Small-Scale Adhesive Wear Behavior of Rough Solids in the Presence of Adhesion

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ABSTRACT

Wear has been studied in great detail both theoretically and experimentally and a plausible wear equation based on physical observations exists. However, an analytical approach to predict wear taking into account the surface characteristics is rare. In addition to the surface topographic effect, the effect of adhesion between solids arising out of surface forces that operate at short distances needs investigation. The paper describes analysis of wear between rough solids taking into consideration the effect of both the surface forces and surface roughness and also considering that asperities may deform at the contact either elastically or plastically. The well-established elastic and plastic adhesion indices are used to consider the different conditions that arise as a result of varying surface and material properties.

Key Words: adhesive wear, adhesion, roughness.

1. INTRODUCTION

In recent years, due to the rapid progress in the development of micro-machines, micro-electro-mechanical-systems (MEMS), nano-electro-mechanical-systems (NEMS) and high density magnetic storage systems, it has become increasingly important to study the friction and wear phenomena in the nanometric scale and under ultra-low loads, since in the above applications the sliding surfaces are inherently smooth and loads are very small. Adhesion force arising out of the surface forces acting between the contacting or near-contacting surfaces may dominate wear behavior of such systems. Despite the need of modeling wear in such

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situations, researchers /1-5/ have largely relied on careful experimentation using AFM (atomic force microscope), FFM (friction force microscope) etc. Archard's linear wear law /6/, based on simple observation, is probably the most successful one in predicting general engineering scale wear and is essentially based on the classical concept of junction growth proposed by Bowden and Tabor /7/. The basic idea is that the 'welded' junctions are formed at the peaks of the asperities due to high-localized pressure and the subsequent shearing of the junctions within the weaker material gives rise to material removal. The fundamental cause of the junction formation is still unclear and no valid correlation between adhesive wear and adhesion between solids arising out of surface forces has been proposed.

In principle, when two smooth and clean surfaces are brought together surface molecular forces come into operation and a finite force is required to separate the surfaces or to cause sliding. The forces are conveniently expressed in terms of surface energy per unit area that equals the work done in separating the surfaces. The effect of surface forces on the contact configuration between solids and their roughness characteristics has been studied in great details both theoretically and experimentally /8-14/. A good deal of theoretical studies have also been carried out to understand the friction and wear process at the atomic scale /15/. The Independent Oscillator (IO) model /16/ to explain wear-less friction and large-scale molecular dynamics simulations of atomistic mechanisms of adhesion, friction and wear has cleared some of our basic doubts in understanding the small-scale contact phenomena. The simulations are able to provide details of contact models and processes, connective neck formation, atomic scale stick-slip, material-transfer and wear processes. A need for predicting wear rate at small levels of asperity interactions within the continuum concept still arises, and in any such analysis surface energy effect must be taken care of due to the extremely small separation between the surfaces. The present work attempts to analyze adhesive wear mechanism at the contact between surfaces with nanometric level asperities under low load conditions taking into account the effect of surface forces at the contact.

