Contents lists available at http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: http://qu.edu.iq/journaleng/index.php/JQES

A review of modelling and inspection techniques in micro/nanoscales of dry friction of rough surfaces

Muhammed A. Shallal* * and Nabeel Almuramdy

Department of Mechanical Engineering, College of Engineering, Al- Qadisiyah University, Al-Diwaniyah +964, Iraq

ARTICLE INFO

Article history:
Received 00 January 0000
Received in revised form 01 February 0000
Accepted 00 May 0000

Keywords:
contact
friction
Microscale
nanoscale
roughness

ABSTRACT

In reality, there are a number of tiny contact asperities on the contact surface, which may be seen at the micro/ nano scales. The total mechanical behavior is the product of all asperities that are involved during the contact. There are still a lot of unresolved issues in the study of contact and dry friction behavior of rough surfaces because of the variety of surface topography, complexity of the contact scale, and nonlinearity of the constitutive materials. The complexity of the friction mechanism and its misunderstood nature pose significant challenges in this study. This paper provides a comprehensive review of typical dry friction behaviors observed at the micro- and nanoscales. The significance of surface roughness, the role of contact mechanics, and the impact of experimental and theoretical approaches in modeling and simulation have been examined at this study. Additionally, the manuscript highlights the crucial role of proximal probing techniques, particularly the Atomic Force Microscopy (AFM) technique.

1. Introduction

Friction represents a complicated phenomenon arising when surfaces come into contact. It may be defined as the resistance accounted by one body if another body rolls or slides over it. This frictional resistance is not a material property, but a response to moving, sliding or rolling. In some applications, the maximum friction force is necessary like vehicle tires, machining processes, clutches, brakes, and so on. On the other hand, friction force in some applications is desired to be low like machines sliding parts, bearings, and so on. Wear in sliding bodies and heat generation which is consuming nearly one-third of world energy and reduces efficiency and reliability are other evidence of friction damage. Failure of material components often occurred because of inadequate estimation of friction and wear manners.[1] Though, understanding frictional phenomenon characteristics of different metal pairs is ¬necessary for pre-manufacturing ¬equipment and tools [2]. Using lubricants is the main way to reduce friction, which is not always applicable especially in space-vacuumed environments and in micro/nanomachines miniaturized industry, so, dry friction has no substitution in such cases [3]. The studies of micro/ nanotribology are trying to find a new understanding of these interfacial phenomena on micro or nano levels and to study interfacial phenomena in micro and nanostructures, which are used in magnetic storage systems, micro or nano-machines and other micro applications. The nature of the bonding and the interactions between molecules in different materials,

* *Corresponding author.*
E-mail address: mech.post.2022-2@qu.edu.iq (*Muhammed A. Shallal*)

https://doi.org/10.30772/qjes.2023.141737.1008

combined with advance techniques in modelling and simulation methods allowed for the theories and the studies of complicated interfacial phenomena with high resolution in time and space. In this paper, dry friction of rough surfaces in micro/nano-scales is reviewed based on five aspects: surface roughness role, the role of contact mechanics, the role of proximal probs specially the Atomic Force Microscopy (AFM), experimental studies and computational simulation studies.

2. Roughness role in micro/nano-scale dry friction

Roughness is an important parameter in tribological modelling. A small degree of roughness change will surely make a difference between the true and apparent contact areas of interfaced bodies. Antoine et al. [4] classified Surface roughness parameters into three types according their functionality: amplitude, spacing, and hybrid parameters and found the mathematical formulae for more than fifty roughness parameters and used them in developing a new software for this job.Patrikar [5] used numerical methods to compute changes in electrical properties such as resistance, capacitance, and noise due to surface roughness. although they seem to be smooth for normal eye, all surfaces naturally are rough in the micro scale, so, researcher developed a software used to simulate the surface roughness. Pawlus et al. [6] analyzed the Abbott–Firestone curve and its benefits and the parameters gained from this curve like mean deviations of profile heights, the maximum height of the peaks, maximum height, Roughness Arithmetic Average (Ra), and Roughness root mean square average(Rq) in the manufacturing process. This curve represents the properties of surface roughness in various profile types as the triangular periodic profile and S-letter shape profile and other profiles, that result from industrial elements machining. It had been concluded that a great care must be taken when using this method as errors happening is probable.

