Non-contact microsphere–surface adhesion measurement via acoustic base excitations

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Abstract

A non-contact adhesion measurement technique based on acoustic base excitation and laser interferometry has been introduced and demonstrated. The vibrational motion of 21.4-µm polystyrene latex particles (PSL) microspheres on surfaces were excited in the frequency range of 0–3.5 MHz, and their axial displacement responses were measured by an interferometer. It is shown that the rolling motion is dominant compared to the axial displacement of the bond. Using a formula for the rotational moment resistance of the particle–surface adhesion bond and the equation of rotational motion, the natural frequency of the rotational motion is related to the work of adhesion of the particle and substrate materials. The substrate materials used in the experiments include copper, aluminum, tantalum, and silicon. Measured work of adhesion values are compared to the data reported in the literature and good agreement is found.

Keywords: Rolling resistance; Work of adhesion; Microspheres; Adhesion measurements

1. Introduction

The work of adhesion measurements are primarily based on the adhesion force between the particle and the substrate. Several models have been developed since 1881 (Hertz) to predict the force of adhesion. Some of the widespread adhesion models that are used to describe the nature of force of adhesion include: Hertz model, Johnson–Kendall–Roberts (JKR) model [1], Derjaguin–Muller–Toporov (DMT) model [2], Maugis–Dugdale (MD) theory [3] and Bradley model [4]. The JKR model takes the surface energy and the particle deformation into consideration [1]. The DMT theory predicts that the contact area of the particle tends to zero at the moment of separation [2]. The JKR model is considered to be good approximation for soft particles, while the DMT model for hard particles [5,6]. However, among many theories developed, the JKR theory and DMT theory have gained wider acceptance [7].

Hertz, JKR, DMT, MD and Bradley have been proposed and transition between them has been established for ranges of external loads and an elasticity parameter.

According to the JKR theory, a particle in contact with a flat substrate induces short range forces (adhesion and elastic forces) between the substrate and the particle, this leads to deformation of the particle and the substrate at the point of contact. When an external force is applied on the particle, a moment at the contact point could be induced. This moment results in rolling of the particle. Rolling motion involves changes of contact area at the leading edge and at the trailing edge of the contact with the surface, resulting in asymmetry of the pressure field, i.e. the leading edge of the contact area establishes new contact area and peeling of the trailing edge takes place [8,9]. This asymmetric pressure distribution results in shifting of contact area and due to this the particle could undergo free rotational oscillations with respect to the contact area [10].

Measurement of adhesion forces in the micro/nano scale and relating it to the work of adhesion of the particle–
substrate system is often a technical challenge. Adhesion forces can be determined either by measuring the force required to adhere to a particle/surface or by measuring the force required to detach a particle from a surface [11]. Some of the currently used measurement techniques are discussed below. Advanced techniques (e.g., force microscopy) are needed for measuring the properties during adhesion while conventional techniques are used to measure adhesion properties during detachment. Some of the commonly-used methods include centrifuge technique, aerodynamic method, hydrodynamic technique [12], impact-spectrum method and ultrasonic vibration method [13]. In the centrifuge technique, the centrifugal force required for detaching a particle from the substrate, while the substrate is in rotation, is measured. In the aerodynamic and hydrodynamic techniques, the flow generated force is used to detach a particle from the substrate and the threshold force is used to determine the force of adhesion. Whereas in the impact-spectrum technique, the particles are detached from a substrate by the impact given at the opposite sides of the substrate and the force is measured. In the ultrasonic vibration method, the frequency and hence the force required to detach a particle from the substrate using an ultrasonic probe is measured. In [14], a device set-up developed for determining the adhesive bonding stiffness between a particle and a substrate from the natural frequency shift of the oscillatory system is presented.

