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Multiscale simulation approach of journal bearings with short carbon fiber reinforced PEEK - Predicting friction and wear under steady state conditions

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ABSTRACT – The use of new polymeric composites leads to new challenges in mixed lubrication simulations like high temperature dependence of mechanical properties as well as heterogeneity on the microscale. This work focuses on the mixed lubrication simulation of journal bearings with polyetheretherketone (PEEK) with 30 % short carbon fibers (SCF). The presented approach considers semi deterministic heterogeneity on the microscale. A finite element (FEA) microscale model based on the real measured roughnesses combined with the fiber distribution obtained from light microscopy is developed. The macroscale simulation is extended by temperature dependent stiffness matrices and by a post-processing wear simulation based on Archard's law. The proposed simulation approach can predict friction and wear of a lubricated short fiber reinforced polymers (SFRP) in tribological systems under steady state conditions.

1. INTRODUCTION

Till today, the tribological behavior of PEEK with SCF must be determined experimentally [1] for the lack of sufficient simulation methods. To achieve a deeper understanding of the tribological mechanisms on the microscale, appropriate simulation models are inevitable, since it is not possible to observe the micro contact experimentally to the fullest. In the last decade, several simulation approaches arised to receive a better understanding of the microscale contact. GRÜN ET AL. [2] performed thermomechanical simulations on the microscale with heterogeneous materials and artificial orientation of reinforcements and ideally smooth surfaces to understand the thermal behavior. ALBERS AND REICHERT [3] developed a micromechanical model of two contacting rough surfaces including friction and wear based on material and damage parameters to predict friction and wear based only on roughnesses and material parameters. Currently this approach is constrained to homogeneous materials. The mixed lubrication simulation approach shown in [4] based on PATIR AND CHENG [5] predicts the ratio of fluid and solid pressure in lubricated contacts on the macroscale while considering the roughness on the microscale. All known mixed lubrication models assume homogeneous material behavior on the microscale [6, 7]. This work shows enhancements in the mixed lubrication simulation approach. Especially heterogeneity on the microscale and temperature dependencies as well as wear behavior on the macroscale are investigated for SFRP based on an example of a journal bearing.

2. SIMULATION APPROACH

The shown simulation is based on the separation of scales: Microscale and macroscale. Two main software tools are used. *Abaqus FEA* is used to model the rough contact on the microscale and to get the stiffness matrix of the components (shaft, bushing) on the macroscale. An inhouse tool called *TriboSim* is used for solving the average Reynolds equation [4] on the micro and macroscale including the energy equation for non-isothermal (= variothermal) simulations.

2.1 Microscale

Figure 1 illustrates the framework on how to digitalize rough surfaces with short fiber reinforcements and calculate the contact pressure curve and the flow factors. The detailed workflow is shown in [8]. The microscale simulation takes the real measured surface roughness from the experiment after running-in into account (deterministic approach). The roughness of the investigated SFRP is stationary after running-in which was found in experimental results [9]. Therefore this deterministic approach is feasible. Based on these surfaces, previous work investigated the effect of SFRP on the contact pressure [8] as well as the influence on the flow factors [10]. It was shown that the contact pressure and the flow factor calculation are highly dependent on the temperature due to the temperature dependence of the polymeric matrix. The fluid pressure dependency can be neglected for the shown application due to the high mechanical strength of PEEK CF30. It is mandatory to understand, no wear simulation is performed on the microscale. The microscopic topology is taken from worn surfaces and already experienced wear. Therefore, the worn surfaces on the microscale are kept constant und wear is only calculated on the macroscale as a shape optimization.

2.2 Macroscale

Figure 2 shows the overall framework of the macroscale simulation. On the macroscale the average Reynolds equation including flow factors from the microscale analysis is solved iteratively with a multi grid approach. The structural deformation of the solids is calculated with the reduced stiffness matrices (static condensation) from the FEA model. The position of the shaft is changed till a force equilibrium is reached. The energy equation is solved for three dimensions to obtain a 3D temperature field using FEA extracted temperature conductivity matrices for the bodies (similar to stiffness matrix reduction). The temperature field can be used to calculate a new reduced stiffness matrix for the shaft and the bushing till pressure and temperature convergence is reached. After the mixed lubrication simulation converged, a wear calculation only on the macroscale as post-processing is performed. Therefore, the nodal information as solid pressure, velocity and temperature are used in a local Archard's wear law. Wear maps from tribological model tests can be used to get a proper local wear factor on every node. A new bushing geometry is calculated and used as an input for the next mixed lubrication simulation. A Journal bearing with a PEEK CF30 bushing and steel shaft is calculated (diameter = 21 mm, clearance = 37 µm, width = 20 mm, Load = 2 kN, Fluid = 3.4 mPas at 23 °C). The viscosity of the fluid is pressure and temperature dependent. The microscale simulation is performed for three different temperatures (20°C, 100°C, 200°C).

