



Editorial: Contact Mechanics Perspective of Tribology

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Editorial on the Research Topic Contact Mechanics Perspective of Tribology

A time to throw stones and a time to gather stones
(Ecclesiastes 3:5)

It is a time to gather stones. . . The Research Topic (RT) “Contact Mechanics Perspective of Tribology” was planned as a comprehensive overview of recent developments in the areas of contact mechanics and friction. Much has changed in this field in the last few decades. Contact mechanics expanded to qualitatively new fields of application which are at the forefront of the global development tendencies of technology and society, in particular micro- and nanotechnology as well as biology and medicine. The last decade was the time when vital numerical tools for simulating complex contacts, such as the FFT-based boundary element method, were created. The goal of the Research Topic was to review the recently established concepts, tools, and research activities and to outline the most important open issues for future investigations.

The main conceptual idea behind this Research Topic was to show to what extent one can understand tribology with macroscopic contact mechanics. By “macroscopic contact mechanics” we mean any approach based on continuum mechanics, including the corresponding elastic problems, viscoelasticity, adhesion, hydrodynamic and elasto-hydrodynamic lubrication, etc. In short, the papers of this Research Topic address the question: What can and what cannot be described in the framework of the macroscopic continuum mechanics approaches? Certainly, macroscopic approaches do not go to the ultimate (atomic) scale. Based on the advances of contact mechanics achieved during the last decades, it should be tracked where such limits are.

In the following, we briefly discuss the 36 papers comprising the RT.

INTERACTIONS ON ATOMIC SCALE AND SUPERLUBRICITY

The article collection is opened by a review “Influence Factors on Mechanisms of Superlubricity in DLC Films” by Yu et al.. It is devoted to one of the most fundamental achievements of tribology over the last 25 years (Erdemir and Martin, 2007). It clearly shows that a pure mechanical analysis of a tribological system is not sufficient to explain superlubricity of DLC films, since chemical aspects play a major role: passivation of the dangling bonds by hydrogen and formation of an easy-shearing sp²-C rich interface film. However, even these properties can be partially understood macroscopically as the transfer film still has a thickness of 5–40 nm, which can be considered as “macroscopic” as compared to the atomic scale. The excellent self-lubrication properties of DLC films seem to relate to the ability

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of carbon to produce both very hard (diamond) and very soft (graphite) phases as well as self-organization of these phases in the region of high load and shear.

In the second paper of RT, Zhou et al. discuss the fundamental question of whether it is possible to use macroscopic contact mechanics even at the level when thermal fluctuations start playing an important role. The paper is based on the Green-functions method extended to account for thermal fluctuations using the fluctuation-dissipation theorem. The result is simple and very impressive: for the most usual conditions which can be awaited in the praxis, the fluctuations are almost equivalent to a constant shift of the surface. This is approximately $1/1.5$ of the \sqrt{rt} fluctuation of the free surface. This means that thermal fluctuations contribute to a sort of repulsion of surfaces which may essentially influence friction, in particular contributing to the effect of liquid superlubricity.

The opinion-paper “Contacts with negative work of “adhesion” and superlubricity” is an attempt to take a general look on the problem of “adhesion and superlubricity” (Ge et al., 2019). The main conclusion of this paper could be formulated as “Ernest Rabinowicz was right!” In his famous book on “Friction and wear of materials” (Rabinowicz, 1995), he stated that there are two main properties, which determine friction: adhesion and “compatibility” of materials. The less the compatibility (that means the tendency to form alloys) and the less the adhesion, the smaller the friction. The above opinion paper continues: best of all, the adhesion should be negative, then one has the effect of “superlubricity”! Very interesting is also the Rabinowicz’s notion of “compatibility.” According to the well-known Hume-Rothery rules, the materials are incompatible if their lattices are incommensurate, which, however, is a well-established rule for minimizing friction at the atomic scale! Thus, the concept of Rabinowicz looks now really “trivial”: incommensurate (and thus non-intermixable) materials should be combined with the lowest attraction (or even better, repelling!). The paper of RT by Fang et al. illustrates this mechanism in the special case of hydration-lubricated contacts, which e.g., provide the uniquely low coefficient of friction in natural joints [Klein (2013)].