The force microscopy techniques used to measure the force of adhesion during adhesion, include atomic force microscopy (AFM) [15–18], lateral/friction force microscopy (FFM) [19,20], scanning tunneling microscopy (STM) and ultra-high vacuum atomic force microscopy (UHV–AFM) [21,22]. In most of these techniques, a cantilever tip is brought near a particle/surface whose properties have to be measured. The deflection in the cantilever due to the adhesion force is measured. All the above specified force microscopy methods need some form of contact between the cantilever and the particle/surface except the STM, which is a non-contact method. In the STM method the electric current between the tip and the particle/surface is measured, which is proportional to the adhesion force. The main disadvantage of the AFM technique is that the particle has to be glued to the tip of a probe; therefore it is essentially a destructive technique.

In the current study, the rolling vibrations of a particle on a substrate subjected to base motion are measured using a laser interferometer. In this technique, the difference in phase between a scattered/reflected light from a surface and the reference beam is measured and this phase difference is proportional to instantaneous surface displacement [23]. The measured natural frequencies of the vibrations are related to the work of adhesion between the particle and surface. The main advantage of the use of a laser interferometer in adhesion measurements is the ability to measure surface displacements down to couple of nanometers at high vibration frequencies in a non-contact manner. The resulting measurement technique is non-contact and non-destructive.

2. Adhesion theory and particle dynamics

According to the Johnson–Kendall–Roberts (JKR) adhesion model [1], the contact adhesion force between a spherical particle and flat substrate at static equilibrium is proportional to the particle radius (r): $F_A = \frac{3}{2}\pi W_AR$, where $W_A$ is the work of adhesion (Dupré’s energy) between a spherical particle and the substrate material. Since the particle mass is proportional to $r^3$, adhesion forces dominate inertial effects in small length scales (i.e. in micro/nano-scales) and slow time scales (i.e. relatively at low frequencies). One consequence of this scaling effect is the possibility of the generation of low-amplitude high-frequency particle vibrations without particle detachment. Since the adhesion properties can be related to the natural frequencies of a particle on a surface, the vibrational motion of a particle can be used to determine the particle–surface adhesion properties.

High-frequency motion of a particle can be excited on its base by a piezoelectric transducer. A typical experimental set-up for base excitation is depicted in Fig. 1. The resulting displacement of the particle can be resolved into two components: (i) axial displacement (Fig. 2) and (ii) angular displacement with respect to the center of the adhesion contact area (Fig. 3). The latter component is termed as rocking motion in the current study.

2.1. Axial motion

The JKR theory is a one-dimensional (axial) adhesion model. According to the JKR adhesion model, the external

![Fig. 1. Base excitation method diagram for measuring work of adhesion.](image-url)
force–axial displacement relation for a particle attached to a flat substrate (Fig. 2) consists of two components:

\[
F = \frac{1}{\beta} r^{3/2} \delta^{3/2} - \sqrt{\frac{2\alpha}{\beta}} r^{3/4} \delta^{3/4},
\]

(1)

where \(\delta\) is the axial displacement of the centre of the particle with respect to the surface of the substrate due to the applied external force \((F)\) and \(\beta = r/K\) where \(K\) is the stiffness coefficient of the adhesion bond between the particle–substrate system given by

\[
K = \frac{4E_1E_2}{3(E_2(1 - \nu_1^2) + E_1(1 - \nu_2^2))},
\]

(2)

where \(E_1, E_2\) are the Young’s modulus and \(\nu_1, \nu_2\) are the Poisson’s ratios of the substrate and particle, respectively, and \(\alpha = 3\pi W_A r\). The stiffness expression (Eq. (1)) is non-linearly related to the applied external force as shown in Fig. 4. To determine the axial natural frequency of the particle–substrate system around its stable equilibrium, the stiffness expression is linearized at the stable equilibrium point at \(\delta^* = (2\alpha\beta)^{3/2} / r\):

\[
K^* = \frac{dF}{d\delta}_{\delta=\delta^*} = \frac{3r\alpha^{1/3}}{2^{5/3}\beta^{2/3}}.
\]

(3)

