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Adhesion and Adhesional Friction of Micromechanical Surface Contact

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Abstract: In this study, a model that predicts the effects of roughness parameters on the adhesion and adhesional friction in MEMS interfaces is presented. The multiasperity contact model is developed based on assumption of Johnson adhesion model. It is found that adhesion and adhesional friction of MEMS surfaces increases with increment of smoothness of surfaces. Very smooth surface contact produces high adhesive force and adhesional friction force whereas rough surface supports high external force through high asperity deformation.

Key words: Single asperity contact, multiasperity contact, adhesion, adhesional friction, MEMS surfaces, assumption

INTRODUCTION

Macroscopic friction behavior of rough surface contact has been made by pioneering researcher of Amontons in 1699 and Coulomb in 1785. Thereafter, microscopic analysis of friction process was described by Tabor in 1981. It is based on following two statements:

- The true area of contact between mating rough surfaces
- Shearing strength of bond formed at the asperity contact of rough surfaces

However, micromechanical surface contact has become very important for present state of understanding of friction. When two clean and smooth surface comes in contact, they should adhere and behave as if a single body at there interface and tangential force is required for their relative sliding. The tangential force is called adhesional friction and it depends on normal external force and adhesive force of the micromechanical surface contact.

Adhesion of the rough surface contact is related with integration of adhesive single asperity contact which depends on adhesion model of solid sphere. Although, there have been several adhesive theories offered for rough surfaces each have their own limitations. Jhonson *et al.* (1971) found the first solution between elastic sphere using an energy balance approach. Jhonson determined the pull-off force to be $3/2\pi\gamma R$ where, γ is the work of adhesion and R is the effective radius. Derjaguin *et al.* (1975) subsequently solved the same problem numerically and determined the pull-off force to be $2\pi\gamma R$. The Johnson model considers adhesive force within contact area of elastic sphere. The Derjaguins model assumes adhesive force out side of contact area of sphere. Chang *et al.* (1988) developed adhesion model of multiasperity rough surfaces of metallic contacts based on Derjaguin model. Chowdhury and Ghosh (1994) also developed adhesion model of rough surface contact based on Johnson model considering modified expression of Jhonson model

In the present study, adhesive force of rough surface contact would be developed considering adhesion of contacting asperity based on original expression of Johnson model (Jhonson *et al.*, 1971).

Here, assumption of single asperity contact of Johnson model is considered also for multiasperity rough surface contact model which imply that adhesive force should be added with external force.

MATERIALS AND METHODS

Rough surface contact model: First of all, Greenwood and Williamson (1966) developed statistical multiasperity contact model of rough surface under very low loading condition. It is based on following assumption:

- The rough surface is isotropic
- Asperities are spherical near their summits
- All asperity summits have the same radius R but their heights very randomly
- Asperities are far apart and there is no interaction between them
- There is no bulk deformation. Only, the asperities deform during contact

Multiasperity contact of rough surfaces has shown in Fig. 1. According to Greenwood model, two rough

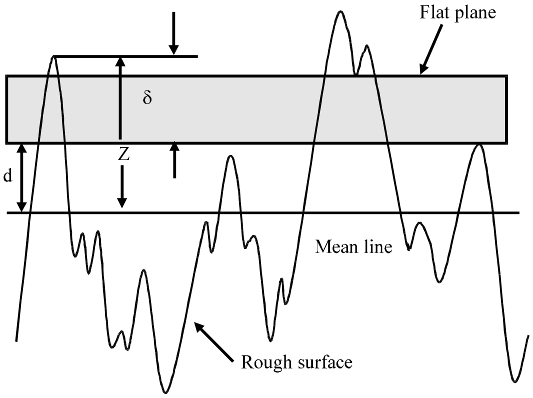

Fig. 1: Contact between a rough surface and a rigid flat plane

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 asperity contact is:

$$N_c = N\int_d^{\infty} \phi(z)dz \tag{1}$$

Where:

N = Total number of asperity

ϕ (z) = Asperity height distribution function. Hertzian load supported by each asperity deformation is:

$$P_a = KR^{0.5}\delta^{1.5} \tag{2}$$

Or:

$$P_a = KR^{0.5}(z-d)^{1.5}$$

Where:

$$\frac{1}{K} = \frac{3}{4}\left(\frac{1-\vartheta_1^2}{E_1} + \frac{1-\vartheta_2^2}{E_2}\right)$$

and E_1, E_2, γ_1 and γ_2 are Young's modulus and poisson's ratios of the contacting surfaces, respectively. So from Eq. 1 and 2, total external load supported by all contacting asperity is:

$$P = N_c P_a$$

Or:

$$P = NKR^{0.5}\int_0^{\infty}(z-d)^{1.5}\phi(z)dz$$

Or:

$$\overline{P} = (\eta R\sigma)\left(\frac{R}{\sigma}\right)^{-0.5}\int_0^{\infty}\Delta^{1.5}\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta \tag{3}$$

where, P^{∞}, Δ, η and σ is dimensionless load, dimensionless asperity deformation, dimensionless mean separation, asperity density and standard deviation of asperity height, respectively.

Adhesion model for rough surfaces: Jhonson theory has modified Hertz theory of spherical contact. It predicts a contact radius at light loads greater than the calculated Hertz radius. As asperity tip is considered spherical, the Adhesion model of single asperity contact could be extended to multiasperity of rough surface. According to Johnson model (Jhonson *et al*., 1971), the expression of adhesive fo rce for each asperity contact is:

$$F_a = 3\gamma\pi R + \sqrt{\left(6\gamma\pi RP_a + (3\gamma\pi R)^2\right)}$$

$$F_a = 3\gamma\pi R + \sqrt{\left(6\gamma\pi KR^{1.5}\delta^{1.5} + (3\gamma\pi R)^2\right)} \tag{4}$$

or

$$F_a = 3\gamma\pi R + \sqrt{\left(6\gamma\pi KR^{1.5}(z-d)^{1.5} + (3\gamma\pi R)^2\right)}$$

So from Eq. 1 and 4, total adhesive force for multiasperity contact is:

$$F = N_c F_a$$

$$F = N\int_d^{\infty}\left[3\gamma\pi R + \sqrt{\left(6\gamma\pi KR^{1.5}(z-d)^{1.5} + (3\gamma\pi R)^2\right)}\right]\phi(z)dz$$

$$\overline{F} = \int_0^{\infty}\left[3\pi(\eta R\sigma)\left(\frac{\gamma}{K\sigma}\right) + \sqrt{\begin{matrix}6\pi(\eta R\sigma)^2\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{-0.5}\Delta^{1.5} + \\ 9\pi^2(\eta R\sigma)^2\left(\frac{\gamma}{K\sigma}\right)^2\end{matrix}}\right]\times \frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta$$

$$\overline{F} = \int_0^{\infty}\left[3\pi A_0 B_0 + \sqrt{6\pi A_0^2 B_0 R_0^{-0.5}\Delta^{1.5} + 9\pi^2 A_0^2 B_0^2}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta \tag{5}$$

Where, dimensionless surface roughness parameter:

$$A_0 = \eta R\sigma$$

and dimensionless surface energy parameter:

$$B_0 = \gamma/K\sigma$$

Adhesional friction model for rough surfaces: Savkoor and Briggs (1977) extended Jhonson model considering tangential force on the contact of elastic solids in adhesion. According to Savkoor friction model, the expression of adhesive force for each asperity contact is:

$$T_a = \frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\left(2\gamma\pi RP_\alpha + 3(\gamma\pi R)^2\right)}$$

$$T_a = \frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\left(2\gamma\pi KR^{1.5}\delta^{1.5} + 3(\gamma\pi R)^2\right)}$$

or;

$$T_a = \frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\left(2\gamma\pi KR^{1.5}(z-d)^{1.5} + 3(\gamma\pi R)^2\right)} \quad (6)$$

So from Eq. 1 and 6, total adhesional friction force for multiasperity contact is:

$$T = N_c T_a$$

$$T = N\int_d^\infty \left[\frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\begin{pmatrix}2\gamma\pi KR^{1.5}(z-d)^{1.5} \\ +3(\gamma\pi R)^2\end{pmatrix}}\right]\phi(z)dz$$

or;

$$\overline{T} = \int_0^\infty \left[\frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\begin{pmatrix}2\pi(\eta R\sigma)^2\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{-0.5} \\ \Delta^{1.5} + 3\pi^2(\eta R\sigma)^2\left(\frac{\gamma}{K\sigma}\right)^2\end{pmatrix}}\right] \frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta$$

$$\overline{T} = \int_0^\infty \left[\frac{4}{\sqrt{\left(K/G\right)}}\sqrt{\begin{matrix}2\pi A_0^2 B_0 R_0^{-0.5}\Delta^{1.5} + \\ 3\pi^2 A_0^2 B_0^2\end{matrix}}\right] \frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^2}{2}\right]d\Delta \quad (7)$$

