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Interrelation of Friction-Wear and Mechanism of Energy Dissipation for MEMS Application

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ABSTRACT
Adhesion is a predominating force in Micro electro mechanical System (MEMS) due to high surface to volume ratio. In the present study of MEMS surfaces contact, adhesional friction force and adhesive wear volume have been computed numerically and new interrelation in between the wear and friction is developed after, finding their ratio. Also, mechanism of energy dissipation has been summarized on the basis of Arrhenius theory of mechanochemical reaction under working condition of MEMS devices.

Keywords: *Friction force, Wear volume, Coefficient of friction-wear, Energy dissipation*

I. INTRODUCTION

First of all, Leonardo da Vinci, 1500, studied the friction phenomenon by examining the coefficient of static friction on an inclined plane and developed laws of friction. Thereafter, Amonton, 1699 [1] performed several experiments of unlubricated solids and concluded first two classical laws of friction, according to which the friction force is proportional to the load and does not depend on the apparent contact area. At the same time, Desagulier, 1725 [2] studied friction phenomenon in case of very smooth surface contact and added that it is found by experience, the flat surfaces of metals may be so far polished as to increase friction due to intermolecular adhesion. So, he proposed adhesion as a further cause of friction. The adhesion hypothesis appeared to contradict with the idea that friction is independent of contact area, therefore most scientists rejected Desagulier's proposal at that time. Thereafter, Bowden and Tabor realized that the old conflict between Amonton’s law and Desagulier’s adhesive concept of friction. Bowden and Tabor, 1950 [3] introduced the concept of real area of contact to explain law of friction. According to simple adhesion theory of friction, when two rough surfaces come in contact, they are cold welded by plastic deformation of asperities and produces frictional resistance at interface. Predicted coefficient of friction is 0.2 which is the ratio of shear stress to hardness of material. This is true for very soft surface contact where asperities are naturally cold welded by plastic deformation. On the other hand, Bera 2013 [4][15] has developed adhesional friction theory for smooth and hard surface contact like adhesive MEMS surfaces. In the new adhesional friction theory for the smooth and hard surface contact, it is assumed that all asperities are cold welded due to intermolecular adhesion at the elastically deformed asperity contact zones and produce frictional resistance under full stick condition of without junction growth. It is found that normal loading stress and tangential friction stress are not constant and decreases with the decrease of mean separation of two surfaces keeping constant value of coefficient of friction. Also, it is reported that coefficient of friction increases with increase of smoothness of contact surfaces which supports the Desagulier's adhesive concept of friction.

Simultaneously, there are development of adhesive wear law and theory with progress of friction law and theory. Holm, 1958 [5] first proposed that wear was an atomic transfer process occurring at the real area of contact formed by plastic deformation of the contacting asperities. He developed the expression of wear rate considering real area of contact and the atomic layer transfer per encounter. Performing extensive experiments under the various combinations of material, Burwel and Strang, 1952 [6] confirmed that the simple wear law predicted by Holm could be applied in many operating conditions. However, they did not accept the concept of material removal in individual atomic encounter and they concluded that an equation for the volume of material is multiplication of wear coefficient, area of contact of asperity and sliding distance of asperity. Archard’s hypothesis (Archard, 1953) [7] enables one to distinguish between the various possible mechanism of wear followed by a layer or lump material removal. Considering, wear volume of hemispherical shape of a wear particle, he found also, that wear volume is the multiplication of wear coefficient, area of contact of asperity and sliding distance of asperity. Still, now, Archard’s adhesive wear law is well accepted but it does not quantify the adhesive wear volume theoretically as wear coefficient have to be determined experimentally. On the other hand, Bera 2013 [8][14] studied adhesive wear theory of micromechanical Surface Contact. Cconsidering cold welding of asperities by elastic deformation, 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 new adhesive wear law has been developed for one pass of sliding mentioned as follows;

Wear volume = Wear coefficient × Area of contact of asperity × rms surface roughness

In the present study, it is focused to develop the interrelation in between adhesional friction force and adhesive wear volume, and the new relationship has been mentioned for MEMS application. Thereafter, mechanism of energy dissipation has been described newly on the basis of Arrhenius theory of chemical-mechanical reaction of the two MEMS surface contact.