The linearized force becomes \(F^* = K^*(\delta - \delta^*)\) in the neighborhood of this equilibrium point. Thus, the natural frequency of the adhesion bond in the axial direction (normal to the flat substrate) is obtained as

\[
\omega_n = \sqrt{\frac{K^*}{m}} = \frac{3\alpha^{1/6}}{2^{11/6} r \sqrt{\pi} \beta^{1/3}}.
\]

(4)
where \( m \) is the mass of the particle. The axial frequency \( (f_a) \) for a 21.4-µm PSL on silicon substrate is calculated as \( f_a = 1.83 \) MHz and stiffness coefficient as \( K^* = 707.4 \) N m\(^{-1}\) while on copper substrate is given as \( f_a = 1.85 \) MHz and \( K^* = 718.6 \) N m\(^{-1}\) (from Eq. (4)) based on the Hamaker constants from [24].

2.2. Rocking motion

In addition to the axial motion, the particle can have another mode of vibration on a flat surface: rotational motion with respect to the center of the contact area. To model rotational motion of a particle, a two-dimensional adhesion theory is needed. The non-uniform stress distribution in the rotational motion of a particle, a two-dimensional adhesion theory is needed. The moment associated with this pressure distribution is the integral over the contact area:

\[
M_y = \iint \! xp(x, y) \, dx \, dy = 0,
\]

where \( p(x, y) \) is the pressure distribution in the contact area. However, when an external force or horizontal displacement field is applied to the substrate, the moment associated with rocking motion of the particle results in shifting of contact area, i.e., the contact area is no longer centered around the point which is vertically below the center of the sphere and the pressure distribution is not symmetric any longer. The contact radius of the 21.4-µm PSL particle on a silicon substrate is approximately 231 nm (at zero applied load) and the force of adhesion is 1.18 µN while on a copper substrate is about 235 nm (at zero applied load) and the force of adhesion is 1.24 µN based on the Hamaker constants from [24].

The pressure distribution and the moment associated with rocking motion can be calculated from the following assumptions [10]:

1. The true shifted contact area is approximated by decomposing the contact area into two circles of different radii \( a + \xi \) and \( a - \xi \), where \( \xi \) is the shift in the contact area due to rocking motion.
2. The half circle \( x < 0 \) is one half of a symmetrical contact with contact radius \( a + \xi \) and pressure distribution \( p(r, a + \xi, \delta_c) \).
3. The half circle \( x > 0 \) has a smaller contact radius \( a - \xi \) and a corresponding pressure distribution \( p(r, a - \xi, \delta_c) \).

The total moments due to both the half circles is calculated. Since different contact radii correspond to different values of \( \delta_c \) [10], JKR equations cannot be used in calculation of moments of one half of the contact area for different sizes of contact area. The resulting distribution is discontinuous at \( x = 0 \). According to [25,26], the superposition of the Hertz \( (p_H) \) and Boussinesq \( (p_B) \) solutions describes the pressure distribution in the actual contact zone of the contact, which is affected by the attractive forces:

\[
p(r, a, \delta_c) = p_H(1 - r^2/a^2)^{1/2} + \frac{p_B}{(1 - r^2/a^2)^{1/2}}.
\]

The pressure corresponds to the normal displacement of the sphere:

\[
\delta_c = \frac{\pi a}{2E^*}(p_H + 2p_B).
\]

The asymmetric pressure distribution is obtained by the combination of the symmetric pressure distribution of the contact radii \( a + \xi \) and \( a - \xi \):

\[
p_a(r, a, \xi) = \begin{cases} 
p(r, a + \xi, \delta_c), & x < 0, \\
p(r, a - \xi, \delta_c), & x > 0.
\end{cases}
\]

