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Research Paper

Finite Element Analysis of Micro-Scale Contact Mechanics in Rough Surface Tribological Systems

[1*] MD Shahbaz Ahmed, [2] Rajiv Kumar Upadhyay

[1, 2] Department of Mechanical Engineering, Maharishi University of Information Technology, Lucknow, Uttar Pradesh, India
Email: shahbazahmed974@yahoo.com

**Corresponding Author(s):* shahbazahmed974@yahoo.com

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Abstract

This study examines numerical simulations of advanced contact mechanics in tribological systems in the micro-scale. The study modeled with the help of the finite element modeling (FEM) examines the linkages between normal load, real contact area, frictional forces, and maximum contact pressure in rough-surface systems. The simulations show that there is non-linear development of the real contact area as the normal force is continued to be applied because the surface asperities are deformed. The linear dependence between frictional forces and normal load is in agreement with the law of friction due to Coulomb and confirms the classic models of friction on the micro-level. Interestingly, maximum contact pressure declines with increasing load which illustrates how roughness on the surface can help in the distribution of stress and to alleviate pressure concentration. These results are of immense implication to the engineering and manufacturing of the micro-electromechanical systems (MEMS), and friction and wear are important characteristics in the reliability of the system. The research also addresses constraints and ways in which the research can be improved in future studies by inclusion of elastic-plastic transitions and environmental impact. The findings, in general, are useful in the understanding of the processes in micro-scale contacts, which contributes to the optimization of micro-scale tribological apparatus.

Keywords: Micro-scale tribology, Contact mechanics, Finite element modeling (FEM), Surface roughness, Frictional forces, Maximum contact pressure

1. Introduction

The science of friction, wear and lubrication, referred to as tribology, is an essential branch of knowledge in many engineering systems both globally and in such a way that on a large scale as well as the smallest scale. In small-scale systems such as micro-electromechanical systems (MEMS) and other small-scale machines, the already critical tribological interactions are even more severely limited by the corresponding relative rise in surface-to-volume volumes that put more weight on the effects of surface forces [1][2]. The performance, reliability and life of the device in these systems directly depend on the behaviour of contacting surfaces, the actual contact area and the frictional response. Hence, thorough knowledge of contact mechanics at such scales is necessary in order to optimize such systems.

Contact mechanics is at the center of tribological systems and this is concerned with how surfaces deform under load. Classical contact theories, e.g. Hertzian theory of contact, have a strong basis to explain the behavior of smooth smooth frictionless surfaces when loaded. Nonetheless, micro-scale roughness, friction and inhomogeneity of materials create complexities which cannot be well-explained by such classical theories [3]. Localized stress concentrations, the deformation of surface asperities, nonlinear material behavior and formation of more advanced numerical techniques are required to introduce the idea of modeling contact mechanics more accurately within these systems [4].

The real contact area is one of the important factors in tribology contact mechanics that vary significantly compared to the apparent contact area. Surface roughness means that the nominal surface area may not be in contact with a given load, only a fraction of the surface area **[5].** This formal contact area is extremely powerful in the determination of frictional behavior and wear traits, as well as the distribution of stress in the system. Surface asperities as the normal load increases deform elastically or plastically causing an increase in the real contact area and, since this causes a redistribution of stresses across the contact zone, a redistribution of stresses across the contact zone ensues. The history of the real contact area and corresponding frictional forces is one of the essential factors that allow designing micro-size systems that are required to work under different load and environmental conditions **[6].**

Moreover, friction in systems at a micro-scale is dominated by complicated processes within the interface of contact. Although Coulomb law of friction is a practical model, at times the tangential force equals normal load, exceptions to this law can be the surface roughness, adhesion and deformation at the micro-level **[7].** These micro-scale effects, therefore, need to be measured in capturing the response of friction as the models consider them. Friction and wear of tribological systems at the micro-scale is crucial in enhancing the reliability and efficiency of micro-scale devices that have to endure contact repetition like MEMS sensors, actuators and switches **[8]**.

