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Coefficient of Static Friction of Elastic-Plastic Micromechanical Surface Contact

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ABSTRACT

In this study, the effect of elastic and plastic adhesion index on deformation force and friction force of MEMS surface contact has investigated in term of surface roughness. It is found that at low value of θ, i.e. for smooth surfaces, the contact is mostly elastic in nature and at high value of θ, i.e. for rough surfaces, mostly plastic contact occurs. This supports the elastic-plastic concept of Greenwood and Williamson for rough surface contact. Total deformation force and friction force are mainly supported by plastically deformed asperities. From the study of coefficient of static friction of elastic-plastic MEMS surface contact, it is found that COF is almost constant of the order of value of 0.4

Keywords – **Adhesion index, Deformation force, Friction force, Coefficient of friction**

1. Introduction

Combined study of load and friction of rough surface contact is an important study in the field of Tribology. Empirical correlation in between load and friction was developed by Leonardo da Vanci as well as Amontos [1] which are stated as laws of friction. When two rough surfaces comes in contact due to application of normal force, contact occurs at the tip of asperities and finite tangential force is required for sliding motion which is measure of friction force. Under normal loading condition, asperities of rough surface contact would deform elastically and also, plastically after critical value of deformation. Correspondingly, adhesive bond would be developed at the contact zone of elastically and plastically deformed asperity due to cold welding by interatomic adhesion at contact zone [2]. So, finite force is required for shearing of adhesive asperity junction at real area of contact which is measure of friction force. First, Hertz developed the expression of loading force for elastically deformed spherical contact and thereafter, Chang, Etsion, and Bogy [3] developed expression of loading force for plastically deformed spherical contact considering volume conservation. Also, Chang, Etsion, and Bogy [4] developed expression of friction force for elastically deformed spherical contact considering Hamilton stress field. On the other hand, Bowden and Tabor [5] has developed classical adhesion theory of friction for plastically deformed spherical contact. These theories are revisited for present study of multiasperity contact of adhesive MEMS surfaces. However, Fuller and Tabor [6], and K L Johnson [7] have developed elastic adhesion index and plastic adhesion index respectively for multiasperity contact. Elastic and plastic adhesion index is basically a number which is developed combination of mechanical and tribological parameters of a material. Here, effect of both the adhesion index on deformation force and friction force of MEMS surface contact has investigated in term of surface roughness. Value of both the indices has considered in small range so that study is limited to soft MEMS surface contact. It should be mentioned that adhesive force effect within contact zone of asperity with respect to deformation force has neglected to avoid complexity of the study.

2. Theoretical Formulation

2.1 Single Asperity Contact

2.1.1Single asperity deformation force

2.1.1a Single asperity elastic deformation force

Hertzian Elastic loading force for a single asperity contact is given by

$$P_{ae} = \frac{Ka_e^3}{R} = KR^{0.5}\delta^{1.5}$$

2.1.1b Single Asperity Plastic Deformation Force

CEB Plastic loading force for a single asperity contact on the basis of volume conservation principle is given by

$$P_{ap} = A_{ap}Y = \pi R\delta\left(2-\frac{\delta_c}{\delta}\right)0.6H$$

2.1.2 Single asperity friction force

2.1.2a Single Asperity Elastic Friction Force

CEB elastic friction force for a single asperity contact on the basis of Hamilton stress field is given by

$$T_{ae} = \frac{1}{27^{0.5}c_1}\left(4\pi^2Y^2a_e^4 - 9c_2^2P_{ae}^2\right)^{0.5}$$

$$= \frac{1}{5.2c_1}\left(4\pi^2(0.6H)^2a_e^4 - 9c_2^2P_{ae}^2\right)^{0.5}$$

where

$$c_1 = -1+\frac{3}{2}\tan^{-1}\xi\left(1/\xi\right)-\frac{\xi^2}{2(1+\xi^2)}$$

(Take |C1| value)

$$c_2 = (1+\upsilon)\left[\xi \tan^{-1}\left(1/\xi\right) - 1\right] + \frac{3}{2(1+\xi^2)}$$

2.1.2b Single Asperity Plastic Friction Force

Bowden and Tabor plastic friction force for a single asperity contact is given by

$$T_{ap} = \tau A_{ap}$$
$$= \pi\tau R\delta\left(2 - \frac{\delta_c}{\delta}\right)$$

2.2 Multiasperity Contact

First of all, Greenwood and Williamson [8] developed statistical multiasperity contact theory of rough surface under very low loading condition and it was assumed that asperities are deformed elastically according to Hertz theory. Same theory is extended here in elastic and plastic rough surface contact and it is based on following assumptions:

a) The rough surface is isotropic.
b) Asperities are spherical near their summits.
c) All asperity summits have the same radius R but their heights very randomly.
d) Asperities are far apart and there is no interaction between them.
e) Asperities are deformed elastically as well as plastically.
f) There is no bulk deformation and only, the asperities deform during contact.