The moment associated with this pressure distribution is the integral over the contact area:

\[
M_y = \int_0^{\pi/2} \int_0^{\pi/2} xp(r, a + \xi, \delta_c)r \, dr \, d\phi \\
+ \int_{-\pi/2}^{\pi/2} \int_0^{\pi/2} xp(r, a - \xi, \delta_c)r \, dr \, d\phi,
\]

with \( x = r \cos \phi \), and integration with respect to \( \phi \) results in

\[
M_y = -2 \int_0^{a+\xi} r^2 p(r, a + \xi, \delta_c) \, dr \\
+ 2 \int_0^{a-\xi} r^2 p(r, a - \xi, \delta_c) \, dr.
\]

Evaluating the integrals, keeping \( \delta_c \) constant and neglecting higher order terms of \( \xi/a \), an approximation for \( M_y \) is obtained

\[
M_y \approx 2\xi \left(-E^*a\delta_c + 3P_\delta a^3\right)
\]

substituting Johnson’s [27] solution for \( \delta_c \) corresponding to the contact radius \( a \). The resulting moment is determined as

\[
M_y \approx 4P_\delta a^{3/2}\xi.
\]

Thus, the moment associated with shift in contact area is proportional to the pull-off force \( P_\delta \) and the shift of the center of contact area. For a spherical particle in contact with a flat surface,

\[
P_\delta = \frac{3}{2}\pi W_A r,
\]

where \( W_A \) is the work of adhesion, and if the normal forces stay within the range of \(-P_c < P < P_c\), the factor \( a^{3/2} \) varies in the range 0.5–1.2, and assuming \( a = 1 \), the rolling
resistance moment for a particle on a flat substrate is approximated by

$$M_y \approx 6\pi W_A r \xi.$$  \hspace{1cm} (12)

Using the equation of motion of a spherical particle in free-rotational oscillation on a flat surface

$$I \ddot{\theta} + 6\pi W_A r \xi = 0$$

where $\xi \approx r \theta$ is the shift in contact area due to the asymmetric pressure, the natural frequency of this oscillator for the rocking motion is determined as

$$\omega_n = \frac{1}{r^{3/2}} \sqrt{\frac{45 W_A}{4 \rho}},$$  \hspace{1cm} (13)

where $\rho$ is the mass density of the particle material. It is evident that the rocking natural frequency is dependent on the radius of the particle, work of the adhesion of the particle–substrate system and the density of the particle, while the elastic properties of the particle and substrate material appear to play no role in rocking motion. Note that the natural frequency of the axial motion is a function of the elastic properties of the particle–substrate system. The rocking frequency for a 21.4-µm PSL particle on the silicon substrate is calculated as $f_n = 72.5$ kHz and for PSL particles on copper substrate as $f_n = 74.3$ kHz.

In order to determine the effect of the electrostatic forces on the dynamics of a 21.4-µm PSL particle, the forces of adhesion between the particle and the substrate are calculated and compared to the approximated electrostatic forces. The van der Waals force of attraction on the particle–substrate system is given by $F_{\text{vdw}} = (Ar)/(6z_0^2) = 1.57$ µN, where the Hamaker constant of PSL–silicon system $A = 1.41 \times 10^{-19}$ J (from [24]), $r = 10.7$ µm is the radius of the particle and $z_0 = 4 \times 10^{-10}$ m is the separation distance between the particle and the substrate. The electrostatic forces contributing to the force of adhesion are given by

$$F_{\text{uniform}} = \frac{Q^2}{16\pi \varepsilon_0 (z_0 + r)^2} = 50.3 \text{ pN}$$

and

$$F_{\text{localized}} = \frac{q^2}{16\pi \varepsilon_0 (z_0 + a)^2} = 0.26 \text{ nN},$$

$$F_{\text{electrostatic}} = F_{\text{uniform}} + F_{\text{localized}} = 0.31 \text{ nN},$$

where $F_{\text{uniform}}$ is the electrostatic force due to the charge on the surface of the particle, $F_{\text{localized}}$ is the local charge trapped at the particle–substrate contact due to triboelectrification; $Q$ is the charge on the surface of the sphere, $Q = 10^4$ electrons (assumed) [28] and $q$ is the local charge trapped at the area of contact, $q = 500$ electrons (assumed) [28]; $\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$ is the permittivity of air and $a = 231$ nm is the JKR contact radius (at zero applied force) of the PSL–silicon system.

