euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Simulation concept for surface designs increasing the coefficient of static friction

Franz Walther[1], Sebastian Wieland[1], Jörg Schneider[1], Jan Edelmann[1]

[1]*Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany*

jan.edelmann@iwu.fraunhofer.de

Abstract

The objective of the simulation concept for the design of surfaces is the prediction of trends relating to the coefficient of static friction of two friction partners. For the overall consideration, further influencing variables have to be considered, since an exclusive focus on the coefficient of static friction can only inadequately describe the complex tribological behaviour when two surfaces come into contact. To calculate these characteristic values, a multi-stage simulation and calculation approach was developed in which, starting from the generation of experimentally measured or artificially generated surface topography data (stage 1), the true contact area as well as the stress and deformation behaviour when two surfaces come into contact are simulated in contact simulations (stage 2). Finally, the coefficient of static friction is calculated based on a micro-roughness model taken from the literature and statistical homogenization (stage 3). The accuracy and validity of the workflow was demonstrated in the experimental validation using ground sample surfaces. Trends with regard to the coefficients of static friction were reliably represented. In addition a method for generating synthetic stochastic surfaces as simulation input was developed. Due to the given comparability with experimental surfaces in terms of the geometric properties and the resulting friction behaviour, virtual surfaces can also be used in the future as input of the multistage calculation workflow and applied in simulative parameter studies.

Keywords: Friction, Roughness, Simulation, Surface

1. Objectives and design strategy

In accordance with the function of a tribological system, applications such as clamping systems for fixing rotary axes in machine tools require an increase in the coefficient of static friction μ_s or the frictional force F_f in order to realize a minimization of the construction space or an increase in the tolerable process forces. Against this background, the functionalization of the surfaces of the friction partners is to be investigated by means of a defined finishing.

With the aim of increasing the static friction, numerous scientific investigations have been carried out in the past. These showed that the increase of the static friction coefficient requires a complex application-specific design of the tribological system under consideration, since the interactions between the mechanical boundary conditions, the material properties of the friction partners and their surface topography must be comprehensively considered [1,2,3,4].

The basic research approach for increasing the static coefficient of friction while avoiding wear processes is to increase the elastic deformation components of the true contact area so that lower local stress concentrations and thus a lower probability of the onset of plastic deformation of the surfaces of the friction partners result in stable friction behavior over many load cycles. Against this background, the complex interrelationships for the formation of the static coefficient of friction are to be modeled in the best possible way on the basis of a multistage simulation environment in order to enable a targeted design of the friction partners on the basis of defined parameters. Since the mechanism of static friction still is an current field of research, the presented simulation approach is aiming to show qualitative trends in contact mechanical behaviour and static friction between different friction partners and not to calcute the coeffizient of static friction in an quantitative precisely way.

2. State of the art

The determination of the true contact area A_{true}, as the sum of the areas of all microcontacts, forms the basis for the consideration of solid state friction. In the past, various approaches have been developed for this purpose, which are essentially based on the finite element method (FEM) and on elastic-plastic half-space models. The latter are increasingly used in tribology, since only a two-dimensional mesh has to be created. In this way, either larger surface sections can be considered or existing surface sections can be discretized more finely with the same computing time. Both increase the representativeness and informative value of the simulations based on the considered surface segments while maintaining a high computational efficiency. A half-space is assumed to be semi-infinite, with the space defined as infinite in the plane and bounded in the normal to the plane. The material behavior is assumed to be linear elastic - ideal plastic.

The adaptation to surfaces of tribological contact partners is achieved by assigning discrete height values (e.g. experimentally determined surface topography data) to the mesh nodes. At the beginning of the calculation, both contact surfaces are assumed to be opposite each other with a defined distance. The number of contacting surface points is successively increased by the gradual approach of both surfaces, resulting in a normal force and deformation distribution (cf. Figure 1). The solid contact pressure results from the integration of the normal forces over the calculation area. To represent the mechanical material behavior, the indentation modulus E_{IT} (function of the elastic modulus) and the plastic yield pressure p_{lim} (yield criterion) are integrated as input variables. These quantities originate from ultra-microhardness measurements and reflect the material behavior of near-surface regions under a triaxial compressive loading condition.

