Modified Kinetic Model of Particle Detachment by Aerodynamic Drag and Vibration

Nakorn Tippayawong, and Ittichai Preechawuttipong

***Abstract*—This work is about detachment of deposited particles in turbulent air flow with external excitation. A kinetic model was modified and applied to the resuspension of microparticles. The modified model was based on the energy accumulation approach with combined aerodynamic drag and in-plane vibration to separate particles from a surface. Moments of adhesion, aerodynamic drag, and vibration acting on particles deposited to the surface were considered. An expression was obtained for the resuspension rate from surfaces where a spread of adhesive forces due to surface roughness was taken into account. The model prediction showed similar trends to the experiments. Frequency of particle-surface interaction was found to influence removal rate of particles from the surface.**

***Index Terms*— adhesion, kinetic model, particle resuspension, removal, vibration.**

I. INTRODUCTION

Removal of small particles from surfaces is important in many engineering applications. In microelectronics industry, adherent particulate contaminants generated during fabrication and assembly may deposit, detach and resuspend repeatedly in the assembly line and containment. Consequently, particle resuspension can produce fatal flaws in finished products. Understanding particle adhesion and removal from surfaces is crucial in quality control of these products. As feature sizes continue to shrink [1], methods to deal with increasingly finer particles will be required by this industry. Preparation of ultraclean surfaces has become one of the key technologies in the fabrication of microelectronic and computer components and devices [2]. Other practical areas of importance are clean rooms, indoor air contamination, etc.

It is generally known that small particles are held by very strong surface forces which are a combination of physical attractions, chemical bonds, and mechanical stresses. This is referred to as adhesion force. It is therefore necessary to consider various means of removal. Common methods include fluid flow over the particle laden surface, high velocity fluid jets, high frequency waves in the medium where the surface is submerged. Modes of inceptive motion leading to detachment of a particle from the surface of a substrate include [3]:

(a) *lifting-off*, when the normal component of a force applied to an adhered particle exceeds the pull-off force, the particle will be lifted off the surface,
(b) *sliding*, when the tangential component of an applied force exceeds the total normal force multiplied by a coefficient of static friction, the particle will start to slide and detach,
(c) *rolling*, when the total moment about a point on the edge of the contact circle is equal to zero, the particle will begin to roll about that point and detach off the surface.

There has been development of a number of different models for the resuspension process of particles adhering to a surface where excellent and comprehensive reviews are available [2], [4], [5]. The models may be categorized into two classes; (i) quasi-static model referred to those based on force and momentum balance, and (ii) kinetic model referred to those based on energy accumulation. The first class of models assumes that once a threshold for removal is exceeded, particle is removed. This threshold is based on a balance between surface adhesion and instantaneous aerodynamic lift or drag from the flow. The second class of models is based on possibility of resonant energy transfer from the flow that could lead to the breaking of adhesion bonds. Aerodynamic force does not exceed the surface forces, but there is a transfer of energy to a particle. The particle is detached when it has accumulated sufficient energy to escape the adhesive potential well. Apart from the influence of the flow, particle removal can be achieved using external excitations, such as high frequency sonic wave, laser and wall vibration [6].

It is apparent that vibrations normal and parallel to the surface can enhance the detachment process. Attempts have been made to investigate the effect of vibration on particle detachment from surfaces. Examples of such studies were carried out by Soltani and Ahmadi [7], Theerachaisupakij, Matsusaka, Kataoka, and Masuda [8], and Ilic, Krylov, Kondratovich, and Craighead [9].

In this work, detachment of a deposited particle by fluid flow and vibration is investigated. The aims of this study are to propose a modified kinetic model of particle detachment, taking into account the influence of aerodynamic drag and surface vibration, and to predict if enhanced particle resuspension rate is possible from the combined technique.

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II. MODELING PARTICLE DETACHMENT

A. Particle Motion

Behavior of particles depends upon their size range or size regimes. These size regimes can be classified into four categories, namely continuum, slip flow, transition and free molecular regimes ranging from large to small particles in order. When large particles can be treated as being submerged in a continuous gaseous medium or fluid, this is said to be in the continuum regime. When particles, especially those less than 0.1 µm diameter are affected by the motion of individual gas molecules, the flow is in the free molecular regime. Slip flow and transition regimes are in intermediate range between the two. Equations governing the particle motion are based on the particle acceleration as a result of all forces acting upon it. A number of these forces depend on the nature of flow and particles that are being investigated. The surface is assumed to be smooth. A spherical particle of micrometer size is assumed to move horizontally along the airflow and submerge in a viscous sublayer where the shear flow is steady and undisturbed by the presence of particle.

