Adhesive Wear Theory of Micromechanical Surface Contact

Biswajit Bera
Department of Mechanical Engineering National Institute of Technology Durgapur, India

Abstract: Microscopically, when two surfaces come in contact, strong adhesive bond is formed at the tip of the asperities and consequently, adhesive wear particle is formed by shearing the interface caused by sliding. On the basis of JKR adhesion theory, dimensionless real area of contact and wear volume are computed numerically for multiasperity contact and It is found, their ratio is almost constant for different pair of MEMS surfaces. From which adhesive wear law is derived and accordingly, adhesive wear volume is the multiplication of real area of contact and rms roughness (sigma).

Keyword: JKR adhesion theory, Real area of contact, Adhesive wear volume, Coefficient of adhesive wear

1. Introduction

Wear is a complex process of material removal from the interface of mating surfaces under sliding motion. According to adhesive wear theory, when two smooth and clean rough surfaces come in contact, cold welded junctions are formed at the pick of the asperities through plastic deformation and the subsequent shearing of the junctions from softer material causes adhesive wear particle. Existing almost all laws of adhesive wear are based on experimental findings and empirical in nature. Holm [1] assumed that adhesive wear was an atomic transfer process occurring at the real area of contact formed by plastic deformation of the contacting asperities. Holm proposed an equation for adhesive wear, as $V = \frac{P}{H}Z$ where P, H and Z are load, hardness and number of atoms removed per atomic encounter respectively. Similarly, Archard [2] quantified adhesive wear for rough surface contact based on single asperity contact as adhesive wear, $V = K\frac{P}{H}L$ where L is sliding distance and K is wear coefficient which should be evaluated experimentally. Still, now, Archard's adhesive wear law is well accepted but it does not quantify the adhesive wear volume theoretically. In this study, effort has paid to quantify adhesive wear volume theoretically. It is considered that asperities would deform elastically and they cold weld due to intermolecular adhesion at the contact zone of asperity. Strong adhesive bond is formed according to JKR adhesion theory [3] i.e. adhesive force would act within Hertzian contact zone of deformed asperities. This idea is implemented to find adhesive wear volume and real area of contact for multiasperity contact of rough surfaces such as adhesive MEMS surface contact. Thereafter, from the interrelation of both the parameters, new adhesive wear law has developed and finally, the new adhesive law is compared and interrelated with existing Archard's adhesive wear law.

2. Theoretical Formulation

2.1 Single asperity contact

2.1.1 Single asperity real area of contact

JKR 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 contact. So, real contact area of sinle asperity is

$$A_a = \pi\left[\frac{R}{K}\left(F_0 + 3\pi\gamma R + \sqrt{6\pi\gamma R F_0 + (3\pi\gamma R)^2}\right)\right]^{\frac{2}{3}}$$

Substituting $F_0 = \frac{K(R\delta)^{1.5}}{R}$, we get

$$A_a = \pi\left[R^{1.5}\delta^{1.5} + \frac{3\pi\gamma R^2}{K} + \sqrt{\frac{6\pi\gamma R^{3.5}\delta^{1.5}}{K} + \frac{9\pi^2\gamma^2 R^4}{K^2}}\right]^{\frac{2}{3}} \quad \text{--(1)}$$

2.1.2 Single asperity adhesive wear volume

If wear particle is in the shape of hemispherical and is cut off from tip of the asperity through shearing of cold welded junction, wear volume,

$$V_a = \frac{2}{3}\pi a^3$$
$$= \frac{2}{3}\pi\left[\frac{R}{K}\left(F_0 + 3\pi\gamma R + \sqrt{6\pi\gamma R F_0 + (3\pi\gamma R)^2}\right)\right]$$

Substituting $F_0 = \frac{K(R\delta)^{1.5}}{R}$, we get

$$V_a = \frac{2}{3}\pi\left[R^{1.5}\delta^{1.5} + \frac{3\pi\gamma R^2}{K} + \sqrt{\frac{6\pi\gamma R^{3.5}\delta^{1.5}}{K} + \frac{9\pi^2\gamma^2 R^4}{K^2}}\right] \quad \text{--(2)}$$

2.2 Multiasperity contact

First of all, Greenwood and Williamson [4] developed statistical multiasperity contact model of rough surface under very low loading condition and it was assumed that asperities are deformed elastically according Hertz theory. Same model is modified here in adhesive 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 vary randomly followed by Gaussian distribution.
d. Asperities are far apart and there is no interaction between them.
e. Asperities are deformed elastically and adhesive bonded according to JKR adhesion theory
f. There is no bulk deformation. Only, the asperities deform during contact.