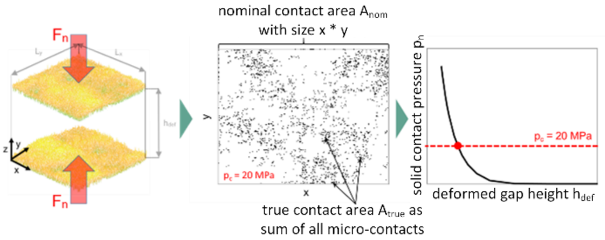

Figure 1. Schematic illustration of the model setup of the contact simulation with the simulation software Tribo-X.

As a result of the contact pressure simulation, parameters such as the true contact area A_{true}, the locally acting solid contact pressures p_c and the local elastic deformations w_{el} can be determined [4].

The friction force required by Coloumb's law to calculate the static friction coefficient can be estimated on the basis of a semi-empirical micro-roughness model and a statistical homogenization based on it. Examples of microroughness models derived from FE calculations are the parameterized models of Kogut and Etsion (KE model) [5] and the model of Li, Etsion and Talke based on them (LET model) [6]. Their basic assumption is based on the fact that the real motion or the loosening of the friction partners when a critical tangential force is exceeded causes a local plastic failure of interacting roughness peaks. The magnitude of the tolerable tangential force depends on the one hand on the mechanical properties of the surface materials and on the other hand on the geometry of the roughness peaks.

3. Methodology and Validation

3.1. Multi-stage calculation approach

A multistage model and simulation approach was developed to calculate the static friction coefficient and other target variables for characterizing the tribological behavior of two friction surfaces. Figure 2 shows the sequence of steps in the calculation process.

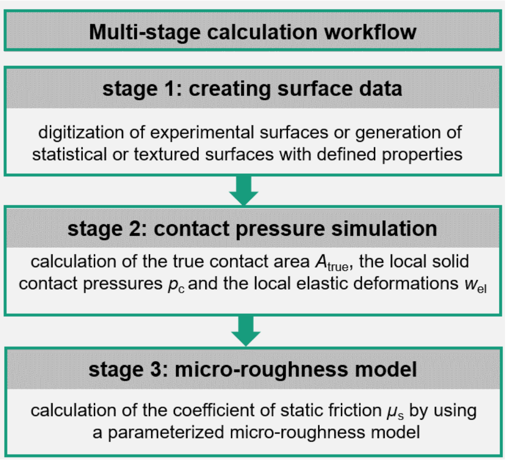

Figure 2. Developed multi-stage calculation workflow

The representative surfaces or topography data of the friction partners either originate directly from experimental measurements using confocal laser scanning microscopy or are generated virtually or synthetically (stage 1).

For the contact simulation, the commercial calculation software Tribo-X from Tribo Technologies GmbH was used to calculate the true contact area and the solid contact pressure curve derived from it (stage 2). The software is based on the elastic-plastic half-space model approach presented in Chapter 2. The following values derived from the results of stage 2 were included in the design as optimization criteria:

- Proportion of true contact area $A_{\text{t,rel}} = A_{\text{true}}/A_{\text{nominal}}$
- Stress state θ, as quotient of acting mean solid contact pressure $p_{\text{c,r}}$ and plastic flow pressure p_{lim}

The calculation of the static friction coefficient μ_s (stage 3) was performed by linking the contact simulation with the presented parameterized micro-roughness models (KE and LET models) and a subsequent statistical homogenization over the computational domain. The programming was carried out in the environment of the commercial software Matlab. To apply the micro-roughness model, the roughness peaks are first identified from the height values of the surfaces and their geometric properties (roughness peak height, slope and radius of curvature) are derived. Then, depending on their position in the computational domain, their respective deformations w, calculated in stage 2, are assigned to them. On this basis, the deformation state of each identified roughness peak can be estimated depending on the roughness peak geometry and the material properties according to the KE or LET model. This allows the calculation of the individual maximum tolerable friction force F_f and adhesion force F_a for each roughness peak.

Since each roughness tip contact makes its own contribution to the macroscopic adhesion of the friction partners, the static friction coefficient μ_s is first determined individually for each roughness tip contact according to Coulomb's friction law $\mu_s = F_f / (F_n\text{-}F_a)$. The transfer of the calculated static friction coefficient from the local contact of the roughness tips to the representative surface segment and beyond that to the complete contact surface is carried out by averaging and weighting the individual static friction coefficients as well as by a final statistical homogenization, i.e. by linking with determined statistical surface characteristics of the total surface.

