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MEASUREMENT OF ADHESION FORCES IN AIR WITH THE VIBRATION METHOD

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Abstract The vibration method represents a practical method for the measurement of adhesion forces and adhesion force distributions. This method causes sinusoidally alternating stresses and yields detachment and contact forces between particles and substrate of the same order of magnitude. Alternating contact forces of the vibration method can cause an adhesion force intensification through flattening of asperities. The measuring principle of the vibration method and the analysis of experimental results are described in the article. Normal adhesion forces (pull-off forces) are measured using the vibration method and the colloidal probe technique. The results of both methods show good agreement for small particle sizes. The influence of the detachment force direction is shown by comparing tangential and normal adhesion forces measured using particle reentrainment in a turbulent air flow and the vibration method, respectively. The surface roughness of the substrate and the relative humidity are shown to significantly influence the measured adhesion forces. For the calculation of the adhesion forces, an approach by Rabinovich was combined with approximations of plastic micro asperity flattening. The Rabinovich approach accounts for roughness effects on the van der Waals force by incorporating the rms roughness of the interacting surfaces. rms-values of the particles and substrates were measured with atomic force microscopy at different scanning areas.

Keywords adhesion force, vibration method, roughness

1. Introduction

Adhesion phenomena in particle-wall systems are a current problem in several operations of process engineering, such as dosing procedures in the pharmaceutical industry or the removal of abrasive particles after polishing operations. Such adhesion phenomena can arise from several adhesion mechanisms whose intensity depends among other things on the topography of the interacting surfaces, the environmental conditions and the stresses between the surfaces in contact. Furthermore, the direction of the detachment force has significant influence on adhesion phenomena. The “colloidal probe technique”, the centrifuge technique and particle reentrainment in a turbulent air flow have become established tools for studying particle–wall interactions. The vibration method represents a complementary and practical method for the measurement of adhesion forces and adhesion force distributions. Its alternating detachment and contact forces are comparable to the dynamic stresses acting on particles during commonly applied unit operations.

2. Methods and Materials

Normal adhesion forces (pull-off forces) between particles and substrate were measured using the vibration method. Mode shape and acceleration of the vibrating surface were spectrally measured with a laser-scanning-vibrometer (LSV 200, Polytec). The measurement results of the vibration method were compared with those obtained through the colloidal probe technique (Nanoscope 3A, Digital Instrument) at the Lehrstuhl für Maschinen- und Apparatekunde (TU München, Germany). Tangential adhesion forces were measured using particle reentrainment in a turbulent air flow. Topography and surface roughness of the particles and substrates were characterized using tapping AFM (Nanoscope 3A, Digital Instruments) and SEM (Gemini 982, Zeiss).

2.1 The vibration method

The measuring principle of the vibration method is based on particle detachment from a vertical-sinusoidally vibrating surface caused by inertial forces at a certain acceleration. Consequently, the vibration of the substrate not only yields a detachment force to overcome the adhesion force, but also causes contact forces between particles and substrate of the same order of magnitude. Particle detachment events are continuously recorded and correlated with acting acceleration and particle mass, allowing for the calculation of the pull-off forces. A screen sequence of a pull-off force measurement with the vibration is shown in Fig. 1.

Our technical conversion of the measuring principle, first described by Deryaguin and Zimon (1961), is illustrated in Fig. 2. The sinusoidal oscillation of the substrate is realized using an ultrasonic piezo actuator (UPA 25, Cedrat Technologies) with adjustable frequency and excitation voltage as well as a temperature sensor. The test substrate (4 mm×4 mm) is mounted above an adapter which is attached to the actuator.

