right: Loose red oxide particles and oxide layers after a test.

Most import property is the particles hardness which often is in the same range or higher than the hardness of the base steel material. It can be said, that fretting wear of steel contacts inherits a self supplying abrasive particle process. From the usual appearance αFe_2O_3, Fe_2O_3 and Fe_3O_4 occur mostly when fretting wear is present in iron / steel contacts.

Contact mechanics considering fretting wear

The results given in [MD53] by MINDLIN and DERESIEWICZ and in [Cat38] by CATTANEO for the special cases with tangential forces show for the first time analytically the behavior of a contact with initially increasing and with changing tangential load with constant normal force. Similarly, [MD53] deals with cases of increasing arbitrarily angled force. Also in the works [Joh87] and [Pop10] the basics from [MD53] and other special cases are clearly described.

In the case of **planar and conformal contacts**, which do not terminate the contact with a radius in the peripheral area, in the theoretical-analytical case it applies that there is either only sticking or only sliding in the contact, [Pop10]. Analytical treatment of flat contacts with marginal radii lead to results similar to those for spherical contact, [NDH06]. The great importance of flat contact results from its practical use in engineering. The shape and position of this surface cannot be reliably predicted in a practical experiment. Therefore, test specimens are manufactured with the best possible flatness tolerance, roughness parameters or topography should already meet the requirements. Manual reworking usually rounds off the entire surface (to speak of manual sanding). The installation and alignment of the surfaces to each other need an adjustable alignment and tension-free fastening. Also a a kinematic guided application of tangential and normal forces is needed. Forces applied eccentrically to the contact create a momentum. In the direction of oscillation, this can induce a changing asymmetrical surface load or a rolling movement and the contact pressure distribution becomes asymmetrical in the normal load direction.

Characterization in experimental design

In order to better express the idiosyncrasies and peculiarities of fretting wear, to expand the possibilities of interpreting experiments and to promote understanding, some papers give insight in special methods of experimental engineering for fretting. The state of the art in experimental design is described for discussion.

Fretting Maps in the representations of the works [FKV00] and [ZNZ+06] based on [VS88], [VBDG92] and [ZFV92], the ball / plate or cylinder / plate contact main parameters of fretting wear can be systematically used to represent different regimes. This can be done if characteristic results of a combination of two test parameters, e.g. Normal force (or contact pressure) and displacement amplitude are plotted in a diagram. This shows characteristic stress areas of another parameter, e.g. the material pairing. HERTZ in [Her81], CATTANEO in [Cat38] and MINDLIN and DERESIEWICZ in [MD53] created the theoretical basis for this approach.

Friction / displacement cycle diagram: The determination of the friction / displacement cycle diagram in a single test consists of the detection and application of frictional force FT and the deflection s via an oscillation. For example, viewed on an oscilloscope, there are characteristic signal figures for the sliding condition in the friction point. By plotting force over distance, the energy balance of the friction point is also directly visible. Accordingly, energetic considerations are also possible, as shown in Fig. 4. The hysteresis curve can be calculated via the formulas given by MINDLIN and DERESIEWICZ [MD53]. The maximum friction force is limited to the global coefficient of friction μ multiplied by the normal force N. The findings from the friction / displacement cycle diagram should be referred to as the instantaneous sliding characteristic. During an ongoing test, it is possible to deduce the sliding state solely by measuring the frictional force and deflection. The behaviour over time can be shown in the experiment by recording the frictional / displacement cycles. Transitions from sliding states become visible, as are changing friction values. The amount and preparation of the measurement data to display the sliding characteristics require appropriate preparation and systematic (including statistics, sample rate, filtering, display).

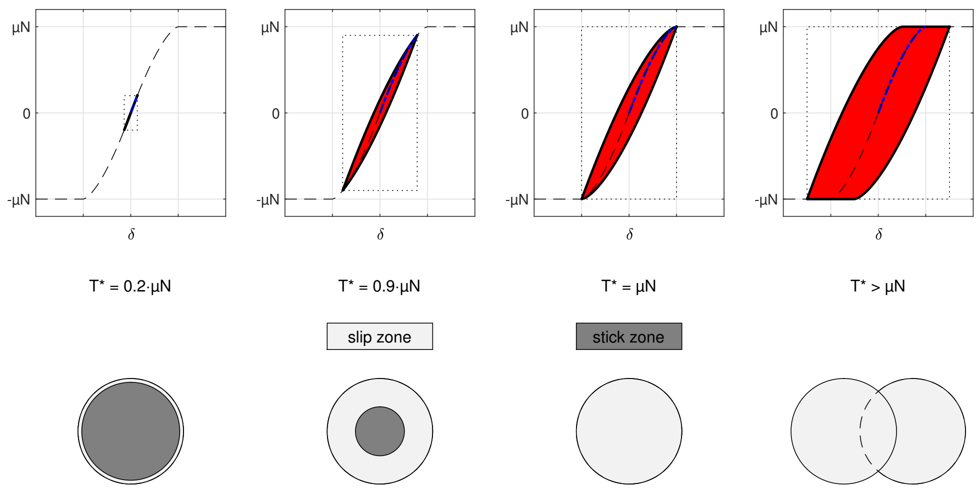

Figure 4: Qualitative representation of characteristic friction / displacement cycles in connection with the sticking and sliding zone of a point contact

Tribological systems theory and test chain

The tribological system theory, as published by CZICHOS both in German in [CH10] and in English in [Czi09], forms the basis for the later development of the system-theoretical consideration of fretting wear.

A basic idea here is the view of the tribological system (tribo-system) as a system structure made up of interactive components. This describes the function of the tribological system, the energy, matter and information flow. Fig. 5 briefly gives the basic definitions of terms and the methodology on a tribological system.

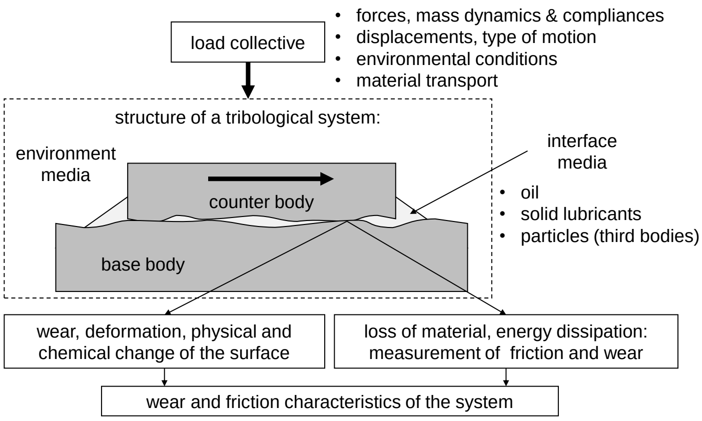

Figure 5: Definition of terms and methodology of a tribological system. System theory according to [CH10]

Compared to the abstract representation in Fig. 5 , the system structure of tribo-systems can often be specified more precisely by means of a structure consisting of a pair of active surfaces, intermediate material and surrounding medium. The pair of active surfaces can be divided into clear basic and counter bodies if the system does not have several pairs of active surfaces. The system is described within the freely defined system boundaries in order to enable the best possible mapping for the theoretical and practical development of design and problem-solving approaches. The acquisition using the methodology of system theory is particularly useful for the preparation and interpretation of model experiments. The system limiting boundaries of a tribological system can often be set by geometrically delimiting a machine element with its environmental conditions.

The concept of the tribological test chain in Fig. 6 supplies a reasonable scheme from complex field tests to simplified model tests. An evaluation of friction and wear topics can start on a low effort and cost model test with a large abstraction. Most abstractions of application will not have the same properties like size, shape and therefore contact conditions on a model test (testing category VI). Often Materials, surface roughness or coatings can be on an application level in a category V to VI test. The advantage is to save time and resources by reducing the amount of variations (e.g. Lubricants or coatings) with each testing category.

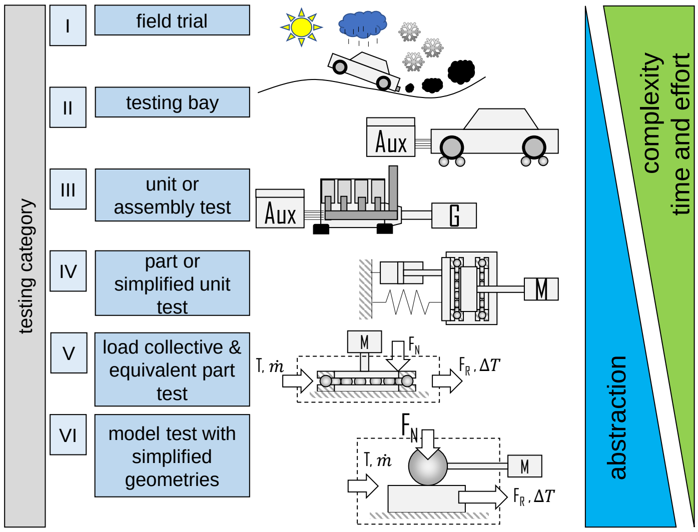

Figure 6: Definition of terms and methodology of a tribological test chain. Reinterpreted from [CH10]

It can be assumed, for a certain application, a test chain can be described and proven useful for separate tests with different abstraction. In case of a test chain for fretting wear on shaft / hub connections this could start as a unit test of a gear drive coupled through a shaft / hub connection in a category III assembly test. In this case resource and time requirement are at a very high level. A category IV test on a shaft / hub connection, where only the shaft, hub and a relatively basic test bench are needed for testing. Category V may use smaller parts or prepared segments of a shaft and hub for testing and the test bench itself can be scaled down accordingly. Category VI may only use simple specimens (ball on plate) of the same material. Chances on Category IV to VI are the possibility to add additional measures which are quite expensive or intricate to get in an Cat. III or higher test. Considering also the following state of the art, the later developed test bench should be useful, novel and unique in category V to VI tests for fretting wear.