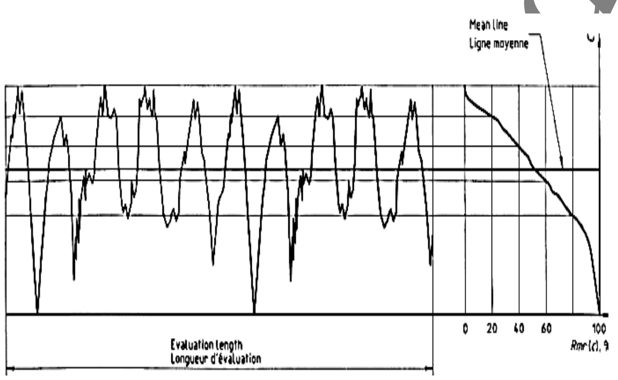
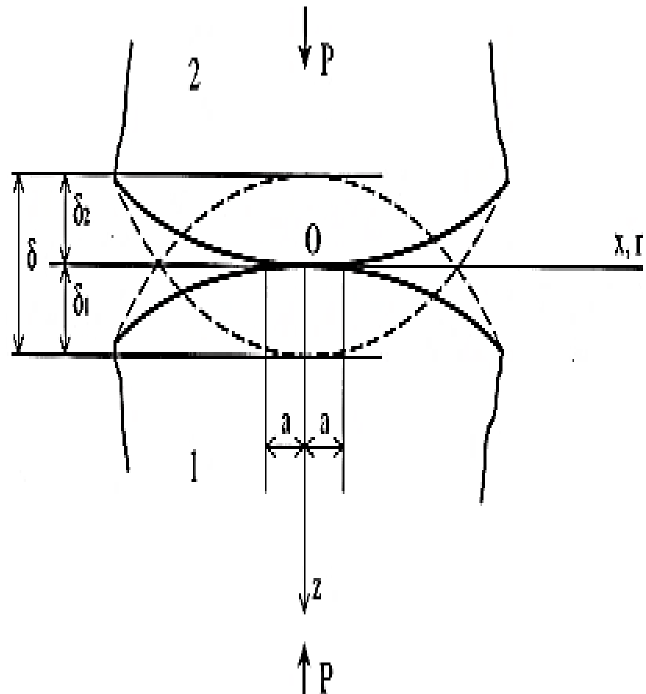


Figure1. Abbott–Firestone curve for roughness profile of surface [6]

Adams [7] reviewed contact modelling with an emphasis on the forces of contact and their relationship to the geometrical, material, and mechanical properties of the contacting bodies. The authors discuss single asperity contact models, including simple Hertz contacts for spheres, cylinders, and ellipsoids, as well as more complex models that account for the effects of friction, plasticity, adhesion, and higher-order terms that describe the local surface topography. The paper also covers multi- asperity contact models, such as the Greenwood-Williamson contact model (GW), which represents



various modifications of the basic theory. Additionally, the authors describe wavy surface contact models, with and without the effects of friction, which inherently account for the coupling between each of the contacting adrafinil, they briefly reviewed experimental investigations and recent work that addresses the dynamics and associated instabilities of sliding contact. Thimons. et al. [8] investigatesd the effect of different length scales of surface roughness on adhesion of hard-material contacts. The authors used diamond coatings of varying roughness and measure adhesion using large ruby probes. They perform more than 2000 measurements of pull-off force and use numerical analysis to extract geometry-independent material parameters. The analysis reveals that a critical band of length-scales between 43 nm and 1.8 µm in lateral size has the strongest effect on the total adhesive force for these hard, rough contacts. topography for a better understanding to the topography dependence of soft-material adhesion. The results showed a difference between the apparent and intrinsic work of adhesion. Further, the total energy dissipated at the contact and removal is equal to the product of the intrinsic work of the adhesion to the real contact area. The concepts can be collected together with analytical and numerical models of rough surface behavior to predict the surface properties.

3. Role of contact mechanics in dry friction in micro/ nanoscales studying

Contact mechanics is so important and useful to predict the life and sudden failure of bearings, gears, etc. Contact models were found to evaluate normal contact, tangential loading, adhesion, and surface layers. Amontons law, which states that the force friction is proportional to radial load with a coefficient of friction (µ) equal to one- third had been applicable for more than 500 years at all scales and materials with all types of deformation. Taylor[9] try to understand this fact by reviewing papers concerned with rough surfaces contact and recording any deviations from it, after the conclusion was that Amontons law in many cases is just an approximation, despite that many successful and simple models derived depending on this law and still used to this time as: Greenwood -Williamson (GW), Greenwood – Tripp (GT), and Bush– Gibson – Thomas (BGT). More accurate models were developed like Persson model. All these models tried to interpret the conflicts in Amontons law that concerned with the relationship between normal load and true surface area and whether the asperities of contacted surfaces deformed elastically or plastically.

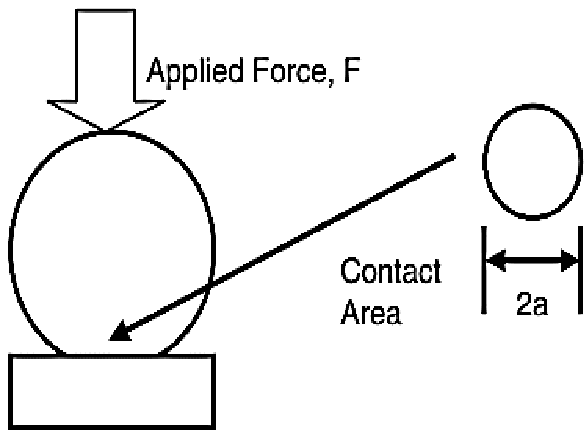


Figure2. Relation between load and radius of contact [10]

Menezes [10] provided a comprehensive overview of Tribology and Contact Mechanics, including: Hertzian contact theory, which describes the contact between two elastic bodies under a normal load also discussed the latest research in contact mechanics, including: The effect of surface roughness on contact mechanics and other concerning subjects.