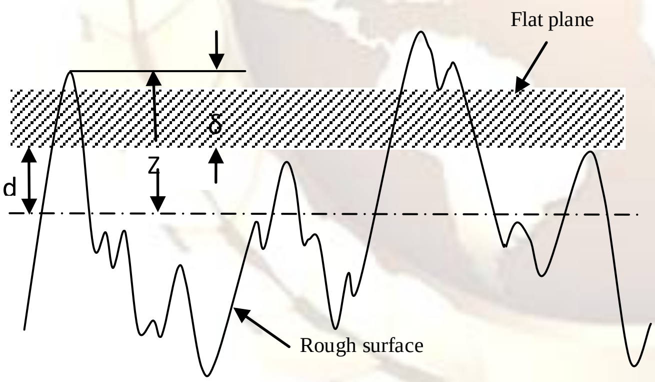

Fig. 1 Rough surfaces contact

Multiasperity contact of elastic and plastic rough surface has shown in Fig.1. Two rough surface contact could be considered equivalently, contact between rough surface and smooth rigid surface. Let z and d represents the asperity height and separation of the surfaces respectively, measured from the reference plane defined by the mean of the asperity height. δ denotes deformation of asperity by flat surface. Number of contacting asperity per unit cross-sectional area is

$$\eta_c = \eta\int_d^{\infty}\phi(z)dz = \underbrace{\eta\int_d^{d+\delta_c}\phi(z)dz}_{Elastic asperities} + \underbrace{\eta\int_{d+\delta_c}^{\infty}\phi(z)dz}_{Plastic asperities}$$

where η is number of total asperity per unit cross-sectional area and φ(z) is the Gaussian asperity height distribution function.

2.2.1 Multiasperity Deformation Force

2.2.1a Multiasperity Elastic Deformation Force

Elastic deformation force due to multiasperity contact is given by

$$P_e = \eta\int_d^{d+\delta_c} KR^{0.5}\delta^{1.5}\phi(z)dz$$

Dividing both side by $\eta R\gamma$, we have

$$P_e = \int_0^{\Delta_c}\theta\Delta^{1.5}\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta$$

2.2.1b Multiasperity Plastic Deformation Force

Plastic deformation force due to multi asperity contact is given by

$$P_p = \eta\int_{d+\delta_c}^{\infty}\pi R\delta\left(2-\frac{\delta_c}{\delta}\right)H\phi(z)dz$$

Dividing both side by ηRγ, we have

$$P_p = \int_{\Delta_c}^{\infty}2.19\theta^{0.5}\lambda^{0.25}\Delta\left(2-\frac{\Delta_c}{\Delta}\right)\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta$$

Total deformation force due to all asperities is given by

$$P = \eta\int_d^{d+\delta_c} KR^{0.5}\delta^{1.5}\phi(z)dz + \eta\int_{d+\delta_c}^{\infty}0.6\pi R\delta\left(2-\frac{\delta_c}{\delta}\right)H\phi(z)dz$$

Dividing both side by ηRγ, we have

$$P^* = \int_0^{\Delta_c}\theta\Delta^{1.5}\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta + \int_{\Delta_c}^{\infty}2.19\theta^{0.5}\lambda^{0.25}\Delta\left(2-\frac{\Delta_c}{\Delta}\right)\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta$$

2.2.2 Multiasperity Friction Force

2.2.2a Multiasperity Elastic Friction Force

Elastic friction force for multiaspirity is given by

$$T_e = \eta\int_d^{d+\delta_c}\frac{1}{5.2c_1}\left(4\pi^2(0.6H)^2R^2\delta^2 - 9c_2^2K^2R\delta^3\right)^{0.5}\phi(z)dz$$