For a experimental classification and understanding of fretting wear a general overview of the state of the art up to 1990, the literature research by SIMON [SST90] gives an overview for understanding the damage pattern and the methods for tribological testing of fretting wear. As indicated in the GLOEGGLER literature study in [Glö03], the main problem with the development of tribological test systems arises from the numerous possibilities of system definition and the different approaches to research fretting wear. It shows that a large part of the test benches can be used in the categories IV, V and VI of the tribological test chain [CH10], Fig. 6.

The State of the Art for test benches and tribometers from HEINZ [Hei88], [Hei89] and [SHS10] show a tribometer which can execute biaxial vibrations with additional impact load. The specimen configurations and possible loading situation show, that HEINZ developed the most versatile fretting wear test bench of its time. Furthermore, the shown results in his works lead to the conclusion, that it is possible to achieve a planar contact model test with a quadratic contact area of 3 x 3 mm.

The German abbreviated **S**chwing**r**eib**v**erschleiss tribometer (translated: Oscillating friction wear), SRV for short, from Optimol Instruments are frequently encountered tribometers of the lubricant industry, which also provided the impetus for the development of the SRV test stands. Tribometers and model tests are standardized in DIN 51834 (1). Also a standard, the ASTM 7421-19, for model testing of lubricants for fretting wear protection exists.

The Fafnir test bench [Sch82], which confuses and generalizes the fretting wear term to a large displacement motion amplitude to a prorietary axial ball thrust bearing. The testing procedure is described in the ASTM standard D4170. When considering typical fretting wear conditions an apparatus with adjustable stroke from ±3°to just a few angular minutes [GF06] allows investigations into the wear phenomenons known as false brinelling and standstill marks. The engagement conditions as contact ratio remain close to 1.

Further servo-hydraulic pulsators / hydropulsers and resonance pulsators which are used for fretting wear and especially fretting fatigue. Examples are [RBC84] (direct test of a turbine blade anchor geometry), [RE88], [KB97a], [KB97b] (shows test options and power flows), [GF09] (extended structure with active lateral force control), [FMM03], [MMF09] and [KOK^{+}12] mentioned.

Elaboration of system theory

System theoretical development process: With a new problem, e.g. the (near) failure of a component due to tribological stress or the development of new machines, a system-theoretical development process can be initiated for the damaged or newly developed tribological system. The benefits of such a development are a holistic view of the tribological system: cause, effect, influences on the origin and avoidance of vibrational wear. The Documentation-based processing, including definition of terminology and a targeted assessment of damage cases. It also gives an an extension of the decision criteria for the design assessment (technical / economic evaluation criteria in the design methodology)as well as a basis for planning, execution and evaluation of tests.

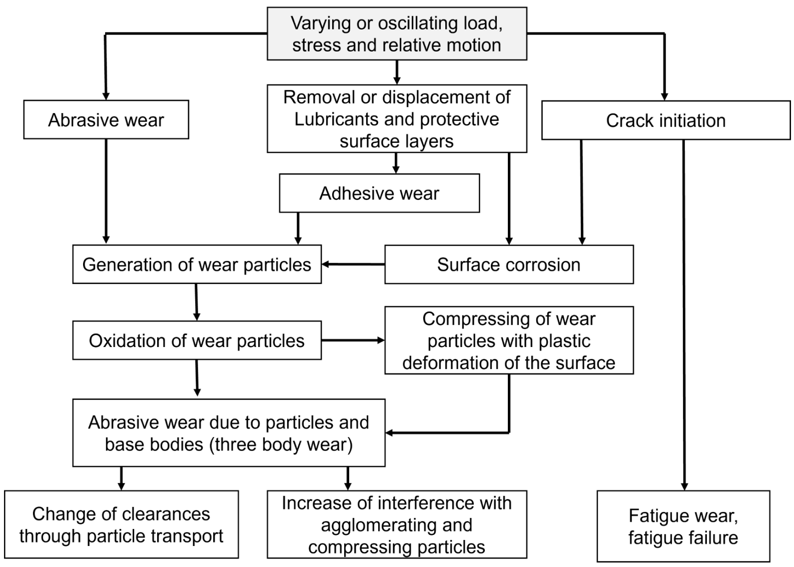

Figure 7: Schematic damage cause by fretting wear, based on [PL75]

Depending on the topographical properties, the wear pattern and wear characteristics can vary fundamentally. **Incorporation of signs of wear and particle influences** can be included in the analysis of the tribological system. Both particle influences and the initial damage mechanism can be essential for the system. The diagram shown in Fig. 7 was developed based on PETERSON in [PL75] for an overview of the occurrence of fretting wear damage. The inclusion of particle influences on the tribosystem in the event of fretting wear represents an important step.

Influences of time lapse: The time-lapse of systems whose wear can only be measured in weeks under normal conditions or which only leads to a failure after years can have a strong impact on the comparability of the practice system and the model system. A common time-lapse is achieved through increased temperatures, frequencies or loads (smaller areas or larger forces). Elevated temperatures result in greater tribochemical activity and thus e.g. a better effect of additives in lubricants and also a faster ageing of the lubricants themselves. Likewise, a temperature induced reduction in the viscosity of the lubricant can allow a better flow into the friction point. Higher frequencies and loads require a higher energy input in the friction point. Whereby higher loads increase the real contact area. Likewise, higher loads affect the base material differently. Depending on the form of contact (point, line, conformal contact), there may be major deviations from the system to be mapped. This means that increasing the frequency tends to remain the most expedient means of elapsing time. The smallest number of system-relevant parameters is changed. The most significant influence when increasing the frequency, in addition to the linearly increasing energy input, is the greater displacement of lubricants at the friction point. The reason for this is the shorter period for wetting and flow processes. In systems with low-frequency loads, the lubricant has a greater impact on damage formation. In this case, increasing the frequency can shift the influence from the lubricant to the base materials. Time lapse in the case of fretting wear problems can be omitted if the wear pattern or amount can be assessed reliably even with initial damage. In a starting series of experiments, no time lapse should therefore take place at first.

Insights from system theory treatment: The more precisely a tribological system analysis is carried out, the fewer iterations of solution development, implementation, testing and proof of effectiveness or rejection with an understanding of failure ("Why did something not work?") are necessary. This general statement applies not only to fretting wear problems. However, the special influence of the particles and the high engagement ratio of both bodies should be dealt with in detail in order not to come to the point after the first system analysis and first attempt that e.g. Particle influences are essential.

Experimental Design

The state of the art in fretting wear research shows some specialties of interpretation and tribological testing tendencies. Especially the fretting wear maps explained by [VS88] can be seen as still actual context. They may need a huge amount of experimental effort depending on conditions where lubrication or coatings often deliver results which can best be interpreted by a time to damage statement. The metrological requirements for the maps are based on the fretting loops which have to be measured by at least one displacement and one friction force measurement. The maps span over different displacement amplitudes (stroke) and normal forces (or more general with contact pressures). Therefore closed loop control of the stroke and normal force is mandatory. With the normal force, as a product of contact area and contact pressure, the required displacement forces to overcome the frictions are coupled. As the earlier chapters showed, friction coefficients can be 0.8 or greater, therefore the drivetrain for fretting wear has to have at least the same force potential as the normal force drive. Depending on occasional requirements and on the initial experiments in this work, a temperature and environment control can be worth the additional effort. Also a displacement measurement in the contact normal direction allows a measurement of online wear, but this also includes thermal gradient effects depending on the path between sensor mount and contact point.

The tribological testing in general tends mostly to point contact geometries because of their much easier or not required alignment. There is not one standard which requires larger planar contacts. Actual standards also tend to stretch the term of fretting to some high pressure test (ASTM D7594-11 iterated to ASTM D7594-19 within the development and commissioning period) with a ball on plate setup. Since most applications have planar or nearly conformal contact suffering from fretting wear, the main motivation in application near fretting wear testing is therefore the use of planar contacts with a focus on easy alignment and a general low effort testing method viable as a standard proposal.

The done experiments on an initially used voice coil drive showed, that it was not feasible for fretting wear, because induced sudden raises in required friction force (adhesive events, micro welds) let the amplitude control usually overshoot by the raising force in the contact until a micro weld is broken. The voice coil displacement drive was replaced by a novel dual eccentric drive configuration during development. Also the normal force drive is designed to with the novel intention of completely opening the contact for further image acquisition details within the test run. Fig. 8 shows the specimen alignment setup with the image acquisition procedure in a schematic.It has to be mentioned for later experimental results, that the moving mirror for the upper specimen image acquisition was included as a small iteration to the tribometer. The novel two-axis alignment adjustment allows a quick iterative specimen alignment.