2. ADHESION BETWEEN ROUGH SURFACES

There are two basic competing adhesion models for the contact between an elastic sphere of radius R and a rigid flat. Johnson, Kendall and Roberts /8/ developed one of the two basic adhesion models, widely known as JKR model which assumes that the contact area increases beyond that predicted by the Hertzian contact theory when the surface forces at the contact are taken into account. The force required to separate the bodies in this case is given by $1.5\pi R\gamma$, where γ is the work of adhesion given by $\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$, with γ_1 and γ_2 being the surface energy for the two surfaces and γ_{12} their interfacial energy. Derjaguin, Muller and Toporov /17/ presented the other basic adhesion model widely known as the DMT model assuming that the attractive surface forces are exerted outside the contact area. Deformation may be predicted by a Hertzian equation and the area of contact is unaffected by the surface forces. The pull-off force according to this model is given by $2\pi R\gamma$. Although the pull-off forces predicted by the two theories are comparable the analytical models based on the two theories differ significantly owing to the difference in their basic assumptions. Muller *et al.* /18/ pointed out that the two models are the limiting cases of a general solution depending on the value of a parameter $\phi_0 = \left(R\gamma^2 / E^2 Z_0^3\right)^{1/3}$, where Z_0 is the inter-atomic distance and the equivalent elastic modulus E is given by $E = \left[\frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2}\right]^{-1}$; E_1, E_2 and υ_1, υ_2 being the elastic moduli and Poisson's ratios of the contacting surfaces respectively. The DMT model is applicable if $\phi_0 < 0.3$ and the JKR model holds if $\phi_0 > 3$. It can be seen that the DMT model is favored for small values of R and γ and large values of E. Both surface roughness and cleanliness affect the adhesion between solids significantly. Fuller and Tabor /12/ demonstrated that roughness reduces adhesion considerably and the effect of surface roughness is described in terms of an elastic adhesion index that may be defined in the present notation as $\theta = K\sigma^{3/2}R^{1/2} / \gamma R$, with K=4E/3. The index is merely a ratio of the elastic force needed to push a sphere of radius R to a depth σ into an elastic solid of equivalent modulus of E to the surface force experienced by the sphere. Johnson /19/ likewise introduced an adhesion index for plastic deformation assuming an exponential distribution of asperity heights. This may be defined as $\lambda = \pi^2 RH^4\sigma / (18K^2\gamma^2)$, in the present notation where H is the hardness of the softer material. Limiting values of θ and λ are usually quoted as 10 and 0.125 respectively, beyond which the effect of surface roughness becomes significant, causing a reduction in adhesion.

In loading analysis it is considered that surfaces will always have some asperities elastically loaded and some fully plastically loaded. This is based on Greenwood and Williamson's /20/ postulate that the average size of a micro-contact is almost constant and is independent of load. The proportionality of real area of contact to normal load arises more from the statistics of asperity height distribution rather than the mode of asperity deformation. Following the analysis of Johnson *et al.* /8/ of contact between a smooth sphere and a flat in the presence of surface forces, the load on an elastically deformed asperity is given by

$$P_0 = \frac{Kr^3}{R} - \left(6\pi\gamma Kr^3\right)^{1/2} \tag{1}$$

where r is the contact radius.

The load on a plastically deformed asperity may be obtained from an energy balance criterion at the contact /13/ and is given by

$$P_p = \pi r_p^2 H - 2\pi R\gamma \tag{2}$$

where r_p represents the contact radius during plastic loading, H the hardness and from geometric considerations $r_p = (2R\delta)^{1/2}$ with δ being the deformation of the asperity.

Plastic deformation will start simply when

$$\frac{P_0}{\pi r^2} \geq H \tag{3}$$

Replacing the radius of apparent Hertzian contact of a small-scale asperity by $(R\delta_1)^{1/2}$ and combining equations (1) and (3), we get,

$$KR^{1/2}\delta_1^{3/4} - (6\pi K\gamma)^{1/2} R^{3/4} - H\pi R\delta_1^{1/4} > 0 \tag{4}$$

Here δ_1 represents apparent displacement due to an apparent Hertz load P_1 given by $P_0 + \left(6\pi K\gamma r^3\right)^{1/2}$ and following Johnson /19/ this may be expressed in terms of actual displacement δ by

$$\delta_1 = \delta + \frac{2}{3}\left(\frac{6\pi\gamma r}{K}\right)^{1/2} \tag{5}$$