3. RESULTS AND DISCUSSION

Figure 3 shows the average contact pressure over the average gap height for the contacting two rough surfaces. The heterogeneous microstructure (MS) is calculated according to Figure 1. The homogeneous MS is modelled with E = 28 000 N/mm², which equals the yield modulus from tensile stress tests for *Victrex PEEK450CA30* at 23 °C. Evidently, the MS is more compliant if heterogeneity is taken into account. Local displacements on the microscale are highly affected by the surrounding polymeric matrix. These flow factors and contact pressures can be used temperature dependent on the macroscale.

Figure 4 illustrates four different Stribeck curves with a solid-solid coefficient of friction (COF) of 0.9 and ideally cylindrical geometry (no wear). The heterogeneous microstructure leads to lower COF due to its more compliant nature. This effect is dominated by a lower viscosity at variothermal calculations which causes a massive decrease of hydrodynamic fluid pressure and therefore an increase in COF.

Figure 5 shows the wear progress over time for a constant local wear factor on every node at a high viscosity (75 mPas) and 100 rpm. Although the wear factor is constant, a non-linear running-in is observed by geometrical changes of the bearing shape.

The proposed simulation approach can lead to qualitatively different COF compared to the homogeneous simulation approach. The heterogeneous microscale analysis leads to less stiff contact pressure curves. These compliant contact pressure curves induce smaller gap heights with a higher amount of hydrodynamic fluid pressure. Additionally, it is observed that solid contacts lead to local heating which reduces the stiffness locally. For the shown working conditions, these two effects are entirely dominated by a lower viscosity due to temperature increase. For that reason, the COF increase for the shown variothermal calculations.

If wear is taken into account, the worn geometry can hold optimum hydrodynamic properties as it is the nature of the running-in process. After running-in, a global steady state wear factor based on the local solid to solid wear factors can be calculated for the whole bearing. All in all, this approach is able to predict steady state friction and wear of SFRP in lubricated contacts. It may lead to a better understanding of tribological performance of SFRP at micro- and macroscale and help engineers for future design and material decisions.

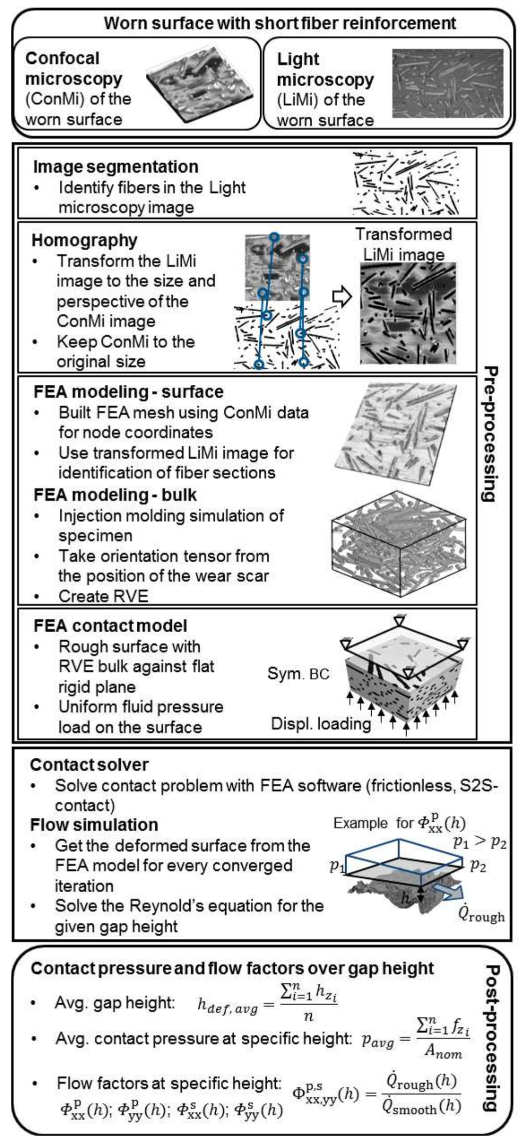

Figure 1 Simulation framework for calculating average contact pressure and flow factors of rough short fiber reinforced polymer surfaces [5].