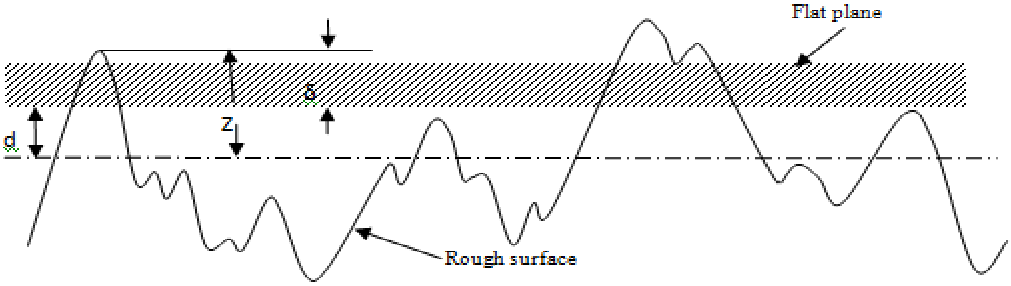

Fig. 1 Rough surfaces contact

Multiasperity contact of adhesive rough surface has shown in Fig.1 According to, GW model, 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 asperity contact is

$$N_c = N\int_d^\infty \phi(z)dz \quad \text{--(3)}$$

where *N* is total number of asperity and $\phi(z)$ is the Gaussian asperity height distribution function.

2.2.1 Multiasperity real area of contact

So, from eq^n (1) and (3), total real area of contact for multiasperity contact is

$$A = N\int_d^\infty A_a \phi(z)dz$$

$$= N\int_{d}^{\infty}\pi\left[R^{1.5}\delta^{1.5}+\frac{3\pi\gamma R^{2}}{K}+\sqrt{\frac{6\pi\gamma R^{3.5}\delta^{1.5}}{K}+\frac{9\pi^{2}\gamma^{2}R^{4}}{K^{2}}}\right]^{\frac{2}{3}}\phi(z)dz$$

Dividing both side by apparent area of contact A_n

$$A^{*}=\int_{0}^{\infty}\left[\pi^{1.5}(\eta R\sigma)^{1.5}\Delta^{1.5}+3\pi^{2.5}(\eta R\sigma)^{1.5}\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{0.5}+\sqrt{6\pi^{4}(\eta R\sigma)^{3}\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{0.5}\Delta^{1.5}+9\pi^{5}(\eta R\sigma)^{3}\left(\frac{\gamma}{K\sigma}\right)^{2}\left(\frac{R}{\sigma}\right)}\right]\phi(\Delta)d\Delta$$

$$=\int_{0}^{\infty}\left[\pi^{1.5}A_{0}^{1.5}\Delta^{1.5}+3\pi^{2.5}A_{0}^{1.5}B_{0}R_{0}^{0.5}+\sqrt{6\pi^{4}A_{0}^{3}B_{0}R_{0}^{0.5}\Delta^{1.5}+9\pi^{5}A_{0}^{3}B_{0}^{2}R_{0}}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^{2}}{2}\right]d\Delta$$

2.2.2 Multiasperity adhesive wear volume

So, , from eq^{n} (2) and (3) adhesive wear volume for multiasperity contact is

$$V=N_{c}V_{a}$$

$$=N\int_{d}^{\infty}V_{a}\phi(z)dz$$

$$=N\int_{d}^{\infty}\frac{2}{3}\pi\left[R^{1.5}\delta^{1.5}+\frac{3\pi\gamma R^{2}}{K}+\sqrt{\frac{6\pi\gamma R^{3.5}\delta^{1.5}}{K}+\frac{9\pi^{2}\gamma^{2}R^{4}}{K^{2}}}\right]\phi(z)dz$$

