Cleaning of Dust between Interactive Contact Surfaces by Application of Normal Loads of Artificial Stainless-Cantilever in AFM*

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Abstract
In this study, we investigated that interactive contact surfaces were affected by dust and applied normal loads of cantilever such as bristles. In order to study the effect of interactive contact surfaces, spherical particles (dry borosilicate glass sphere, plastic sphere) with curvature radius \( R = 5 \mu m, R = 10 \mu m \) were glued to artificial stainless cantilevers (spring constant \( k = 576.7 \text{N/m} \)). The experiments were performed on various normal applied loads using an AFM (Atomic force microscope). The results indicate that spheres with a small curvature radius removed dust more effectively than did either of those with a large curvature radius, abraded by using the stainless cantilever, over the wide contact area (50 \( \mu m \times 50 \mu m \)). The plastic spheres tend to deform more than do the borosilicate glass spheres under the same applied load and the spheres with a smaller curvature radius tend to deform than do those with a larger curvature radius and the same material properties. Therefore, it had an influence on interactive surface forces. Restructuring dust aggregates by sliding a cantilever, as well as applying loads and contact pressure, forms a new micro contact area, which influences micro surface forces.

Key words: Dust, Interactive Contact Surfaces, Micro Brush, Stainless Cantilever, Curvature Radius, AFM (Atomic Force Microscope).

1. Introduction
In the electronics industries of semiconductor production, electron device production, mounting, display productions, etc., dust cleaning technology is essential for not only high-density but also high-precision performance. Although dust and contamination influence the performance of micro devices, cleaning them is generally difficult because of restrictions generated by the atmosphere and the conditions under which they are used. There are various dust cleaning methods for semiconductor (1). Because surface force can harmfully affect micro devices and systems, dry cleaning methods to remove dust and contamination are desirable. As one possible method, nano and micro brushes have been proposed. The limitation of such brush cleaning is that only exposed places can be cleaned