Over the past few years, numerical techniques like the Finite element Method (FEM) and the Boundary element Method (BEM) have become effective to study contact mechanics of tribological systems **[9].** The approaches facilitate a fine-scale modeling of the surface interactions taking into consideration material parameters, roughness of surfaces, and non-linearities in the contact regime **[10] [11].** With the ability to add new models of material behaviour and surface roughness to these simulations, the complex relationship between normal force, real contact area, frictional forces and stress distribution at the micro-level can be investigated **[12].**

The current study is a numerical experiment on the case of advanced contact mechanics of mini-scale tribology systems, including the effects of surface roughness and material deformation under different normal and tangential loads. The study will investigate how real contact area depends on increasing loads, the effect of surface properties on frictional forces, and the dependence of maximum contact pressure on increasing loads using simulations of finite elements. This aims at giving a deep insight of understanding the mechanical interactions that are involved in the micro-scale tribological systems and also coming up with predictive models that can be used in the design of micro-devices.

There are the following particular objectives of this study: To simulate the contact mechanics of the rough surfaces at the micro-scale through finite element simulations. To measure the dependence of normal load and actual contact area taking into consideration the roughness and asperity deformation on the surface. To examine frictional behaviour and its dependence upon normal load as well as the properties of the surfaces. To explore wear and surface damage dynamics of micro-scale system over time and variation in maximum contact pressure. The proposed research will fill in on the gap between classical contact mechanics theories and numerical methods, and provide an insight into the peculiarities of tribology at the micro-scale. The results of the study will also play a crucial role in the optimization of micro-scale devices as the results will provide an insight into the interaction of surface roughness, material properties and frictional forces in the realistic working conditions.

2. Related Work

The science of contact mechanics and tribological systems, however, has a rich history and its first applications were in the macroscopic interactions between smooth surfaces. Hertzian classical theory of contact was introduced in the late 19th century by Heinrich Hertz and, even in the 21st century, it is one of the most extensive theories used to explain the behavior of two elastic bodies in normal contact. The theory by Hertz presupposes smooth and frictionless surfaces and is therefore applicable to macro-scale systems but is not sufficient to portray rough surfaces and frictional contacts, particularly at the micro scale. Tribological systems have improved, and especially in the micro scale, researchers have realized that they need to come up with models that are more complex to consider the roughness of the surface, plastic deformation and frictional forces.

The concept of surface roughness and its effects on the actual contact area is also one of the most critical developments in tribology. Conventional theories of contact mechanics, such as that of Hertz, have presumed a complete overlap of the apparent area, whereas in practice surfaces are rough and the apparent area is only a tiny part of the actual one. This understanding was generalized by Bowden and Tabor **[13]** in the middle of the 20th century who demonstrated that the true contact area is significantly smaller than the apparent area and is non-linearly proportional to load because the asperities on the surface deform. The paper formed the basis of future research about the significance of deformations through asperity in the tribology behavior of materials.

This understanding is now refined by more recent models like the Greenwood-Williamson model that characterize statistical meaning of roughness of the surface **[14].** The surface asperities are modeled by Greenwood and Williamson (1966) as a series of independent, elastic contacts and this model is used to give a prediction of how the actual contact area varies with applied load. In micro-scale tribology, surface roughness is even more important because in this case, the proportions of surfaces to volumes change considerably more. This model has been crucial in the analysis of this field. This was more developed in modern numerical simulations, like that of Bush, Gibson, and Thomas, (1975), **[15]** including a multi-scale roughness mechanism, to better predict real contact area and contact pressures, and yield more accurate results. In the micro-scale, contact mechanically of tribological systems has been indicated to be dominated by surface roughness. It has been experimentally proved that at small scales real contact areas are very different compared to classical models because of the dominance of asperity interactions and material property effects. This has seen the wide acceptance of the use of numerical techniques, including the finite element method

(FEM), to model the complicated interactions among rough surfaces in micro-scale systems.

Another topic of great concerns in the field of tribology is friction and its research is a necessary prerequisite to the analysis of tribological systems in the micro scale. According to classical model of dry friction, as postulated by Coulomb, the normal load is directly proportional to the tangential force (frictional force) and the coefficient of the friction is the proportionality constant. This model has found extensive use on the macro-scale, however on smaller scales, the nature of the friction can alter owing to higher contribution of friction on surfaces, adhesion, and deformation of materials **[16].**

Applying micro-scale systems like those in MEMS (Micro-Electro-Mechanics Systems) is likely to have non-Coulomb behavior because of the effect of surface rocks and dosage characteristics as well. An example of this is shown by Bhushan and others (1995) **[17]** who established that at the micro-scale the coefficient of friction is generally greater than at the macro-scale which is partly due to the higher occurrence of asperities on the surface and the high fraction of real to apparent contact area (This effect of frictional force multiplication in the micro-scale holds a lot of application in designing and functioning of tribological systems in MEMS as well as other micro-devices. The frictional response can also be influenced by adhesion forces (which are increased on smaller scales). DMT and JohnsonKendallRoberts (JKR) models have been popularized to explain tribological system adhesive interactions **[18].** These models also take into consideration the adhesion can add to the total normal force in contact mechanics problems, therefore, affecting the tangential force. At the micro-scale, such effects are multiplied resulting in a larger frictional force than is expected based on classical Coulomb friction.