Adams et al. [7] reviewed modeling of contact with concentering on the forces of contact and how related contacted bodies properties such as their geometry and other material and mechanical properties. Starting with Hertz theory of elastic contact, Greenwood–Williamson and other important models were reviewed with a connection with experimental trials in dynamics of sliding. Contact friction can be modeled mathematically or analytically, so, Berger [11] analyzed the literature about the application of different friction models. The survey leads to the conclusion that the system and friction models are deeply linked and cannot be selected separately. The argument was that multi-scale factors can affect friction contact performance including critical sliding distance, sliding speed, acceleration, normal load, temperature, humidity, surface preparation, and, of course, material combination, affect functional qualities.

4. Experimental studies of dry friction in the micro/ nano scales

Syam et al.[12] discussed the use of topological data analysis for friction modelling. The complexity of dry sliding friction and the need for adequate frictional models had been high lighten. It had been argued that most models are phenomenological rather than deduced from fundamental principles and focused on identifying relevant degrees of freedom for the development of adequate frictional models, such as the state-and-rate models. The topological data analysis had been used and a mathematical method for dimensionality reduction, to analyze datasets characterizing surface roughness, contact of rough surfaces, and frictional sliding had been discussed. The tribological systems had been studied, including the surface roughness and multi- asperity contacts, using 3×3, 4×4, and 5×5-pixel patches. The data tends to concentrate at certain "primary" and "secondary" circles, depending on whether the surface is isotropic or anisotropic with particular lay directions. Muna and Abbass .[13] utilized the Taguchi method to optimize the friction parameters in the stir processing which are effected on ultimate tensile strength of a certain aluminum alloy of 6 mm thickness plate when applying a number of tensile tests to determine the important parameters of friction inducing ultimate tensile strength. when different rotation and transverse speeds and different number of passes in the same direction and fixed tool tilt angle. The best parameters for best strength and best hardness were determined. It has been found that high hardness magnitude was found in the stir zone center and then it decreases toward the outside terminals of the graph which showed experimentally that the most affecting friction parameter was the sliding speed. Alobaidi and Almuramady [14] had studied the effect of temperature degree on the rubber-epoxy composite with different composition ratios for two cases: heat-aged samples and unaged ones using tensile test. Founding was a decrease in elongation and tensile strength when samples exposed to thermal aging where temperature increase leads to ductility diminish and increase of its hardness. the ability of the material to stretch and elongate were among affected characteristics. Researchers said nothing about the effect of temperature and aging on the roughness and friction properties of the materials in spite of the importance of these properties in the mechanical applications of such materials. Oudah and Hassan.[15] had fabricated an Aluminum-Nickel-steel alloy and investigated its mechanical properties with necessary tests as like hardness test, tensile test, transmission electron microscope (SEM) and X-ray to estimate the modulus elasticity, homogenous layer's density, and other critical characteristics of this crucial alloy is also obtained experimentally. Alwan[16] proposed a mathematical formula to evaluate the dynamic stresses due to dry friction between robotic mechanism components in case of non-ideal mechanism joints using MATHCAD software. It had been found that dry friction forces in the mechanism actuators increased about ten percentages than that in case of ideal robotic joints where special materials of low friction coefficient and ideal design are used. Zhang B..et.al [17] presented a novel approach for microscale dry contact stiction and friction assessment. The authors stated that accurate and quantitative evaluation of friction is of fundamental interest for materials science and manufacturing. They also mentioned that micro metal forming techniques with characteristic forming dimensions approaching a few microns have developed rapidly over the past two decades, but the assessment of microscale friction is lagging. High-rate data acquisition enabled direct measurements, for the first time, of microscale stiction and friction forces during disengagement between the punches and the molded Al under dry contact conditions. The authors deduced and analyzed stiction and friction stresses. They estimated the average friction coefficient. Weymouth et al. [18] argued that sliding friction is an obstructing kinetic force that, through a variety of events, is converted to dissipated energy. they used the lateral force microscopy for measuring the energy dissipated when the tip is oscillating laterally above the surface with a range of sub-Angstrom amplitudes. This observation allowed for the identification of the necessary modelling components and demonstrated how sensitive friction is to the dissipated potential energy. Sandeep et al. [19] implemented tests with in-house micromechanical apparatuses on glass specimens at different scales from particle to micro and macro scales to investigate the influence of roughness on contact behaviours. They found that tangential and normal stiffness increased with increasing scale length but decreased with increasing surface roughness. while friction increased with increasing surface roughness but did not affect with scale length. Afshar-Mohajer et al [20] used scanning electron microscope (SEM) to test micro/nano-hierarchical surfaces manufactured with two photon lithography technique. They had discovered the relation between micro-scale deformation and nano- asperities height. the bending and buckling of long nano- asperities assist sliding forces, and develop lateral force even before sliding starts. They supported their findings, with finite element modelling to the tests

