lubricants

MDPI

Editorial

Adhesion, Friction and Lubrication of Viscoelastic Materials

Giuseppe Carbone * and Francesco Bottiglione *

Department of Mechanics Mathematics and Management, Via Orabona 4, 70125 Bari, Italy
* Correspondence: giuseppe.carbone@poliba.it (G.C.); francesco.bottiglione@poliba.it (F.B.)

The mechanical behavior of viscoelastic materials is a key factor of many physical phenomena occurring at the interface of contacting bodies. Understanding how the interface between two polymers fails, shedding light on the mechanisms leading to frictional forces when a rubber material comes into sliding contact (dry or lubricated) with a rough surface, are relevant topics in a countless number of practical applications. To achieve this aim, theoretical and numerical modelling as well as experimental investigations of the behavior of the contact pair need to be carried out. However, overcoming the high degree of complexity due to the time-dependent stress–strain relations governing viscoelastic material responses is a very demanding task covered, at least in part, by this Special Issue.

The purpose of this Special Issue is to foster the growth of new ideas in the field, by discussing the most recent advances in adhesion, friction, and lubrication of viscoelastic materials. We are very pleased to notice that our call stimulated the discussion at both the fundamental and the applications level. Theories, numerical simulations, and experimental characterization of viscoelastic materials and interfaces are the subjects of the articles collected in this Special Issue. It gathers, indeed, a total of seven research articles, one technical note and one review article where these topics are discussed from different perspectives.

A first block of four papers tackles the effects of the viscoelastic behavior of materials, adhesion, and roughness on the friction force.

In [1] the authors have studied the linear and nonlinear viscoelastic properties of two tire tread compounds. They focused on the differences in nonlinear responses between the oscillatory tensile and shear modes, aiming at providing the reader with an assessment of the measurement which seems to be more accurate in characterizing the viscoelastic modulus of the material. This fundamental topic is very relevant in practical applications where large deformations cannot be neglected.

Some of the results discussed in [1] were relevant for the study presented in [2] where the authors studied the adhesion and friction for three tire tread rubber compounds. Adhesion tests were conducted on a smooth silica glass ball in contact with smooth sheets of the rubber in dry conditions and in water. Friction studies were performed on rubber treads sliding on smooth glass, concrete, and asphalt road surfaces. Different experimental set-ups were presented, depending on the sliding velocity range under investigation. The linear and non-linear viscoelastic properties of the rubber compounds were measured in shear and tension modes using two different dynamic mechanical analysis (DMA) instruments, with procedures widely discussed also in [1]. The surface roughness of the road specimens was also characterized. The viscoelastic properties of the rubber compounds and the road characteristics were necessary to analyze experimental data with the support of the Persson's theory of contact mechanics. Interestingly, the authors found that one of the compounds exhibited adhesion in water only for a short time and that the same rubber compound exhibited a smaller sliding friction in water than the other two compounds, highlighting the importance of the adhesion strength on the friction behavior. The measured friction coefficients were found to be in good agreement with the Persson's contact mechanics theory predictions. The results showed the importance of the contribution to the friction coefficient from the area of real contact and thus to the adhesive contribution.

check for updates

Citation: Carbone, G.; Bottiglione, F. Adhesion, Friction and Lubrication of Viscoelastic Materials. *Lubricants* **2021**, *9*, 23. https://doi.org/10.3390/lubricants9030023

Received: 19 February 2021
Accepted: 22 February 2021
Published: 25 February 2021

Inspired by [2] and recalling that the theory of Klüppel and Heinrich and that of Persson suggest that viscoelastic losses crucially depend on the "multiscale" aspect of roughness and on the cutoff at the finest scales, the authors of [3] have commented on both theories. Using Persson's theory, they give some examples on the uncertainties involved in the truncation of the roughness spectrum. They argue that it is still unclear how the adhesive and the viscoelastic contributions can be separated from the experiments, which leaves room for further interesting investigation in this field.

The effect of adhesion and viscoelastic behavior of material on friction for a multiscale rough surface was also studied in [4]. The author presented a model for calculating the hysteretic friction force for a multilevel wavy surface sliding in dry conditions over the surface of a viscoelastic foundation, considering the adhesion force acting in the direction normal to the contact surface. Different regimes of contact and adhesion interaction were possible, including partial and saturated contact. The friction force was calculated as a sum of two terms: the first due to hysteretic losses occurring when asperities of the superior scale level cyclically deform the viscoelastic foundation during sliding. The second was the law of friction determined from the solution of the contact problem at the inferior scale level. For the case of a two-level wavy surface, the contribution of both levels into the total friction force was calculated and analyzed depending on the sliding velocity and specific energy of adhesion of the contacting surfaces. In cases where the analytical solution was evaluable, e.g., full contact condition, it was demonstrated that the curve of friction force vs. sliding velocity can exhibit more than one peak as also obtained in other theories discussed in [1–3].