B. Forces and Moments

For the present study, a flow over a particle on a vibrating surface was considered, shown in Fig. 1. Vibration was excited along the plane of the surface. The mean aerodynamic drag force, F_d, acted in the forward horizontal direction parallel to the surface. The tangential pull-off force may be expressed in terms of adhesion, F_{po}, considered as acting at the edge of contact circle when the particle was about to roll. It was assumed that through a rigid contact at a pivot P, the particle inertia had a vibrating acceleration at its center of mass equal to that of the surface excitation.

The adhesion force consists of the van der Waals force, the force arising from surface tension of adsorbed liquid, and electrostatic force. The latter two forces can be neglected when relative humidity and particle charge are low. Thus, the mean adhesion force, F_a, is given [10] as

$$F_a = \frac{3}{4}\pi\gamma D_p \tag{1}$$

The surface pull-off force can be estimated from

$$F_{po} = C_{fa} F_a \tag{2}$$

where C_{fa} is a contact parameter. Ibrahim, Dunn and Qazi [11] estimated it, based on surface asperity height. Tsai, Pui and Liu [12] suggested a following expression,

$$C_{fa} = 0.5\exp\left(0.124(\Pi - 0.01)^{0.439}\right) + 0.2\Pi \tag{3}$$

in which

$$\Pi = \left(\frac{25\pi^2\gamma^2 D_p}{8\varepsilon^3 K^2}\right)^{1/3} \tag{4}$$

where ε is the distance of closest approach between contact bodies, ρ_p is the particle density. The moment about P of the adhesion is

$$M_a = F_{po} s \tag{5}$$

where γ is the surface energy of adhesion, D_p and s are the particle diameter and diameter of the contact circle, respectively. The contact diameter is evaluated from [13]

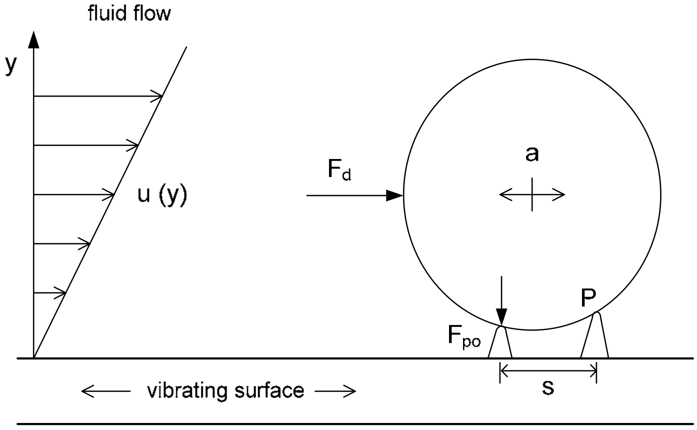

Fig. 1 Rocking of a particle on a surface due to external forces.

$$s = \left(\frac{12\pi\gamma D_p^2}{K}\right)^{1/3} \tag{6}$$

in which, K is the composite Young's modulus given by

$$K = \frac{4}{3}\left[\frac{1-\nu_p^2}{E_p} + \frac{1-\nu_s^2}{E_s}\right]^{-1} \tag{7}$$

where E_p and E_s are the values of Young's modulus and ν_p and ν_s are the values of Poisson's ratio for the particle and the surface, respectively.