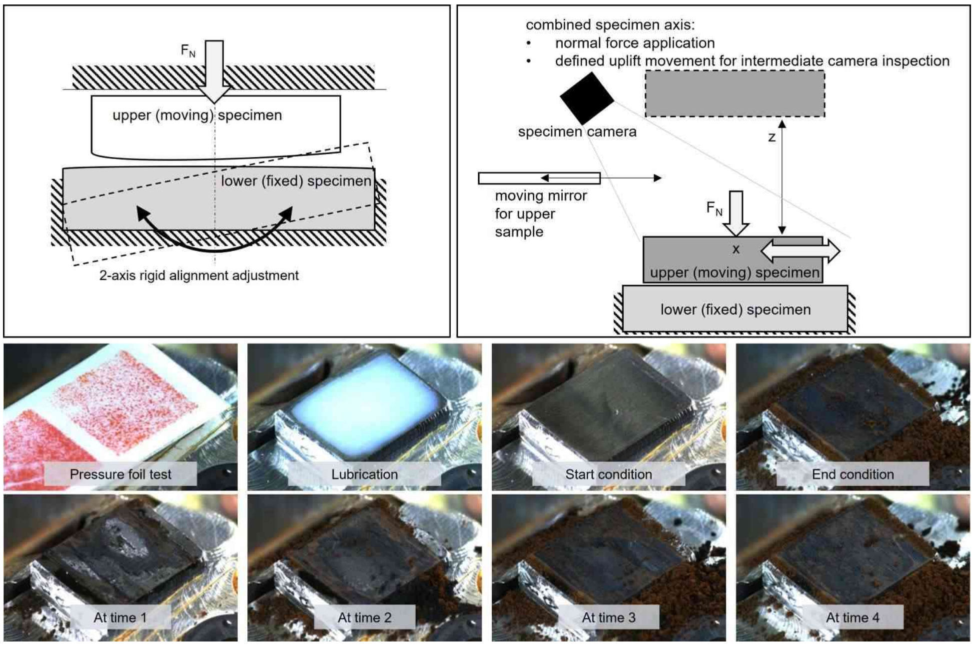

Figure 8: Specimen alignment setup, Image acquisition principle and exemplary image sequence

The clearance of between the two specimens is enough to fit an picture frame over the entire lower specimen if the optical axis is aligned under 45° and heading in the specimen center. For accessibility, the optical axis is also swiveled to the left. With the used telecentric camera lens, no perspective distortion is present in the acquired images. Figure 8 shows an example of an aquired image sequence using the contact opening and closing feature throughout a test. Pictures after the assembly of the tribometer, in this stage called "Big Fret", are shown in Fig. 9. The bench top unit has the advantage to have a spare space to prepare test specimens and tools as well as the monitor, keyboard and mouse to control the unit itself.

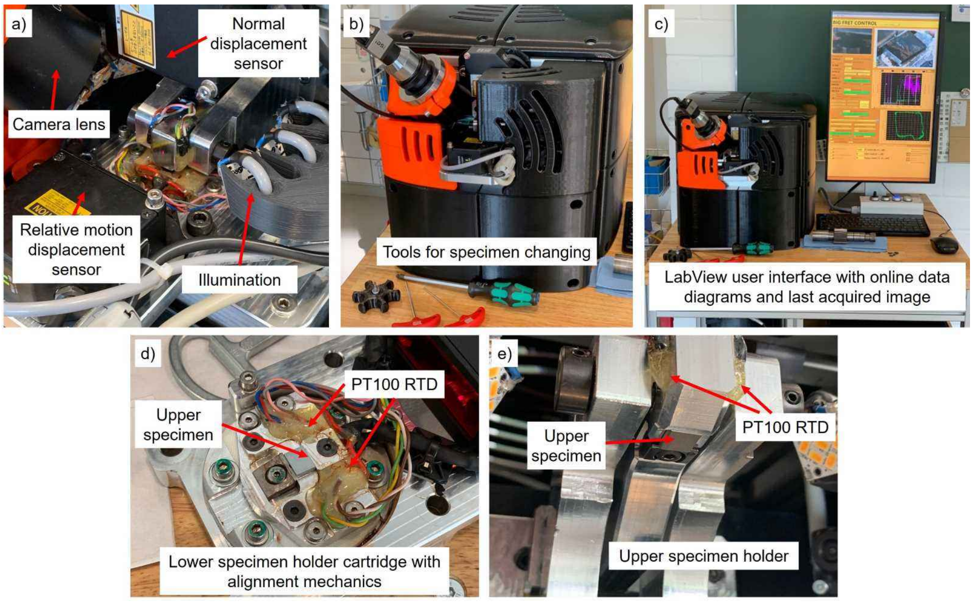

Figure 9: Pictures of tribometer. a) specimen area, b) outer periphery, c) bench top and software, d) lower specimen cartridge, e) upper specimen holder

Experimental Design: Test Series Evaluation

To evaluate the before-mentioned prototypes performance several test series were designed on purpose or by a general interest in fretting wear problem solution finding. The test series are divided in the following sections and are described for their preparation, unique parameters and results. Based on the different test series, a evaluation of the final prototype test bench is conducted.

Solid Lubricants Test Series

The solid lubrication test series uses known solid lubricants like calcium di-hydroxide ($CaOH_2$) work under fretting conditions. Other solid lubricants are more or less unknown for their specific fretting wear avoiding performance. The final results of this test series are published under public access [BSH21]. The test series focus on the performance of CaF_2 and other solid lubricants which were not tested for anti fretting performance in actual research. . The specimens are analyzed in depth via SEM (Scanning electron microscope) and EDX (energy-dispersive X-ray spectroscopy) to get information about the solid lubricant surface reactions and wear. All solid lubricants are mixed into white mineral oil with a viscosity of 70 mm^2/s at 40 °C. The interval image acquisition is set to 120 seconds to get images about the lubricant behaviour inside the contact region. This could be a reaction layer or signs of mild or catastrophic wear.

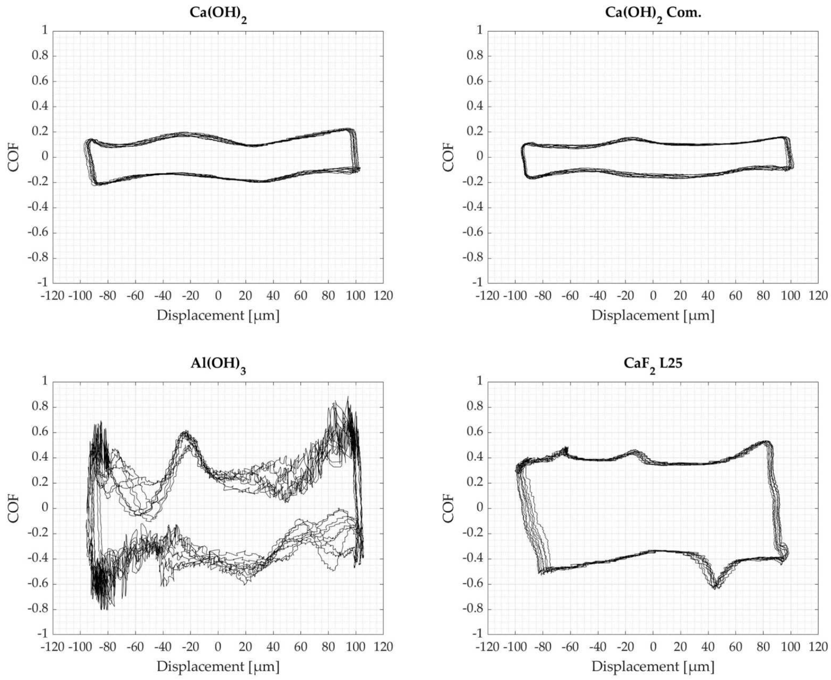

Figure 10: Coefficient of Friction over displacement as fretting loops for different solid lubricants

Solid Lubricants Test Series: Results: The fretting loops for $CaOH_2$, the $CaOH_2$ commercial paste, $Al(OH)_3$ and CaF_2 are shown in Figure 10. The fretting loops can change their shape through a test especially when the friction force rises or if effects like stick slip happen, where displacement and friction measures are very unstable. The COF of $Al(OH)_3$ is quite high and is could be assumed, that there is also excessive damage visible on the specimens. The images of the $Al(OH)_3$ steel specimens of Figure 11 show only slight damage without any progressive failure mechanics. Therefore $Al(OH)_3$ could be a good candidate for an high friction anti fretting paste since higher friction in interference fits may help reduce the relative motion as the primary cause of fretting wear.

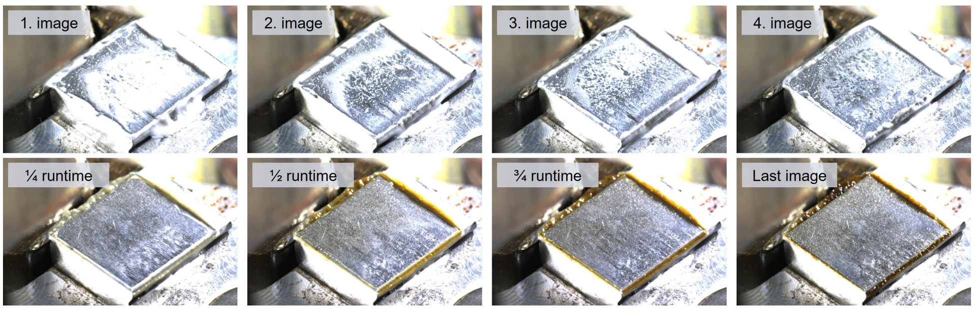

Figure 11: Interval image overview for the $Al(OH)_3$ lubricant.