Dividing both side by $A_n\sigma$

$$V^{*}=\frac{2}{3}\pi\int_{0}^{\infty}\left[(\eta R\sigma)\left(\frac{R}{\sigma}\right)^{0.5}\Delta^{1.5}+3\pi(\eta R\sigma)\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)+\sqrt{6\pi(\eta R\sigma)^{2}\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{1.5}\Delta^{1.5}+9\pi^{2}(\eta R\sigma)^{2}\left(\frac{\gamma}{K\sigma}\right)^{2}\left(\frac{R}{\sigma}\right)^{2}}\right]\phi(\Delta)d\Delta$$

$$=\frac{2}{3}\pi\int_{0}^{\infty}\left[A_{0}R_{0}^{0.5}\Delta^{1.5}+3\pi A_{0}B_{0}R_{0}+\sqrt{6\pi A_{0}^{2}B_{0}R_{0}^{1.5}\Delta^{1.5}+9\pi^{2}A_{0}^{2}B_{0}^{2}R_{0}^{2}}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^{2}}{2}\right]d\Delta$$

3. Results and Discussion

Tayebi and Polycarpou [5] have done extensive study on polysilicon MEMS surfaces and four different MEMS surface pairs. Here, surface roughness, surface energy, and material parameters of the clean and smooth MEMS surfaces are being considered for present study as input data as given in Table.1.The material properties of MEMS surface samples are modulus of elasticity, $K = {}^{4}/_{3}E$ = 112 GPa, modulus of rigidity, G = 18.42 GPa hardness, H = 12.5 GPa, and poisions ratio, $\nu_1 = \nu_2 = 0.22$

Johnson et.al. first mentioned that deformation of spherical contact would be greater than the deformation predicted by Hertzian spherical contact. It is mentioned that only attractive adhesive force acts within Hertzian contact area and it increases deformation of sphere resulting higher contact area. From Fig.2, dimensionless real area of contact increases with decrement of dimensionless mean separation exponentially. It is found that maximum real areas of contact for the all cases of MEMS surfaces increase as smoothness of MEMS surfaces increase. Dimensionless real area of contact for super smooth MEMS surface is very high almost near to the apparent area of contact due to presence of strong attractive adhesive force. On the other hand, real area of contact is very small for the rough MEMS surface contact.