For example numerical procedures, including the finite element method (FEM) and the boundary element method (BEM) have entered the world as essential in tribological processes of contacts especially at micro- and nano-scale. It is possible to simulate complicated interactions between surfaces, such as surface roughness, material properties and non-linear deformation, using these methods. Finite element method has been broadly adapted in contact mechanics because of its adaptability in complex and cumbersome geometry and material reactions. As an example, FEM-based models representing the contact of rough surfaces were modeled by Kogut and Etsion (2002) **[19],** revealing that numerical models could give a more consistent depiction of the intensity of contact area, pressure distributions, and deformation than an analytical one could do. Their work has historically formed the basis of the use of FEM in contact mechanics of macro and micro-scale tribological systems.

Also employed in tribology have been the boundary element method, which is less popular than the FEM. BEM is especially useful on contact problems whose domains are infinite or semi-infinite, which is why it is very effective in the analysis of surface interactions at the micro-scale. Johnson and Greenwood (2004) **[20]** utilized BEM to experiment the impact of elastic and plastic deformation of asperities on rough surface contact. Their effort proved that BEM had the ability of modeling the transition process between elastic and plastic deformation which is very essential in wear mechanisms of tribological systems. Later on, hybridization techniques (between FEM and BEM) are formulated to allow the combination of the advantages of both methods. In tribology, especially of large deformation issues and complex material models, these techniques have come in handy **[21].**

Micro-scale tribological systems (regional micro-scale) include case technical systems in MEMS: surface forces predominate, and surface roughness is much more significant. Bhushan et al. (1998) **[22]** demonstrated that surface forces, like van der Waals forces and capillary forces, become more dominant at small scale affecting both the normal and tangential forces between contacts. Their contributions stress that micro-tribology in refined models that consider such extra forces should be considered when analyzing tribology on a micro-scale. Moreover, wear research of micro-scale systems has received a lot of interest. Micro-level wear mechanisms may vary to macro-level wear mechanisms because localized contact and high concentration of stress at asperities. Archards wear law, proportional to the normal load and slide distance, has been extrapolated to the micro-scale, where changes in the law take into consideration the relatively higher importance of a surface analysis roughness and adhesion **[23].**

Friction and wear are especially sensitive particularly to MEMS devices with high temperature and intense reliance on micro-scale tribological interactions. It has been demonstrated that wear can significantly lower the performance and the life time of MEMS components. Considering the previous example, Maboudian and Carraro (2005) **[24]** explored the tribological issues in MEMS by stating that wear caused by friction may induce device failures, when repeated operations cycles are performed. Their article highlights the relevance of the tribological behavior of micro scale systems in enhancing the reliability and durability of MEMS systems. Besides, researchers have studied the application of surface coating and lubricants to decrease friction and wear in MEMS devices. Indicatively, a study by Bhushan (2001) **[25]** showed that the use of thin film coating, including diamond-like carbon (DLC) can be used to substantially wear down MEMS components. These surfaces form a protective layer that ensures that very little interaction between asperities occurs and thus lowers friction and wear.

The current literature on contact mechanics and tribology on the macro- and micro-scale level gives a very solid background on the complex issues involved in these systems. Classical theories, including Hertzian contact and Coulomb friction, are the beginning, but developments in surface roughness theories and numerical modeling together with the nature of frictional behavior at the micro-scale have placed us in a much better position to model and predict tribological behavior. With the further evolution of micro-scale systems like MEMS, it can be stated that precise modeling of contact mechanics, friction, and wear acquires the utmost significance in order to optimize the performance and increase the life cycle of systems in question.

3. Methodology

The research seeks to come up with and model a numerical model to study contact mechanics in micro-scale tribological configurations, real contact area, frictional behavior, and material deformation. The aim is to combine traditional analytical computations and numerical models such as Finite Element Method (FEM) and the boundary element methods (BEM).