The CaF_2 variants in Figure 12 shows an insight on the period of higher friction. All CaF_2 tests show some agglomeration with higher reflectivity in the middle of the contact on the upper row of images of hour 1. Within 10 hours in the second row these agglomerations are gone except for the CaF_2 L55 sample, show a small spot of the initial agglomeration remaining. Also on the second image row an brown layer has been formed, darkest brown on the CaF_2 L25 variant, and similar light brown on the other variants. From second to third row, the optical appearance does not change much in relation of the much longer time between the images. The time also varies between the variants since for all but the CaF_2 L25 variant it is the last image before typical fretting wear starts with adhesion, abrasion and the generation of oxide particles. The fourth row shows the end state of each specimen and the CaF_2 L25 is deliberately stopped for analysis.

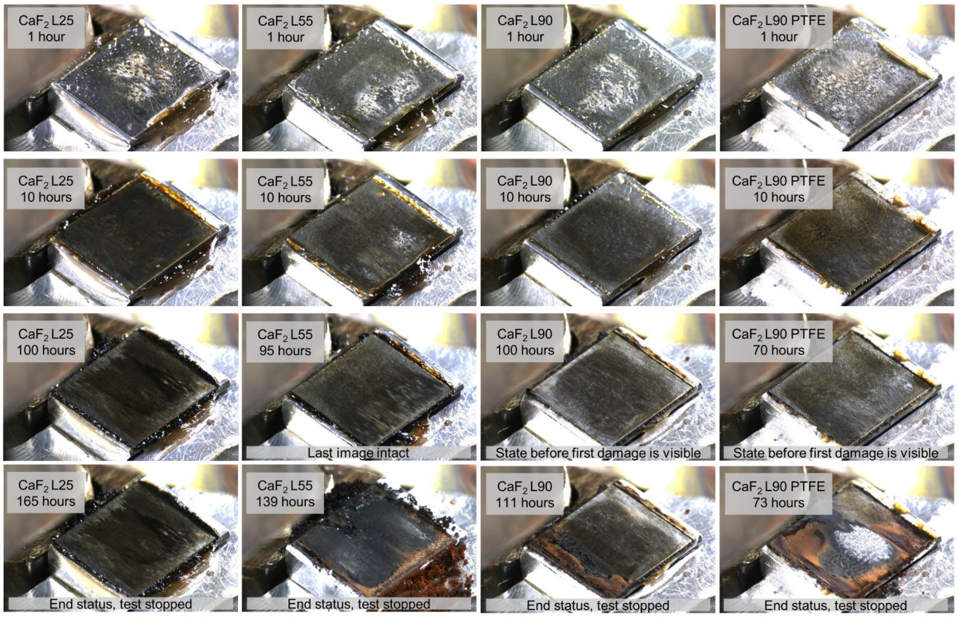

Figure 12: Interval image overview for the CaF_2 lubricants.

The summary of the SEM EDX analysis in Figure 13 for the $CaOH_2$, CaF_2, $CaOH_2$ commercial, $Al(OH)_3$ and $Ca(SO)_4$ pastes shows the corresponding SEM images of each steel specimen surface.

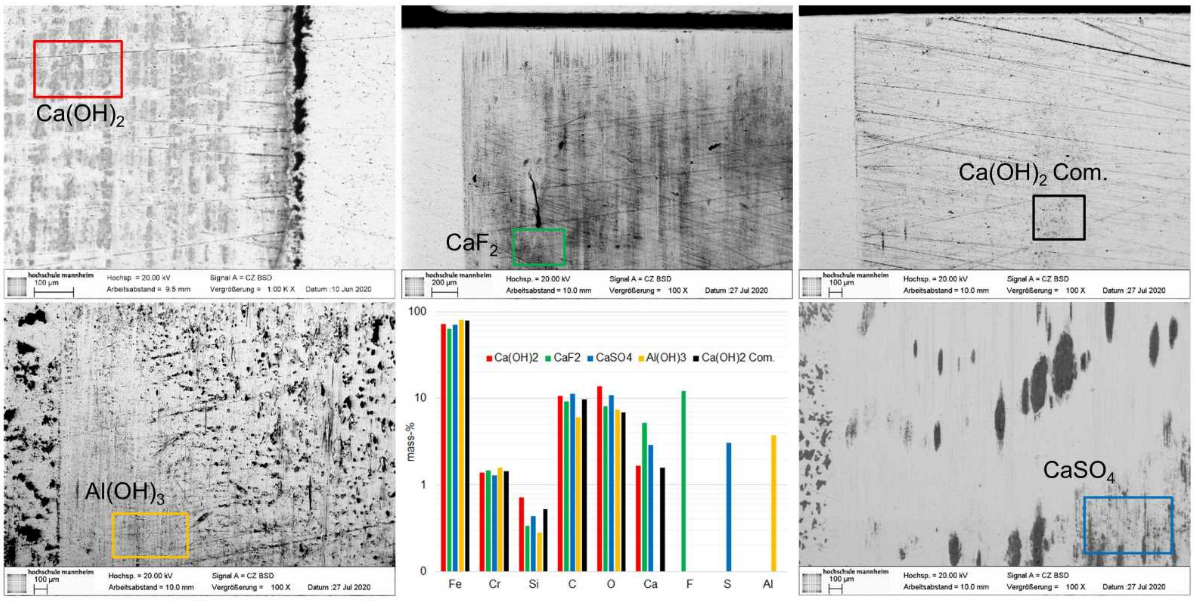

Figure 13: SEM EDX Analysis of the different solid lubricants.

The colored rectangles show the location where the EDX spectra were sampled. A location where the reaction layer is mostly uniform is chosen on each sample, the images position on the sample also shows the edge of the plain contact so, that the original surface of the steel specimen is visible. It can be seen that $Al(OH)_3$ and $Ca(SO)_4$ have the least uniformity, with $Ca(SO)_4$ only covering some spots on the surface. Also $Al(OH)_3$ and $Ca(SO)_4$ react with non contacting surface regions. All formed layers are darker in the SEM images, therefore their density should be less than that of the brightly displayed iron surface. The spectra for each shown lubricant in the middle of the bottom row shows the calculated mass percentage on the EDX surface analysis as a logarithmic scaled bar plot. The colors of the bar match the shown rectangular areas in each lubricants SEM image.

Bronze Materials Test Series

The bronze materials test series is comparing different bronze materials as well as two different lubrication greases. Motivation for this series is the upcoming further reduction of the lead amount in bronze alloys. In a large machinery application where fretting wear is likely to happen, the actual bronze part contains to much lead and therefore an alternative alloy with comparable or less fretting wear rate has to be found. The specimen counter-body was in every test a case hardened steel.

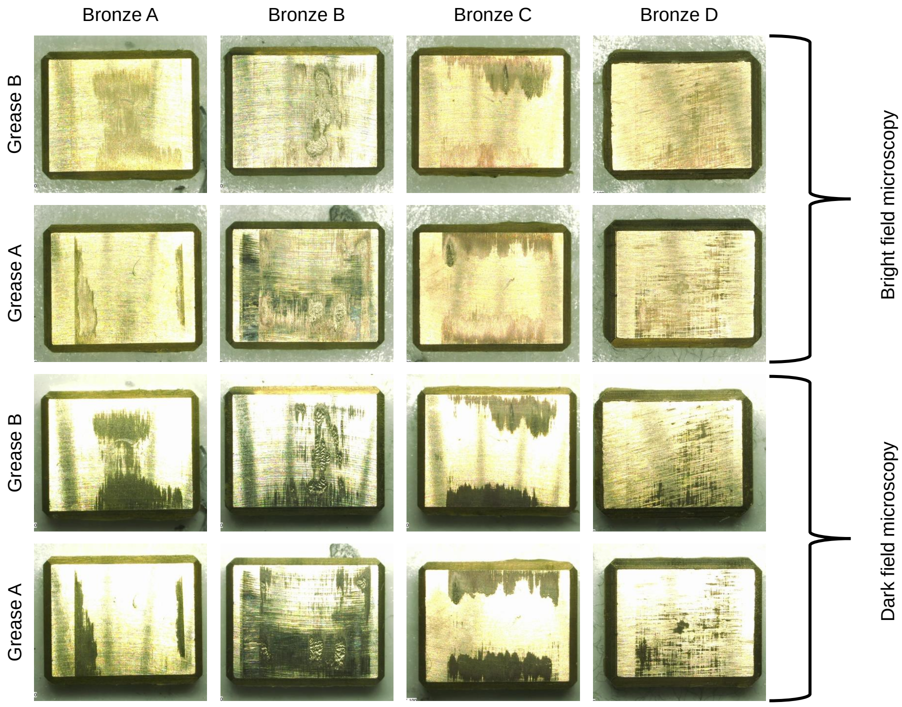

Figure 14: Comparison of different bronze materials and lubrication greases lead to wear patterns on the shown bronze counterpart

The results are shown with the microscopy of the lower bronze specimen on Fig. 14. Throughout all specimens, the wear pattern is strongly dependent on the shape deviation on both specimens. In the worn surface parts, a clear difference can not be seen between grease A and grease B. With the dark field illumination in the lower two rows of both figures, a distinct wear pattern can be seen between the bronze materials. Bronze A and bronze B show more of a fine and full abrasion on large areas. Bronze B shows some ripple fields on contacting area, which are also visible on the steel specimen, where the bronze is adhesive sticking and maybe agglomerating. Bronze D shows almost no wear, some contact is visible with slight abrasive scratches. The wear pattern on the bronze materials is mirrored as material transfer to the steel specimen in all tested combinations. Not shown is the online friction force data,a which in all cases shows a coefficient of friction of around one. Therefore material contact with boundary friction leads to the adhesive material transfer.