Dividing both side by $\eta R\gamma$, we have

$$T_e = \int_0^{\Delta_c}\frac{1}{5.2c_1}\left(19.2\lambda^{0.5}\theta\Delta^2 - 9c_2^2\theta^2\Delta^3\right)^{0.5}\phi(\Delta)d\Delta$$

2.2.2b Multiasperity Plastic Friction Force

Plastic friction force for multiaspirity is given by

$$T_p = \eta\int_{d+\delta_c}^{\infty}\pi R\delta\left(2-\frac{\delta_c}{\delta}\right)\phi(z)dz$$

Dividing both side by ηRγ, we have

$$T_p = \int_{\Delta_c}^{\infty}3.65\left(\frac{\tau}{H}\right)\lambda^{0.25}\theta^{0.5}\Delta\left(2-\frac{\Delta_c}{\Delta}\right)\phi(\Delta)d\Delta$$

Total friction force due to all asperities is given by

$$T=\eta\int_{d}^{d+\delta_c}\frac{1}{5.2c_1}\left(4\pi^2(0.6H)^2R^2\delta^2-9c_2^2K^2R\delta^3\right)^{0.5}\phi(z)dz+\eta\int_{d+\delta_c}^{\infty}\pi\tau R\delta\left(2-\frac{\delta_c}{\delta}\right)\phi(z)dz$$

Dividing both side by ηRγ, we have

$$T^*=\int_{0}^{\Delta_c}\frac{1}{5.2c_1}\left(19.2\lambda^{0.5}\theta\Delta^2-9c_2^2\theta^2\Delta^3\right)^{0.5}\phi(\Delta)d\Delta+\int_{\Delta_c}^{\infty}3.65\left(\frac{\tau}{H}\right)\lambda^{0.25}\theta^{0.5}\Delta\left(2-\frac{\Delta_c}{\Delta}\right)\phi(\Delta)d\Delta$$

where,

$$\frac{z}{\sigma}=\frac{d+\delta}{\sigma}=h+\Delta,\ h=\frac{d}{\sigma},\ \Delta=\frac{\delta}{\sigma},$$

$$\Delta_c=\frac{\delta_c}{\sigma}=1.256\left(\frac{H}{K}\right)^2\left(\frac{R}{\sigma}\right)=1.7\frac{\lambda^{0.5}}{\theta},$$

$$\xi=0.3,\ \frac{\tau}{H}=0.2$$

3. Result and Discussion

In this combined analysis of deformation force and friction force of adhesive MEMS surface contact, elastic adhesion index (θ), plastic adhesion index (λ) and dimensionless mean separation (h) have used as input parameters. Before analyzing the results on the basis of surface roughness point of view, the definition and physical significance of these indices should be mentioned. First, Fuller and Tabor introduced an elastic adhesion index for elastic solid which is defined as ratio of elastic deformation force to adhesive force experienced by elastically deformed sphere and given in following form;

$$\theta=\frac{K\sigma^{1.5}}{R^{0.5}\gamma}$$

Similarly, Johnson developed a plastic adhesion index for plastic solid which is the ratio of plastic deformation force to adhesive force experienced by plastically deformed sphere and given in following form;

$$\lambda=\frac{\pi^2RH^4\sigma}{18K^2\gamma^2}$$

From roughness parameters data of rough surface contact, it is found that value of rms surface roughness (σ) and asperity radius (R) are inversely proportional and multiplication of both the two parameter is almost constant. Present study, low θ value is considered from 5 to 25 for soft polymeric MEMS material and λ value is considered almost constant, 2.5 or 5. It is assumed that soft material parameters, modulus of elasticity (K) and hardness (H), and surface energy (γ) are almost constant and θ values slightly increases from 5 to 25 due to only variation of surface roughness keeping constant of λ value. So, keeping same λ value, as θ value increases, soft surface becomes much more rougher.