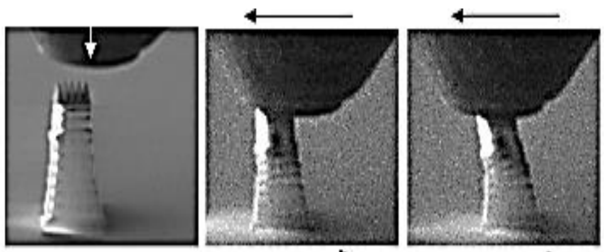


Figure4. SEM photo show bended nano and micro- asperities [20]

5. Micro/ nano- scales dry friction simulation with energy dissipation technique

Vadgama et al. [21]argued that as physical experiments are an expensive and time consumption therefore, the alternative is modeling and simulating for gaining a deep understanding of characteristics and predicting events at micro, nano, and molecular or atomic scales the vast majority of the frictional work for all the cases was converted to thermal energy dissipation Thus, the amount of frictional work that contributes to asperity deformation and heat dissipation, kinetic energy change, and frictional work have all been determined in such simulations. Hanaor et.al [22] examined static friction occurring at fractal counter- surfaces in mutual contact using computationally methods. Molecular Dynamics (MD) finite element analysis (FEA) are used in order to predict static friction coefficient on the basis of a hierarchical surface texture taking in regard physical-chemical interactions and contact mechanics. They found that frictional coefficient depends on molecular bonding, fractality of surface, and adhesion. They also found that friction had been reduced at middle value regime of surface fractality under certain conditions and make certainty for the fact that the macro- scale friction coefficient in a system can be lower than the coefficient of friction of an atomic- scale roughness surface of the same material.

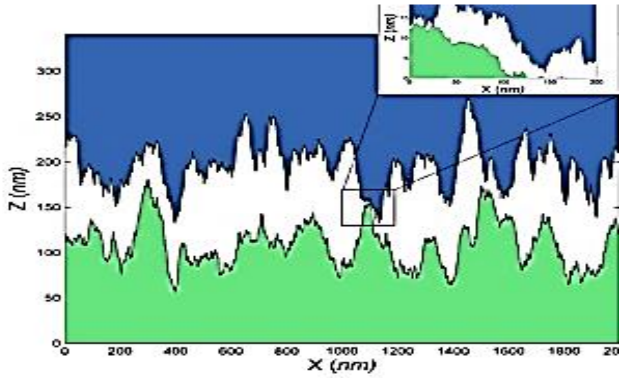


Figure5. Hierarchical structure of two fractal counter- surfaces [22]

Kshirsagar et. al [23] proposed a mathematical model dpending on Greenwood Williamson (GW) model for computing the actual coefficient of friction. An analytical and experimental evaluations was implemented upon vehicle's brake system and a MATLAB program had been put for simulating real interface between the counter- surfaces. Samples of the brake surface were analyzed for surface by means of AFM. Finally, for validation verification the analytical and experimental results were compared.

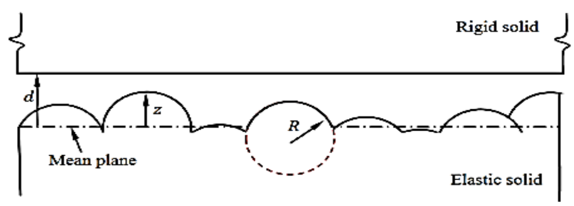


Figure6. GW model for counter rough surfaces, first surface is rigid, while the second consist of circular- arced asperities [23]