Thus by comparing the van der Waals forces (1.57 µN) and electrostatic forces (0.31 nN), it can be seen that the van der Waals force of attraction is four orders of magnitude higher than the electrostatic forces of attraction and hence the electrostatic forces of attraction can be neglected for the particle–substrate system employed in the current study.

### 3. Experimental procedure

In the proposed non-contact work of adhesion measurement approach, the relation between the rocking natural frequency and adhesion properties is utilized (Eq. (13)). To determine the rocking frequency of a particle on a flat substrate, a set of experiments were designed and conducted. The schematic of the experimental set-up and instrumentation diagram is depicted in Fig. 5.
Dry 21.4-µm spherical polystyrene latex particles (PSL) (Duke Scientific, Inc.) were deposited on a piece of wafer. The wafer piece was then placed on a 3.5 MHz transducer (Panametrics, V682). Coupling gel was applied between the wafer sample and the transducer for good acoustic transmission. The transducer was mounted on a xy-translation stage of an optical microscope. A CCD camera is attached to the optical microscope to monitor the experiments. A Laser Doppler Vibrometer (LDV) (Polytec, Vibrometer controller unit (OFV 3001), Fiber interferometer unit (OFV 511) and Ultrasonic Displacement Decoder (OVD 030)) is integrated with the microscope; the laser beam of the fiber interferometer unit is transmitted through the microscope objective. The size of laser spot of the fiber interferometer unit can be reduced to 0.5 µm using a 100× objective of the optical microscope. The laser spot is directed to the top of the particle on the surface. The transducer was excited by a square pulse from pulser/receiver (Panametrics, Model 5077PR). The particles on the wafer participate in complex motion due to the combination of vibrational modes (axial and radial) of the irregular wafer piece. The axial response of the particle to this complex vibration field was measured using the LDV. It consists of a vibrometer controller unit and a fiber interferometer unit and a displacement decoder. The frequency band of the displacement decoder is 50–30 MHz. The LDV measures the axial motion of the particle by comparing the frequency and phase difference of the emitted and the reflected laser beam. This difference in phase is decoded into displacement by the displacement decoder while the difference in frequency is decoded into velocity by velocity decoder. The decoders generate a waveform in time domain. The trigger line to the digitizing oscilloscope (Tektronix TDS 3052) was provided from the pulser/receiver for synchronizing data acquisition. The laser spot of the fiber interferometer unit was focused onto the particle. This procedure was repeated to measure the response of the surface of the wafer piece to characterize the base motion. The sequential procedure for measuring the displacements of the rocking particles is discussed below.

3.1. Measurement of resonance frequencies

Dry 21.4-µm PSL particles were deposited on a small piece of silicon wafer and sufficient time was allowed for the particles to relax and adhere to the wafer. As the expected axial motion frequencies are in the mega-Hertz range (1.83 MHz for PSL–silicon system and 1.85 MHz for PSL–copper system) while the expected rocking motion frequencies are in kilo-Hertz range (72.5 kHz for PSL–silicon and 74.3 kHz for PSL–copper system), there is a good frequency band separation and thus the components of the motion of particles subjected to base excitation can be identified easily. The transducer was excited with a pulse of amplitude 400 V and 100 Hz PRF from the pulse/receiver unit. It was observed that some of the particles on the wafer tend to agglomerate and form clusters, while some others tend to oscillate as single particles. These single oscillating particles on the wafer were located for rocking frequency measurements. The laser spot of the fiber interferometer unit was focused on a particle using 100× magnification of the optical microscope as shown in Fig. 6(a). The transient axial motion of the particle was recorded from the oscilloscope for signal processing. The xy-translation stage was adjusted to focus the laser spot on the wafer (Fig. 6(b)) and the surface response was recorded. This procedure was repeated for different particles on the substrate and the corresponding waveforms were digitized and saved. The experiment was repeated on copper, aluminum and tantalum sputtered silicon wafers and the results were compared.

