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Combined numerical and experimental investigations on Fretting wear

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Abstract

In mechanical engineering applications, cyclic loadings are most commonly seen. In many assemblies of moving components, contact problems under various lubrication conditions are lifetime-limiting. There, the relative motion of the contacting bodies combined with high loads transmitted via the contact surface leads to fretting fatigue and fretting wear failure. The present contribution gives first promising results within a long-term research project concerned with developing a methodological approach for the design and lifetime estimation of components under tribo-mechanical loading.

Keywords: Fretting wear, fretting, simulation

1. Introduction

Fretting describes various wear and fatigue phenomena of contacting surfaces due to small oscillatory movement and severe loading. A wide range of mechanical engineering applications are affected by fretting, e.g.: dovetail connections of turbinerunners, fitting key connections or shrink fitted connections of bearing seats.

The wide range of fretting threatened applications explains the relevance of the here described project. Furthermore due to economic considerations in modern engineering practice light weight design concepts gain importance. Due to stiffness reductions new fretting hotspots emerge even at formally non critical components. The impact of fretting on economy is huge, about 8% of all wear caused component failures are fretting dominated. [1]

As a global term fretting includes several appearances, wear, fatigue and corrosion.

Fretting wear describes the surface modification of the contact zone. The modification includes microwelds, surface and subsurface cracking and local plastification. Fretting fatigue describes the reduction of the component fatigue limit. Fretting corrosion is a tribo chemical process commonly known as bleeding.

Obviously it is not possible to separate these forms from each other in a real component. Therefore it is necessary to conduct model experiments to characterize the wear and fatigue processes separately from each other. These

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examinations will be used to quantify the influences on the fretting process and to deviate a global model. This model has to be evaluated at the component. Notably a tribological system can not be transferred therefore to gain quantitative statements of the system, its loads lubrication and the production influence have to be examined. Above this constitutive problem the influences on the fretting process like the COF hardness and eigenstresses and their impact on each other are not clear yet. [2]

In this long term project an integral characterization approach has been chosen. On different test benches fretting wear was characterized and input data for the tribo pair generated. Furthermore a close to component test concept has been established. The generated data is implemented in a numerical simulation.

2. Experimental set up

2.1. Experimental methodology:

Several different test rigs were used to conduct the experiments. Some of them had been developed during a previous work [3], some are commercially available, e. g.: linear tribometers, and some are developed by the authors. The linear tribometer creates a linear movement under a constant normal load which is only suitable for wear characterization. To enable fretting fatigue tests too, a test rig suitable for the use at any servohydraulic test bench has been developed Fig. 1.

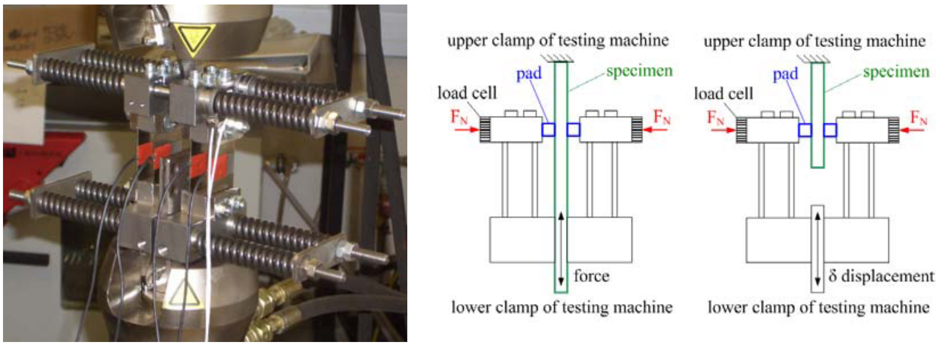

Fig. 1. (a) fretting test rig; (b) fretting fatigue test setup, (c) fretting wear test setup

When testing fretting fatigue Fig. 1b, a long specimen is clamped between the lower jaws of the rig, pads are clamped in the upper jaws and pressed against the specimen by a defined normal force which is monitored by load cells. For fretting wear testing a dummy is fixed between the lower jaws. In this configuration the whole rig is clamped between the jaws of a servohydraulic test bench which applies a constant force for fretting fatigue testing and a constant displacement amplitude for fretting wear testing. Required force or resulting displacement depending on the test mode was recorded for later analysis.