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properly, whereas crevasses and detailed areas remain untouched. Pulickel M. Ajayan et al. (2) showed the possibility of using selective chemical adhesion and removal whereby a carbon nano tube is used to clean the coating of dirt in nano-sized crevasses and holes. In the future, due to the environmental impact of using solutions and due to the fact that cleaning using micro devices wielded by cleaning robots may be an impossibility, brush cleaning is a viable alternative that does not require the use of liquid solutions. As for the characteristics of brush cleaning under dry conditions, simply, if there is no mechanical force to remove contaminants, cleaning can not be done. Improvement concerning the lifetime of brushes and making the mechanical force more efficient are problems under consideration. As shown in Fig. 1, if a micro brush is abraded on a surface by way of an applied load, various significant phenomena occur on a nano/micro scale. Cleaning using micro brushes is primarily used for removing dust from surfaces. By recognizing that coagulation of submicron-sized dust grains by dust processing mechanisms have some importance in interstellar space, C. Dominik et al. (3) attempted to improve the situation by including the effects of tangential force on the contact of dust. And, they performed detailed simulations of the coagulation process and of the collisions between dust aggregates. Among the methods used to elucidate the surface effects, such as micro particles, cantilevers are primarily used. Actions like brush work are able to be predetermined by way of cantilever scanning. Much research has been done in conjunction with cantilevers in order to understand the phenomena which occur on the interactive contact surfaces. (4)-(9). In order to measure the surface force between the colloid sphere and the flat surface in the solution condition W. A. Ducker et al. (4) (5) used a cantilever attached to micro spheres 1µm and 50µm in size. J. Drelich et al. (6) employed a method which removed particles of polyethylene and polystyrene from the silicon substrate using a cantilever glued to micro spheres, and they reported the force, which is able to be removed by means of 0.8-4µN. A. Castellanos (7) used a cantilever glued to a polymer particle 10µm in diameter and compared the elastic contact and Van der waals force between the particles with the theory value. D. M. Schaefer et al. (8) determined that the non-linear relations between pull-off force and applied load are dependent on contaminants present and the humidity of the surface by using the micro spheres the polystyrene (PS) and polyethylene (PE) against the silicon wafer surface utilizing a commercial silicon cantilever. Additionally, in concurrence with D. S. Rimai et al. (9), they mentioned that changes in the contact areas between the substrate and sphere are non-linear but they did not clearly mention the reasons behind this. R. D. Boyd et al. (10) recognized that the roughness and surface shape of the substrate influenced the attachment and resistance against bacteria over substrate, and requested the force, which is needed for the removal of the bacteria cell, by decreasing abrading using a commercial cantilever against the bacteria cell over a stainless substrate. Also, there are reports on controlling the various surface effects in a micro contact surface, effectively. B. Gady et al. (11) revealed the relationship between static electric force and Van der waals force by using polystyrene micro sphere of HOPG (Highly Oriented Pyrolytic Graphite), recognizing the surface roughness with regard to the JKR theory (12). L. Heim et al. (13) reported on changes of adhesive forces by roughness of the particle using the silicon surface and CIP (Carbonyl Iron Powder). Also, although they mentioned about the influence of contamination with respect to adhesive force, they did not clearly elaborate on the reason behind this. H. Onoe et al. (14) reported that the binding force decreased by controlling the density of the solution in the micro contact surfaces of SiO₂, and that the Van der waals force and adhesive force have an influence on the binding force against the particle of the surface. B.M. Moudgil et al. (15) experimented by using a sphere and a flat plane based on the consideration that the liquid bridge force solidifies micro particles by condensation. A. A. Feiler et al. (16) investigated using AFM experimentation controlling the relative humidity regarding the characteristics of the adhesion and friction in the micro contact surface between the
hydrophilic silica surface and colloid probe. The adhesive force increased more by the Kelvin radius associated with the increase of humidity than the characteristic of the roughness of surface, whereas frictional force decreases. Z. Xu et al. (17) reported on the adhesive force between the hydrophilic silica surface and polymer sphere by controlling the density of the solution. It is expected that the roughness of the surface changes, since micro particles like dust are absorbed over the surface and exert some influence on the surface forces between micro contact surfaces. Based on the tenet that surface force is influenced by contact shape, Y. Ando et al. (18) investigated the frictional force and pull-off force of the contact area by controlling the contact shape at the submicron scale. G. W. Tormoen et al. (19) demonstrated that roughness is a contingent cause of pull-off force, and that pull-off force relies on the contact position of the asperity array by experimentation on an AFM using a cantilever glued to a glass sphere and the asperity array. From the above research, when cleaning is performed using a micro brush, we must consider the physical phenomenon which occurs on the interactive surfaces affected by dust using a broad perspective. Therefore, we attempt to measure the model by using cantilevers, which were glued to micro spheres on an AFM (Atomic Force Microscope), to see the contact phenomena between the interactive surfaces with dust. We investigated the force needed for cleaning dust which is adhered over glass substrates under dry conditions, and the changes of the interactive contact surface due to the curvature radius, like brush top, by applied loads.

![Figure 1. A illustration of deformed micro bristle tip (a) and the bending of cantilever (b) by applied loads.](image)

![Figure 2. The designed cantilever](image)

Table 1. Properties of the material used in the experiment

<table>
<thead>
<tr>
<th>Material</th>
<th>Young modulus (E) (GPa)</th>
<th>Poisson’s ratio</th>
<th>Density (ρ) [g/cm³]</th>
<th>Radius (R) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless cantilever</td>
<td>193</td>
<td>0.32</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Glass substrate</td>
<td>77</td>
<td>0.23</td>
<td>2.72</td>
<td>-</td>
</tr>
<tr>
<td>Bolosilicate glass</td>
<td>72.4</td>
<td>0.2</td>
<td>2.4</td>
<td>5,10</td>
</tr>
<tr>
<td>Plastic sphere</td>
<td>12.4</td>
<td>0.4</td>
<td>0.913</td>
<td>10</td>
</tr>
</tbody>
</table>