The equation (4) gives a plasticity condition and may be solved to give the critical value of asperity-displacement δ_{C1}, which distinguishes between the elastically and plastically deformed asperities. Considering now the contact between a rigid smooth surface and a rough deformable surface with a Gaussian distribution $\phi(z)$ of asperity height z such that the separation between the mean plane and flat surface during loading is d, we have

$$\phi(z) = \frac{1}{\sigma(2\pi)^{1/2}} e^{-z^2/2\sigma^2} \tag{6}$$

where the actual displacement $\delta = z - d$

If N is the number of asperities per unit area of the rough surface, the total applied load on all the asperities per unit area is given by

$$P_a = N\int_{d}^{d+\delta_{c1}}\left[\frac{Kr^3}{R} - \left(6\pi\gamma Kr^3\right)^{1/2}\right]\phi(z)\,dz + N\int_{d+\delta_c}^{\infty}\left[\pi r_p^2 H - 2\pi R\gamma\right]\phi(z)\,dz \tag{7}$$

where δ_{c1} and δ_c are the apparent and actual critical displacements respectively. Here the 1st integral represents the elastic contribution and the 2nd integral represents the plastic contribution to total load. The expression for applied load can be written in non-dimensional form in terms of adhesion indices θ and λ as

$$\bar{P}_a = \int_{\Delta_0}^{\Delta_{c1}} \left[\Delta^{3/2} - (4.34)\frac{\Delta^{3/4}}{\theta^{1/2}} \right] \bar{\phi}(\Delta) d\Delta + \int_{\Delta_c}^{\infty} \left[(7.3)\frac{\lambda^{1/4}\Delta}{\theta^{1/2}} - \frac{6.28}{\Delta} \right] \bar{\phi}(\Delta) d\Delta \quad (8)$$

where

$$\bar{P}_a = \frac{P_a (2\pi)^{1/2}}{KNR^{1/2}\sigma^{3/2}}; h = \frac{d}{\sigma}; \Delta = \frac{\delta}{\sigma}; \bar{\phi}(\Delta) = e^{-(h+\Delta)^2/2}$$

Δ_o and Δ_{c1} are the non-dimensional apparent displacement corresponding to actual displacements $\delta = 0$ and $\delta = \delta_c$ respectively. With these substitutions equations (4) and (5) may be written as

$$\Delta_{c1}^{3/4} - (3.65)\frac{\lambda^{1/4}}{\theta^{1/2}}\Delta_{c1}^{1/4} - \frac{4.34}{\theta^{1/2}} \geq 0 \quad (9)$$

and

$$\Delta_1 = \Delta + \frac{2.89}{\theta^{1/2}}.\Delta_1^{1/4} \quad (10)$$

Δ_o and Δ_c to be used in equation (8) then reduce to

$$\Delta_o = 4.125/\theta^{2/3} \quad (11)$$

and

$$\Delta_c = \Delta_{c1} - \frac{2.89}{\theta^{1/2}}\Delta_{c1}^{1/4} \quad (12)$$

Equation (11) is obtained from equation (10) by substituting $\Delta = 0$ and $\Delta_1 = \Delta_o$. Equation (12) is obtained from equation (10) by substituting $\Delta = \Delta_c$ and $\Delta_1 = \Delta_{c1}$.

3. PREDICTIONS OF SMALL-SCALE WEAR

Although predictions of small scale wear rate of the sliding or rotating parts in micro-machines and other such applications are important, there exists no separate theory for such predictions. As discussed earlier, the results of a number of sophisticated experimental studies /1-4/ using AFM, FIB (focussed ion beam) and FFM are not conclusive enough to develop a wear theory on the nanometric level. While the adhesion or pull-off forces are important in the contact phenomena at this level the wear mechanism does not seem to be clear. Although the evidence from macro and micro-scale experiments on adhesive wear demonstrates the formation of micro-welds at the asperity peaks theoretically there can be no objection in the formation of 'nano-welds'. The small-scale welded junctions may form by the same mechanism as that responsible for asperity peak junctions on typical engineering surfaces. Since the diffusion process is not scale dependent and the concentration gradient is an important factor, nano-scale welded junctions may ideally form by molecular diffusion process. Indeed in some experiments by Ando /3/ deposits of wear debris and wear craters were observed on steel ball surfaces even at low loads (of the order of a few μN) and very smooth surfaces (roughness a few nm). It therefore seems that the wear mechanism on the nano-scale may include typical adhesive wear with nano-scale 'welded', surface force induced junction-formation at the asperity peaks and their subsequent tearing or even abrasive ploughing if one of the rubbing surfaces carries hard asperities, for example, the diamond tip rubbing against silicon surfaces in the small-scale wear experiments. The possibility of detachment of nano-scale fatigued layers as an alternative wear mechanism cannot be ruled out if contacts are elastic. Depending on the material combination, surface and loading conditions wear-less rubbing may also occur at nano-scale contacts. In any one of the above mechanisms of wear, the surface force would indirectly influence the process by modifying the contact area and the wear volume can be given in the well known form as