2.2. Test program

To quantify the tribologic properties of the material pairing 5 different load cases have been investigated. The experiments differed by the static contact pressure and the displacement amplitude. All conducted test series follow this investigation plan. They differ among each other by the surface quality and the coating pairing. In the following a non coated steel steel test pair and two coated specimen pairs are compared. The coatings are a hard coating and a soft copper coating.

Table 1. Experimental program

Displacement Amplitude δ [µm]	Load F_N [N]		
70	800	1000	1600
120		1000	
170		1000	

Table 2. Tested material configurations

Description	Pad material	Specimen Material
P4	steel – hard coated	steel – hard coated
P8	steel – soft coated	steel
P10	steel	steel

2.3. Specimen geometry:

The specimen geometry is applicable for the use at the linear tribometer as well as at the fretting test rig.

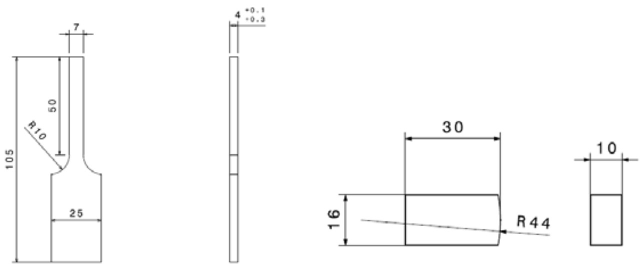

Fig. 2. (a) flat specimen; (b) pad

2.4. Experimental results

The evaluation of the experiments was carried out by gravimetry and derivated quantities such as the evolution of the COF or the dissipated Energy. Further more the wear energy density was calculated and fractografic investigation was carried out.

The general procedure will be explained for three contact pairs, the coated P4 and P8 as well as for the non coated P10. All of them have been tested with 70 µm displacement amplitude and 1000 N load.

The COF gives a first good impression of the suitability of the tribo couple. For the specimen P10 we see three main evolutionary stages. The first stage is a constant value over the run time. After approximately 200000 cycles the COF starts to rise up to values of 0.4. After that it stays at this level for the rest of the test cycles. For P4 the result gives a different impression. The COF stays at a very low level for the whole run time. It can be assumed that the surface of P4 is not modified by wear processes. In opposite to the low COF of P4 P8 shows a high COF right from the start of the test, at 200000 cycles it reaches its lowest value just before rising to higher levels at the end of the test which lie in the region of the uncoated P10.

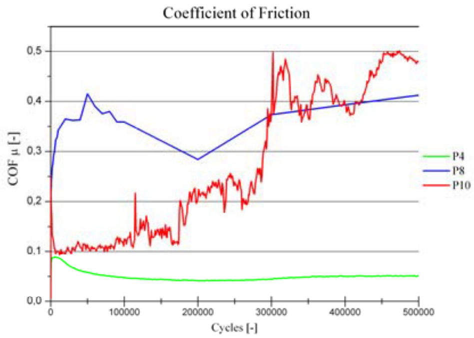

Fig. 3. Evolution of coefficient of friction

Besides the COF, fractography of the worn surfaces give an indication on the suitability of the coating. Fig. 3, Fig 4 and Fig. 5 show light microscopic pictures as well as SEM micrographs. Uncoated P10 Fig. 4 shows micro welds a jagged surface and cracks at the surface. P4 Fig. 5 shows only a plastically deformed surface in the fretting zone. The soft coated P8 specimen Fig. 6a also shows lesser damage than the uncoated P10 but in opposite to the hard coating it is visible that small parts of the coating were torn off during the testing cycle. This leads to the assumption, that the bond between coating and original surface was not strong enough to withstand the outer loading, but it provides protection to the original steel surface. For P8 Fig. 6a and Fig. 6b the higher lying flat regions represent undamaged spots situated close to damaged regions where the layer has come off. When analyzing the chemical composition in the grooves, a high amount of the coating material and oxygen was found, but only less iron of the base material. This shows, that not the whole coating was destroyed than only layers. This expresses that there is still a protective layer of the original coating present. Obviously the coated specimens show lesser and different wear marks than the non coated one.