In summary of the bronze materials test series, the results show a good differentiation of the bronze materials and a possibility to be optimized via the lubricant. As an outlook on fretting wear on bronze material testing, the final prototype can help to understand long term wear mechanics if the adhesion process is steady or escalating. The initially lubricated tests may also show effects from lubrication starvation in longer tests which is more likely through the larger contact area.

Cross Comparison Test Series with Stand Still Marks

The comparison with stand still marks, a special case of fretting wear, is main task of this test series. Stand still marks are a significant roller bearing service life reducing type of wear and often a correct lubrication can avoid this type of wear (for a certain time). For this test series lubricants were chosen which have to be tested for their stand still mark behavior. The lubricants are used in train gearboxes which can suffer from external vibrations while in idle operation. This test series for the stand still marks gives the opportunity to test how well the contact alignment can be performed. Comparison and conclusion on the findings are published and presented in detail [BHG19].

Materials and Coatings Test Series

The materials and coatings test series is the first series to implement the interval image acquisition functionality of the final prototype. The functionality is also used to acquire an image of the uses pressure sensitive foil as well as the lubricant amount applied. The test materials and coatings test series is searching for a solution on an disclosed application problem and therefore the testing procedure is divided into several sub-series with anonymous declarations. Since application load collectives are not clearly known, a small parameter study for different load collectives is also developed. The tests are normalized to have the same sliding distance, therefore, the test with 100 µm stroke have doubled runtime compared to the test with 200 µm stroke. Since the testing frequency is not changed, the energy density is linear depending on the stroke, the normal force and the resulting friction.

The coatings test are divided in polymer or soft coatings and hard coatings. Since the soft coatings are considered a working solution for the given fretting wear case and load collective, the tests are further done in a series of endurance tests to quantify wear rates and failing conditions of any promising combination. Material specimens are each hardness measured on the Rockwell C scale and the wear amount is determined by gravimetric measuring before and after a test. The final prototype interval image acquisition is activated to acquire an image every 120 seconds of runtime.

Materials and Coatings Test Series Results: Base Materials: Beginning with the series of the relevant base materials of a shaft and hub application, Figure 15 shows the results with the measured hardness and the amount of wear as a measure of specimen weight before and after a test. The 100Cr6 / 1.3505 steel samples with different hardness show the least wear in their original state of around 60 HRC.

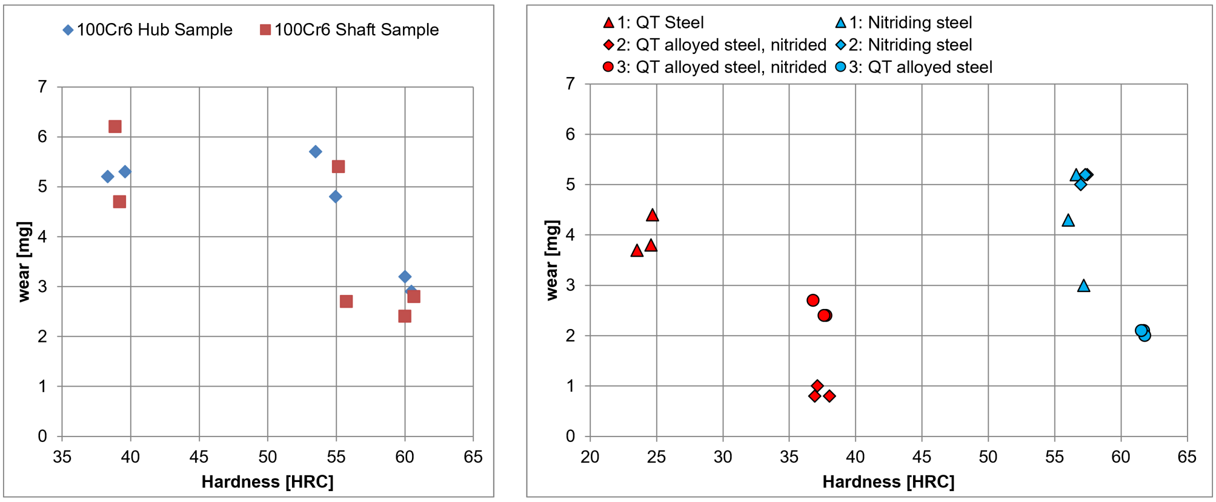

Figure 15: Hardness and wear measurement of the base material tests

Comparing the relevant application alloys on the left of Figure 15 shows very different results. Combination 1 with a QT steel / nitriding steel shows around 4 mg of wear for both specimens, summing up to 8 mg for this combination. Combination 2 with a QT alloyed and nitrided steel / nitriding steel shows very low wear of 1 mg for the QT alloyed steel specimen and around 5 mg for the nitriding steel specimen, summing up to around 6 mg for this combination. Combination 3 with a QT alloyed and nitrided steel / QT alloyed steel shows around 2,5 mg of wear for the QT alloyed steel specimen and 2 mg for the QT alloyed steel specimen, summing up to 4,5 mg for this combination. There is no direct dependence on the hardness and the amount of wear after the test, clearly stating, that the hardness can not be the only measure for fretting wear performance of steel alloys. The focus on further understanding the mount of wear for each combination is therefore on the crystalline structure and the interaction with wear and oxide particles.

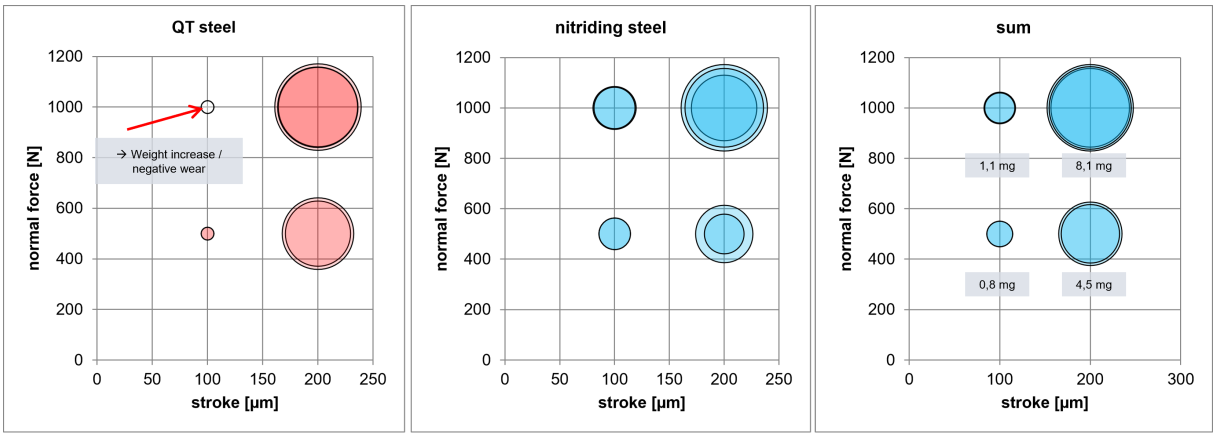

Figure 16: Wear amount as bubble area for the combination 1: QT steel / nitriding steel from parameter study.

Materials and Coatings Test Series Results: Parameter Study: The test series parameter study with different normal forces and strokes shows very distinctive results depending on the normal force or stroke. Figure 16 shows the resulting wear of each specimen. The amount of wear is represented as the circle area. The sum wear on the left gives numeric values to the quantitative area representation. The combinations of parameters show clearly a significant decrease in wear for 100 µm stroke of to around a fifth compared to 200 µm. The normal force only seems to relate to a doubling wear for a doubling in the normal force. With the given material combination, a normal force of 1000 N and a stroke of 100 µm leads to an embedding of wear and oxide particles at the QT steel specimen and a weight increase. A relatively soft steel (25 HRC) may be protected by embedding the particles but then also wear out the opposing hard body (around 57 HRC).