Where:

$$\frac{1}{G} = \left(\frac{2-\vartheta_1}{G_1} + \frac{2-\vartheta_2}{G_2}\right)$$

So, coefficient of friction from Eq. 3, 5 and 7 is:

$$\mu = \frac{\overline{T}}{\overline{p} + \overline{F}} \quad (8)$$

RESULTS AND DISCUSSION

Tayebi and Polycarpou (2006) have done extensive study on polysilicon MEMS surfaces and four different MEMS surface pairs as shown in Table 1 were taken for the study. Similarly, tribological properties of the MEMS surfaces are being considered for present study as input datas. The roughest case (simulation A) is for deposited polysilicon on substrate with combined σ = 15.8 nm, R = 0.116 μm and η = 14.7 μm^{-2} and the intermediate case (simulation B) is for polished polysilicon on substrate with σ = 6.8 nm, R = 0.45 μm and η = 11.1 μm^{-2}, the smooth case (simulation C) is for polished polysilicon on itself with σ = 1.4 nm, R = 1.7 μm and η = 17 μm^{-2} and the super smooth case (simulation D) is for polished single crystal silicon on itself with σ = 0.42 nm R = 3.36 μm and η = 26 μm^{-2}. The material properties of MEMS silicon samples are modulus of elasticity, E_1 = E_2 = 160 GPa, hardness, H = 12.5 GPa, poisions ratio, ϑ_1 = ϑ_2 = 0.22 and surface energy, γ = 0.5 J m^{-2}.

Figure 2 shows external force (Eq. 3) supported by asperity deformation increases with decrement of mean separation. Maximum load supported by multiasperity increases with increment of roughness of MEMS surfaces. Figure 3 shows adhesive force (Eq. 5) increases with increment of smoothness of MEMS surfaces. Smooth and very smooth surface produces very high adhesive force than that of rough and intermediate MEMS surface. The result supports practical result of adhesion of very

Table 1: Roughness parameters for MEMS surfaces

Individual surfaces	Deposited polysilicon	Typical substrate	Polished polysilicon	Polished Single crystal silicon
σ (nm)	14.30	6.70	1.0	0.30
R (μm)	0.12	0.46	2.4	4.75
η (μm^{-2})	15.00	11.00	17.0	26.00
Combined surfaces	Rough 1 on 2	Intermidiate 2 on 3	Smooth: 3 on 3	Super smooth 4 on 4
σ (nm)	15.800	6.80	1.4	0.42
R (μm)	0.116	0.45	1.7	26.00
η (μm^{-2})	14.700	11.10	17.0	26.00