Almuramady et al. [24] had modeled the friction and adhesion between silicon-based micro gears operating in a vacuum environment. Roughness, which was evaluated using atomic force microscopy (AFM) techniques, is represented as a multi-block structure. The micro damage, porosity, and fracture surface effect of isotropic and anisotropic materials are study expensive in Kyle [25-26]. A multiscale hierarchical model of two distinct scales was employed: the adhesive van der Waals interactions subscale, and the atomic chemical interactions subscale. A computerized simulation had been done by using of the hierarchical model, the total energy lost had been computed, and as a result frictional force, coefficient of friction for the micro- silicone pair, simultaneous stresses, and true area of contact had been obtained numerically. Michałowski [27 discussed a simulation model for the contact between two micro- surfaces with separation between adhesion and mechanical portions of friction, the model which is based on the Tabor friction theory, the Lennard-Jones energy of contact, and the Winkler's layer model enables the prediction of friction forces. The Surface topographies, surface elasticity and free energy, Poisson's ratio, are inputs to the model. The results of simulations were verified with experimental literature. when applied to flat surfaces, the adhesive portion of friction is predominant and greater than mechanical portion by 40 times. Asperities of both surfaces were merged and reattached to one of the contacted surfaces with regarding the other completely flat and rigid surface. Validation was employed with AFM experimental reads on elastic surfaces. Vadgama [28] explained steps for modeling and simulating friction and wear at different scales. Firstly, researcher has to obtain roughness profile of contacted surfaces with Atomic Force Microscope (AFM). The complicated process known as sliding friction explains the transformation of kinetic energy into different forms like dissociation of chemical bonds, broking of Van der Waals bonds, elastic and plastic material deformation or ploughing...etc. and collecting these dissipated thermal energies from all sources is the next step. As a result, the friction values at the nanoscale are identical to those at the macroscale. Finally, the finding was that of friction coefficients estimated with the energy dissipation modeling and simulation method agrees its values in the macro scale. Friction's negative impacts maybe diminished by enhancing the tribological characteristics of the surface materials, coatings, or effective lubrication. Mu et al. [29] focused on a novel method for high-precision simulation and interface contact performances analysis of rough surfaces.Numerical simulations with hierarchical, multiscale, multilevel models were implemented assuming that friction is equivalent to total energy dissipated over the sampled distance. The physical and chemical interactions that is naturally combined to dry friction at different length scales are presented. Adhesion assumed to play a double effect: a normal to the surface force, which increases the actual area of contact, and tangential to the surface, which contribute dissipated energy and hence directly increasing friction. The obtained coefficient of friction was valid when had been verified experimentally. Due to their small size, MEMS devices are more susceptible to stiction and adhesion because of how clean and smooth their surfaces are and because surface forces are typically greater than body forces, resulting in a wider contact area. In order to determine which scales of roughness adhesion will become significant, Jackson [30]used stacked multi-scale sinusoidal surface profiles modeling. The finding was that adhesion can be reduced by increasing the sharpness or the ratio of amplitude to wavelength, and as a result, a parameter of critical pressure was obtained which can be connected to the original adhesion parameter derived by Tabor. Stiction in micro electro mechanical systems (MEMS) between micro gear silicon-based teeth are a problem at such devices especially in vacuum and clean environment, so, Borodich et.al [31] made a model of multi scale single level hierarchical structure. Tooth roughness produced by AFM was modeled at atomic and nano- scales. Friction force and coefficient of friction were estimated via a simulation with the total energy dissipation technique during dry sliding contact in a vacuumed environment. The numerical simulation showed that stiction between clean surfaces of counter- teeth rotating in a vacuumed environment is of a high probability, so, to avoid device failure, they suggested to functionalize teeth surfaces with eliminating material to prevent cold welding. Taylor [9] stated that the

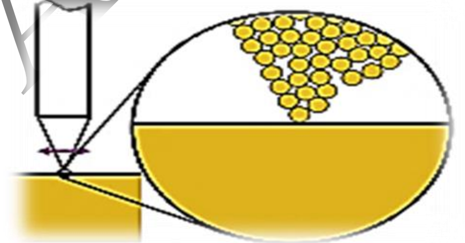


Figure7. AFM tip with single atom sliding on a flat surface [18]

trend recently is to adopt numerical simulations by obtaining roughness data of surfaces by means of profilometer or AFM, in order to predict and estimate friction amount and true contact area in rough surfaces quickly and roughly, a suggestion had been admitted to focus on numerical simulation and validation with experimental data; at the same time, engineers and iridologist had been couraged to still making use of the simple models derived from Amontons law. Zhu and Li [32] proposed a model for the static friction of dry contact between two rough surfaces at the micro/nano scales for estimating dry friction based on the dissipation of energy mechanism states that varying in the potential energy of the contacted surfaces due friction. It was assumed that the sphere asperities in contact meet the conditions of the interfacial friction. The results of the simulation showed that: in accordance with the earlier static friction models, the friction force in the current work growths when the external normal force is increasing in at a given plasticity index and it is decreasing with an increase in the plasticity index at a given external force. The results were extremely similar to the results of the Kogut and Etsion model.

Yuan et al. [33] reviewed the research advance of the friction procedure of metallic materials in the sight view of at different temperatures and magnetic field intensity. They analyzed and summarized the wear mechanism of ferrous and non-ferrous metals. They argued that study on the dry friction properties of metallic materials is mostly focused on the laboratory research's, while research's in industrial production need to be expanded by using various analysis software for simulating and predicting material changes, friction, and wear.

Zhai et al. [34] had reviewed the challenges, future aspects, achievements, and progress in the wear-resistant materials field from the point view of properties, designs, and applications and their roles in the wear reduction. The good design of surface coatings with adequate surface roughness helps to achieve anti-wear properties of surfaces at so high contact forces. Another finding is that the surfaces with hierarchical structures decrease wear to the degree of three orders lower than the unprocessed ones.

Kurdi et al [35] had made a simulation study based on machine learning and deep learning techniques put in focus effect of lubrication on the simulation to understand the phenomenon of wear across length scale from the nano- to macro, and then discussed the limitations of such simulation and gave applicable examples. Conclusions and directions for future work. The authors reviewed recent works in simulation practices for modelling tribo-contacts in the presence of modern computing power. simulation, which not only saves time and resources but also provides meaningful results. Within limitations they found were the uncertainty included in the model. A quantitative comparison with experimental results were done to verification the simulation validation.