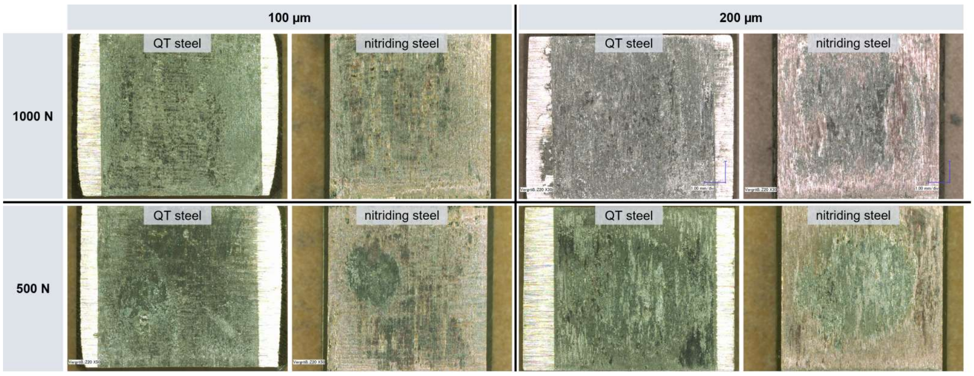

Figure 17: Upper and lower specimen microscopy for the combination 1: QT steel / nitriding steel from parameter study.

The microscopy images of Figure 17 show a black oxide layer at the the QT steel specimen on all parameters. The visible layer on the samples with 100 µm stroke seems very thin and the original surface roughness can be seen through. Linking the amount of wear and the image is only possible between the different stroke length. Concluding the small parameter study leads to the comprehension of the works of HEINZ [Hei88], [SHS10] where wear rate is disproportionately depending on the relative displacement under a specific threshold. If the relative displacement is not clearly known or is varying strongly, a parameter study is recommended for clarification.

Materials and Coatings Test Series Results: Hard Coatings Screening: The results of the hard coating screening is shown in Figure 18. It is obvious, that not every combination of materials and initial lubrication could be tested. Instead of the specimen weight difference before and after the test, the hard coating screening uses a time to damage approach. Here the time until the first visible obvious damage in form of abrasion or seizing by adhesion is noted by the online measurements as well as the interval image acquisition every 120 seconds. The images are used to show the first damage in Figure 18. A oil lubricant is used for testing, since every hard coating combination from 1 to 10 failed with visible damage within several minutes from test start. With initial lubrication, DLC3 and DLC4 show good performance on the combination with a hard 100Cr6 counter-body. Especially combination 12 of DLC3 reached a runtime of 150 hours until a first adhesive damage. As a conclusion, the tested hard coatings are very dependent on an initial lubrication, as well as a suitable counter body to avoid early initial damage and long term fretting wear.

Figure 18: Hard coating screening results as a image table with corresponding run times until damage is visible.

Materials and Coatings Test Series Results: Soft Coatings Screening: The weight change by wear or transfer built up of the soft coating screening is shown in Figure 19. All soft coating but combinations with coating 3 work well within the 4 hour runtime. The steel specimen shows a weight gain and a transfer film built up. The transfer film is well visible on the steel specimens and is exemplary shown for coating 2 and coating 4 in Figure 20.

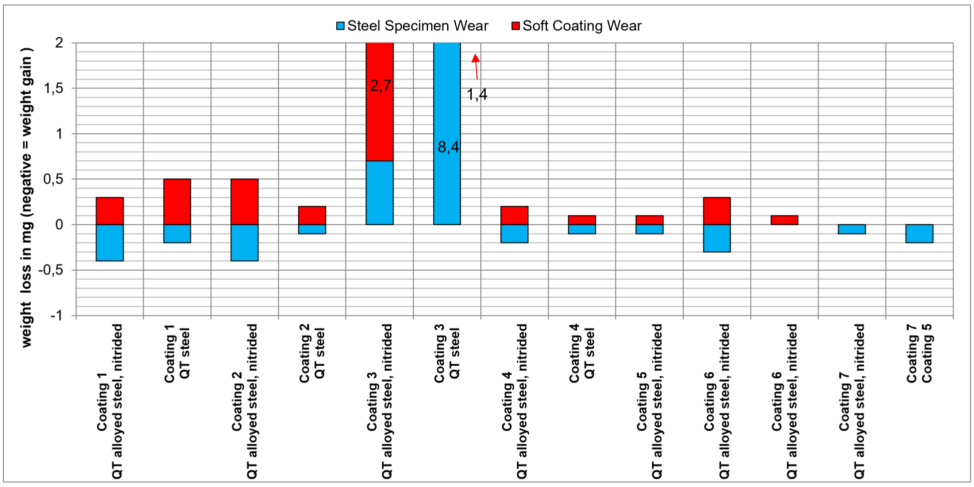

Figure 19: Soft coating screening results for 1000 N Normal force, 200 μm peak to peak, 4 hours at a frequency of 49.5 Hz and 120 °C.

Within the soft coating screening results, the coatings can be rated by their amount of wear and by the sum of wear. If a coating is able to transfer its weight loss completely as transfer film to the steel specimen, the absolute loss for the tribological system can be zero. Coating 4, 5 and 6 are able to have a net zero sum. The combinations with coating 7 seem to gain weight without any loss on the opposing specimen and lead to the assumption, that the used scale is not providing enough precision to weight the specimens or the coatings are able to absorb moisture within the measurement range.

Based on the results of the soft coating screening, coating 4, 5, 6 and 7 were chosen to be tested with increased run time. The also low wearing combination of coating 7 and 5 was not further tested, since the application is not suitable for a coating both machine parts.

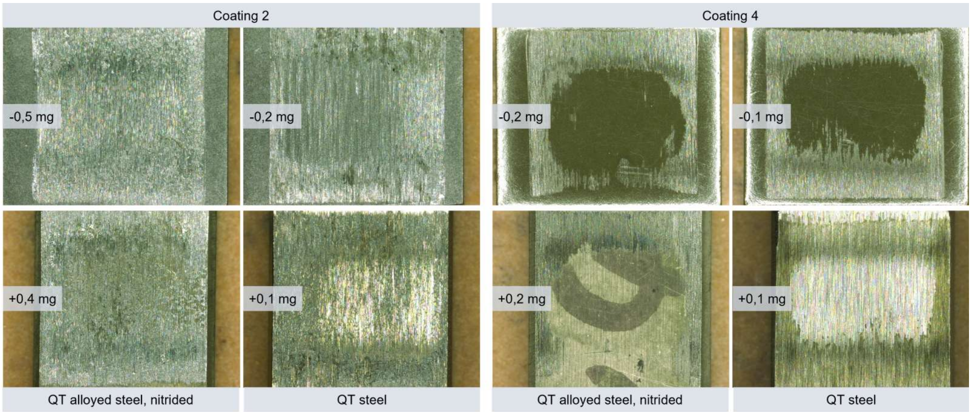

Figure 20: Microscopy together with weight change for coating 2 and 4

Materials and Coatings Test Series Results: Soft Coatings Endurance: The endurance tests are conducted with the chosen coatings 4, 5, 6 and 7. In the first endurance test with coating 4, a error for the heating PID control led to an heating shut off and in return showed, that the coefficient of friction of the coatings is much more dependable on the temperature than expected. When heating failed, the COF is rising dis-proportionally of more than double the level at the set-point temperature. Because higher friction may also cause a change in wear rate this can be critical behaviour of the soft coatings. Therefore the following endurance tests introduced a variable temperature program, which changes the temperature set-point in fixed time steps.

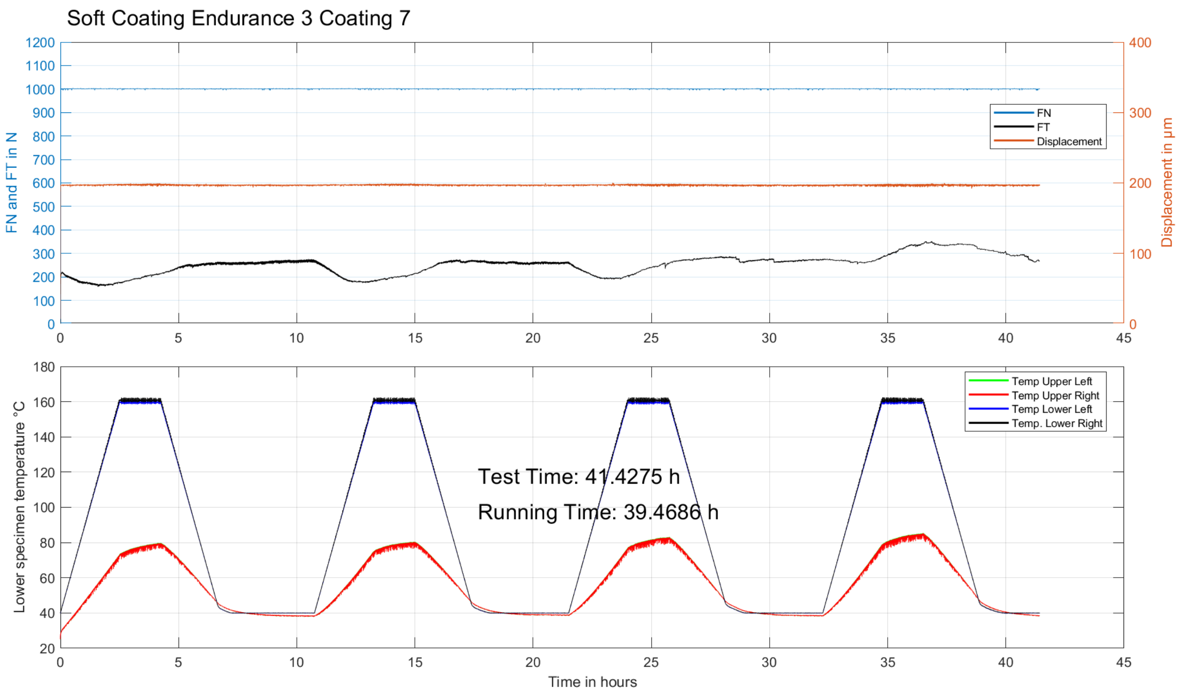

Figure 21: Endurance Test 3 coating 7: Online data plot of temperature set-point and resulting friction force data.