II. MATERIALS AND METHOD

2.1 Interrelation of friction and wear

2.1a Adhesional friction force

Adhesion is a predominating force in Micro electro mechanical System (MEMS) due to high surface to volume ratio. As MEMS surfaces are running under lightly loading condition, so, it is assumed that all asperities of MEMS surfaces would deform elastically and is cold welded by JKR adhesion theory [9]. Then due to the application of tangential force under running condition, energy stored by the MEMS pair would reach to maximum and produces adhesional friction which could be quantified by Savkoor and Briggs friction theory [10]. As asperity tip is considered spherical, the adhesion model of single asperity contact could be extended to multiasperity rough surface contact on the basis of Greenwood and Williamson model [11]. Corresponding adhesional friction force for multiasperity MEMS surface contact (T) is given by following equation;

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

Dividing both side by A_nK, dimensionless adhesional friction force (T^*),

$$T^* = \int_{0}^{\infty}\left[\frac{4}{\sqrt{\left(K/G\right)}}\sqrt{2\pi(\eta R\sigma)^{2}\left(\frac{\gamma}{K\sigma}\right)\left(\frac{R}{\sigma}\right)^{-0.5}\Delta^{1.5} + 3\pi^{2}(\eta R\sigma)^{2}\left(\frac{\gamma}{K\sigma}\right)^{2}}\right]\phi(\Delta)\,d\Delta$$

$$= \int_{0}^{\infty}\left[\frac{4}{\sqrt{\left(K/G\right)}}\sqrt{2\pi A_0^{2}B_0R_0^{-0.5}\Delta^{1.5} + 3\pi^{2}A_0^{2}B_0^{2}}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^{2}}{2}\right]d\Delta \qquad (2.1)$$

2.1b Adhesive wear volume

Under normal loading condition of MEMS surface, asperities of MEMS surfaces are cold welded by elastic deformation following JKR adhesion theory [9], and if a wear particle is in the shape of hemispherical and is cut off from tip of the asperity through shearing of cold welded junction, total wear volume for multiasperity MEMS surface contact (V) could be given by the following equation;

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

Dividing both side by $A_n\sigma$, dimensionless adhesive wear volume (V^*)

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

$$= \frac{2}{3}\pi\int_{0}^{\infty}\left[A_0R_0^{0.5}\Delta^{1.5} + 3\pi A_0B_0R_0 + \sqrt{6\pi A_0^{2}B_0R_0^{1.5}\Delta^{1.5} + 9\pi^{2}A_0^{2}B_0^{2}R_0^{2}}\right]\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{(h+\Delta)^{2}}{2}\right]d\Delta \qquad (2.2)$$

where $\frac{1}{K} = \frac{3}{4}\left(\frac{1-\nu_1^{2}}{E_1} + \frac{1-\nu_2^{2}}{E_2}\right)$, $\frac{1}{G} = \frac{2-\nu_1}{G_1} + \frac{1-\nu_2}{G_2}$, E_1, E_2, ν_1 and ν_2 are Young's modulus and Poisson's ratios of the contacting surfaces respectively, surface energy of both surfaces, $\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$, Dimensionless surface roughness parameter, $A_0 = \eta R\sigma$ and Dimensionless surface energy parameter,

$B_0 = \frac{\gamma}{K\sigma}$, and here Δ = dimensionless asperity deformation, h = dimensionless mean separation, η = asperity density, R = asperity radius, σ = rms surface roughness, γ = surface energy, and φ(Δ) = Gaussian distribution function of asperity height. Details of formulation and input data are available from earlier papers [4][8][14][15].

On the basis of numerical simulation of the Eqs. (2.1) and (2.2) by Fortran Programming, results for adhesional friction force and adhesive wear volume has been shown in Tables (2.1) and (2.2) respectively. Now, from the ratio of dimensionless average wear volume to dimensionless average adhesional friction force, we get

$$\frac{V^*}{T^*} = \frac{\frac{V}{A_n\sigma}}{\frac{T}{A_nK}} = \frac{VK}{T\sigma} = \text{Cons} \quad \tan \quad t$$

As modulus of elasticity, K is constant for all the Silicon based MEMS pairs, so, by replacing the value of modulus of elasticity, K and normalized by rms surface roughness, σ, as shown in Table [2.3], we get the following form of equation;

$$\frac{V}{T\sigma^2} = \psi = \text{Cons} \quad \tan \quad t$$

$$\text{or}, \ V = \psi T \sigma^2 \qquad (2.3)$$

where ψ is the coefficient of friction-wear and it has unit of $\frac{1}{n/m}$.