3.2. Experimental validation

The objectives of the experimental validation were, on the one hand, to demonstrate the error-free feasibility of the multi-stage workflow on the basis of experimentally determined topography data of real specimen surfaces and, on the other hand, to illustrate trends in the resulting static friction values for the design. For this purpose, the static coefficients of friction were determined experimentally in a test rig on the basis of a total of 20 grinded specimen pairs of the material 1.0037 for three grinding grains of surface S II, corresponding to the root mean square roughnesses of S_q = 0.38, 1.19 and 1.50 µm, for contact with the grinded mating body S I with S_q = 1.19 µm.

The topography data of the contact surfaces of both friction partners required for stage 1 of the multistage approach were determined experimentally by confocal laser scanning microscopy to measure surface sections of the area 1 953 x 1 953 µm² on all sample variants with a resolution of $\Delta x = \Delta y$ = 0.556 µm. In a further step the S-F surface was calculated, eleminating short scale measurement errors and skewness as a result of the orientation whilst measuring. Figure 3 compares exemplary recorded surface sections and the respective roughness levels in the initial state.

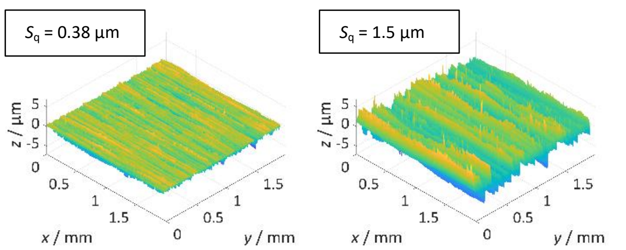

Figure 3. Measured surface topographies (S-F) as input for simulations and derived root mean square roughness (S_q) of the investigated sample surfaces (exemplary).

The required mechanical material properties were obtained from ultramicrohardness measurements and were taken from the literature.

In the contact simulation, the average distance between the two surfaces was gradually reduced until the specified break-off criterion was reached at a resulting solid contact pressure of p_c = 20 MPa.

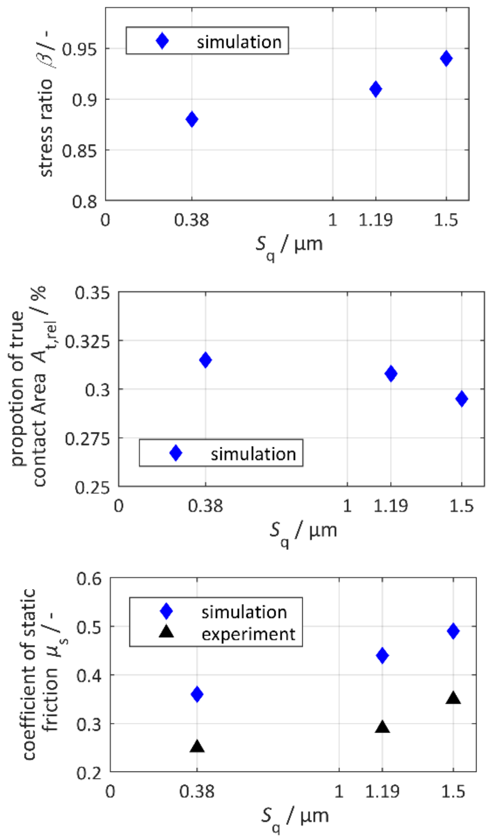

Figure 4. Results of contact simulations based on experimentally measured ground surface topography with the determined characteristic values a) stress ratio β b) proportion of the true contact area $A_{t,rel}$, and c) coefficient of static friction μ_s.

The contact simulations within the multilevel model were numerically stable even when including experimentally determined topography data for surfaces of large dimensions and resolution. Based on the presented results (Figure 4), a high repeatability and representativeness of the surfaces can be concluded. Regarding the trends, the increase of the propotion of the true contact area $A_{t,rel}$ with smaller S_q values as well as the reduction of the mean stress ratio β acting on the true contact area and the increasing adhesive fractions could be observed. Comparison with the experimentally determined μ_s values showed an analogous increase in the static friction values calculated in stage 3 with increasing S_q values, but the static friction values determined from the multistage approach were on average about 0.1 higher than the values determined experimentally in the test rig. The quantitative deviations between the experimentally and simulatively determined static friction values can be explained, among other things, by the fact that material characteristic values from the literature were used. Against the background of mapping a trend in the static friction coefficient between different friction partners, the calculation approach could be assumed to be valid.