ANALYTICAL AND SEMI-ANALYTICAL METHODS IN CONTACT MECHANICS

Despite the rapid development of numerical simulation methods, analytical and semi-analytical solutions remain of immense importance. They are employed as benchmark for numerical methods, to achieve the “analytical understanding” of problems, or for empirically capturing numerical results in multi-dimensional parameter spaces. An example of a combination of exact analytical solutions with a “nearly exact” approximation provides the *localization principle* (Goryacheva, 1998) which is exploited in the paper by Goryacheva and Tsukanov for the analysis of a great variety of surfaces with regular microgeometry.

The paper by Forsbach shows simple yet numerically efficient way to determine the complete stress tensor and the hydrostatic pressure gradient in the half-space beneath the contact of an arbitrary axisymmetric indenter (under normal and/or tangential

load). The calculation method is based on the same “trick” as is used in the Method of Dimensionality Reduction [see e.g., Heß (2011) and Popov et al. (2019)].

Impact tests are an important tool to analyze dynamic material properties of viscoelastic media in technology and biology. In this context, rigorous contact mechanical models of the collision problem are necessary to adequately interpret data from impact experiments. Willert shows theoretically that the coefficient of restitution in this type of testing is mainly a function of one specific material property, namely, the ratio between the loss and storage moduli of the viscoelastic probe at the characteristic timescale of impact. This, for the first time, gives a concise, comprehensive statement about what (regarding material properties) is actually measured in low-velocity viscoelastic impact or rebound tests.

For the pure normal contact problem, a closed analytical solution is possible. For tangentially loaded contacts, on the contrary, semi-analytical methods must be applied. A review and application possibilities of such methods is given by Aleshin. The semi-analytical solutions, such as the Method of Memory Diagrams or MDR, allows to calculate hysteretic responses to extremely complex loading histories, such as random vibrations. As an example, the author shows that a single elastic body with a frictional contact to the substrate demonstrates rich dynamic behavior when excited even by a simple harmonic signal.

FFT-ASSISTED BOUNDARY ELEMENT METHOD

In the last years, the FFT based Boundary Element Method became the standard tool for contact simulations of real surfaces both in research and industry. The basic development of the FFT-based BEM took place in the late 1990s and early 2000s and is associated first of all with the groups of Leon M. Keer and Q. Jane Wang from the Northwestern University. The paper “FFT-Based Methods for Computational Contact Mechanics” is a concise and instructive review of the basics and the current state of the FFT-based BEM. The FFT-based BEM is, however, restricted to macroscopically plane geometries. Benad shows a way in which the BEM can be generalized to arbitrary shapes of contacting bodies without increasing the computational complexity.

Soft matter attracts ever greater attention of researchers. The softer the body, the more visible becomes the influence of the *surface tension* of the contacting bodies (which is neglected in the classical contact mechanics of “stiff bodies”). In the paper by Yuan and Wang, a BEM-version is formulated accounting for the surface tension. Li and Popov generalize this approach further by considering a non-adhesive contact with different surface tension inside and outside the contact area.

CONTACT RESPONSE OF ROUGH SURFACES

Contact mechanics of rough surfaces was one of the most debated topics in contact mechanics of the last decades. These debates

seem to come to a consensus summarized in the “contact challenge”-paper by Müser et al. (2017). The central tool which is now accepted by the most researchers is the FFT-based BEM (see previous Section). But even this extremely efficient simulation method is computationally expensive when the identification of optimal roughness and texturing of surfaces is a matter of research, to achieve desired tribological responses for industrial applications. One further possibility to shorten the simulation time may be the use of genetic algorithms (Cinat et al.) or artificial neural network architectures (Kalliorinne et al.) that open new perspectives in data-driven identification and machine learning techniques applied to contact mechanics.

While the BEM allows simulating contact with an arbitrary shaped surface (as long as the half-space-approximation for the response is valid), most studies on rough surfaces focused on the so-called randomly rough surfaces. Borodich et al. stress in their paper that randomly rough surfaces are only a small sub-class of all surfaces and correlated roughness may completely change the contact mechanical properties even if the power density of roughness remains unchanged. A comparative study of the effect of structural parameters on the contact area for randomly rough, anisotropic and correlated random surfaces is undertaken by Zhou and Müser. In particular, the authors show that the famous parameter κ (coefficient connecting the real contact area with normal load and rms slope) is not a function of the Nayak parameter alone [Nayak (1971)]. The study also attracts attention of researchers to the fact that at small contact area the statistics of the contact profile is not the same as that of the full rough surface. This dependence maybe the reason for the weak dependency of the coefficient of friction of elastomer materials on the normal load [Popov et al. (2018)].