2. Experiment

2.1 Samples and Preparation.

The primary interest of the measurements performed on these specimens was to see the effect of cleaning by interactive contact surfaces on the abrading behavior. By observing variations in the traces of dust on the substrate surface by means of applied loads in the AFM (Olympus Co. Ltd. Japan) (20), the effect of cleaning on the abrading behavior can be identified. To investigate the cleaning force at the micro contact range, the behavior of the bristles shown in Fig.1, a stainless (SUS304, Nilaco Co. Japan) (21) cantilever was designed (Fig.2), and the spring constant is calculated by equation (2) and table.1, respectively. Additionally, the stainless cantilevers are glued to various spheres (Dry borosilicate glass, Duke Scientific Co.) (22), plastic (Expancel, Co. Sweden) (23) by epoxy resin on the AFM,
and then it was dried in air for 24 hours, as shown in Fig.3. The glass spheres and plastic spheres were dispersed over the Si-substrate. As shown Fig.3-(b), it is able to be distinguished by transparency of spheres over the same substrate. The spheres were glued to one end of the stainless cantilevers were allowed to abrade against the substrate of glass during scanning on the AFM. The dry borosilicate glass and plastic spheres with curvature radiuses of 5\( \mu \)m and 10\( \mu \)m were used as being correspondent to the top of the micro brush. As for the experimental conditions, window glass (Na2O-CaO-SiO2) (24) was used as the flat glass substrates. It was cut into segments 10mm x 10mm using a dicing saw machine. We let dust settle naturally on the flat glass substrates on the outdoor side of the window over 110 days. The atmosphere in which the dust was allowed to accumulate on the flat glass substrates was negligible because dry conditions were maintained throughout the duration of experimentation (25-30\( ^\circ \)C). The normal load applied during the abrading test was varied from 57.6 \( \mu \)N to 922.7 \( \mu \)N, gradually. The normal load was applied on the specimen surface by using an AFM, and the applied load for cleaning was measured by abrading a cantilever glued to micro spheres. The applied loads, which could be varied using the bending force of the cantilever by way of the PZT scanner of the AFM, were added and the sliding conditions set to scan line=64, scan rate=3 sec/line and scan line=64 on cleaning work (scan size=50\( \mu \)m x 50\( \mu \)m). We taken three-dimensional topography (scan size=100\( \mu \)m x 100\( \mu \)m, scan size of spherical sphere=10\( \mu \)m x 10\( \mu \)m) of the volume and roughness by using a silicone nitride cantilever (OMCL-TR800PSA) (20). The measurement conditions set to scan line=256, scan rate=4 sec/line and spring constant \( k=2 \) N/m, \( k=0.004 \) N/m (the scan of spheres), respectively. A measurement environment had been maintained for all experiments in air at room temperature (24-26\( ^\circ \)C, humidity: 25%Rh-40%Rh). According to the affected displacement on the AFM, the cantilever is bent and cleaning forces between the stainless cantilever and the glass substrate could be measured with micro-scale cleaning ability. The abraded trace of stainless cantilevers and glass substrates could be monitored under the AFM while scanning was being done. As is shown in Fig.4 and Fig.5, the roughness (=\( Ra \)) of the bare substrate of window glass, and the bare dry borosilicate glass sphere, and the bare plastic sphere without abrading were \( Ra=2.5\)nm, \( Ra=12.6\)nm for the glass sphere and \( Ra=25.16\)nm for the bare plastic sphere, respectively. The three-dimensional AFM topography images are taken by using digital camera on the AFM monitor.