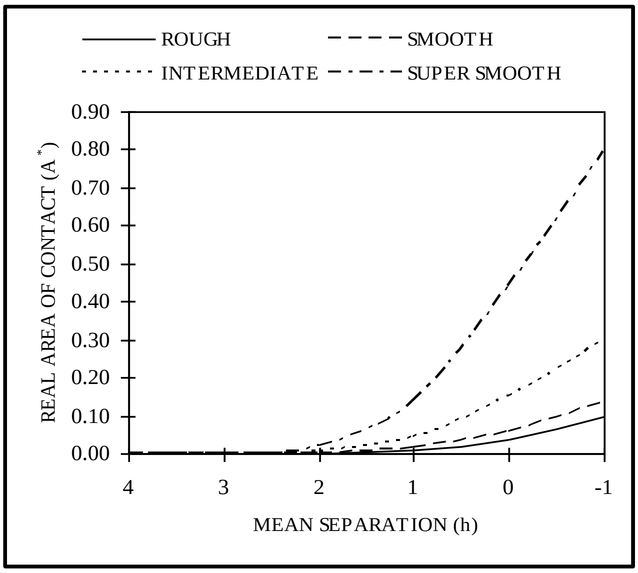

Fig.2 Real area of contact

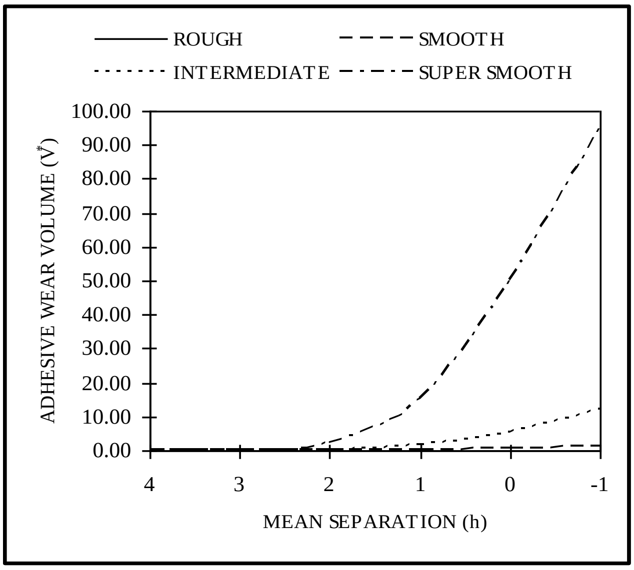

Fig.3 Adhesive wear volume

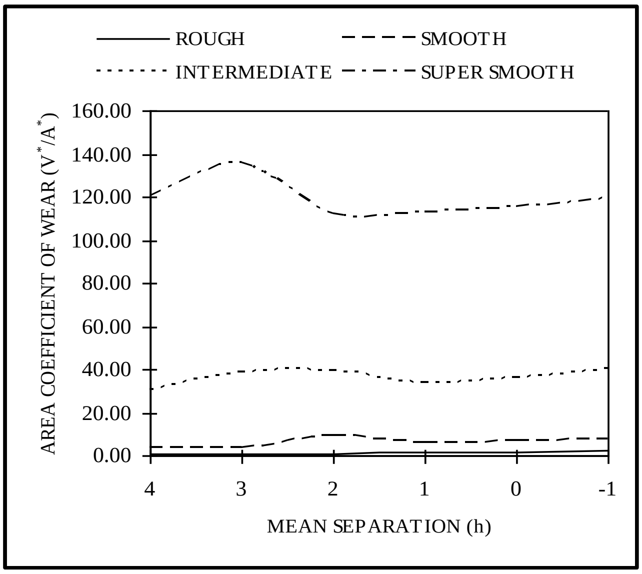

Fig.4 Area coefficient of wear

Fig.3 depicts variation of adhesive wear volume with mean separation. It is found that maximum adhesive wear volume for the all cases of MEMS surfaces increase as smoothness of MEMS surfaces increase. So, super smooth MEMS surface produces maximum adhesive wear volume whereas rough MEMS surface produces very low adhesive wear volume. Fig.4 shows area coefficient of wear verses dimensionless mean separation. This coefficient is considered to understand the relationship in between real area of contact and wear volume. From the nature of curves, it is found that dimensionless adhesive wear volume is almost linearly proportional with dimensionless real area of contact. So, area coefficient of wear is almost constant.

So, Area coefficient of wear $= \frac{V^*}{A^*} = \frac{V}{A\sigma} = K_{adh}$

$$\text{or,}\quad V = K_{ad} A\sigma$$

Considering yielding of asperity of asperity tip due to loading force, real area of surface contact, $A = \frac{P}{H}$

So, $V = K_{adh}\frac{P}{H}\sigma$

where V= Wear volume, K_{adh} = adhesive wear coefficient (i.e. area coefficient of wear), P = loading force (i.e. Contact force), H = soft material hardness, σ = rms roughness of surface

According to new adhesive wear law, adhesive wear coefficient increases with increment of MEMS surface contact. And K_{adh} = 0.25 for rough surface, K_{adh} = 5 for smooth surface, K_{adh} = 30 for intermediate surface, and K_{adh} = 120 for super smooth surface.