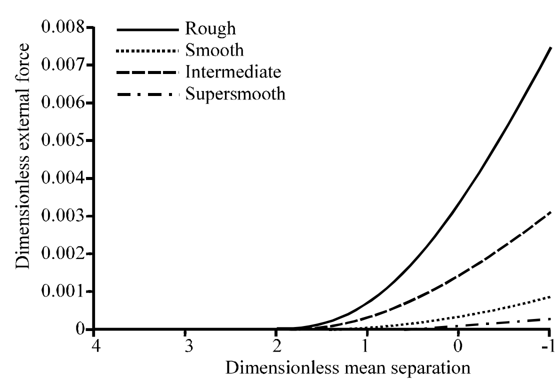

Fig. 2: External force vs. mean separation

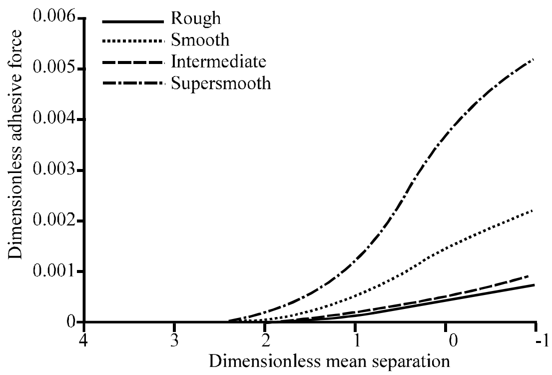

Fig. 3: Adhesive force vs. mean separation

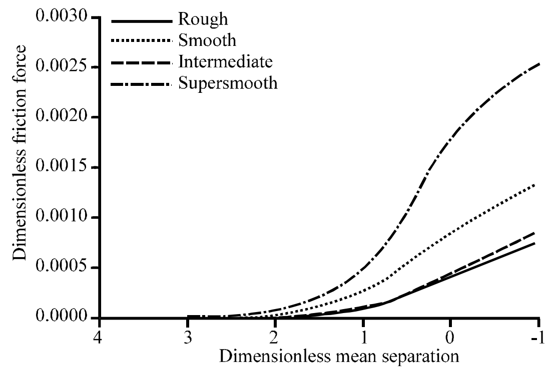

Fig. 5: Friction force vs. mean separation

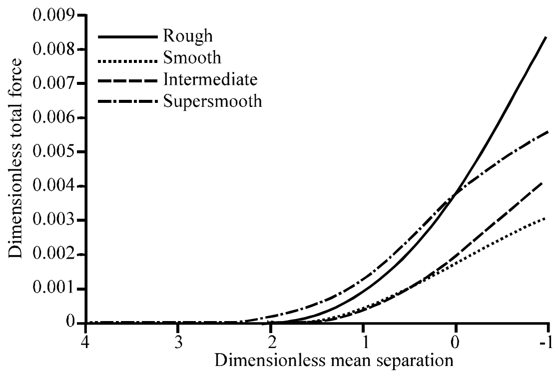

Fig. 4: Total force vs. mean separation

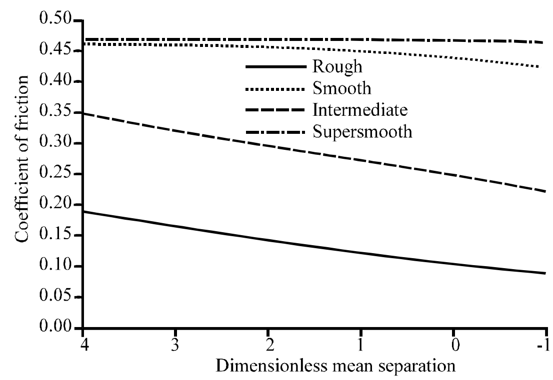

Fig. 6: Cofficient of friction vs. mean separation

smooth surface. As adhesive force increases significantly with increment of smoothness of surface, considerable amount of pull off force is required to separate the smooth surface. Figure 4 shows total force acting on rough surface contact (Eq. 3 and 5). According to Jhonson adhesion theory, contact area of elastic sphere is greater than that of Hertzian contact area due to presence of adhesive force within contact zone. Similarly for the multiasperity contact of rough surface, total load should be addition of external force and adhesive force due to presence of adhesive force at each of the asperity contact area.

Figure 4 shown total force increases with decrement of mean separation. It is found that highly total load is supported by either rough surface or very smooth surface whereas intermediate and smooth surface supports less amount of total load. Figure 5 shows very significant results of adhesional friction force of contacting MEMS surfaces (Eq. 7).

Adhesional friction increases with decrement of mean separation and increases highly after dimensionless mean separation of 2. Variation friction force is similar with the variation of adhesive force of the MEMS surface contact. As adhesion of smooth surface is significantly high, adhesional friction force of the MEMS surfaces increases with increment of smoothness of the surfaces. It imply that very high amount of tangential force is required for sliding of very smooth and smooth surface. From the overall study of Fig. 2-5, it is found that variation of result occurs within dimensionless mean separation 2 to -1. Possibly before dimensionless mean separation of 2, there is almost not contact of asperity of rough surfaces and after dimensionless mean separation of -1, value of all parameter decreases due to very intimate contact of asperity (which is not shown).

Figure 6 shows variation of coefficient of friction of MEMS surface contact (Eq. 8) with mean separation. Smooth and very smooth surface shows high coefficient of friction just above 0.45. Coefficient of friction for intermediate and rough surface contact is 0.35 and 0.20, respectively and it decreases with decrement of mean separation.

CONCLUSION

From the study of micromechanical contact of rough surfaces, it is found that adhesion and adhesional friction increases with increment smoothness of the surface. It also explains the stiction phenomena of

MEMS surfaces. In final conclusion, the micromechanical friction analysis would be help full for understanding of friction theory for macromechanical rough surface contact.

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