$$V = kA_r L \tag{13}$$

where A_r is the real area of contact, L is the sliding distance and k the wear coefficient. If the adhesive wear due to formation of 'welded' junctions is considered the A_r reduces to only plastic area of contact A_{rp}, but if the junctions induced by surface forces are also considered the real area of contact may also include the elastic contact. This would, of course, depend on the strength of these joints. Although an exact evaluation of the strength of the bonds due to surface forces alone is difficult, a rough estimation is possible based on some existing experimental results /5/. Considering the Hertzian contact between steel ball of radius R and a smooth flat silicon surface, following JKR theory /8/ the frictional force may be given by

$$F = \mu[P_o + 3\pi\gamma R + \sqrt{6\pi\gamma R P_o + (3\pi\gamma R)^2}\,] \tag{14}$$

where P_0 is the applied load and γ is the work of adhesion . The contact radius 'r' is here given by $r^3 = RP_1 / K$ where P_1 is the apparent Hertz load. Considering typical data from reference /5/, [pp. 18-20] for these experiments R = 0.3 mm, μ = 0.1 within the load range between 50-100 μN, the friction forces read from the experimental plot are as follows:

P_0 (μN)	20	110	140	220
F (μN)	6	14	18	26

The average value of γ from equation (14) is about 0.1 N/m and the average bond-strength defined as $F / \pi r^2$ works out to be approximately 65 Mpa. This strength is low for any sub-surface damage to occur in steel but this is probably sufficient to cause tearing within the bulk material in silicon. If wear occurs at both the plastic and elastic asperities then A_r is the total real area of contact. The total real contact area may be determined as a certain probability and expressed in non-dimensional form as

$$\bar{A}_r = \int_0^\infty \Delta.\bar{\phi}(\Delta).d\Delta \tag{15}$$

where $\bar{A}_r$ = non-dimensional total contact area = $A_r\sqrt{2\pi}/(\pi NR\sigma)$.

Now volume of wear may be written in non-dimensional form using equation (13) and (15) as

$$\bar{V} = \int_0^\infty \Delta.\bar{\phi}(\Delta)d\Delta \tag{16}$$

where $\bar{V}$ = non-dimensional wear volume = $V\sqrt{2\pi}/(k\pi NR\sigma L)$; Here the expression for wear volume appears simple but it includes surface adhesion that exists between the contacting asperities.

4. RESULTS AND DISCUSSION

The equations established in the previous sections are solved and evaluated for different combinations of non-dimensional mean separation h, elastic adhesion index θ and plastic adhesion index λ. Before proceeding to interpret the results it is imperative to recapitulate that the elastic and plastic adhesion indices θ and λ merely indicate the relative importance of surface-force-induced adhesion for elastically and plastically deformed asperities as compared to the elastic and plastic forces on an individual asperity. The plots of wear volume against applied load for typical combinations of the above parameters are shown in Figures 1 - 4. A linear dependence of wear volume on applied load is observed for all parametric combinations. It is also noted that for θ values at or below the transitional value of 10, the wear volume is significantly larger than that at large θ value. It is clear from equations (13) and (16) that the wear volume is dependent on contact area which in turn is influenced by surface forces and the results indeed depict that in cases where surface roughness effect is less ($\theta < 10$) wear volume is influenced by adhesion. The same observations can be made at $\lambda < 0.125$ (the transitional value) where the wear volume is large due to enhanced adhesion. It may also be noted from Figure 1 that at low λ wear rate is more for low values of θ since the slope of the plots of wear volume vs applied load is more. But for high λ, wear rate is more or less the same for all θ values as observed in Figure 2. On the other hand, wear rate is more for low λ in case of both low and high values of θ as observed in Figures 3 and 4. Thus it may in general be stated that wear rate is influenced by adhesion both in elastic and plastic ranges. However, Ando /3/ has reported the results of his wear test with a single gold asperity and a silicon leaf spring in nanometric dimensions under nanometric level load. His results indicate a