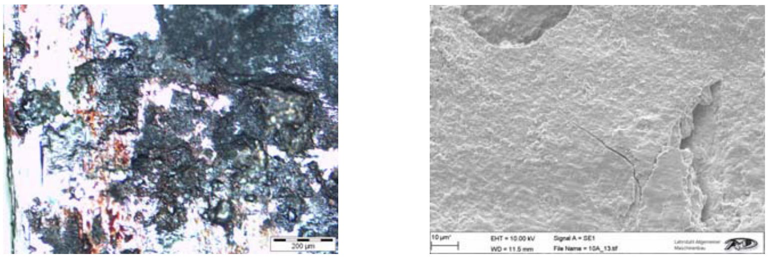

Fig. 4. (a) light microscopy of P10; (b) SEM image of P10

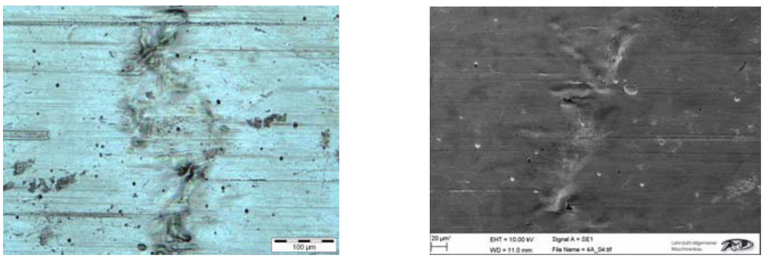

Fig. 5. (a) light microscopy of P4; (b) SEM image of P4

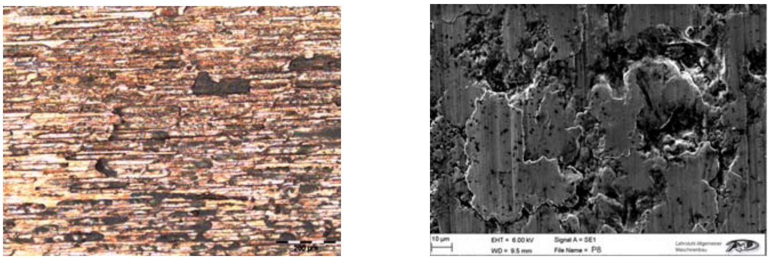

Fig. 6. (a) light microscopy of P8; (b) SEM image of P8

In addition to the COF which represents the friction force in dependence of the normal force, it is also possible to plot hysteresis loops in which the friction force is plotted over the amplitude of displacement which is depicted in Fig. 7. The area of this hysteresis loops is representative for the amount of dissipated energy during a testing cycle. The area was calculated by a MATLAB® code. P10 Fig. 7a in the beginning shows small open cycles which are representative for slip in the fretting zone, later in the testing cycle the hysteresis are getting bigger and in addition stick – slip starts to emerge which is harmful for the surface due to the steadily changing state of stress in the fretting zone. Hysteresis loop shape of P4 Fig. 7b and P8 Fig. 7c is quite similar although the coefficient of friction of P8 is much higher than the one of P4. Both show slip over the whole testing cycle. This explains that the soft P8 coating reduces stick in the fretting zone but with a higher coefficient of friction than P4. Fig. 8a represents the sum of dissipated energy over the whole testing cycle for P10, P4 and P8 in accordance with the shape of hysteresis loops. P8 shows the highest amount of dissipated energy. Due to the stick – slip of P10 the dissipated energy is lower, than the one of P8.

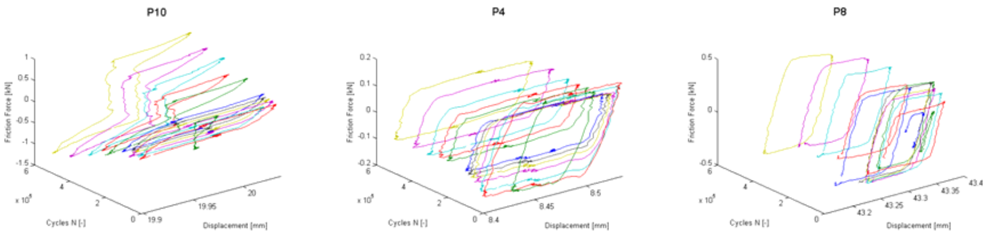

Fig. 7. (a) hysteresis loops of P10; (b) hysteresis loops of P4, (c) hysteresis loops of P8

Gravimetry has been performed to obtain the amount of worn surface volume during the testing cycle. Therefore pad and specimen have been weighed before and after the test. The difference in weight represents the amount of worn surface volume Fig. 8b. Although the steel surface seems to be much more damaged than coated P8 the difference in worn material volume is only small while coating P4 shows nearly no worn material and also no damage on the surface.