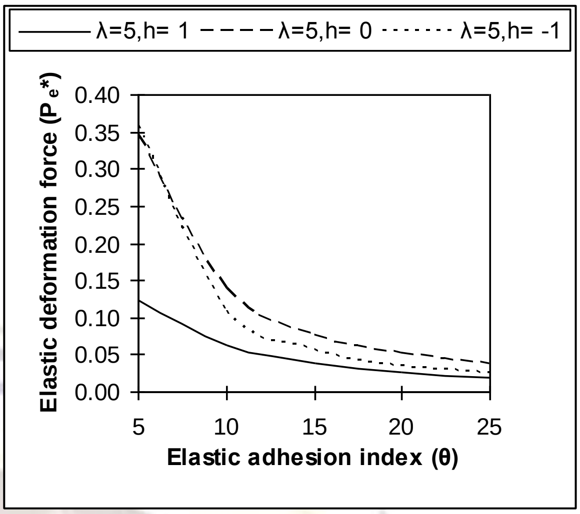

Fig.2a Elastic deformation force Vs Elastic adhesion index

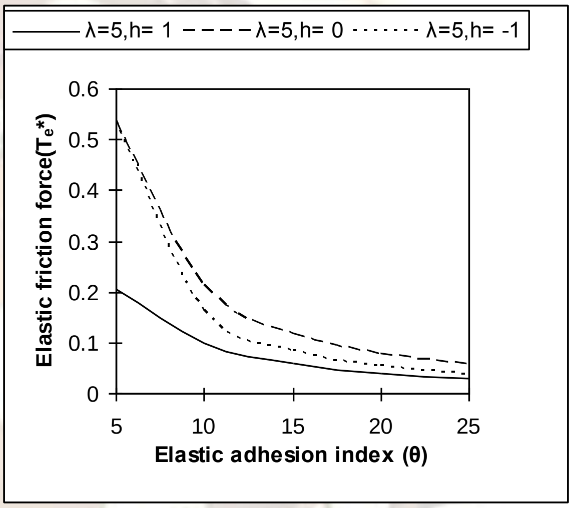

Fig.2b Elastic friction force Vs Elastic adhesion index

Fig.2a and Fig.2b shows that for particular mean separation, elastic deformation force and friction force is maximum at θ=5 and thereafter decreases and converges exponentially to a same value as the elastic adhesion index (θ) increases. So, it indicates rough surfaces are not able to support external load and friction load by elastic deformation. Conversely, smooth surface contact mainly occurs due to elastic deformation of asperities. Fig.3a and Fig.3b shows that for particular mean separation, plastic deformation force and friction force is minimum at θ=5 and thereafter increases and diverges linearly to a maximum value as the elastic adhesion index (θ) increases. So, it indicates rough surfaces are much more able to support external load and friction load by plastic deformation. Conversely, smooth surface contact is not supported by plastic deformation of asperities.