The time dependent temperature set-point can be seen in the exemplary online data plot of Figure 21. With the example of the endurance test 3 with coating 7 it can also be seen, that the friction force as tangential force (FT) is steadily rising while the temperature changes to the defined levels.

Endurance test 1, 3 and 5 were tested until the coating is worn out or failed. Endurance test 2 and 4 are stopped at 107 hours of runtime and compared by their weight loss as they both show a stable state and no metallic particles or oxide are formed, which can influence a clear conclusion on the wear rate. As Figure 22 shows coating 4 has much less wear than coating 5 under the same conditions and run time. The results of the final soft coating endurance tests conclude to select the coating 4 for the application purposes and to further test on a field scale prototype.

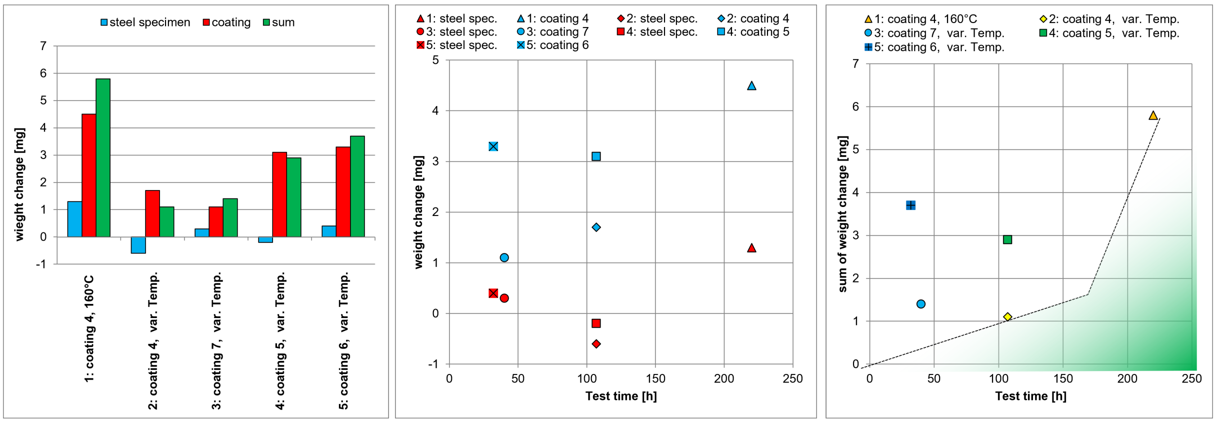

Figure 22: Weight measurement and run time results of the soft coating endurance tests.

Influence of Contact Opening Test Series

Since the final prototype has the functionality to open and close the contact for an interval image acquisition it has to be test on how the opening influences the outcome of a test in terms of fretting wear amount and characteristics. There may be also some applications where the opening may occur during operation, for example, a shaft / hub connection with rotational clearance and direction changes. For the non-lubricated / dry tests, the wear amount is determined by gravimetric measuring before and after a test. The lubricated tests use the time until a first damage is registered as the main criteria. The registration for this damage is via the online friction force measurement as well as the interval image taken if the contact is opened. The influence of contact opening is published with further details [BH21].

Prototype Design Evaluation

The accomplished research on the first and the later final prototype shown in the preceding chapter allow a first evaluation of this special fretting tribometer. Pictures of both prototype stages are shown in Figure 23. Most parts from the first prototype could be reused for the final prototype. The voice coil drives are stored for upcoming new purposes.

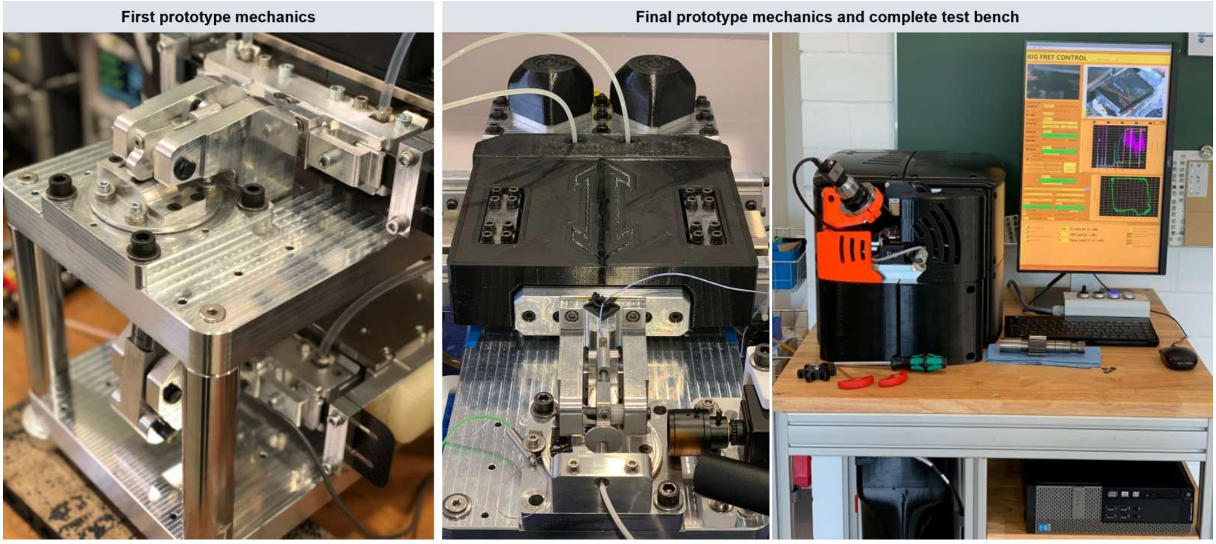

Figure 23: Picture of the first prototype on the left and pictures of the final prototype with its mechanics and complete test bench

The change from the voice coil drive to a dual eccentric drive lead to a much more improved friction force capability. Also a simple but robust displacement or stroke control loop via a simple software PID controller was possible. The second voice coil drive for the normal force drive is considered a very ineffective force application method for normal force higher than a few hundred Newton. Apart from the best possible resolution of the Lorentz force principle, the ohmic resistance losses are quite high and also need additional cooling. The change to a servo motor driven ball screw allowed a larger travel range and has now much less energy requirements. The normal force resolution also increased in the final prototype, because the knee lever construction of the first prototype was to sensitive to the stroke motion. The drive trains for displacement and normal force of the final prototype are now used for at least 3 years without any downtime and no signs of excessive wear is visible on the ball-screw, linear guides and rails and the eccentric motion parts. The total runtime of the test bench is estimated to be at least around 8.000 to 12.000 hours and could be clarified with the stored measurement data. Problems appeared with the USB communication which lead to several re-connection procedures in the LabView software to check connected peripheral devices frequently and force a re-connection if necessary. Those problems were solved with a replacement personal computer since the device was the common reason for all occurred problems.

Besides the dual eccentric drive as a main function, the rigid contact alignment function and the interval image acquisition function are proven useful and reliable. The function of contact alignment is also supported by the possible documentation with an image of the pressure sensitive foil when the foil is still in the testing position on the lower specimen. The lastly added moving mirror function allows a reliable image acquisition of the upper specimen with the same camera and lens setup. But this addition came after the different test series of the preceding chapter.The final test bench is established within its limit in different non disclosure projects and the mirror images could help to understand effects and wear mechanisms with images of the upper specimen. Also the final test bench could be introduced to a work group research on soft coating applications, so called anti friction coatings, for a time frame of at least three years. The results are exclusive to the members of the work group but may be disclosed in the future.

Discussion: Experimental Approach to solve Fretting Wear Problems

Based on the done work on fretting wear research, different experimental approaches could be useful depending on the economic and technical resources. The state of the art of fretting wear research shows, that the topic of fretting wear is very broad but can seldom be broken down to a common approach. All in common is a source of the relative motion and any avoiding even microscale motion zero will avoid fretting wear. Depending on the machine functions and elements this is often not reasonable due to operation conditions, clearances and tolerances. A good example on avoiding fretting wear on roller bearing application is the correct interference fit on shaft and bearing. But with excessive shaft bending under operating condition a correct fit may also be sensitive to fretting wear.