![Figure 3. The glass sphere and a plastic sphere were glued to the top of the stainless-cantilever using epoxy resin. (a) Glass sphere, (b) The glass spheres and plastic spheres were dispersed over the Si-substrate. (c) Plastic sphere.](image)

(Figure 4)  (Figure 5)
Figure 4. Roughness of window glass (Na2O-CaO-SiO2), scan size=5µm x 5µm, scan line=256, scan rate=4 sec/line, Roughness \( (Ra=2.5\text{nm}) \)

Figure 5. The bare appearance of the borosilicate glass sphere \( (R=5\mu m) \), scan size=5µm x 5µm, Roughness \( (Ra=12.6\text{nm}) \)

Figure 6. The bending angles were calculated from the force curve.

2.2 The manufacture of cantilever and measurement principle

The glass spheres and plastic spheres were dispersed over Si-substrate. Figure 3(a) shows the borosilicate glass sphere \( (R=10\mu m) \) glued to the top of the stainless steel cantilever. As shown Fig. 3(b), the spheres are able to be distinguished by transparency over the same substrate. Figure 3(c) shows the plastic sphere \( (R=10\mu m) \) glued to the top of the stainless steel cantilever. A bending \( (=\Delta y_{\text{max}}) \) and spring constant \( (=k) \) for the manufactured stainless cantilevers are represented by equation (1), (2). When the spring constant is calculated based on the specified values of Fig. 2 and Table 1, we obtained \( k=576.7\text{N/m} \) for the stainless cantilever. Also, concerning the 30 stainless cantilevers \( (N=30) \), by measuring the inclination and bending distance between (d) and (e) of Fig. 6 on the basis of the principle of the force curve of AFM, the bending angle of the stainless cantilever can be calculated to obtain accurate cantilevers. The distribution of the bending angle of each 30 pieces is shown in Fig. 7. In this experiment, the cantilevers were used within a standard deviation range of bending with a mean angle of 38.16 degrees. We performed cleaning work in the contact mode (Olympus, NV2000) (25) of AFM to measure the cleaning of the dust by applied loads. A glass substrate with dust placed on the specimen table of the PZT scanner is shown in Fig. 8-a, b. The displacement of the stainless cantilever, by moving toward the Z direction of the cantilever and by scanning (Fig. 8-c) in the X-Y direction of PZT, detected changes in the reflected direction of laser light by utilizing a photodiode detection device. We have measured the forces to remove the dust by multiplication of the
spring constant and bending displacement of the cantilever. The measurement procedure is as follows: (a) We investigated the distribution of dust and the volume of dust on the glass substrate in a measurement range of 50 µm x 50 µm by using a silicon cantilever ($k=2$ N/m, curvature radius of tip $R=10$nm) (Fig. 9-a, Fig. 11, Fig. 12-a).

$$y_{max} = \frac{2W}{E \cdot b \cdot h^3} \left(3L^3 - a^3\right) + 3(La^2 - L^2a)$$

(1)

$$k = \frac{E \cdot b \cdot h^3}{2(3L^3 - a^3) + 6(La^2 - L^2a)}$$

(2)

(b) We performed scanning by means of weak force ($F=57.6$ µN) at a range of 50 µm x 50 µm by using the stainless cantilever in the same position as previous. (c) We performed scanning on a wide range (100 µm x 100 µm) using a commercial silicon cantilever against the previous loaded place (50 µm x 50 µm) and observed the existence of removed dust on the monitor (Fig. 9, Fig. 11, and Fig. 12). (d) The surface observation of the sphere was scanned. Spheres $R=5$ µm in range of the scan size of 5 µm x 5 µm and $R=10$ µm were scanned in the range of the scan size of 10 µm x 10 µm by using a commercial triangle cantilever with a spring constant $k=0.004$ N/m. From here, we judged the volume and the roughness of the surface. Dependent upon the existence of dust on the surface, we performed the same work repeatedly. The photograph shown was the digital image taken of the monitor with the digital camera. We measured pull-off forces on the surfaces of the micro spherical sphere using the cantilevers glued on the glass sphere $R=10$ µm, which was made as shown in Fig. 13-f. It was cut probe of cantilever using a FIB (Focus Ion Beam, Hitachi Co.) (26), and the micro glass sphere is glued on the top of cantilevers over AFM. Using the cantilevers, the pull-off forces are measured by means of calculating the mean value, which was measured at 12 point for all sides from the peak of the contacted surface.