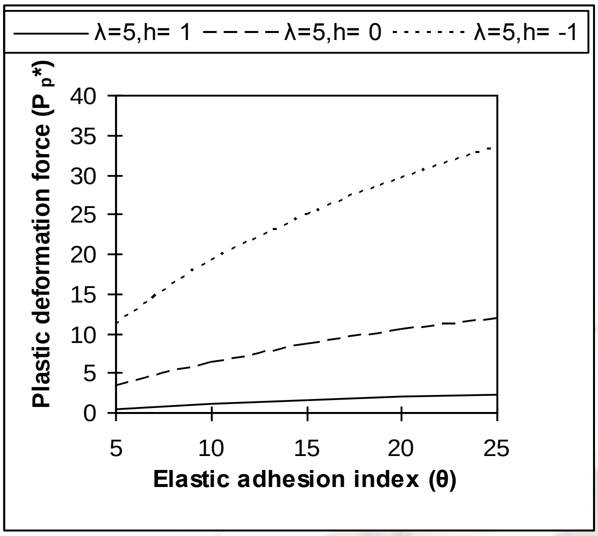

Fig.3a Plastic deformation force Vs Elastic adhesion index

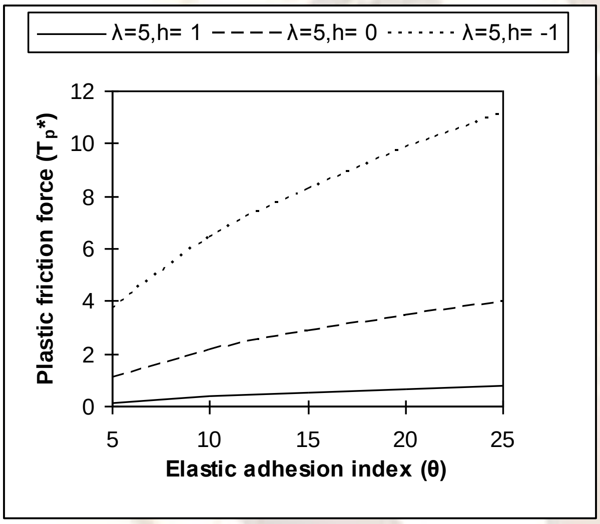

Fig.3b Plastic friction force Vs Elastic adhesion index

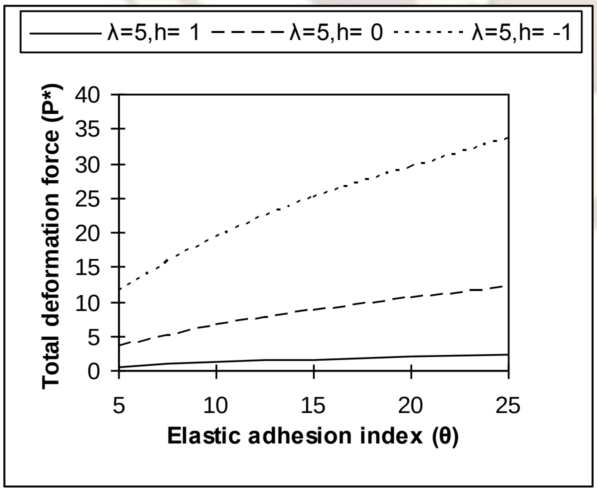

Fig.4a Total deformation force Vs Elastic adhesion index

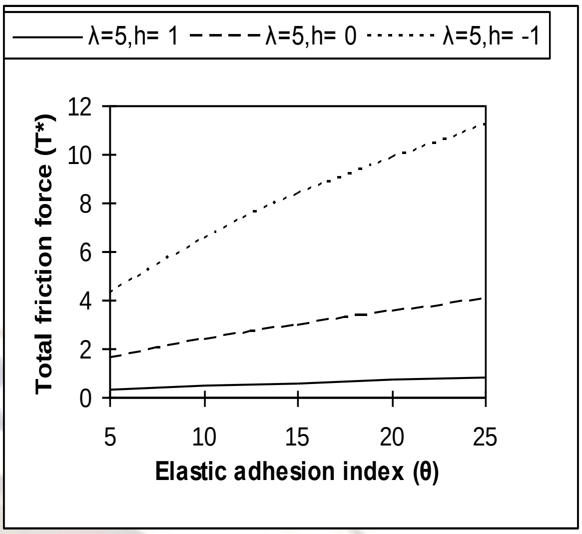

Fig.4b Total friction force Vs Elastic adhesion index

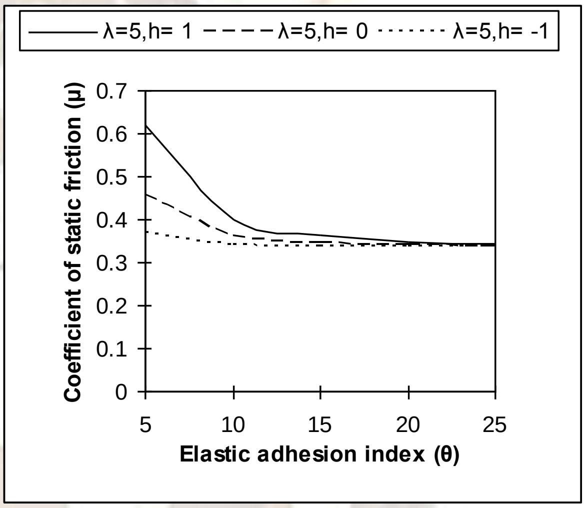

Fig.5 Coefficient of static friction Vs Elastic adhesion

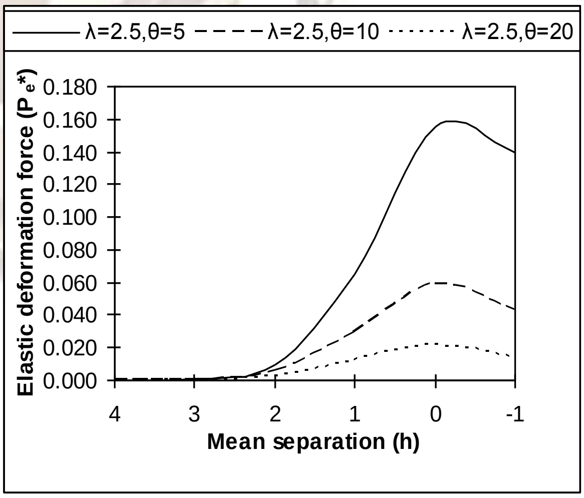

Fig.6a Elastic deformation force Vs Mean separation

Fig.4a Fig.4b shows that nature of curves for variation of total deformation and friction force with adhesion index for a particular value of h is same with Fig.3a and Fig.3b. Contribution of elastic deformation force and friction force is negligible with respect to plastic deformation force and friction force and so, total forces are mainly contributed by plastically deformed asperity. Fig.5 depicts the variation coefficient of friction with elastic adhesion index for a particular value of h. It is found that COF gradually decreases and converges to a constant value of 0.4. It is noted that COF is constant after the value of θ=10 and independent with roughness effect.