The aerodynamic drag is modeled as Stokesian drag on a sphere near a surface in simple shear flow, with corrections made for inertial, wall and slip effects [14].The buoyancy, virtual mass, and Basset forces are much smaller than the drag force because the particle density is much larger than air. The mean aerodynamic drag force is given [4] as

$$F_d = 8\frac{\mu^2}{\rho C}\left(D_p^+\right)^2 \tag{8}$$

with

$$D_p^+ = \frac{\rho D_p u_\tau}{\mu} \tag{9}$$

and

$$C = 1 + Kn\left[1.257 + 0.4\exp\left(\frac{-1.1}{Kn}\right)\right] \tag{10}$$

where ρ is the air density, μ is the air viscosity, u_τ is the friction velocity, C is the Cunningham correction factor, and Kn is the Knudsen number. The aerodynamic moment of the drag force may be written as

$$M_d = 0.5 F_d D_p \tag{11}$$

The force due to vibration may be derived from a product of inertia and its acceleration

$$F_v = \rho_p \frac{\pi}{6} D_p^3 a \tag{12}$$

where a is the maximum vibrating acceleration. The moment due to vibration may be expressed as

$$M_v = 0.5 F_v D_p \tag{13}$$

With no vibration, order of magnitude analysis of the moment balance showed that the aerodynamic lift and gravitational moments are negligible, compared to the aerodynamic drag and adhesion moments. Hence, the condition for detachment becomes [15], [16]

$$\frac{M_a}{M_d} < 1 \tag{14}$$

It was shown that the condition for detachment obtained from the moment balance coincided with the condition of the following force balance [17]

$$\frac{F_{po}}{F_d} < 1 \tag{15}$$

The values of these forces and moments showed that rolling provides the least resistance for incipient detachment, compared to lifting off and sliding. In this work, rolling is therefore considered as the mechanism of initial detachment and resuspension. It is expected that when detachment occurs, the particle will roll to a new position. Since the new equilibrium position takes finite time to establish, adhesion force is smaller at the new position. The particle will continue to roll and a small but finite vertical force helps lifting the particle from the surface. It is worth noting that added complications such as surface roughness, turbulent burst, and vibration may affect the likelihood of resuspension.

C. *Resuspension Rate*

The kinetic model proposed here was extended from those by Vainshtein, Ziskind, Fichman and Gutfinger model [17] and the Rock 'n Roll model of Reeks and Hall [15]. In this modified model, drag and vibration were accounted by the rocking of the particle about the asperities in the contact zone. So the particle will oscillate about the pivot P. Resuspension refers to the process of breaking the adhesion bond between the particle and the surface. The model was based on the assumption that a particle is attached from a surface when it has accumulated enough energy to escape from the potential energy well. Such consideration led to a formula for the resuspension rate factor R similar to the desorption rate of molecules from a surface,

$$R = f_o \exp\left(-\frac{Q}{2 < PE >}\right) \tag{16}$$

where f_o is the typical frequency of particle-surface deformation in the potential well, Q is the height of the potential barrier, and $<PE>$ is the average potential energy of a particle in the well. Vainshtein et al. [17] showed that the exponent may be expressed in terms of drag and adhesion forces.

$$R = f_o \exp\left(-\left(\frac{F_{po}}{F_d}\right)^{x_f}\right) \tag{17}$$

where x_f has a default value of 4/3 and f_o was adopted from a bursting frequency in a turbulent boundary layer. Typical frequency proposed by Reeks, Reed, and Hall [18] is

$$f_o = \frac{\rho u_\tau^2}{300\mu} \tag{18}$$

With vibration, extra excitation energy was put into the particle-surface system. Hence, in this work, the modified resuspension rate factor may be expressed as

$$R = \frac{f_0}{c_f} \exp\left(-\left(\frac{M_a}{M_d + M_v}\right)^{x_f}\right) \tag{19}$$

where c_f is the particle-surface interaction factor taking into account effects of turbulent burst, surface excitation, fluid and mechanical damping on particle rocking frequency.

Most surfaces involved in resuspension are rough. Surface roughness leads to reduction and spread of the adhesive force. The force of adhesion and the tangential pull-off force should be calculated using the asperity height, h_a, rather than the particle radius. The surface topography can be characterized by a distribution in asperity height. A normalized adhesive radius may be defined in terms of asperity height as;

$$h' = \frac{2h_a}{D_p} \tag{20}$$

For a log-normal distribution of normalized adhesive radii, the probability density function is of the form given in [18] as;

$$\varphi(h') = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{h' \ln \sigma'} \cdot \exp\left(-\frac{\left[\ln h' - \ln \bar{h}'\right]^2}{2(\ln \sigma')^2}\right) \tag{21}$$

where $\bar{h}'$ is the geometric mean of h' and a measure of the reduction in adhesion due to surface roughness, and σ' is a measure of the spread in adhesive forces due to the surface roughness.