4. Experimental results

The time and frequency responses of the transducer employed for exciting the wafer are shown in Fig. 7. The transducer was excited by a square pulse from pulser/receiver. It is clearly visible that the central frequency of the transducer is around 3.1 MHz. A relatively strong low-frequency component of surface vibration in the range of 50–200 kHz is also observed. These low-frequency and high-frequency components are useful for exciting rocking and axial modes of vibrations of the PSL particle used in the experiments.
The axial displacement (nm) waveforms of the 21.4-µm PSL particle on silicon, copper, aluminum and tantalum substrates are depicted in Figs. 8–11, respectively. The axial displacement (δ) measured by the interferometer is related to the angular motion of the particle (θ) (Fig. 3) as
\[ \delta \approx 2r(1 - \cos \theta) \]. This is because, as will be demonstrated below, the contribution of the axial extension of the adhesion bond to the measured axial displacement \( \delta(t) \) is negligible compared to the measured axial displacement due to the rocking mode of vibration. The maximum rocking angle (θ) for an instance of the PSL particle on a silicon substrate is measured as about 0.16°. Then the corresponding shift in contact area for the PSL–silicon system is calculated as \( \xi = 29.96 \text{ nm} \). Note that the radius of the contact area is approximately \( a = 231 \text{ nm} \) (at zero applied load).

The maximum surface acceleration of the silicon and copper substrates is approximated from the axial displacement waveforms as shown in Figs. 8 and 9. The numerical values of maximum surface acceleration for silicon and copper substrates can be estimated from the displacement amplitude and frequency data (Figs. 8 and 9) \( (a_{\text{max}} \sim d_{\text{max}}(2\pi f)^2) \) and determined as \( a_{\text{max}} \sim 10^5 \text{ ms}^{-2} \). Using these acceleration values, the maximum force \( F_{\text{max}} \) at the surface of the substrate is estimated by \( F_{\text{max}} = ma_{\text{max}} \). The correspond-
Fig. 8. (a) Time domain response of PSL–silicon system (P5). The dash line corresponds to particle response while the solid line corresponds to wafer response. (b) Close-up of waveforms in (a).

Fig. 9. (a) Time domain response of PSL–copper system (P5). The dash line corresponds to particle response while the solid line corresponds to wafer response. (b) Close-up of waveforms in (a).
Fig. 10. (a) Time domain response of PSL-aluminum system (P1). The dashed line corresponds to particle response while the solid line corresponds to wafer response. (b) Close-up of waveforms in (a).

Fig. 11. (a) Time domain response of PSL–tantalum system (P1). The dashed line corresponds to particle response while the solid line corresponds to wafer response. (b) Close-up of waveforms in (a).
Fig. 12. (a) Time-frequency spectrograph of PSL particle on silicon substrate. The dash line represents the calculated frequency ($f^* = 72.5$ kHz). (b) Close-up of spectrograph in (a).

Fig. 13. Time-frequency spectrograph of PSL particle on copper substrate. The dash line represents the calculated frequency ($f^* = 74.3$ kHz).

The maximum extension of the particle–surface bond in axial mode of vibration is in the order of $\delta_{\max}^* \approx F_{\max}/K^*$, where $K^* = 707.4$ and $718.6$ N m$^{-1}$ for silicon and copper substrates, respectively, is the stiffness coefficient of adhesion bond at the stable equilibrium point which is reported in Section 2.1. The numerical value of the axial motion amplitude for PSL particle on silicon and copper substrates is approximately 0.9 nm. This order analysis indicates that the axial motion amplitude is two orders of magnitude lower than that reported in Figs. 8–11. Thus, it is established that the obtained amplitudes are predominantly due to the rocking motion of the particle.