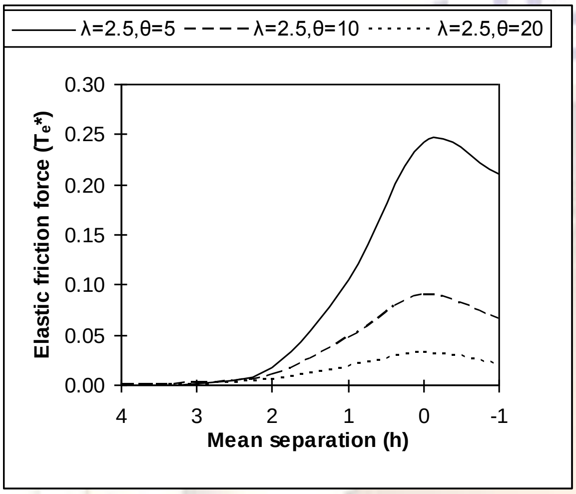

Fig.6b Elastic friction force Vs Mean separation

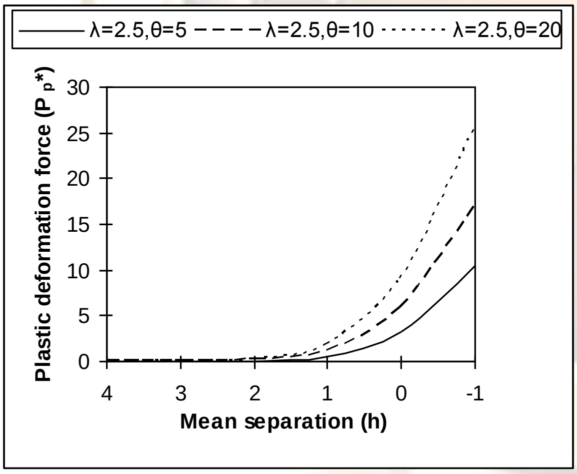

Fig.7a Plastic deformation force Vs Mean separation

In Fig.6a and Fig.6b the graphs are plotted showing the variation of elastic deformation force and friction force with variation in dimensional mean separation at λ=2.5 and θ=5, 10, 20. It shows that deformation force and friction force for elastically deformed asperities increases exponentially with decrease in dimensionless mean separation upto h=0 and thereafter it decreases to a finite value. For a particular mean separation value, elastic deformation force and friction force decreases with increase in elastic adhesion index (θ) value as discussed earlier.