The fraction of particles remaining on the surface at time t is given by

$$\Lambda_R = \int_0^\infty \exp(-R(h')t)\varphi(h')dh' \tag{22}$$

D. *Calculation*

Resuspension was worked out for a system of spherical alumina particles on a stainless steel substrate exposed to a fully developed turbulent air flow in a channel. Flow conditions are obtained at standard temperature and pressure. The relevant properties for the calculation are listed in Table 1. The moments of the three main forces were analyzed for a range of particle diameters. Typical values of mean asperity height h_a = 0.01 µm and spread factor σ' = 4.0, as recommended by Stempniewicz, Komen, and de With [4], are used in the calculation.

Initial detachment may be characterized in terms of either a free stream velocity, U_∞, or a friction velocity. They were correlated by [11]

$$u_\tau = 0.0375 U_\infty + 0.0387 \tag{23}$$

Prediction of particle fraction remaining over a fixed time of 1 s was undertaken for a set of different friction velocities and effective frequencies. Comparison was made between the prediction from this work and published results in the literature, including experiments obtained from [15].

Table 1. Properties of particle, substrate, and fluid.

Properties	value	unit
particle density	1600	kg/m^3
particle Young's modulus	350	GPa
particle Poissons ratio	0.30	-
substrate density	7830	kg/m^3
substrate Young's modulus	210	GPa
substrate Poissons ratio	0.29	-
surface energy of adhesion	0.56	J/m^2
fluid density	1.18	kg/m^3
fluid kinematic viscosity	1.54 x 10^{-5}	m^2/s

III. RESULTS AND DISCUSSION

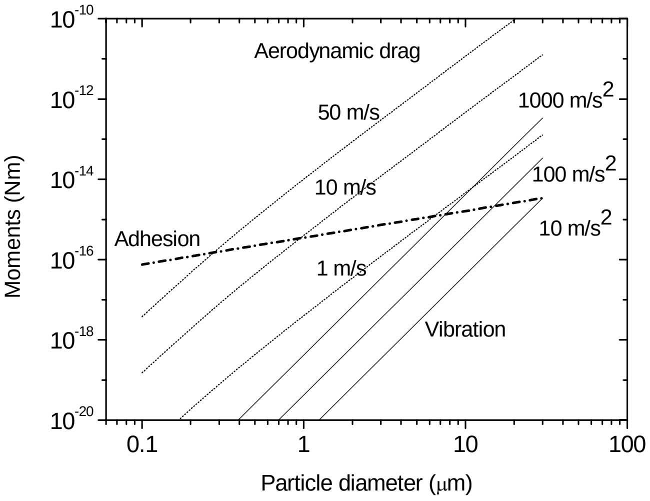

Fig. 2 Comparison of moments between adhesion, aerodynamic drag, and vibration at different conditions.

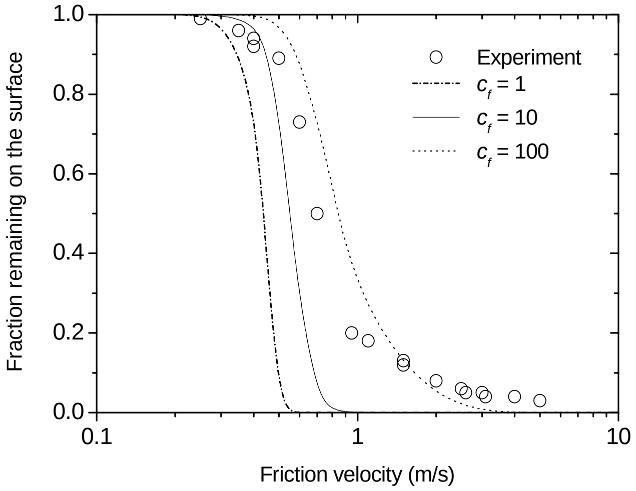

Fig. 3 Comparison of model predictions and experimental data for 10 μm alumina particles on stainless steel surface (*t* = 1 s, no external excitation).