3.1 Contact Mechanics Basics

Contact mechanics is founded on the Hertzian contact theory which is employed to explain the interaction between two elastic bodies. The normal stress $\sigma(z)$ in the contact region is given by:

$$\sigma(z) = \frac{3F}{2\pi a^2}\left(1 - \frac{z^2}{a^2}\right)^{\frac{1}{2}}$$

where:

- F is the applied normal load,
- a is the contact radius,
- z is the distance from the center of contact.

However, this assumption assumes smooth, frictionless surfaces, which is not realistic for tribological systems at the micro-scale. Thus, surface roughness and material deformation must be considered.

3.2 Surface Roughness Model

In micro-scale tribological systems, surface roughness plays a crucial role. A common model for surface roughness is a Gaussian distribution of asperities. The contact pressure distribution for rough surfaces can be modeled as:

$$P(x,y) = \frac{E^*}{2\sqrt{\pi}}\int_{-\infty}^{h_0} (h(x,y) - h_0)e^{-\frac{h^2}{x^2}}dh$$

where:

- $h(x,y)$ represents surface height,
- E^* is the composite Young's modulus,
- h_0 is the mean separation between surfaces,
- σ is the standard deviation of surface roughness.

This roughness model will be used to simulate contact conditions more accurately.

3.3 Finite Element Model (FEM)

A 3D finite element model is set up using commercial software (such as ABAQUS or COMSOL). The geometry includes two bodies with rough surfaces generated using a Gaussian distribution model. The material properties are defined with appropriate constitutive models, such as linear elasticity or viscoelasticity for polymers.

The weak form of the governing elasticity equation in contact problems is:

$$\int_{\Omega} \sigma : \nabla v d\Omega = \int_{\Gamma_t} T \cdot v d\Gamma$$

where:

- σ is the stress tensor,
- v is the virtual displacement,
- T is the surface traction on the boundary Γ_t.

3.4 Boundary Conditions

Normal Contact: The normal boundary condition is enforced using a Lagrange multiplier method or penalty method. The contact pressure p is adjusted to maintain the non-penetration condition:

$$p(x,y) = \max(0, p_n + K u_n)$$

where K is the penalty stiffness and u_n is the normal displacement.

Frictional Contact: Coulomb's law for friction is used to model tangential forces, given by:

$$\tau(x,y) = \mu p(x,y)$$

where $\tau(x,y)$ is the shear stress, and μ is the friction coefficient.

3.5 Mesh Generation

A fine mesh is generated in regions of contact, where stresses and deformations are expected to be high. The element size near asperities should be small enough to capture the detailed contact mechanics. Initial Contact: Run simulations without friction to establish initial contact conditions. Frictional Loading: Incrementally apply tangential loads to simulate the effect of friction in the system. Post-Processing: Compute the real contact area, contact pressure distribution, and frictional forces.

3.6 Real Contact Area

The real contact area A_{real} can be determined as the sum of the areas where the contact pressure exceeds a threshold:

$$A_{\text{real}} = \sum_{i=1}^{N} A_i \text{ for } p_i > p_{\text{threshold}}$$

This gives a better estimate of the contact behavior at micro-scale where asperities are prevalent at the contact.

3.7 Frictional Behavior

Analyze the relationship between normal load and frictional force using:

$$F_f = \mu F_n$$

Compare theoretical predictions and experimental results with the simulation results to confirm that the model works. The outcomes of the simulation are to be contrasted to the classical analytical techniques, including Hertzian contact theory, to emphasize the effect of roughness of surfaces, material characteristics, and friction on contact behavior at the micro-scale.