3. The experimental results and discussion

3.1 The cleaning of dust by applied loads

We investigated the cleaning ability in relation to dust which had adhered to the glass
substrate over 110 days, in addition to the influence in relation to the contact radius by micro spheres of different materials. To see the cleaning effect from the changes on contact surfaces along with applied load of cantilever, we investigated the volume ($V$) and plane roughness ($Ra$) of the substrates using a commercial silicon cantilever ($k=2N/m$). To find out the previous abraded surfaces ($50\,\mu m \times 50\,\mu m$) of substrates, we performed scanning over the wide ranges ($100\,\mu m \times 100\,\mu m$) using commercial silicon cantilever ($k=2N/m$). The traces of the scan range ($50\,\mu m \times 50\,\mu m$), in which the contact force was applied to the glass substrate, shown clearly in Fig. 9-12. The results are shown in Fig. 9-12. The stainless cantilevers are glued the glass sphere ($R=10\,\mu m$) at the top. Each of those represented in Fig. 9 performed the cleaning of the dust at the same place of the previous place acted normal load. As shown in Fig.10-a, the volume of dust reduced from $V=1.74e11\, nm^3$ to $V=2.12e9\, nm^3$ by applied load. Also, the height ($H$) of dust decreased to $H=416\, nm$. The scan size of the first photo was $50\,\mu m \times 50\,\mu m$, the others were $100\,\mu m \times 100\,\mu m$. Fig. 10-b shows the glass sphere which adsorbed the dust after the cleaning in $F=922.7\, \mu N$. The scan range is $10\,\mu m \times 10\,\mu m$. Figure 11 show the results and appearance that cleaning work of dust performed by using the stainless cantilever in which a plastic sphere ($R=10\,\mu m$) is glued. Compared with the case of the borosilicate sphere, dust does not decrease from the substrate. The volume of dust remaining on the surface was observed.

![Figure 10](image1.png)

Figure 10. Changes of in volume and height against applied load (a). Glass spheres whose curvature radiuses are $R=10\,\mu m$ are used (b). The dust was remained on the glass sphere, scan size=$10\,\mu m \times 10\,\mu m$. scan line=256, scan rate=4 sec/line, $F=922.7\, \mu N$.

![Figure 11](image2.png)

Figure 11. Changes of the volume of dust against applied load (a). A plastic sphere whose curvature radius is $R=10\,\mu m$ is used. The photos shown with the graph correspond to the first step, middle step and last step of cleaning, respectively. Scan size of the first photo: $50\,\mu m \times 50\,\mu m$, all others scan size: $100\,\mu m \times 100\,\mu m$. Fig.11-(b) is the deformed appearance of a plastic sphere. The scan size is $5\,\mu m \times 5\,\mu m$, scan line=256, and the scan rate=4 sec/line.

The photographs (Fig.11-a) of the graph show the appearance of the first step, intermediate
step \((F=461.3\mu N)\) and last step \((F=922.7\mu N)\), respectively. Although we had predicted that the micro spheres have elastic deformation against the load of \(\mu N\) scale, Fig.11-b shows the appearance of a plastic sphere that was destroyed by an applied load. Also, although the volume of dust decreased in conjunction to the applied force \((F=57.6\mu N)\) that was given in the first step, the changes in volume appeared to fluctuate along with increases of forces. By using the stainless cantilever in which the glass sphere having a radius of \(R=5\mu m\) are glued, the cleaning of dust was performed against the substrate in which dust was allowed to accumulate for 110days, and the changes in volume and height of dust on each applied load was shown in Fig. 12. Figure 12-a shows the volume distribution \((V=1.73e11nm^3)\) of the dust on the no abrading substrate. According to applied loads, the volume of dust increased gradually. Also, compare the case (Fig. 12) of the cantilever of radius \(R=5\mu m\) with the cases (Fig. 9, 10) of the cantilever having a radius of \(R=10\mu m\) under the same applied load \((F=230.6\mu N)\), we found out that dust cleaning is easier than the case of a larger radius in the case of a small radius.