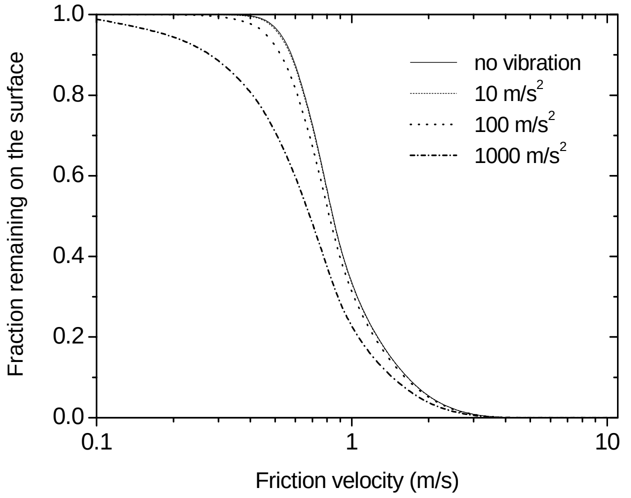

Fig. 4 Effect of vibrating acceleration on detachment of 10 μm alumina particles on stainless steel surface (*t* = 1 s).

Fig. 2 shows comparison between resistive moment from adhesion and rocking moments from aerodynamic drag and vibration force. Drag was calculated for friction velocities of 1, 10 and 50 m/s, corresponding to free stream velocity of 25, 265, 1350 m/s, respectively. Excitation of 10, 100, and 1000 m/s^2 was simulated for vibration. It can be seen from the quasi-static models' point of view that the magnitude of resisting adhesion moment can be approached and exceeded by the external moments due to aerodynamic drag and vibration force. For aerodynamic moment, increasing friction velocity would be required to detach smaller sized particles. Similarly, extremely high vibrating acceleration would be needed to detach micrometer sized particles. However, detachment mechanism was suggested to be dynamic [19] that could not be accounted for by using quasi-static adhesion models. From energy accumulation approach, particles can be detached from the substrate more easily than predicted from a moment balance consideration.

With regards to particle resuspension rate, comparison of model predictions with the experimental data of Reeks and Hall [15] for a deposit of 10 µm alumina particles on stainless steel substrate was performed and shown in Fig. 3. Exposure to the flow was one second. A range of interaction factors, hence effective rocking frequency, was parametrically studied. Dynamic model predictions showed similar trends to the experimental data [15], [20] and those produced from Vainshtein, Rock's Roll, and Lazaridis models [15], [17], [21]. For a default value of $c_f = 1$, the model predicted that resuspension will occur at lower friction velocities than experimentally observed. Adjustment of c_f value to 10 and 100 appeared to improve the agreement between the simulation and the experiments. Change in the particles' effective rocking frequency was found to have considerable effect on the fraction remaining. When the adhesion moment was greater than drag and vibration moments, detachment could occur if effective excitation frequency was sufficiently high. It is interesting to note that the effective frequency of particle-surface interaction in the potential energy well taken from the bursting frequency from a turbulent boundary layer ranged from about 50 Hz at friction velocity of 0.5 m/s to about 5000 Hz at 5 m/s. The range was very far below the natural frequency of vibration of the particle-surface system, estimated to be about 1 GHz [22]. It should be noted that experimental results of smaller particles in micrometer and submicrometer ranges are not yet available. Such data is needed to further verify the existing models used in the current investigation.

Nonetheless, attempt has been made to investigate the effect of in-plane vibration force on particle detachment rate. Fig. 4 shows results of the model for the fraction of particles remaining on the surface as a function of friction velocity at different accelerations. As expected, an increase in vibration force resulted in higher fraction of particle resuspended. But it should be noted that small accelerations in the range between 10 – 100 m/s^2 contributed only slightly to further improvement in detachment without vibration. To get high degree of detachment, large acceleration in 1000 m/s^2 range or above would be required.

IV. CONCLUSION

Investigation of particle resuspension from a surface has analytically and empirically been studied. The forces and moments acting on fine particles were modeled, taking into account aerodynamic drag, adhesion, and vibration. Factors influencing resuspension process such as flow conditions, particle size, vibration acceleration and effective frequency have been investigated. Empirical models describing forces and moments on particles can be used as preliminary analytical tools to offer some qualitative insight into detachment and resuspension of deposited particles on a surface. Prediction of resuspension rate as a function of particle size has been obtained and compared with available experimental findings. Results indicated that the present modified kinetic model was able to qualitatively predict the resuspension of microparticles.

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