Now, wear rate, $\dot{V} = V \times$ no. of pass per revolution × RPS $= V \times n_p \times RPS$

Generally, Pin on Disk tester are commonly used to measure wear rate. If circular cross sectional pin of diameter, d is placed on disk at diameter, D,

no. of pass per revolution, $n_p = \frac{\text{Total area crossed}}{\text{Cross sectional area of pin}} = \frac{\pi Dd}{\pi d^2/4} = 4\frac{D}{d}$

In comparison of new adhesive wear law with Archard's law of adhesive wear, the new law is much more appropriate from the point view of volume concept. In case of well accepted Archard's law of adhesive wear, sliding distance is on the plane of real area of contact and so, how does multiplication of both the two parameter produce volume whereas in case of new law of adhesive wear, r.m.s. roughness perpendicular to the plane of real area of contact which produces volume removal in the form of adhesive wear.

Now, let us see the interrelation in between new adhesive wear law and existing Archard's adhesive wear law. Archard's adhesive wear law was developed from single asperity contact directly as follows;

Elementary wear volume of hemispherical shape of wear particle, $V_a = \frac{2}{3}\pi a^3 = \frac{1}{3}(\pi a^3).(2a)$

=1/3 Area of contact of asperity × sliding distance of asperity

Now, for multiasperity contact of rough surface, we have wear volume; V=K_{adh}.Real area of contact×Apparent sliding distance $= K_{adh}A.L = K_{adh}\frac{P}{H}L$

First, Archard have developed interrelation of wear volume with real area of contact and apparent sliding distance but wear volume could not be calculated theoretically because coefficient of adhesive wear have to be quantified experimentally. Experimentally, it is found that coefficient of adhesive wear is of the order of 10^{-6} to 10^{-9}. Actually, for unit meter sliding distance, $K_{adh}.L$ is real sliding distance of truncated asperities only which is of the order of 10^{-6} to 10^{-9} m. In comparison with new adhesive wear law, real sliding distance is the parameter of rms surface roughness (σ) which is also of the order of 10^{-6} to 10^{-9} m. So, new adhesive wear law is an alternative law of adhesive wear by which wear volume could be calculated theoretically.

4. Conclusion

Finally, alternative adhesive wear theory could be developed according to Mindlin's concept of stick-slip mechanism as follows.

- Microscopically, when two rough surfaces come in contact, spherical tip of asperity would deform elastically and it will stick and cold weld at the contact zone due to interatomic adhesive force under loading condition.
- Subsequent impending sliding produces maximum frictional traction at the junction of asperity contact. After maximum limit, it would slip radialy inward at the circular contact zone of asperity and correspondingly, real area of contact of asperity decreases producing ultimate gross slip / sliding.
- During slipping, if shearing strength at asperity junction is much more than bulk shear strength of one of the surface, fragment of material would be removed from the softer surface. As a result one adhesive wear particle would be formed.

- At the end of one pass of sliding, volume of adhesive wear would be proportional to Real area of contact × rms roughness. It would be of the order of nm^3 to μm^3.
- So, Adhesive wear rate is linearly proportional to real area of contact (= Load / Hardness), rms roughness and no. of pass per unit time.

References

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Table.1 Input data

Combined MEMS Surfaces	**Rough**	**Smooth**	**Intermidiate**	**Super Smooth**
Asperity density η (m^{-2})	$14.7.10^{12}$	$11.1.\ 10^{12}$	17.10^{12}	26.10^{12}
Asperity radius R (m)	$0.116.10^{-6}$	$0.45.10^{-6}$	$1.7.10^{-6}$	26.10^{-6}
Stadandard deviation of asperity height σ (m)	$15.8.10^{-9}$	$6.8.10^{-9}$	$1.4.10^{-9}$	$0.42.10^{-9}$
Surface energy γ (N/m)	0.5	0.5	0.5	0.5
Modulus of elasticity K (N/m^2)	112.10^9	112.10^9	112.10^9	112.10^9
Modulus of rigidity G (N/m^2)	$18.42.10^9$	$18.42.10^9$	$18.42.10^9$	$18.42.10^9$
Roughness parameter A_0	27.10^{-3}	34.10^{-3}	41.10^{-3}	53.10^{-3}
Surface energy parameter B_0	$2.825.10^{--4}$	$6.565.10^{--4}$	$31.887.10^{--4}$	$74.405.10^{—4}$
Asperity radius parameter R_0	7.342	66.176	1214.285	5600.000