\[
\begin{align*}
(a) V &= 1.73e11nm^3, \\
(b) V &= 3.82e9nm^3, \\
H &= 673nm, F &= 115.3\mu N, \\
(c) V &= 3.33e9nm^3, \\
H &= 351nm, F &= 230.6\mu N, \\
(d) V &= 4.24e9nm^3, \\
H &= 612nm, F &= 461.3\mu N, \\
(e) V &= 6.37e9nm^3, \\
H &= 581nm, F &= 922.7\mu N.
\end{align*}
\]

Besides, we can understand that the contact areas are affected by contact pressure force from Hertz’s elastic equation \((27)\).
\[ P = \frac{W}{A} = \frac{W}{\pi (KRW)^{\frac{3}{2}}} \]  

where,

\[ K = \frac{3}{4} \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right) \]

The elastic pressure equation of Hertz is represented in equation (3) whereby contact pressure force \((=P \text{ [Pa]})\), curvature radius \((=R \text{ [µm]})\), contact area \((=A)\), and applied load \((=W \text{ [N]})\). From the relationship between pressure force and applied loads against curvature radius by Hertz’s elastic equation, since curvature radius becomes smaller, the contact area also becomes small. Then, the contact pressure force on the surface increases, relatively. In the Fig.12-(f), concerning the cause of the volume increases from \(F = 230.6 \mu\text{N}\), it seems to be caused by recontamination of the plastic deformation or wear in the interactive surfaces by considerable pressure force. Also, from changes in the height of dust, the surfaces are considered as being reason for the repeated separation and attachment by fragments. Comparing the results (Fig.9-12), the plastic spheres tend to deform more easily upon loads than the borosilicate glass spheres. It seems to be caused that adhesive wear (28) was allowed plastic deformation to occur at an adhesive area composed true contact area between the interactive solid surfaces with micro dust along with shear stress (29), which was affected by repeatedly sliding with an applied load. By analysis using FEM (Finite Element method) concerning the sliding interaction between elasto-plastic spheres, which described the average tangential and normal contact forces, R.L. Jackson et al. (30) reported that plastic deformation of the spheres increases as the interference or normal load between the surfaces increases. M. Troyon et al. (31) mentioned that the friction due to deformation rather than adhesion mainly governs the lateral force during a nanoscratch test. The micro plastic spheres show plastic deformation means that the fragments of the sphere interfere between interactive contact surfaces.

(a) \(F=57.6 \mu\text{N}\) (b) \(F=115.3 \mu\text{N}\) (c) \(F=230.6 \mu\text{N}\) (d) \(F=461.3 \mu\text{N}\) (e) \(F=922.7 \mu\text{N}\) (f) A glass sphere \((R=5 \mu\text{m})\) glued to the triangle cantilever \((k=0.004 \text{N/m})\).

Figure 13. The appearance of the micro glass sphere’s surface \((R=5 \mu\text{m})\) at a scan range of \(5 \mu\text{m} \times 5 \mu\text{m}\) against each applied load. The abrading had conducted over a surface of glass substrate without dust. Scan line=128, Scan Rate=4 sec/line. The measurement environment had been maintained for all experiments in air at room (temperature: 24-26 °C, humidity: 25-40%Rh).

3.2 The changes between interactive contact surfaces

In this chapter, we investigated the aggregation of dust over the glass sphere’s surface with a curvature radius of \(R=5 \mu\text{m}\) by applied normal load.
(a) The change of contact areas over the glass sphere against applied loads. (b) The changes of roughness over a glass sphere and a glass substrate after abrading by applied loads. (c) The changes of volume over a glass sphere and a glass substrate after abrading by applied loads. (d) The average changes of pull-off force over the surface of glass sphere after abrading by applied loads. When the pull-off forces are measured, temperature and humidity are maintained next condition in air at room, room temperature: 24℃, humidity: 25 %Rh.