Table 2.1 Friction force data

	Mean Separation	Rough	Smooth	Intermediate	Super Smooth
Dimensionless Friction Force (T^*)	4	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	3	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	2	1.00000E-05	1.00000E-05	2.00000E-05	6.00000E-05
	1	3.00000E-05	4.00000E-05	1.20000E-04	3.30000E-04
	0	7.00000E-05	9.00000E-05	2.50000E-04	6.80000E-04
	-1	6.00000E-05	7.00000E-05	2.00000E-04	5.40000E-04
Average value		2.83333E-05	3.50000E-05	9.83333E-05	2.68333E-04

Table 2.2 Wear volume data

	Mean Separation	Rough	Smooth	Intermediate	Super Smooth
Dimensionless Wear Volume (V^*)	4	0.000	0.000	0.000	0.003
	3	0.000	0.000	0.010	0.122
	2	0.000	0.006	0.178	2.088
	1	0.013	0.066	1.388	15.021
	0	0.074	0.339	5.283	50.250
	-1	0.234	1.020	11.960	94.590
Average value		0.054	0.239	3.136	27.012

Table 2.3 Coefficient of friction-wear

MEMS Pair	Avg Wear Volume (V^*)	Avg Friction Force (T^*)	Ratio of Wear to Friction (V^*/T^*)
Rough	0.054	2.83333E-05	1,892.471
Smooth	0.239	3.50000E-05	6,816.857
Intermediate	3.136	9.83333E-05	31,895.305
Super Smooth	27.012	2.68333E-04	1,00,666.988
MEMS Pair	Modulus of Elasticity (K)	Surface Roughness (σ)	Normalized Ratio of Wear to Friction ($V/T\sigma^2=\psi$)
Rough	1.12E+11	1.58E-08	1.069
Smooth	1.12E+11	6.80E-09	8.951
Intermediate	1.12E+11	1.40E-09	203.414
Super Smooth	1.12E+11	4.20E-10	2140.029

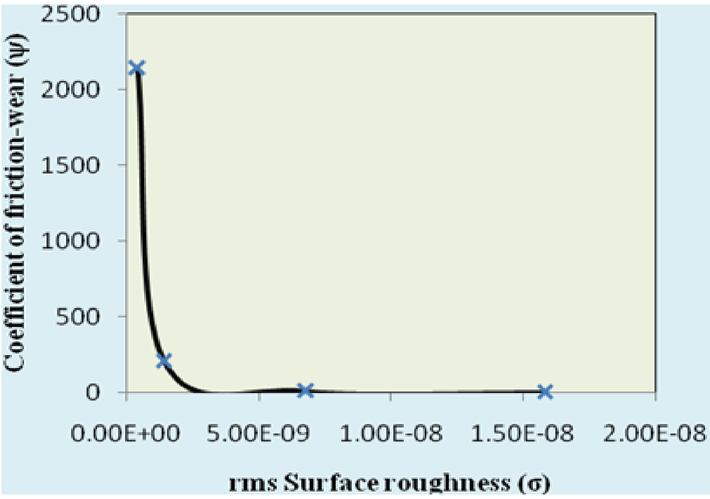

Fig.2.1 Coefficient of friction-wear

Fig.2.1 shows the variation of coefficient of friction and wear with surface roughness for the four MEMS surface pair. It is found that the coefficient increases as smoothness of MEMS surfaces increase. Up to intermediate smoothness of MEMS surface, the coefficient is very small but thereafter, it increases significantly. It indicates adhesive wear volume is nonlinearly proportional with the adhesional friction force for smooth and hard MEMS surfaces contact. Above relationship for Eq.(2.3) predicts wear volume directly, from friction force if surface roughness of the tribo-pair is known.