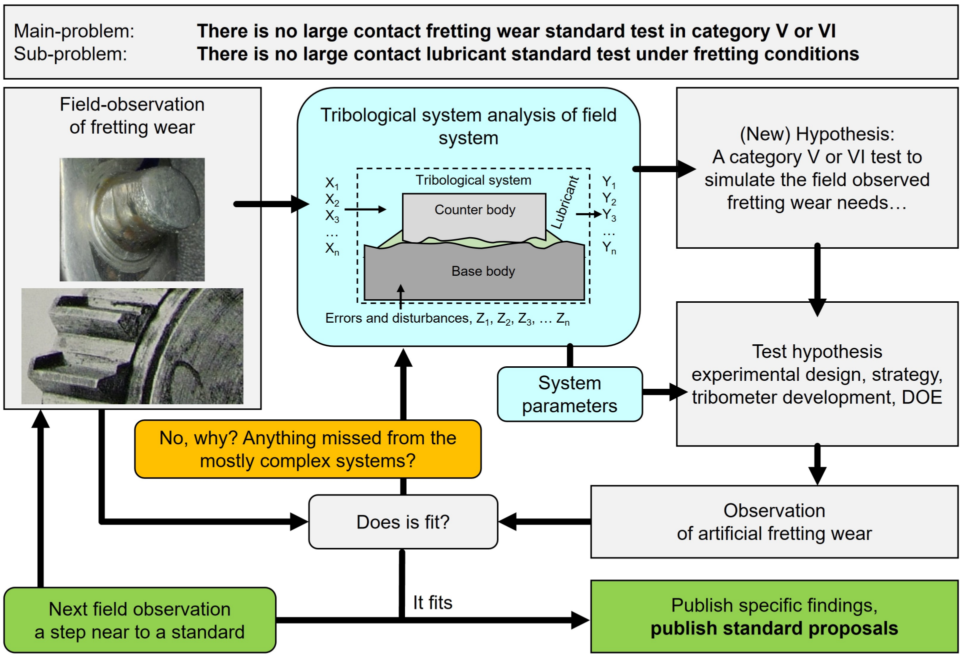

Figure 24: Schematic for an approach on finding a fretting wear standard

One experimental approach to solve a fretting wear problem, where the relative motion is not avoidable, is looking for standards providing a tool to alter materials, lubricants or additional measures like treatments or coatings. Also a long term approach is to specifically develope and contribute a standard for a typical fretting wear problem. It is to discuss if state of the art standards actually meet typical fretting wear applications, can be modified to meet the application tribo-system or that new standards have to be developed. Exemplary, there is no fretting wear testing with a large contact and a schematic suggestion to achieve a suitable standard is shown in Figure 24.

First step is the applications tribo system analysis and reproduction with a simplified test setup via a viable test hypothesis and experimental design. Key step is the comparison of application wear mechanics with inital adhesive or abrasive damages and wear rate. Furthermore, according to the tribological test chain (chapter 6, page 8) category V to VI testing can be supported with part or simplified unit tests with less abstraction. Often this is even necessary since application data is often not readily available because of the high complexity, time and effort on field tests.

An application data source is typically from machines in regular (customer) operation and can have a single sample up to a large sample size if production quantities are high.

The few standards using the term fretting wear often in a very general fashion. Like the FAFNIR Test[1] using the term for a axial thrust ball bearing under non-fretting conditions. Representing only one relatively low energy test and it would be far fetched to use it for finding a assembly paste for shaft hub connections. Non regular disclosed information may also show huge problems on the axial thrust ball bearing quality for standard testing purposes. Nevertheless, the FAFNIR apparatus itself is cost efficient and the testing procedure is well suited for a standard test on false brinelling or standstill marks. Also the apparatus could be used to test any axial bearing under small swivel motions and the concept could easily modified to fit any small angle swiveling motion. The use of readily available cost effective equipment for a standard proposal is preferable.

The fretting wear standard[2] uses a 10 mm 100Cr6 ball on an 100Cr6 disc with a test load of 100 N, frequency of 50 Hz and a displacement of 300 µm for 4 hours at 50 °C. Because of the small radius ball contact pressures reach over 1 GPa and the contact diameter with around 240 µm is smaller than the displacement. The lubricants has to have extreme pressure additives or itself is suitable for high pressure application. Also the contact surface on the disc is revealed every cycle and the lubricant can flow back if its consistence allows it. In short, the fretting standard tests for the most extreme conditions. This could be more useful for liquid lubricants but anti fretting additives (mostly solid lubricants) may antagonize with EP additives on protective surface reactions. The high contact pressure ball on disc setup seems not suitable for soft and hard coating applications under fretting wear since the coating suffers from the extreme stresses and is more likely to fatigue than wear. Soft coatings may be destroyed on load application.

Besides the approach to solve a fretting wear problem by testing for solutions with the two given standards and their corresponding test machine, any other approach for testing adds additional flexibility and effort to provide the desired relative motion and contact forces. It is useful to limit the effort by preparing an existing machine for fretting wear experiments e.g. hydropulser machines from fatigue testing can reproduce and provide such small oscillation motion without self-fatiguing. The experimental mechanical design can be designed to meet the application parameters as well as a simple reproducible test setup. The built tribometer from scratch with is specific motivation should give an outlook on expected development time and resources. A rough estimation on development time afterwards is around 2.000 engineering hours iterating through the two main prototypes. Material resources depend on the part material choice and component quality. The final prototypes complexity and resource consumption reaches comparable levels to the SRV but due to the modular mechanical design and measurement setup and the use of the quasi standard LabView development software leads to a low barrier on user driven software and hardware improvements.

Conclusion

The shown procedures and approaches for fretting wear experiments and examinations with tribometers clarify, that the topic can be explained in the basics, in practical applications and in the

[1] ASTM D4170-16, Feb. 2017: Standard Test Method for Fretting Wear Protection by Lubricating Greases

[2] ASTM D7594:2019: Standard Test Method for Determining Fretting Wear Resistance of Lubricating Greases Under High Hertzian Contact Pressures Using a High-Frequency, Linear-Oscillation (SRV) Test Machine

implementation of a systematic procedure. Tribological system theory offers the possibility of simple approaches for problem description and remains clear even with more complex fretting wear systems.

With the presentation of the current state of the art of special and standard tribometry for fretting wear and the available tribometer at the Competence Center for Tribology in Mannheim, basic possibilities for fretting wear examination are shown. The more concrete implementation and assessment of tribometry is carried out in test series with different forms of contact, from system analysis and experiment to interpretation of results. The characteristics of the SRV tribometer types in the event of fretting wear are limited but well definable. For the evaluation and interpretation of the standard tribometer results, the analysis and examination of the fretting wear is inconclusive and the experiments show limits in the possible load collective parameters. Further, point contacts under partial slip show a idealistic but suitable setup to achieve very small displacement amplitudes. For application issues, where a large planar contact is often present, any further research is aimed to achieve an experimental setup with large planar contacts.

To address the limitations of the standard tribometry, a novel fretting wear test apparatus was developed with design studies for drive train functionality and two prototypes. The evaluation of the prototypes is limited to some of the essential, simple elements of a tribological system. More specific elements such as special materials in the case of bodies (ceramics, polymers) or ambient conditions (high vacuum, high temperature, aggressive media) are not taken into account in their effects on the entire tribological system. Even the approach of examining lubricants in the event of fretting wear requires essential decisions regarding the amount of lubricant, contact geometry, accepted scatter or desired statistical certainty. In addition to resolving the conflict of objectives between practical relevance and testing effort for a component or model test on lubricants, the assessment of the suitability of a tribometer remains an important task in planning.

The drawbacks for the first prototype, like the usage of a strong but intricately controllable voice coil drive and a impractical normal force application resulted in a much improved final prototype. The prototypes evaluations with six experimental test series showed conclusive results on the final prototype. The final prototype incorporates three novel functionalities with a rigid alignment function, a dual eccentric drive for variable but stiff displacement control and a controlled normal force axis capable of opening the contact completely to acquire images in defined intervals. Also an additional mirror is used to swing between the opened specimens to get images of both specimens with only one camera system.

With the done prototype evaluation test series it is demonstrated that fretting wear experiments on tribometers (as model systems) can be developed for specific application problems via theoretical considerations of the tribological systems theory of the application, past experiments and their deduction to a model test system.

Outlook

The future work on the subject of fretting wear can be divided into the main points of this work: Thus, the continuation of the system-theoretical treatment, the extension of the tribometric test and measurement technology, the development of model test systems and the analysis methods for model and practical damage assessment can take place.

In the continuation and expansion of the system-theoretical treatment of fretting wear problems, knowledge of the basic forms of wear and their cause can improve the knowledge gained from system analysis. Furthermore, hypotheses can be developed and empirical tests can be carried out on the influence and behaviour of the particle-induced three-body systems. Applications would be practically conceivable, e.g. A targeted removal of particles or concentration with special geometries specifically and therefore predictably influence the progress of wear and the system behaviour.

The tests on the ball / plate system with partial slip according to MINDLIN can be continued for the possibility of a simple model test for lubricant tests. The system can also be tested to differentiate between different material properties. A correlation investigation between known Wöhler curves and crack formation and their spreading in the event of large partial slip is conceivable. This should be related to the research and development of calculation models of material stresses in the flat body with partial slip. In the course of this, a calculation tool for contact mechanical and tribological problems can also be developed.

In the theoretical investigation of fretting wear, the transfer conditions that link a practice system in use with a model system on a tribometer can be worked out in more detail. For example, the ideal condition recording of the practice system (including natural frequencies of the system structure, downtimes and external excitation, running times and internal excitation, environmental conditions) are developed and used for a questionnaire. The questionnaire can support the system analysis with the most important criteria of fretting wear.

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