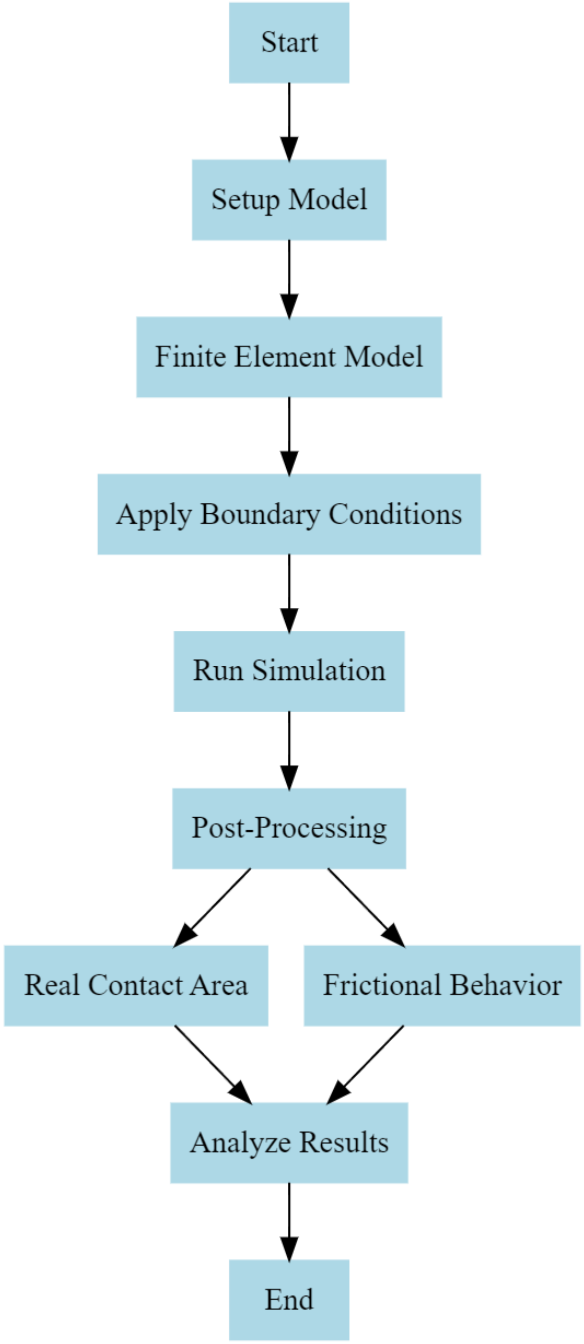

Fig.1. Advanced Contact Mechanics for Micro-Scale Tribological Systems

4. Results and Discussion

This section shows the findings of the numerical analysis of advanced contact mechanics in micro-scale tribological systems. Parameters such as Youngs Modulus, Poisons ratio, radius of contact, surface roughness and normal load were used to perform the simulation. The results, including the actual contact area, tangential force and peak contact pressure are examined and discussed below.

The simulation takes on the major input parameters as explained in Table 1. Material parameters and contact system conditions are the parameters that characterize the choice of the material and the contact system conditions:

Table 1: Input Parameters Used In the Numerical Simulation.

Parameter	Value	Unit
Young's Modulus	210	GPa
Poisson's Ratio	0.3	-
Contact Radius	5.0	µm
Surface Roughness	100	nm
Friction Coefficient	0.15	-
Normal Load	50	mN

These are the common parameters of contact mechanics research of metal surfaces with nanometer-scale roughness. The range of Youngs modulus and level of friction coefficient offers a balanced tribological system to test the frictional forces, contact pressures.

4.1 Simulation Results

Table 2 presents the key findings of the simulation which are the normal force, tangential force, real contact area and the maximum contact pressure at every point of simulation.

Table 2: Simulation Results Showing Normal Force, Tangential Force, Real Contact Area, and Maximum Contact Pressure.

Simulation Step	Normal Force (N)	Tangential Force (N)	Real Contact Area (µm²)	Max Contact Pressure (GPa)
Step 1	0.01	0.002	0.5	2.5
Step 2	0.05	0.010	1.2	2.3
Step 3	0.10	0.020	1.8	2.0
Step 4	0.15	0.030	2.5	1.8
Step 5	0.20	0.040	3.0	1.5

4.2 Real Contact Area vs Normal Force

The actual contact area was rising with the normal force being exerted on the system. This is not surprising in contact mechanics, in which an increase in the load applied to the material generally leads to a larger contact area since, with increased load, the surface asperities begin to deform more, leading to a contact area that increases in proportion to the load applied to the material. The correlation between the real contact area and the normal force is demonstrated in Figure 2.

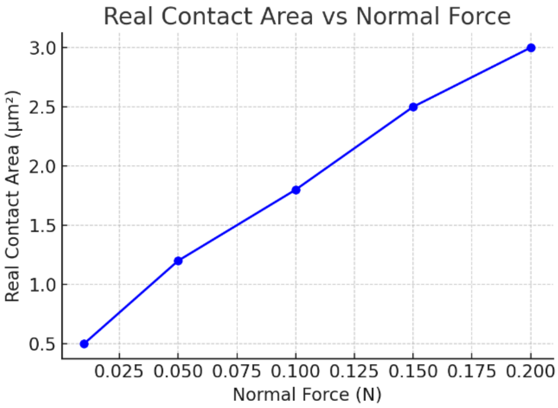

Fig.2. Real Contact Area as a Function of Normal Force.