INFLUENCING FACTORS OF FRICTION

One of the pioneers of the use of Quartz Crystal Microbalances (QCM) for studies of friction, J. Krim, examines together with her co-authors the limits of macroscopic continuum mechanics, by probing where continuum methods break down as the atomic scale is approached. They find that contacts with water solutions are very well described by macroscopic theory up to nanometer scale, but the model failed to adequately describe contacts lubricated with the suspension of nanoparticles with radius 20 nm. However, its continuum nature did not appear to be the dominant factor underlying failure, which is most probably due to other factors not correctly described in the model. Further investigations are necessary.

Ozaki et al. suggest a loop-type coupled analysis scheme to bridge the mesoscale and macroscale domains of friction analysis. Specifically, the mesoscale multipoint contact model was linked with the macroscale finite element analysis model via the rate-, state-, and pressure-dependent friction model previously proposed by the authors.

Kinetics of elastomer friction is an important phenomenon for dynamic applications. Nakano and Kono show that the character and the very existence of kinetics do depend on how stiff the body is fixed normally to the contact surface, which means that the

friction coefficient is not a material constant even in simple sliding contacts.

An old problem of fundamental importance for the understanding of friction and its applications is the interplay between oscillations and friction. Vibrations can strongly influence friction, which in turn often leads to vibrational instabilities [Bowden and Tabor (1950)]. Thus, friction should always be understood as the interplay of dynamics and friction on different spatial and temporal scales. This interplay has many aspects which have been studied intensively in the past decades. The paper by M. Popov gives a high-level overview of active control of friction by normal, lateral and transverse vibrations and derives the main properties of friction under oscillation from a purely macroscopic contact-mechanical model. In addition to classic influencing factors such as frequency and amplitude, the key role of contact stiffness is emphasized and the effectiveness of various oscillation waveforms is discussed. Pohrt extends the discussion by employing a BEM model to include the effect of partial slip. Using the same approach, he introduces rotational oscillations and finds favorable properties to reduce the observable macroscopic friction.

WEAR

The name of James Greenwood is known to every tribologist, first of all due to his works on contact mechanics of rough surfaces [Greenwood and Williamson (1966)]. Even more attention deserves his appeal “Stop studying the purely normal contact of rough surfaces!” In his opinion-paper Metal Transfer and Wear,” he writes: “These thoughts are offered as a reminder that Tribology is not all about the normal contact of fractal surfaces, and indeed, not all about elastic contact of rubber and polymers, or even about dry contact.”

This recalls that wear is one of the most complicated, yet unexplained, phenomena in tribology. The difficulties start already by the definition of this notion. Reichelt and Cappella examine various wear definitions and various experimental methods to measure wear and estimate the error sources.

Just as in frictional processes, wear can be influenced by oscillations—both in the cases of partial slip and gross slip. Oscillations may lead to a specific kind of wear called fretting. On the other hand, they may lead also to the damage of material in form of fretting fatigue. In the review paper by Argatov and Chai, both partial and gross slip situations are considered, and the authors provide a review of recent works on fretting wear. They consider such aspects as the force-controlled steady-state regime, wearing-in period, wear of functionally graded materials, limiting profile, wear accumulation. The authors also discuss various analytical approaches including the MDR-based approach.

While the very often used Archard wear law is a very strong simplification which is not always confirmed by experiments [Meng and Ludema (1995)], it is still used for qualitative estimation of wear processes in a limited range of parameters, as done in the paper by Dimaki. The author provides an analysis of the wear rate as function of time and compares theoretical prediction with available experimental data.

ADHESION

Adhesion has been one of the most debated topics in contact mechanics in the last years. This interest was driven by many factors including the bio-medical applications and general interest to “soft matter.” Adhesion has been incorporated into the FFT-based BEM. The most simple and straightforward implementation is available for JKR-type adhesion [Popov et al. (2017)]. In this case, the inclusion of adhesion not even influence the computation time. However, adhesive contacts have been studied mostly theoretically and experimental results are still sparse. Lyashenko and Pohrt contribute to closing this gap providing a detailed experimental study of the influence of roughness on adhesion between rigid indenter and soft rubber layer.