4. Generation of synthetic stochastic surfaces

Numerical parameter studies, which can be carried out in an increasingly time- and cost-efficient manner, represent a supplement to experiments on real components with the possibility of investigating the influence of specifically set component and surface properties. In the application outlined, the influence of roughness (described by S_q) on the static friction coefficient, the true contact area and the stress state was to be investigated, building on the validation studies on grinded specimens. For this purpose, virtually generated synthetic surfaces served as input for stage 1 of the multistage simulation approach. In the following, the methodology for their generation as well as the comparison with the experimentally measured surfaces included in the multistage calculation approach in stage 1 will be presented in more detail.

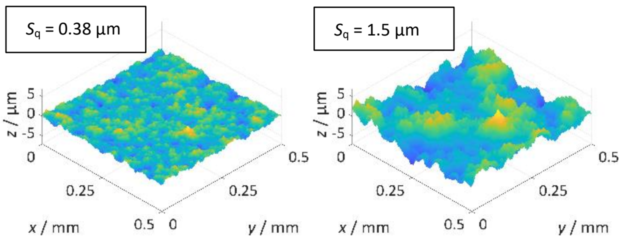

Figure 5. Virtually generated synthetic surfaces with S_q = 0.38 µm and 1.50 µm (exemplary) as input for friction partners S I and S II of the contact simulation (stage 2) within the multi-stage calculation workflow.

Figure 5 shows the virtually generated synthetic surfaces. These were designed with the open-source software Gwyddion [7], which was specially developed for the evaluation and data processing of a wide variety of surface topography data. Grinded surfaces are characterised by the advantage of being less complicated and more economical to produce. Nevertheless, due to the interaction of the abrasive grain with the surface material, they have a very complex surface fineness, which means that any direct attempt at replication carries the risk of simplification. For this reason, no attempt was made to reproduce the surface fineness in a direct way, but to abstract it in terms of statistical parameters. A methodological approach was developed for this purpose. The main focus was to give the artificial surfaces a character as close as possible to reality and comparable with the experimental surfaces in terms of contact behaviour. This refers to their behaviour with regard to the development of the true contact area and the stress-deformation behaviour within the contact simulations as well as characteristic values necessary for the application of the micro-roughness model (e.g. mean roughness tip radius R). For this purpose, the scale invariance (fractality) of the experimental surfaces was taken into account. In addition, the generated surfaces are free of possible measurement errors and residual form deviations, which can influence the result of the contact simulation away from the actually interesting influencing variable - in this case the surface roughness.

For this purpose, the autocorrelation function of the grinded surfaces was evaluated. On the basis of the correlation length determined in each case, the spectral moments of the 1st, 2nd and 4th order could be determined, on the basis of which the variance of the height data, the average slope of the surface and the average curvature of the roughness peaks were derived [8].

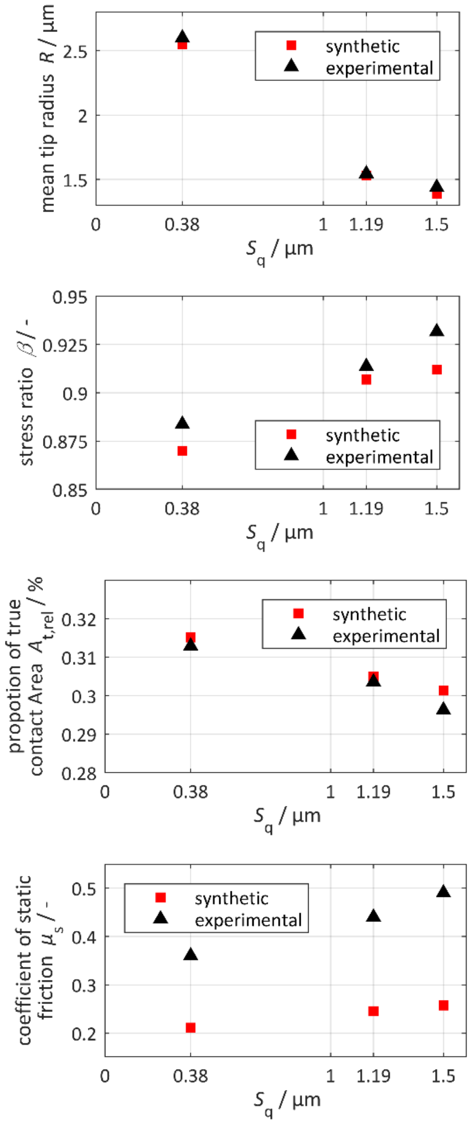

Figure 6. Comparison of a) mean tip radius R b) stress ratio β c) propotion of true contact area $A_{t,rel}$ and d) coefficient of static friction μ_s of experimental ground and synthetic surfaces.