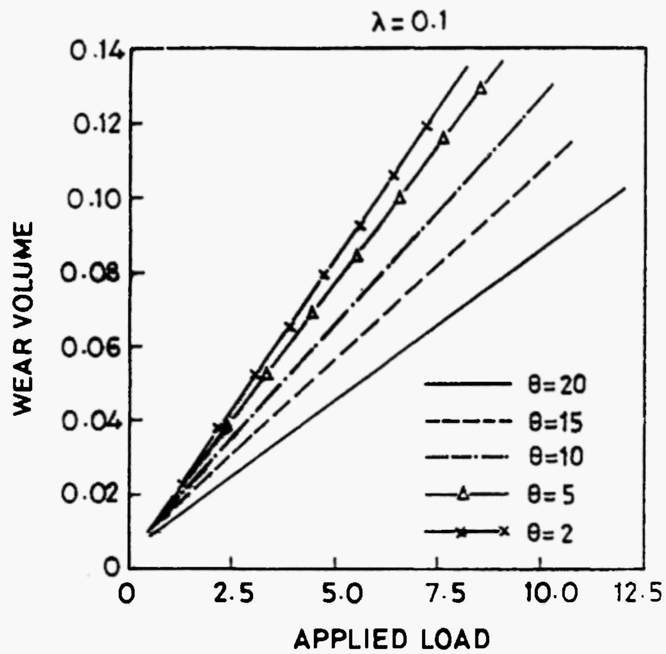

Fig. 1: Non-dimensional wear volume as a function of non-dimensional load at $\lambda = 0.1$ and varying θ

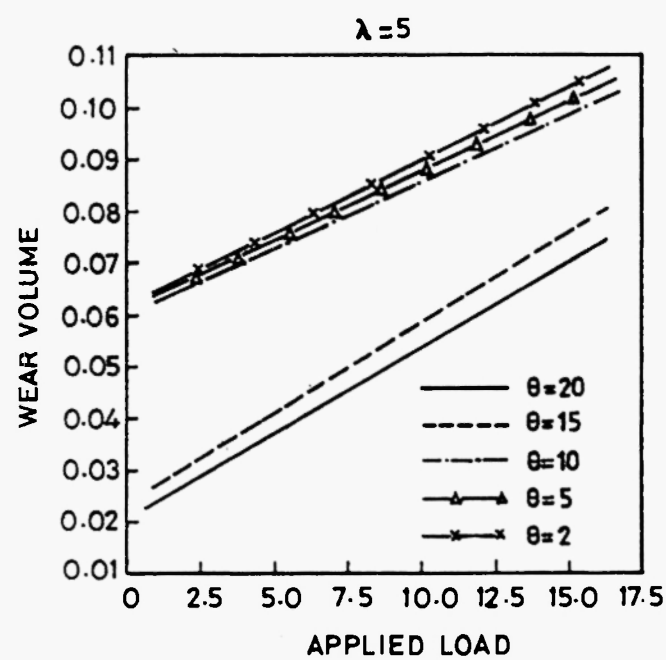

Fig. 2: Non-dimensional wear volume as a function of non-dimensional load at $\lambda = 5$ and varying θ