Moving to the engineering side, this issue also discusses the implications of viscoelastic rubber dissipation in some relevant real-world engineering problems. In [5] the authors studied the steady-state rolling contact of a linear viscoelastic layer of finite thickness and a rigid indenter made of a periodic array of equally spaced rigid cylinders. Such a configuration is useful for analyzing the energy consumption in belt conveyors, for instance. The effect of geometrical quantities (layer thickness, cylinder radii, and cylinder spacing), material properties (viscoelastic moduli, relaxation time) and operative conditions (load, velocity) were all investigated. The physical quantities typical of contact problems (contact areas, deformed profiles, etc.) were calculated and discussed. There was special emphasis put on the viscoelastic friction force coefficient and the energy dissipated per unit time.

In contrast, the fretting behavior of viscoelastic polymers was investigated in [6]. The authors conducted the fretting characterization of five different thermoplastic polyurethanes in reciprocating sliding contact against a steel ball. The differences were identified using dissipated energy. The profiles of wear scars and the counterparts were analyzed using a microscope. The coefficient of friction was calculated separately for the partial slip and gross slip regimes. In the mixed fretting regime, the coefficient of friction was almost at the same level among the five materials. In the partial slip regime, however, it could be distinguished. Temperature measurements were conducted on the counterparts during the tests. Overall, the material that showed the best tribological properties also performed the best in the fretting tests. Interestingly, their results show that their fretting behaviors can be related to the dynamic mechanical properties, which were characterized by dynamic mechanical analysis (DMA).

At a very fundamental level was the "feasibility study", as the authors themselves defined it [7], where they developed and presented a computationally lean model for the coarse-grained description of the contact mechanics of hydrogels. The simulations revealed a wavevector-dependent effective modulus with the following properties: (i) stiffening under mechanical pressure, and a sensitivity of (ii) the degree of crosslinking at large wavelengths, (iii) the solvent quality, and (iv) the hydrophobicity of the mold in which the polymers were crosslinked. Furthermore, the simulations provided evidence that the elastic heterogeneity inherent to hydrogels can suffice to pin a compressed hydrogel to a microscopically frictionless wall that is undulated at a mesoscopic length scale. The hydrogel simulated therein was still not viscoelastic since the time-dependent behavior of the polymeric chains was not considered in [7] but it was mentioned as one of the not-too-hard next ingredients to add to convert such a "feasibility study" into an effective simulation tool.

The Special Issue is then closed by two articles more focused on lubrication and friction in tribological pairs. The former [8] deals with a computational fluid dynamics—smoothed-particle hydrodynamics (CFD-SPH) simulation of the hydrodynamic lubrication at the interface between a slider and a 3D rough surface. It proves the suitability of CFD–SPH in modelling such complex interaction phenomena, which may even stimulate the development of SPH simulation of solid pairs and also in the case of viscoelastic solids. The latter [9] is an experimental investigation of the coefficient of friction of dry-lubricated contacts between hard steel and tungsten carbide ball bearing in a modified four-ball test.

Funding: This work was partly supported by the Italian Ministry of Education, University and Research under the Programma "Progetti di Rilevante Interesse Nazionale (PRIN)", Grant Protocol 2017948, Title: Foam Airless Spoked Tire—FASTire (G.C.).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tolpekina, T.V.; Pyckhout-Hintzen, W.; Persson, B. Linear and Nonlinear Viscoelastic Modulus of Rubber. *Lubricants* **2019**, *7*, 22. [CrossRef]
2. Tolpekina, T.V.; Persson, B.N.J. Adhesion and Friction for Three Tire Tread Compounds. *Lubricants* **2019**, *7*, 20. [CrossRef]
3. Genovese, A.; Farroni, F.; Papangelo, A.; Ciavarella, M. A Discussion on Present Theories of Rubber Friction, with Particular Reference to Different Possible Choices of Arbitrary Roughness Cutoff Parameters. *Lubricants* **2019**, *7*, 85. [CrossRef]
4. Makhovskaya, Y. Modeling Sliding Friction of a Multiscale Wavy Surface over a Viscoelastic Foundation Taking into Account Adhesion. *Lubricants* **2019**, *7*, 13. [CrossRef]
5. Menga, N.; Bottiglione, F.; Carbone, G. The Indentation Rolling Resistance in Belt Conveyors: A Model for the Viscoelastic Friction. *Lubricants* **2019**, *7*, 58. [CrossRef]
6. Wang, C.; Hausberger, A.; Berer, M.; Pinter, G.; Grün, F.; Schwarz, T. Fretting Behavior of Thermoplastic Polyurethanes. *Lubricants* **2019**, *7*, 73. [CrossRef]
7. Müser, M.H.; Li, H.; Bennewitz, R. Modeling the Contact Mechanics of Hydrogels. *Lubricants* **2019**, *7*, 35. [CrossRef]
8. Paggi, M.; Amicarelli, A.; Lenarda, P. SPH Modelling of Hydrodynamic Lubrication along Rough Surfaces. *Lubricants* **2019**, *7*, 103. [CrossRef]
9. Marko, M.D. Friction of Tungsten-Based Coatings of Steel under Sliding Contact. *Lubricants* **2019**, *7*, 14. [CrossRef]