2.2 Mechanism of energy dissipation

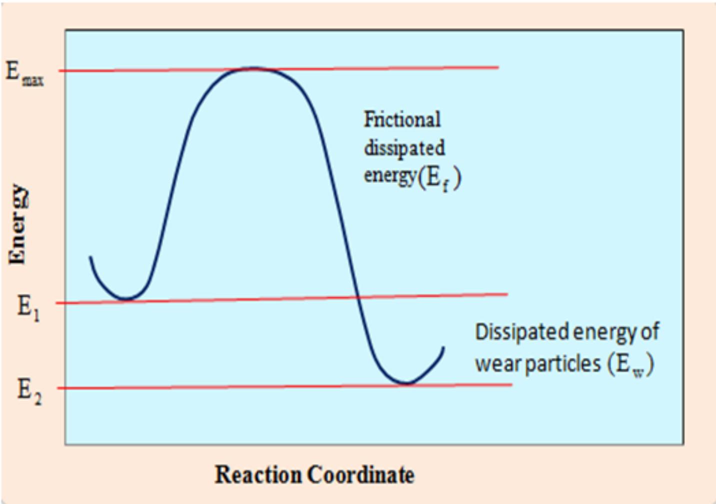

Fig.2.2 Mechanism of energy dissipation

Mechanism of energy dissipation of the MEMS surface contact could be explained on the basis of Arrhenius theory of mechanochemical reaction as shown in Fig.2.2. According to Greenwood and Williamson model, two rough surfaces contact could be considered as a equivalent rough surface contact with a flat surface. Now under normal loading condition, when a flat surface comes contact with a rough surface, strain energy (E_1) would be stored by elastic deformation of asperities of the rough surface according to JKR adhesion theory [9]. Now if tangential force is applied gradually, more strain energy would be stored by elastic deformation of asperities of the rough surface and it reaches to the maximum value of energy (E_{max}) under full stick condition which arises a frictional instability at the interface and SB adhesional friction [10]. Then the system jumps abruptly to another configuration producing gradual slip at asperities interface and releases elastic energy into irregular heat, light, and sound energy, and wear particles from the interface. Thereafter, the system reaches to the energy level, E_2.

After all, the energy state of mechanochemical reaction could be written as follows;

$$E_1 = E_2 + E_w$$

$$E_{max} = E_1 + E_{acv} = E_2 + E_w + E_f$$

where $E_{acv} = E_f$

E_1=initial system energy due to normal loading
E_2=final system energy after energy dissipation
E_{acv}=activation energy supplied by tangential loading
E_{max}=maximum stored energy of the system
E_f=frictional dissipated energy
E_w=dissipated energy of wear particles
E_t=total dissipated energy

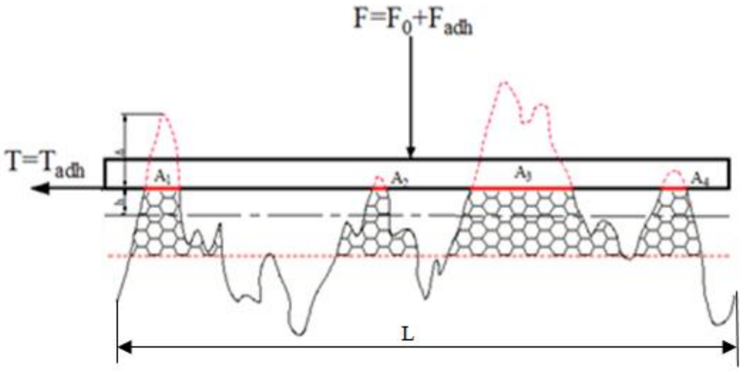

Fig.2.3 Wear particles at surface contact zone

Total dissipated energy is the sum of the frictional dissipated energy and dissipated energy of wear particles.
So, frictional dissipated energy, $E_f = TL$
where T =friction force and L=sample length of rough surface

Now, from the thermodynamics point of view, dissipated energy of a hemispherical wear particle is the sum of volume energy and surface energy.

So, $E_{wa} = \frac{2}{3}\pi a^3 \Delta G_v + 3\pi a^2 \gamma$

(2.4)

Where a=radius of a hemispherical wear particle, ΔG_v= Gibbs free energy of a wear particle, and γ=surface energy of a wear particle

Under stable equilibrium condition of the wear particle, total dissipated energy of the wear particle would be maximum.