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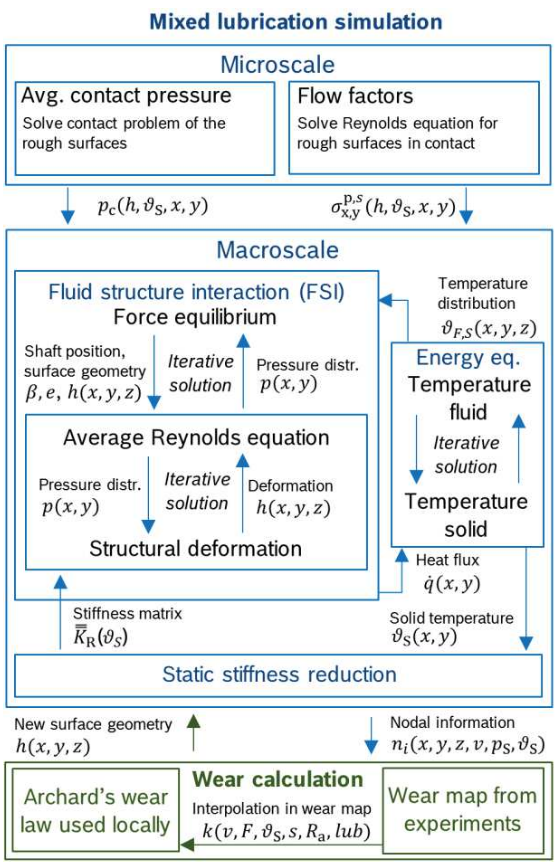
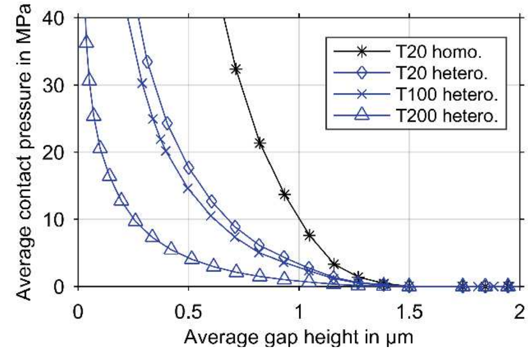


Figure 2 Basic simulation framework of the macroscale mixed lubrication simulation with a wear calculation loop.



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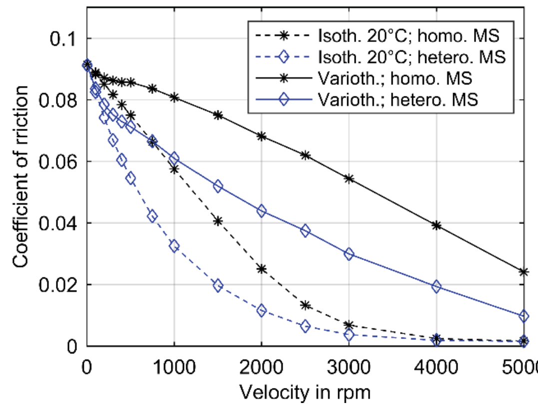

Figure 4 Stribeck curves - Comparison of isothermal and variothermal calculation with homogeneous resp. heterogeneous microstructure (MS) for ideal cylindrical shapes.

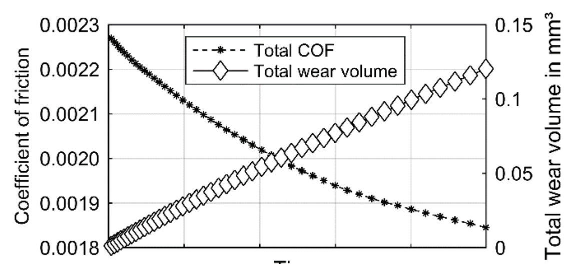

Figure5 Wear and friction progress of 45 mixed lubrication simulations.