The autocorrelation length shows a proportionality to the mean peak height and the true contact area and thus directly influences the friction behaviour [9]. Another characteristic value for quantifying the scale invariance, the Hurst exponent, was determined from the slope of the power spectral density [10]. Both parameters -autocorrelation length and Hurst exponent- were plotted over the S_q value for the grinded surfaces and extrapolated via fit functions in both directions for further S_q values. Finally, based on the geometric data of the surface, the autocorrelation length, the Hurst exponent and the desired S_q value, synthetic surfaces were created using Gwyddion and the three-step calculation workflow was carried out for them.

Figure 6 shows the comparison between experimentally measured surfaces and the synthetically generated surfaces used as input to the contact simulations (stage 2). The synthetic reference surfaces show similar values and trends in the microgeometric properties (e. g. R) compared to the experimental surfaces wich leads to a comparable mechanical behaviour in the contact simulation (e. g. β and $A_{t,rel}$) and also similar trends in the calculated coefficient of static friction μ_s. Thus, the most important precondition for the following performance of parameter studies is fulfilled.

5. Summary and Thanks

A multi-stage simulation and calculation approach was presented which, on the basis of experimentally measured or virtually generated synthetic surfaces (stage 1), links the results of the contact simulation carried out (stage 2) with a micro-roughness model taken from the literature (stage 3) to calculate the static friction coefficient. The workflow was experimentally validated on the basis of grinded surfaces and is capable of reliably representing trends with regard to the coefficients of static friction that occur and will be used in future to carry out simulative parameter studies.

Its implementation for the investigation of the influence of the roughness value S_q by means of the multi-level simulation and calculation approach requires the input of suitable surface topography data, which show a comparable behaviour to experimental surfaces in the contact simulations. For this purpose, a methodology for generating virtually generated, synthetic surfaces was developed. These are based on the evaluation of the autocorrelation function and take into account the fractality of surfaces, which is important for the application of micro-roughness models and the prediction of plastic deformation. The comparison with the results from calculations with experimentally measured surfaces of real sample surfaces shows a good agreement in the contact behaviour for the virtually generated surfaces and, based on this, comparable determined static friction values. Due to the given comparability with experimental surfaces, parameter studies can be carried out in the future using the virtual surfaces as input for stage 1 of the multi-stage calculation workflow.

Acknowledgements

The research project AiF-IGF 20839 BR was funded by the Federal Ministry for Economic Affairs and Climate Protection on the basis of a resolution of the German Bundestag. The authors would like to express their gratitude for this.

References

[1] Leidich, E. et al. (2015) GECKO – Gestaltung und Ermittlung charakterisierender Kennwerte von reibschlussoptimierten Oberflächen. *FVV Heft* **1076.**

[2] Köhler, M. (2005) Beitrag zur Bestmmiung des COULOMB'schen Haftreibungskoeffizienten zwischen zwei metallischen Festkörpern. *Dissertation*. Technische Universität Dortmund.

[3] Lorenz, H. & Köhler, M. (2000) Experimentelle Untersuchung von haftreibungsbestimmenden Mechanismen zwischen zwei metallischen Festkörpern. *Materialwissenschaft und Werkstofftechnik* **31**, 703-707

[4] Bartel, D. (2010) Simulation von Tribosystemen. *Vieweg+Teubner Verlag, Wiesbaden.* Edition 1. ISBN: 978-3-8348-9656-8.

[5] Kogut, L and Etsion, I. (2002) Elastic-plastic contact analysis of a sphere and a rigid flat. *J. Appl. Mech.* **69(5)**, 657-662

[6] Li, L, Etsion I. & Talke, FE. (2010) Contact area and static friction of rough surfaces with high plasticity index. *Journal of tribology* **132.3**

[7] Nečas, D & Klapetek P (2012) Gwyddion: an open-source software for SPM data analysis. *Open Physics* **10.1**, 181-188

[8] Kalin, M et al. (2016) Comparing surface topography parameters of rough surfaces obtained with spectral moments and deterministic methods. *Tribology international* **93**, 137-141.

[9] Megalingam, A and Mayuram, M M (2014) Effect of surface parameters on finite element method based deterministic Gaussian rough surface contact model. *Journal of Engineering Tribology* **228.12,** 1358-1373.

[10] Panda, S. et al. (2017) Spectral approach on multiscale roughness characterization of nominally rough surfaces. *Journal of tribology* **139.3**