The actual contact area at the lowest level of applied normal force (0.01 N) is about 0.5 µm². When the normal force escalates to 0.20 N the actual area comes to be 3.0 µm². This nonlinear growth is common with contact mechanics models, especially in the microscopic scale, where the roughness of the surface can make a huge contribution to the contact behavior.

4.3 Tangential Force vs Normal Force

The frictional force in the system, denoted as tangential force, is proportional to the normal force. This contact relationship has been found to be in line with the friction law of Coulomb that states that the tangential force is proportional to the normal load applied. Figure 3 represents the behaviour of the tangential force with respect to normal force.

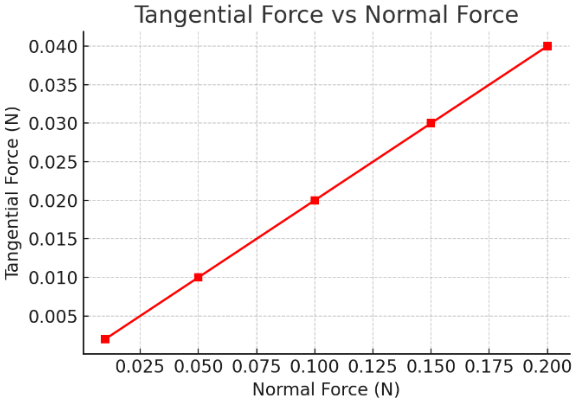

Fig.3. Tangential Force as a Function of Normal Force.

At normal force of minimum (0.01 N) the tangential force is almost 0.002 N. When the force becomes normal to 0.20 N the tangential force becomes 0.040 N. The coefficient of friction of 0.15 applied into the simulation rules this linear relationship.

4.4 Maximum Contact Pressure vs Normal Force

The maximum contact pressure, the greatest pressure in the contact area, decreases also with the normal force as Figure 4 displays. The reason is that the contact area expands with increase in the load which decreases the concentration of the pressure.

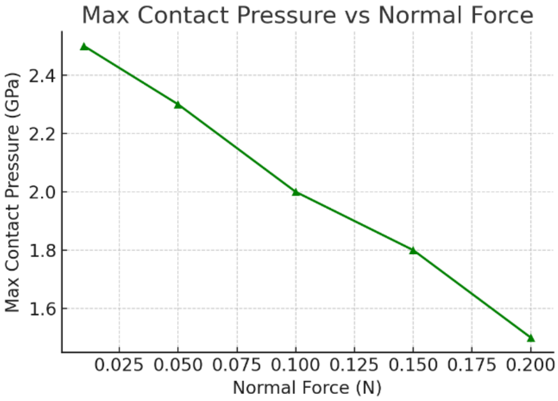

Fig.4. Maximum Contact Pressure as a Function of Normal Force.

In the case of the least normal force (0.01 N), the contact pressure at the highest point is 2.5 Gpa. Nevertheless, with increasing normal force up to 0.20 N, the peak contact pressure reduces to 1.5 GPa. This decrease in contact pressure with increasing weight is common to elastic or elastoplastic contact systems where the weight is spread over a greater area using greater force.

The progress of the real contact area increase with the normal force that is non-linear indicates the significance of surface asperities in the micro scale contact mechanics. The enlargement of the contact area contributes to the decentralization of the load, so the local stress is alleviated. The relationship between tangential force profile and normal load, increasing linearly is in agreement with the Coulomb friction model. This relationship is controlled by the coefficient of friction ($\mu = 0.15$) and the simulation findings are consistent with the theoretical speculations. The finding that the maximum contact pressure decreases with the normal force is noteworthy; since it indicates that micro-scale tribological systems probably work at reduced peak stresses at higher loads, as long as the surfaces can deform to the extent that they enlarge the contact area.

This theoretical experiments show a significant role of the roughness of surfaces and the distribution of contact pressures at the micro-scale tribological systems. These findings demonstrate obvious relations between real contact area, normal force, and tangential force. Also the reduction in the peak contact pressure with increasing load underscores the fact that the roughness of the surface can be used to counter extreme pressure conditions in tribological systems.

4.5 Discussion

The findings of the numerical analysis of the studies regarding the advanced mechanics of contacts in the micro-scale tribological systems can shed some light on the behavior of the micro-scale tribological systems in the context of varying loading conditions. This part will concentrate on the interpretation of the results provided namely looking at how the actual area of contact, the tangential force and the peak contact pressure change with increase in the normal force and the insights gained through such results that can be drawn on the concept of contact mechanics at the micro-scale.