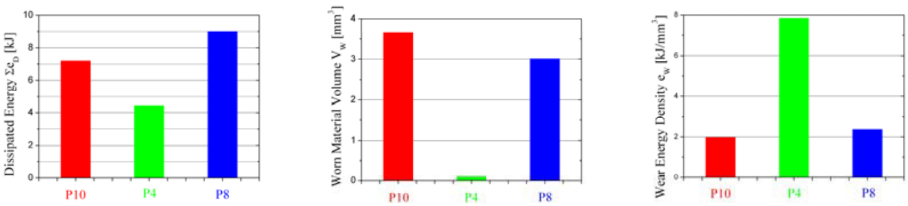

Fig. 8. (a) Dissipated Energy Σe_D, (b) Worn Volume V_W, (c) Wear Energy Density e_W

By combining test data to an easy to calculate value [3] the so called Wear Energy Density e_W allows a numerical quantification of fretting damage.

$$e_W = \Sigma e_D / v_W \qquad (1)$$

This is done by dividing dissipated energy e_D by the worn volume V_W and gives the value of wear energy density e_W in [kJ/mm^3]. The higher the value of e_W the higher is the resistance against fretting damage. A very important fact is, that only tests which are performed under the same loading conditions can be compared in this way as the area inside the loop will get larger when applying higher amplitude of displacement or normal force. Fig. 8c depicts that P4 shows a much higher e_W than P8 and P10 which correlates well with the optical- and SE microscopic observation of the surfaces. It is worth mentioning that the value of e_W without combined optical observation of the fretting surfaces might lead to wrong interpretations of the fretting resistance, which is the fact for P8 and P10 where P10 shows a totally destroyed surface in opposite to P8 although both of them show similar values of e_W.

3. Numerical approach

The identified material properties serve as input data for a numerical simulation. Therefore a FORTRAN 77 routine was imlemented into a multi purpose FE program for calculation of the wear induced surface modification in the model. An energy like parameter P describes the wear evolution. There exists a wide range of different wear models taking several different material parameters into account as the chosen approach does. [4]

$$P(u) = \mu p u \qquad (2)$$

This equation is governed by the COF μ, the contact pressure p and the current displacement u. The parameter P will serve as a first approach to implement fretting driven wear into the product development process. The main goal is to identify fretting threatened regions at an early stage. To minimize the calculation effort needed a 2D model of the test setup was generated. The parameter P was used to modify the mesh similar to the real process. [5, 6]

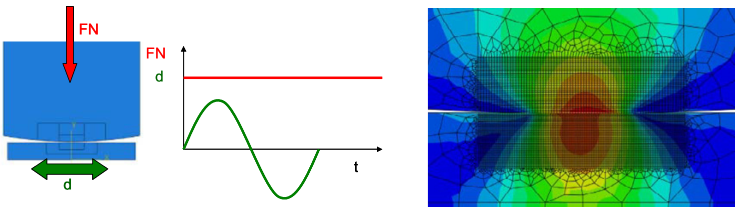

Fig. 9. (a) FE model and loading situation; (b) Mises stress after 500000 cycles

This geometry modification is presented below .

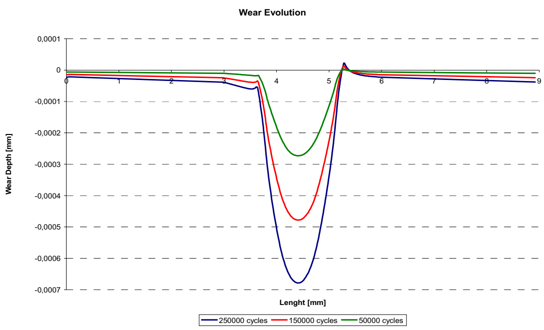

Fig. 10. geometry modification due to the wear process

4. Conclusion

Fretting wear is a surface modification process with rising impact on industry. It is of importance to know fretting threatened regions at an early stage and to be able to take measures against it. In this work a method was presented which combines numerical and optical results of performed fretting wear tests to give a prediction of fretting wear resistance of different surface modifications for later use in components. To evaluate fretting vulnerable zones in the design process an energy based approach has been implemented into a FE-routine.

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