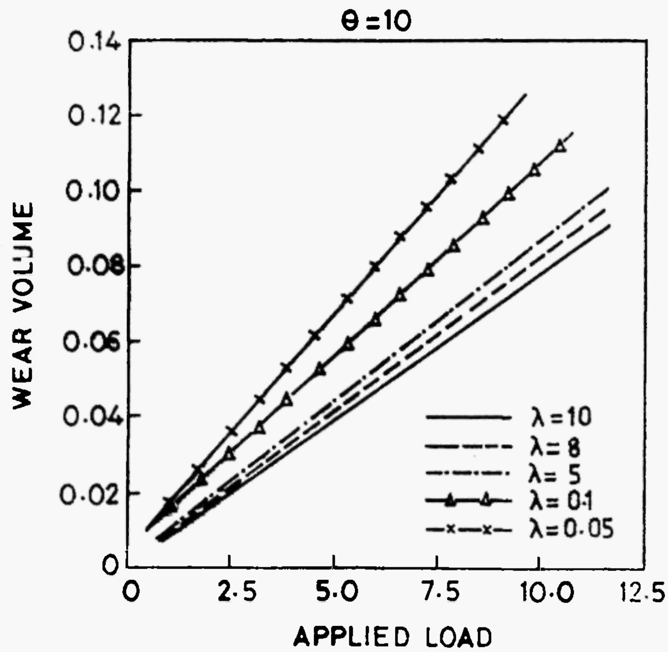

Fig. 3: Non-dimensional wear volume as a function of non-dimensional load at θ =10 and varying λ

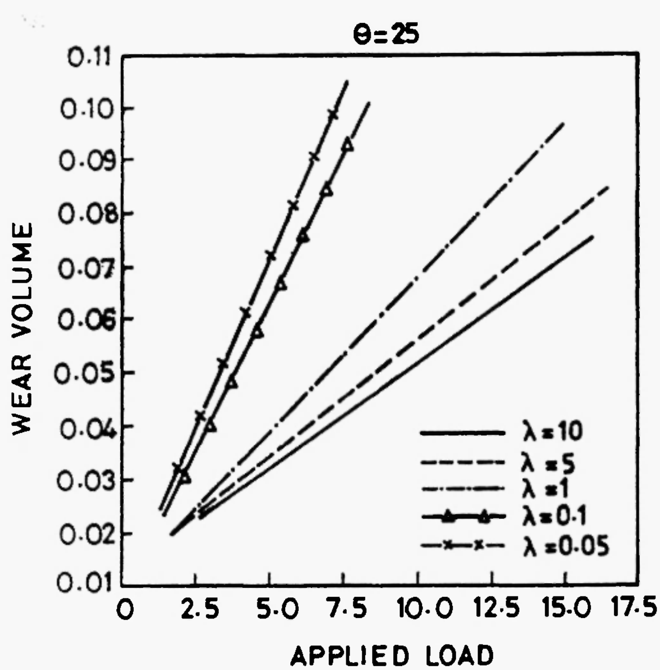

Fig. 4: Non-dimensional wear volume as a function of non-dimensional load at θ =25 and varying λ

clear dependence of contact area on pull-off force and therefore it would be expected that the wear volume that depends on contact area would also depend on pull-off force. But he concludes that his estimated wear volume increased with external load and was relatively unaffected by adhesion. The present prediction cannot explain these results, partly because the experimental technique may have led to an abrasive form of wear which would mean that only the plastic areas would affect the wear rate.

5. CONCLUSIONS

An analysis of adhesive wear between solid surfaces with small-scale asperities is described. The analysis is based on an elastic-plastic model and assumes that both elastic and plastic asperities contribute to wear. The results of the analysis are conveniently described in terms of two adhesion indices θ and λ. It is found that surface forces can influence wear rate. For situations where wear rate needs to be low under low load and smooth surface conditions, material and surface properties may be chosen so as to yield high values of adhesion indices θ and λ.

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