Nosonovsky and Bushan [36] had reviewed and studied various mechanisms of solid–solid friction and their relation to the surface roughness hierarchy. They proposed Mapping for the dry friction mechanisms which is based on the typical length parameters. Also, it has discussed friction mechanisms in the hierarchical system and how it is lead to biological hierarchical surfaces with increased or reduced the adhesion and friction. basic mechanisms of friction mentioned are: adhesion between rough surfaces, scratching or plowing, plastic deformation, formation and dissociation of chemical bond, etc.

6. Studying dry friction in the micro/ nano scales with Atomic Force Microscopy (AFM)

Bhushan [37] made a review studies in micro/ nano friction that conducted using an atomic force microscopy and as a result a finding had been admitted \ that friction coefficients, wear and mechanical properties such as hardness are different on the micro and nano levels from that on the macrolevel, where friction coefficients and wear on micro and nano scales are smaller, whereas hardness is greater, though, regimes for ultra-low friction and near zero wear are possible with studies provide insight to atomic origins of adhesion, friction, wear, and lubrication mechanisms. Wear has been started at nano scratches. In the sliding interface is needing near zero friction and wear, contact stress must be below the hardness of the softer material to minimize plastic deformation and surfaces should be free of nano scratches. Weymouth et. al [18] used AFM to determine the energy dissipated by terminating the tip with one molecule and found that energy the energy dissipation occur at the tip was regarded as a CO molecule. A model had been made in which regard the as a CO torsional spring, and the argument was that studying friction with friction force microscopy (FFM) which is a special case of AFM in where the tip is compressed on the surface and the lateral force is estimated because friction is composed of small asperities in macro- scale components. Sharp FFM tip can make friction with one asperity, note the sketch in figure (7).

Wang et al.[38] proposed a theoretical applicable wear law for sliding materials for the nanoscale contact. For conventional macroscale contact, wear, which results in energy loss and device failures, is proportional to the normal load (FN) and sliding distance Wear, in this work, it had been proved that real contact area different dependence upon normal load is the reason behind the conflict in Archard low so that nanoscale wear results in some experiments obeying the Archard's law while does not in others, energy dissipation mechanism states that varying in the potential energy of the contacted surfaces due friction. It was assumed that spherical contact asperities meet the interfacial friction conditions. The results of the simulation showed that: in accordance with the earlier static friction models, the static friction force in the current work was increasing with the increasing in the external normal force at a given plasticity index and decreasing with the increasing in plasticity index at a given external force. The results were extremely close to the model produced by Kogut and Etsion.

Zhang et al. [39] summarized literature relating to surface contact and friction and show the advance in proper models used for studying them. They argued that statistical model developed by Greenwood and Williamson in 1966 (GW) is still the most commonly used, which estimates the proportional relationship between the area of contact and the normal load, but the unrealistic assumptions of this model have limited it. Fractal theory developed in 1970 had been applied to study contact characteristics of microscopic rough surfaces which is more precise that details of roughness can still be seen after several magnifications.

7. Conclusions

This review study highlights the significance of surface roughness and contact mechanics in understanding dry friction on rough surfaces. The advancements in computer-based models, simulation methods, and proximal probing techniques, such as AFM, have allowed for theoretical investigations of complex contact phenomena with high spatial and temporal resolution. With the growing miniaturization industry of micromachines, there is an expanded opportunity to explore friction phenomena at micro, nano, and atomic scales. Both experimental and theoretical studies have made essential contributions to unraveling the complexities of friction phenomena. Overall, this review emphasizes the increasing importance of theoretical simulations in recent times and the valuable insights gained from a comprehensive analysis of literature focused on dry friction at micro- and nano-scales.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] R. Mufti, A. Putra, S. Pandu, R. Pratama, and R. Prabowo, "Failure of Friction Brake Components against Rapid Braking Process: A Review on Potential Challenges and Developments," Transportation Research Procedia, vol. 55, pp. 653-660, 2021. [Online]. Available: https://doi.org/10.1016/J.TRPRO.2021.07.096

[2] A. Devaraju, "A review on important factors affecting dry sliding friction," Journal of Surface Science and Technology, vol. 32, pp. 73-78, 2016. [Online]. Available:

[3] J. Luo, "Investigation on the origin of friction and superlubricity," Chinese Science Bulletin, vol. 65, no. 27, pp. 2966-2978, 2020. [Online]. Available: https://doi.org/10.1360/TB-2020-0505

[4] S. Antoine, G. Nöhring, L. A. Thimons, T. D. Jacobs, and L. Pastewka, "Scale-dependent roughness parameters for topography analysis," APS Advances, vol. 7, p. 100190, 2022. [Online]. Available: https://doi.org/10.1016/J.APSADV.2021.100190

[5] R. M. Patrikar, "Modeling and simulation of surface roughness," Applied Surface Science, vol. 228, no. 1-4, pp. 213-220, 2004. [Online]. Available:

[6] P. Pawlus, R. Reizer, M. Wieczorowski, and G. Krolczyk, "Material ratio curve as information on the state of surface topography—A review," Precision Engineering, vol. 65, pp. 240-258, 2020. [Online]. Available: https://doi.org/10.1016/j.precisioneng.2020.05.008

[7] G. S. Adams and M. Nosonovsky, "Contact Modeling — Forces," Tribology International, vol. 33, no. 5-6, pp. 431-442, 2000. [Online]. Available: https://doi.org/10.1016/s0301-679x(00)00063-3

[8] L. A. Thimons, A. Gujrati, S. Antoine, L. Pastewka, T. D. Jacobs, and D. B. Tevis, "Hard-material Adhesion: Which Scales of Roughness Matter?," Experimental Mechanics, vol. 61, no. 7, pp. 1-12, 2021. [Online]. Available: https://doi.org/10.1007/S11340-021-00733-6

[9] R. I. Taylor, "Rough Surface Contact Modelling—A Review," Lubricants, vol. 10, no. 5, 2022. [Online]. Available: https://doi.org/10.3390/lubricants10050098

[10] P. L. Menezes, M. Nosonovsky, S. P. Ingole, S. V. Kailas, and M. R. Lovell (Eds.), "Tribology for Scientists and Engineers," 2013. [Online]. Available: https://doi.org/10.1007/978-1-4614-1945-7

[11] Berger, E. J.. Friction modeling for dynamic system simulation. Applied Mechanics Reviews, (2002, November),. https://doi.org/10.1115/1.1501080

[12] H. Syam, M. Nosonovsky, and M. Nosonovsky, "Topological data analysis for friction modeling," EPL, vol. 135, no. 5, p. 56001, 2021. [Online]. Available: https://doi.org/10.1209/0295-5075/AC2655

[13] N. A. B. S. Muna and K. Abbassa, "Optimization of Friction Stir Processing Parameters for Aluminum Alloy (AA6061-T6) Using Taguchi Method," AL-QADISIYAH J. Eng. Sci., vol. 12, pp. 001–006, 2019. [Online]. Available:

https://doi.org/10.1016/j.matpr.2017.02.044

[14] A. Alobaidi and N. Almuramady, "Influence of heat aging on tensile test in rubber-epoxy composites," Al-Qadisiyah Journal for Engineering Sciences, vol. 15, no. 2, pp. 131-134, 2022. [Online]. Available: https://doi.org/10.30772/qjes.v15i2.824

[15] A. A. Oudah and M. A. Hassan, "Semisolid state sintering behavior of aluminum-stainless steel 316L-nickel composite materials in powder metallurgy," AL-QADISIYAH J. Eng. Sci., vol. 15, no. 9, pp. 202-209, 2022. [Online]. Available: https://doi.org/10.3390/ma12091473

[16] H. M. Alwan, "Effect of Friction Forces in Robotic Mechanism Joints on the Dynamic Analysis," Al-Qadisiyah Journal for Engineering Sciences, vol. 7, no. 4, pp. 331-342, 2017. [Online]. Available: https://qu.edu.iq/journaleng/index.php/JQES/article/view/366

[17] B. Zhang, R. Namakian, X. Zhang, W. J. Meng, J. Hay, and K. Johanns, "A novel approach for microscale dry contact stiction and friction assessment: Experimentation and analysis," Materials & Design, vol. 212, p. 110207, 2021. [Online]. Available: https://doi.org/10.1016/J.MATDES.2021.110207

[18] A. J. Weymouth, O. Gretz, E. Riegel, and F. J. Giessibl, "Measuring sliding friction at the atomic scale," Jpn. J. Appl. Phys., vol. 61, no. SL, 2022. [Online]. Available: https://doi.org/10.35848/1347-4065/ac5e4a

[19] S. C. S. Sandeep, S. Li, and K. Senetakis, "Scale and Surface Morphology Effects on the Micromechanical Contact Behavior of Granular Materials," Tribology International, vol. 159, p. 106929, 2021. [Online]. Available: https://doi.org/10.1016/j.triboint.2021.106929

[20] M. Afshar-Mohajer, X. Yang, M. Zou, "Understanding the friction and deformation behavior of micro/nano-hierarchical textures through in-situ SEM observation and mechanics modeling," Tribology International, vol. 165, 2022. [Online]. Available: https://doi.org/10.1016/j.triboint.2021.107271

[21] B. N. Vadgama, R. L. Jackson, and D. K. Harris, "Molecular scale analysis of dry sliding copper asperities," Appl. Nanosci., vol. 5, no. 4, pp. 469-480, 2015. [Online]. Available: https://doi.org/10.1007/s13204-014-0339-9

[22] D. A. H. Hanaor, Y. Gan, and I. Einav, "Static friction at fractal interfaces," Tribology International, vol. 93, pp. 229-238, 2016. [Online]. Available: https://doi.org/10.1016/j.triboint.2015.09.016