From the time responses of particle–substrate pairs under base excitation it is evident that the wafer response due to the base motion diminishes faster than that of the particle. A time-frequency analysis is conducted for distinguishing frequency components of the measured particle vibrations; Figs. 12–15 depict the time-frequency spectrographs of the measured waveforms as presented in Figs. 8–11. From these spectrographs, it is clear that the frequency compo-
ponents above 150 kHz are highly damped while the frequency components in the range of 50–150 kHz are damped much lighter. These lightly damped frequencies are comparable to those of the calculated rocking frequencies (from estimations using the reported mechanical and work of adhesion properties). In addition, it has been noticed that the range of rocking frequencies changes from particle to particle on the same type of substrate, thus indicating that there could be substantial variation in work of adhesion from particle to particle and their locations on a wafer. Vibration of particle with multiple frequencies indicates that the work of adhesion is direction dependent. The range of experimental work of adhesion for the particle–substrate system is calculated from the observed rocking motion frequency band using Eq. (13). For instance, the work of adhesion range for PSL particle on silicon substrate is determined as 23.1–101.5 mJ m\(^{-2}\) from experimental waveforms. The obtained experimental work of adhesion of the particle–substrate system is compared with the reported work of adhesion values. The mechanical properties of the particle and substrate materials and the results of the experimental work are tabulated in Table 1.

Table 1

| Particle–substrate system | Rocking natural frequency (kHz) | Experimental work of adhesion (mJ m\(^{-2}\)) | Expected\(^a\) work of adhesion (mJ m\(^{-2}\)) | Expected axial natural frequency (MHz) | Density (kg m\(^{-3}\)) | Young’s modulus (GPa) | Poisson’s ratio | Particle | Substrate | Particle | Substrate | Particle | Substrate |
|--------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------|--------------------------|----------------------|--------------|-----------|----------|-----------|-----------|----------|
| PSL–copper               | 78–110                          | 27.4–54                                       | 24.7                                          | 1.85                                  | 1040                     | 8833                 | 2.7          | 114.7     | 0.33     | 0.34      |           |          |
| PSL–silicon              | 72–150                          | 23.1–101.5                                    | 23.5                                          | 1.83                                  | 1040                     | 2329                 | 2.7          | 127       | 0.33     | 0.28      |           |          |
| PSL–aluminum             | 90–180                          | 36.21–144.8                                   | N/A                                           | N/A                                   | 1040                     | 2700                 | 2.7          | 74.5      | 0.33     | 0.33      |           |          |
| PSL–tantalum             | 60–150                          | 16.1–100.6                                    | N/A                                           | N/A                                   | 1040                     | 16650                | 2.7          | 186       | 0.33     | 0.34      |           |          |

\(^a\) The theoretical work of adhesion values are calculated from Hamaker constants of materials [24].
5. Conclusions and remarks

A novel non-contact technique for work of adhesion measurements between a micro-sphere and flat surface is introduced and demonstrated. The main advantage of a non-contact method in work of adhesion measurements is that it eliminates reported shortcomings of contact-based methods. For example, in AFM-based measurements, the tip–object interactions are highly non-linear and complex due to gluing of the tip to the object (particle) and, also, the technique attempts to characterize the properties of a single contact (particle–surface) by creating two contact points (particle–surface and particle–probe tip). The natural frequency of the rocking motion of the particle on a substrate, subjected to base motion is identified as the key frequency in determining the work of adhesion properties. A band of rocking frequencies suggests that there could be variation in the work of adhesion due to many possible directions for rocking motion determined by the surface–particle topology and location of particle on the wafer. It is also noted that the particle-displacements measured are predominantly due to rocking motion and the frequencies corresponding to axial motion are absent. The experimental work of adhesion of PSL particles on four different substrates is calculated. These numerical values are compared to the values previously reported in the literature and a good agreement is observed.

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