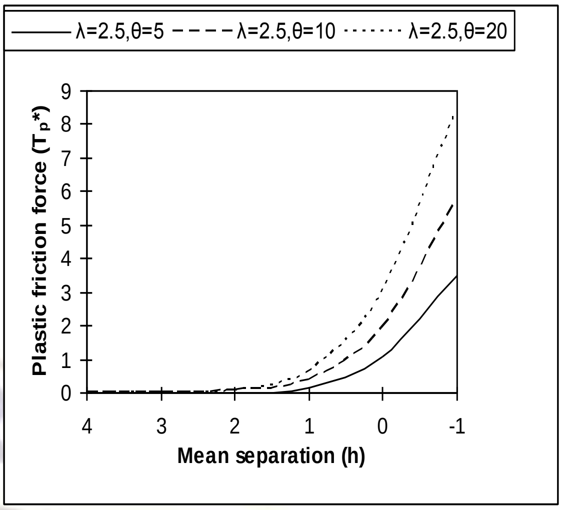

Fig.7b Plastic friction force Vs Mean separation

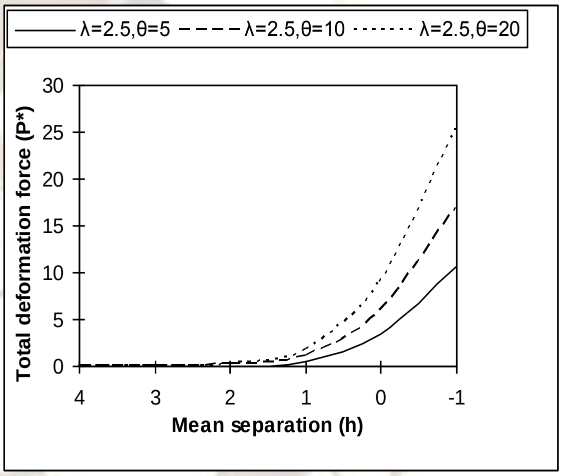

Fig.8a Total deformation force Vs Mean separation

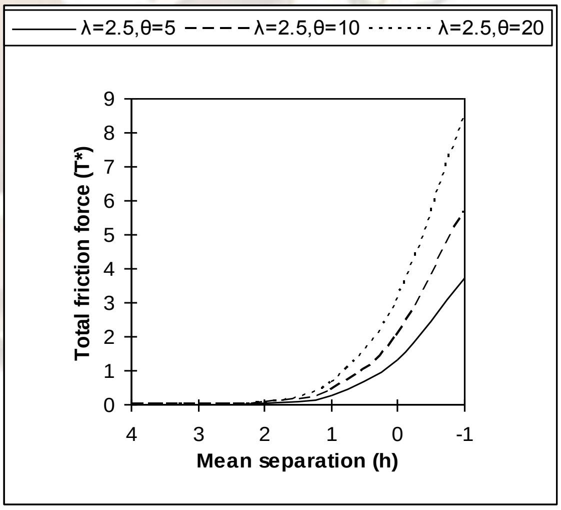

Fig.8b Total friction force Vs Mean separation

Fig.7a and Fig.7b depicts variation plastic deformation force and friction force with mean separation. It shows that deformation force and friction force for plastically deformed asperities increases exponentially with decrease in dimensionless mean separation. For a particular mean separation value, plastic deformation force and friction increases with increase in elastic adhesion index (θ) value as mentioned earlier. Like Fig.7a and Fig.7b, similar nature of curve is obtained in Fig.8a and Fig.8b when the graph is plotted between total deformation force and friction force with mean separation, because high plastic deformation force and friction force value diminishes the effect of low elastic deformation force and friction force value.

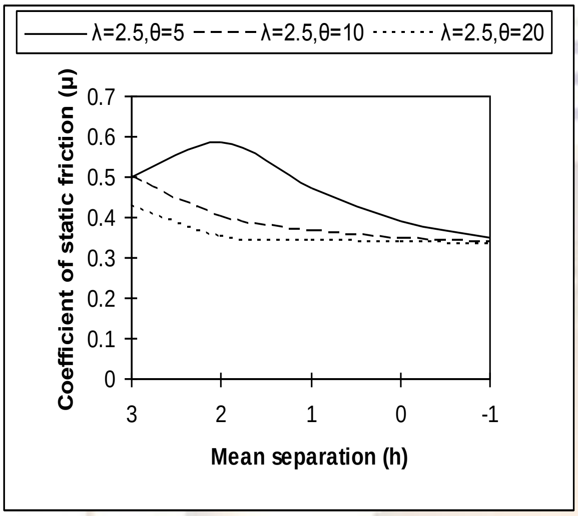

Fig.9 Coefficient of static friction Vs Mean separation

Fig.9 represents variation of coefficient of static friction with mean separation and it shows that COF converges to the value of 0.4 with decrement of mean separation. From the study of coefficient of static friction of elastic-plastic soft surface contact, it is found that COF is almost constant value of 0.4 which is mostly independent of roughness effect (θ) and mean separation (h). So, COF is almost independent of load and friction which supports Amonton's law of dry friction.

4. Conclusion

From the above study, it could be concluded that at low value of θ, i.e. for smooth MEMS surfaces, the contact is mostly elastic in nature and at high value of θ, i.e. for rough MEMS surfaces, mostly plastic contacts occur. This supports the elastic-plastic concept of Greenwood and Williamson for rough surface contact. Total deformation force and friction force are mainly supported by plastically deformed asperities of soft MEMS surfaces. From the study of coefficient of static friction of elastic-plastic soft MEMS surface contact, it is found that COF is almost constant value of 0.4 which is mostly independent of roughness effect (θ) and mean separation (h). The evaluated COF=0.4 is almost equal to experimentally, found COF=0.5.

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