So , $\frac{dE_{wa}}{da} = 0$

hence, $2\pi a^2 \Delta G_v + 6\pi a \gamma = 0$

or , $\Delta G_v = -3\frac{\gamma}{a}$

Substituting above value in Eq^n. (2.4), we get that

$$E_{wa} = \frac{2}{3}\pi a^3\left(-3\frac{\gamma}{a}\right) + 3\pi a^2\gamma = \pi a^2 \gamma$$

So , E_{wa} = Base area of single asperity $\times$ Surface energy

With direct correlation of single asperity contact with multiasperity contact, we can write;

Dissipated energy of wear particles = Real area of contact $\times$ Surface energy

or , $E_w = A\gamma$

Now, total dissipated energy, $E_t = TL + A\gamma$

or, rate of dissipated energy, $\dot{E}_t = TU + A\gamma \frac{U}{L}$

Substituting, $T = A\tau$ and $s = \frac{\gamma}{L}$, where, τ = Shear stress due to friction force, and s = Normal stress due to adhesive surface force, A=real area of contact, F=normal force and Y= yield stress, we get,

$$\dot{E}_t = A\tau U + AsU$$
$$\text{or},\ \dot{E}_t = AU(\tau + s)$$
$$\text{or},\ \dot{E}_t = FU\left(\frac{\tau}{Y} + \frac{s}{Y}\right),\ \left(\text{Substituating}\ A = \frac{F}{Y}\right)$$
$$\text{or},\ \dot{E}_t = FU(\mu + \phi)$$

where, A=real area of contact, F=normal force, Y= yield stress, μ = usual coefficient of friction force, and φ = coefficient of adhesive force

Also, it could be stated that frictional energy (E_f) should be proportional with energy barrier (E_w) due to adhesion at interface of tribo-pair. So, it could be written as

$$\text{Frictional energy} \propto \text{Energy barrier}$$

$$\text{or},\ TL \propto A\gamma$$
$$\text{or},\ T \propto A\frac{\gamma}{L}$$
$$\text{or},\ A\tau \propto As$$
$$\text{or},\ \tau \propto s$$
$$\text{or},\ \mu \propto \phi$$

When external force acts on two mating MEMS surfaces under relative motion, real area of contact is formed by asperity deformation to support the external force and then, intermolecular surface forces arise tangential and normal direction which cause tangential frictional stress and normal adhesive stress at the interface respectively. Total energy dissipates due to overcome resistance in both the two direction in the form of frictional energy dissipation and wear particle energy dissipation respectively. Actually, during rubbing of MEMS surfaces, shearing of asperity junctions occur in a 45^0 incline direction at the interface considering ideal situation according to Mohr's circle stress analysis.

Now, effective coefficient of friction for MEMS application as proposed by Bera, 2013 [4],

$$\mu_e = \frac{\text{Friction force}}{\text{External force} + \text{Adhesive force}}$$
$$= \frac{\tau A}{YA + sA}$$
$$= \frac{\tau}{Y + s}$$
$$= (1 + \phi)^{-1}\mu$$

In exceptional case, if adhesive force is almost zero in between two contact surfaces, coefficient of adhesive force (φ) reaches to zero; i.e., effective coefficient of friction (μ_e) equals to usual coefficient of friction (μ). Practically, this occurs in human synovial joint where hydrophobic bonding of Glycoprotein bilayer and Phospolipid bilayer of synovial boundary lubricants produces almost zero adhesion in between two cartilage surfaces contact and produces human synovial joint is almost frictionless [12].

III. CONCLUSION

Interrelation in between friction and wear have been developed through numerical simulation of multiasperity contact for MEMS application. It is found that wear volume per single pass equal to multiplication of coefficient of friction-wear, friction force and surface roughness square. It could be given by following expression:

$$\text{Wear volume} = \text{Coefficient of friction\_wear} \times \text{Friction force} \times \text{Surface roughness square}$$

This is a new expression to find the wear volume per single pass directly from the friction force if the coefficient and surface roughness are taken justifiably. Also, very important mechanism of friction-wear for the MEMS device has been illustrated on the basis of Arrhenius theory of mechanochemical reaction of rubbing. It is concluded that eenergy nergy of the tribo-system is actually, dissipated by the combination of frictional energy (as activation energy) and energy of wear particles (i.e. energy barrier) Also, it came to know that intermolecular adhesion is the cause of friction for MEMS surface contact as it was hinted by Desagulier, 1725.

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Appendix

Input Data

Tayebi and Polycarpou, 2006 [13] 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. The material and tribological properties of one MEMS surface sample are modulus of elasticity, $K = {}^4/_3E$ = 112 GPa, modulus of rigidity, G = 18.42 GPa hardness, H = 12.5 GPa, poisons ratio, $\nu_1 = \nu_2 = 0.22$, and surface energy γ (N/m) = 0.5 N/m.

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