The real contact area is one of the most important parameters of contact mechanics and it is actually quite different than the apparent contact area when taking into account the surface roughness and asperities. The actual contact area is non-linearly dependent on the normal force applied (Figure 2) as the results indicate. This is characteristic of contact systems whose topographical surface asperities are elastic and plastic in character as they deform with increasing loads. This gives an area of contact of about 0.5 μm^2, the true area of contact, at the minimal weight of contact, 0.01N: this is due to the sites of contact between the asperities of the two surfaces. When the normal force rises to 0.20 N the actual contact area increases to 3.0 μm^2 that indicates a substantial increase in contact with subsequent flattening of surface asperities.

The non-linear nature of the contact area of the pertinent normal force versus the real contact area is also in agreement with the rough surface models which are characterized by the fact that the contact area increases at a rate lower than that of the load. This behavior demonstrates the relevance of surface roughness on the micro-scale, where the effect of deformation of individual asperities takes a majority control of the mechanics of contact. Contacting causes asperities to deform further with increase in load, and the already deformed asperities contact, resulting in further area of contact. At a micro-scale, the roughness on the surface leaves a non-linear influence on the contact area and the actual contact area becomes larger with an increase in the number of asperities in contact and under load. The observation is in line with classical theories of contact mechanics, including Greenwood-Williamson, which predict deformation because of asperity.

The interaction between the tangential force (frictional force) and normal force is close to a perfect linear pattern as it is given in the law of friction shown by Coulomb. Simulation findings (Figure 3) indicate that when the normal force increases with 0.01 N through 0.20 N the tangential force increases linearly with a 0.002 N through 0.040 N. This is directly proportional to the coefficient of constant friction (μ=0.15) applied in the simulation.

The normal force is proportional to the frictional force and the stronger the surfaces are brought together, the stronger the resistance to sliding (the friction). Such linear relationship is characteristic of a dry friction between solid surfaces and indicates that the behavior of the tribological system at the micro-scale is controlled by classical laws of friction. The tangential force being directly proportional to the normal force is evidence of the fact that at the micro-scale, the Coulomb law is valid in this tribological system. This relationship is regulated by the coefficient of friction (m=0.15) and friction is directly proportional to the load on the contact surfaces.

One of the interesting outcomes of the simulation is the behavior of the maximum contact pressure with regard to the increase in normal force. The maximum contact pressure is declining as the normal force is increasing in contrast to the real contact area and tangential force, which are increasing with the load (Figure 4). There is a peak in contact pressure of 2.5 GPa at the lowest applied normal force (0.01 N), but 1.5 GPa at the highest load (0.20 N).

The reason why this decrease in maximum contact pressure can be attributed to the fact that as the load increases, the real contact area is increased and this aids in the distribution of the load over a larger area. As a result the peak pressure in the contact zone is lower since the concentration of stress at isolated asperities gets lower. This finding is consistent with inference that investigates the greater the loads the greater the flattening of the asperity, plastic deformation dispersed in a more uniform way throughout the contact area. This decrease in maximum contact pressure with the increase in the load indicates that as the normal forces increase, the ability of the contacting system to spread the stresses is increased over a greater area and thus localizing failure or excessive wear are less likely to occur. This is of especial concern in micro-scale tribology systems where the integrity of the surfaces can be destroyed by elevated local stresses at asperities.

The findings hold a number of useful implications to the design and operation of micro-scale tribological systems: The results indicate that surface roughness may be significant to minimize the maximum contact pressure through an enhancement of the real contact area with increased loads. Such conduct might aid in increasing the life expectancy of parts of micro-scale devices by minimizing the local wear and stress concentrations that are liable to surface damage. The hypothesis that the relationship between normal and tangential (frictional) forces is linear implies that even the common models of friction like the law of Coulomb are still applicable in the micro-scale. This supports foregoability of frictional traits which associate to greater modelling of tribological interactions in micro environment, e.g. MEMS apparatus. At smaller scales, effects of roughness of surfaces, deformations in materials, and distributions of loads are more vivid. This reduction in the maximum contact pressure with an increase in the real contact area implies that the micro-scale systems can work more efficiently under higher loads as long as the deformation of the surface is accepted.