In the context of contact mechanics, only very simple models of adhesion are considered. For industrial applications, however, material parameters are important which cannot be reduced to the work of adhesion but take also into account the propensity of a material to detach due to cavitation. Material aspects are considered in the paper by Fuensanta and Martín-Martínez.

Adhesion can also lead to elastic instabilities and formation of regular patterns with a characteristic wavenumber. Joe et al. analyze the effect of surface roughness on adhesive instabilities for the elastic layer and find that for moderate to large RMS amplitudes, roughness exerts a stabilizing effect, but low RMS roughness can trigger the instability in ranges where the uniform layer would be stable.

Another much debated topic related to adhesion is adhesive contact under tangential loading. This is an example of a topic where there are as much opinions as are authors. In-depth experimental studies with accompanying theoretical modeling started only very recently. The processes occurring at the onset of sliding of elastomer multicontacts are studied theoretically and experimentally by Scheibert et al..

BIOTRIBOLOGY

Contact mechanics of cells, in particular their adhesion on various surfaces has become an important and intriguing part of contact mechanics. In her review paper “Hallmarks of Life in Single Cell Contact Mechanics: Outstanding Challenges and Perspectives,” Moreno-Flores places the focus on cultured mammalian cells and on experimental techniques that rely on contact mechanics, in particular scanning-probe and traction force microscopies. The importance of time as key variable in theory and experiment is highlighted, together with the cellular structures and organelles needed to correctly understand the mechanobiology of cells.

Electrovibration is one of the key technologies in surface haptics. By inducing controlled electrostatic forces, the friction within a sliding contact between the human finger and a capacitive screen is modulated, which in turn gives effective tactile feedback to the user. Such powerful haptic displays can be built into mobile phones, tablets, navigation devices, games consoles and many other devices of consumer electronics. However, due to the layered structure and complex material of

human skin, the underlying contact mechanical processes have not yet been fully understood. Heß and Forsbach develop a macroscopic model for sliding friction of a fingerpad over a smooth surface under electroadhesion, which is based on new theoretical approaches as well as finite element simulations using the Ogden model to account for skin stiffening. It provides reasonable results for all contact mechanical quantities. In particular, the predicted friction force and friction coefficient show excellent agreement with experimental data over the entire range of relevant voltages and applied normal forces.

In his mini review “Milestones in Natural Lubrication of Synovial Joints,” Ruggiero focuses on the history of research related to lubrication of human synovial joints. He carefully examines existing models of synovial joint lubrication and their fundamental mechanisms: boundary, weeping, elastohydrodynamic, squeeze-film, as well as boosted lubrication and ultrafiltration. The rheology of the synovial fluid which plays a key role in natural joints, is also described; various existing laws of its description are given in the historical vein both in the Newtonian model and in the non-Newtonian one. As often, such historical view allows highlighting the main “milestones” of the research which remain the “pillars” of our present understanding and contribute to scientific cooperation between tribology, biology and medicine in general, as well as to a deep understanding of the complex phenomena acting in biological tribosystems.

One of the central processes in lubrication is cavitation. As a matter of fact, without cavitation no bearing capacity can exist. However, cavitation belongs to the most complicated processes for mathematical modeling. In his mini review, Geike describes the current state of research in this area.

INFLUENCE OF PLASTICITY AND INTERNAL STRESSES

Stiff hard coatings, such as TiN or CrN on metallic substrates, are often used to enhance tribological properties of components. A mismatch of the Young’s moduli at the coating/substrate interface can lead to additional stresses in the coated system. To reduce this effect, functionally graded materials can be used. An even simpler solution is the usage of a single middle-layer, which has an intermediate Young’s modulus between the substrate and coating. Parel et al. show in their paper that both strengthening and weakening effects can be observed in bilayer coated spherical contacts, depending on material and geometric parameters of layers.

Pape et al. study the influence of residual stresses on the fatigue life of rolling bearings in dependence on the production processes.

Very often, formation of the surface topography during frictional sliding is attributed to wear. However, another mechanism of surface roughening is just the volume plastic deformation of a spatially heterogeneous material. Romanova et al. simulate how the internal heterogeneity of a material leads to surface roughening during deformation.

The editors thank all authors of this excellent book which impressively documents the current state of contact mechanics

and friction theory and discusses the prospects for the future. It shows clearly that contact mechanics and friction is not only important but also beautiful branch of science of high technological and esthetical value.

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All authors have contributed equally to this work and share first authorship.

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