[23] M. P. Kshirsagar and H. Khairnar, "Investigation of Coefficient of Friction at The Interface of Automobile Brake Pads Using Greenwood-Williamson Contact Model and Novel Test Rig," FME Transactions, vol. 50, pp. 561-575, 2022. [Online]. Available: https://doi.org/10.5937/fme2203561K

[24] N. Almuramady and F. M. Borodich, "Adhesive Contact Between Silicon-Based MEMs Tooth Surfaces Modelled by The Multiscale Multi-Block Model," International Journal Of Advances On Automotive And Technology, 2017. [Online]. Available: https://doi.org/10.15659/ijaat.17.04.523

[25] Messer, K., Fahem, A., T. Guthai, A., P. Singh, R. (2022). 'The experimental methods and elastic properties of shale bedding planes materials state-of-the-art review', Al-Qadisiyah Journal for Engineering Sciences, 15(2), pp. 126-130. https://doi.org/10.30772/qjes.v15i2.823

[26] Fahem, A.F., Thumbalam Guthai, A. & Singh, R.P. Full-Field Strain Measurement Integrated with Two Dimension Regression Analysis to Evaluate the Bi-Modulus Elastic Properties of Isotropic and Transversely Isotropic Materials. Exp Mech 64, 53–71 (2024). https://doi.org/10.1007/s11340-023-01007-z

[27] M. Michałowski, "Simulation Model for Frictional Contact of Two Elastic Surfaces in micro/nanoscale and Its Validation," Nanotechnology Reviews, vol. 7, no. 5, pp. 355-363, 2018. [Online]. Available: https://doi.org/10.1515/ntrev-2018-0075

[28] B. N. Vadgama, "Molecular Dynamics Simulations of Dry Sliding Asperities to Study Friction and Frictional Energy Dissipation," [Online]. Available: https://doi.org/10.1016/j.biochi.2015.03.025

[29] X. Mu, W. Sun, C. Liu, Y. Wang, B. Yuan, and Q. Sun, "Study on rough surfaces: A novel method for high-precision simulation and interface contact performances analysis," Precision Engineering - Journal of The International Societies for Precision Engineering and Nanotechnology, vol. 73, pp. 11-22, 2022. [Online]. Available: https://doi.org/10.1016/J.PRECISIONENG.2021.08.017

[30] R. L. Jackson, "A model for the adhesion of multiscale rough surfaces in MEMS," in Proceedings of the Annual Southeastern Symposium on System Theory, 2011, pp. 257-262. [Online]. Available: https://doi.org/10.1109/SSST.2011.5753817

[31] F. M. Borodich, A. Pepelyshev, and O. Savencu, "Statistical Approaches to Description of Rough Engineering Surfaces at Nano and Microscales," Tribology International, vol. 103, pp. 197-207, 2016. [Online]. Available: https://doi.org/10.1016/j.triboint.2016.06.043

[32] S. Zhu and L. Ni, "A Static Friction Model for Unlubricated Contact of Random Rough Surfaces at Micro/Nano Scale," Micromachines, vol. 12, no. 4, pp. 368-368, 2021. [Online]. Available: https://doi.org/10.3390/mi12040368

[33] S. Yuan et al., "Research Status of Dry Friction Behavior of Metallic Materials: A Brief Review," Surface Review and Letters, vol. 27, no. 12, pp. 2030003-2030003, 2020. [Online]. Available: https://doi.org/10.1142/s0218625x20300038

[34] W. Zhai et al., "Recent Progress on Wear-Resistant Materials: Designs, Properties, and Applications," Advanced Science, vol. 8, no. 11, p. 2003739, 2021. [Online]. Available: https://doi.org/10.1002/advs.202003739

[35] A. Kurdi, N. Alhazmi, H. Alhazmi, and T. Tabbakh, "Practice of Simulation and Life Cycle Assessment in Tribology—A Review," Materials, vol. 13, no. 16, p. 3489, 2020. [Online]. Available: https://doi.org/10.3390/ma13163489

[36] M. Nosonovsky and B. Bhushan, "Multiscale Friction Mechanisms and Hierarchical Surfaces in Nano- and Bio-Tribology," Materials Science and Engineering: R: Reports, vol. 58, no. 3, pp. 162-193, 2007. [Online]. Available: https://doi.org/10.1016/j.mser.2007.09.001

[37] B. Bhushan, Nanotribology and Nanomechanics: An Introduction. Springer Berlin Heidelberg, 2005, pp. 1-1148. [Online]. Available: https://doi.org/10.1007/3-540-28248-3

[38] Y. Wang et al., "Non-Empirical Law for Nanoscale Atom-by-Atom Wear," Advanced Science, vol. 8, no. 2, p. 2002827, 2020. [Online]. Available: https://doi.org/10.1002/advs.202002827

[39] S. Zhang, D. Li, and Y. Liu, "Friction Behavior of Rough Surfaces on the Basis of Contact Mechanics: A Review and Prospects," Micromachines, vol. 13, no. 11, p. 1907, 2022. [Online]. Available: https://doi.org/10.3390/mi13111907