Figure 14. The results of measurement on the interactive contact surfaces between glass
sphere ($R=5\mu m$) and glass substrate without dust. Applied loads were conducted, gradually.

Figure 13 shows the appearance of the micro glass sphere’s surface at a scan range of $5\mu m \times 5\mu m$ against each applied load. According to the applied load added, the aggregation of dust was increased on the surface. In the previous chapter, we mentioned increment of dust due to the cause of adhesive wear. When curvature radius is small, the concentration of contact pressure force brings about plastic deformation. As can be seen in Fig. 13, the fragments of dust are adsorbed in the glass sphere’s surface along with increasing of applied load. Figure 13-e shows new contact area by dust aggregates along with applied load. We compared these changes in the contact area by the aggregation of dust with the theoretical values of contact area by means of different radiuses based on the equation (3) (Fig. 14-a). Figure 14-b represents the changes in roughness between the glass sphere and glass substrate. The substrate was more significantly changed than the glass sphere in terms of the roughness with an increase of applied load. Also, in Fig. 14-c and Fig. 14-d we see changes in volume and pull-off force against the glass spherical surface. From Fig. 14-c, the increases of the volume on the glass sphere’s surface had correlated with the decrease of the volume on the glass substrate. By using cantilevers ($k=0.004N/m$, glass sphere) as shown in Fig.13-f, the pull-off forces are measured by means of calculating the mean value, which was measured at 12 points at all sides from the peak of the contacted surface. The photograph accompanying the graph represents the force curve in the first, intermediate, and last points (Fig. 14-d). From the Figure 13 and 14-d, we found out that pull-off forces are proportional to aggregated dust due to the increment of applied load. In contrast D. M. Schaefer et al. (8) mentioned that the non-linear relation between pull-off force and applied load depends on contaminants, and the change in contact area between the substrate and sphere is non-linear, although the causes behind these findings was not clarified. In the interactive surfaces, if curvature radius is small, contact pressure force increases. Accordingly, it would seem that the influence of contact fatigue by differences in the mechanical properties of the material at the sliding interactive surfaces is governed by increases in the contact pressure force (32). The forces required to initiate sliding of cantilever are higher than the forces required to break a contact of dust, thus, aggregates of dust can only be restructured without being destroyed by rolling (3). We predict that any change, such as plastic deformation and dust aggregates, between the interactive surfaces in the sliding process takes place after those involving the increase of contact force by large bending of cantilever and shear stress (29). And, the restructuring of dust aggregates seems to be caused by large contact pressure force and bending of the cantilever inducing elastic force in the interactive surfaces by abrading behavior.

4. Conclusion

By using cantilevers of cheap stainless steel (SUS 304) glued to micro spheres, we studied the cleaning ability of dust adhered to the glass (Na$_2$O-CaO-SiO$_2$) substrate. The cleaning work was performed by applied load at a wide range ($50\mu m \times 50\mu m$) on AFM, and we investigated the changes between interactive contact surfaces with contaminant. The results showed the following:

(a) We found that it is generally easier to remove dust from a small radius than a large radius.

(b) The plastic spheres tend to deform more than the borosilicate glass spheres under the same applied load. And, in spheres having the same material properties, those with the small curvature radius tends to deform more than that which has a large curvature radius. From the results, the contact pressure forces are independent of the material properties and contact area.

(d) The apparent contact surface is proportional to changes in the volume of the surface,
approximately, and the roughness of surface affected along with applied loads. It is assumed that there is the immanence of the fragments due to influence of contact fatigue along with contact pressure force.

(e) The restructuring of dust aggregates by sliding of a cantilever along with applied loads formed a new micro contact area, which influenced on contact surface forces.

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