Though the present study offers some interesting conclusions regarding the behavior of the micro-scale tribological systems, there are also several limitations that should be considered in future research: The present work presupposes the elastic deformation of asperities. As a matter of fact, asperities can experience plastic deformation, particularly at increased loads. The elastic-plastic contact models might also be added to a future study to give an accurate depiction of the surface deformation. In the study, isotropic material properties are assumed to be homogeneous. Micro-scale tribological may include composite materials, directionally endowed materials and this would influence the contact mechanics. More elaborate material models may be included in order to get a more detailed insight in tribological behaviour. The present day simulation fails to consider environmental issues like temperature, humidity or presence of lubricants and each of them could have a severe effect on the contact mechanics. The future research might investigate the same effects of these external conditions on the friction and wear in small-scale systems.

The findings of this experiment allow one to see a comprehensive insight into the contact mechanics of micro-scale tribological systems, the importance of surface roughness, load distribution, and efficient forces. The non-linear dependence on real contact area and overlay of decrease in maximum contact pressure point at the micro-scale point out the sophistication of contact mechanics at the micro-scale level where asperity deformation is an important factor. The results can be used in the construction of miniature-sized devices and tribological devices, and their insights can be used to better the ability and increase the working life of such devices.

5. Conclusion

The mechanical investigation of the behavior of surfaces in micro-scale tribological systems in the context of the numerical study of the advanced mechanics of contacts has shown considerable understanding of the behavior of surfaces under the influence of normal forces that vary. Because the contact conditions were simulated including the surface roughness, friction, and deformation, this study has made several important discoveries that have enhanced our knowledge on micro-scale tribological systems. Among the simulation outcomes that pose as one of the most essential ones is the non-linear growth of the real contact area with the force perpendicular to the contacted surface. Contact area at lower forces is small because of the existence of the surface asperities but with increased force the asperities are ravaged and flattened and there is an increase in the real contact area. The observation contributes to the significance of the surface roughness through tribological systems, particularly in the scale of its micro up to the micro level where surface deformation constitutes a vital factor. The surface roughness is a critical issue in the mechanics of micro-contact and the actual area of contact rises with the flattening of asperities at the contact point under load. The outcome is crucial to designing micro-scale devices, whose wear could be reduced by controlling the contact area and therefore enhance system use.

The outcomes of the simulation showed a linear relationship between tangential force (frictional force) and the normal force that is in agreement with the law of friction as put forward by Coulomb. Results generated by the use of a friction coefficient ($\mu = 0.15$) in the simulation were consistent with theoretical predictions, which pointed to the fact that friction is predictable at the micro-scale. The linear relation between the tangential force and the normal load verifies that the more popular laws of friction are valid at the micro-scale, and therefore, the frictional forces in tribological systems can be accurately modelled and predicted. This plays a significant role in the making of small scale systems where friction should be managed in order to avoid wastage of energy and erosion.

The highest pressure of contact also reduced with the increase in the normal force and the discovery is crucial to knowing how the load is distributed in a micro-scale system. This means that the larger the area of contact with the force the more the load is spread out on the surface and the peak stresses on individual asperities are reduced. Such decrease in local pressure is especially valuable when it comes to the reduction of unnecessary wear and damages to the surfaces that may undermine the functionality of micro-scale devices. The self-regulation of contact mechanics at the micro-scale is indicated by the slope of the maximum contact pressure as a function of the applied normal force. The increased pressure is shared with a greater contact area, minimizing the chances of a surface damage and causing bravery of tribological systems.

The findings of this study have enormous importance on designing and functioning the micro-scale tribological systems, which exist in MEMS (Micro-Electro-Mechanical Systems) and other micro-gadgets. These results demonstrate that the roughness on the surface, the friction, and the distribution of pressure should be under good control to achieve the maximum performance and reliability of these systems. Knowing the way in which contact area, friction, and pressure change with load, engineers and designers may create more efficient and reliable micro-scale devices. Such findings help in the comprehension of the connection of surface features and load-bearing capacity in micro-tribological systems, which need to be balanced.

Although this research has brought about positive details, there are still areas that call on more studies to sharpen our knowledge about the micro-scale tribological systems: Contact model based on elastic-plastic contact would give a better representation of the asperity deformed description especially at higher loads. The upcoming research should investigate the impact of anisotropic/composite materials that are frequently found in the high-technology practices at the micro-scale.

The practical applicability of such findings would be improved by investigating the effects of temperature, humidity and lubrication on micro-scale tribology. Overall, this paper has shown that surface roughness, load distribution and frictional forces are important parameters to determining the behaviour of micro-scale tribological systems. The knowledge acquired here may help in designing more robust and efficient micro-devices, which can be used to enhance the development of other knowledge about the MEMS and micro-scale engineering.

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