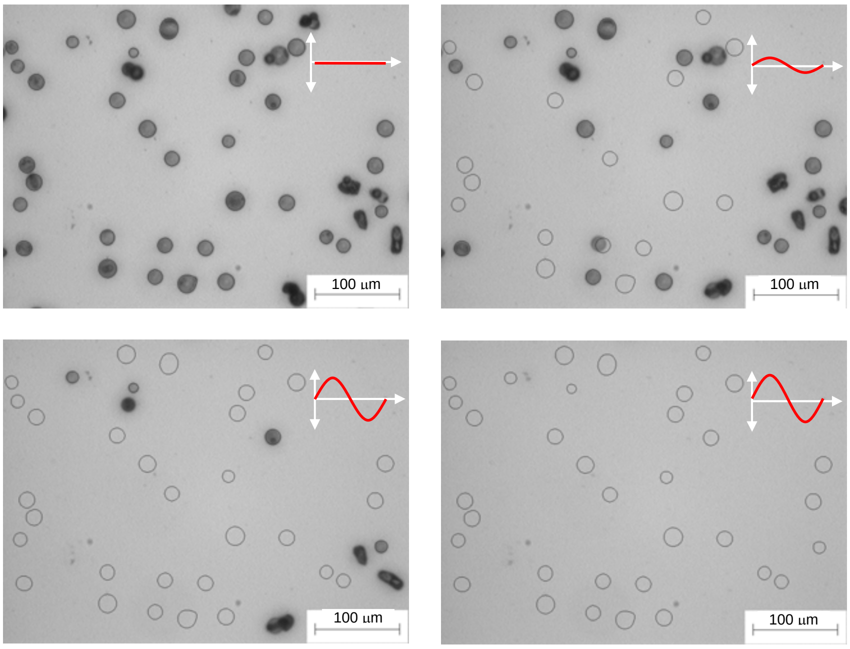

Fig. 1 Detachment of glass particles (10~20 µm) from a vibrating silicon wafer substrate with increasing acceleration of the substrate. Only single particles were used for the calculation of the pull-off forces.

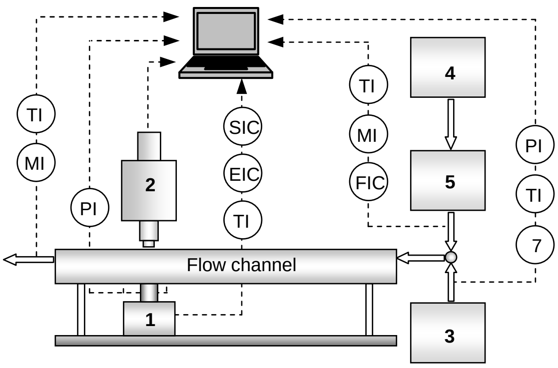

Fig. 2 Experimental set-up: 1 oscillation system with attached substrate; 2 optical unit with microscope, CCD-camera; 3 compressed-air; 4 laminar flow box; 5 climatic exposure test cabinet and flow channel ($l \times b \times h$: 1700 mm×40 mm×4 mm).

The actuator provides a maximum acceleration of approximately 100 000 g at its resonance frequency, which depends on the actuator temperature and the mass of the mounted substrate. The acceleration calibration of the sinusoidally oscillating substrate was carried out as a function of excitation voltage and actuator temperature at fixed frequency with a laser-scanning-vibrometer (LSV).

The actuator with the mounted substrate was placed at the bottom side of an aluminium flow channel with rectangular cross-section. With increasing acceleration of the substrate the acting detachment force exceeds the adhesion force. Particle detachment events are continuously recorded with a microscope (Axiotech, Zeiss), a CCD-camera and an image analysis software (Image Pro Plus, Media Cybernetics). The substrate was exposed to a laminar air flow ($Re_{channel}$=1514) parallel to the substrate for horizontal dislocation of detached particles. A laminar-flow box (VMK 06.15, Steag), a climatic exposure test cabinet (KPK 200, Feutron) and a fan were used to clean and condition the air flow. Optionally dried compressed-air can be used to realize very low relative humidity conditions. A more detailed description of the technical conversion is given by Ripperger and Hein (2005).

Fig. 3 shows a schematic diagram of the forces acting on a single particle adhered to a sinusoidally oscillating surface and exposed to a laminar air flow.

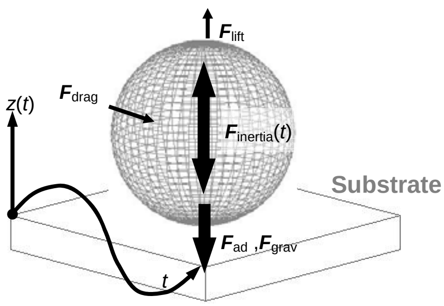

Fig. 3 Forces acting on a single particle exposed to a laminar air flow and adhered to a sinusoidally oscillating substrate.

An estimation of the acting lift ($\boldsymbol{F}_{lift}$) and drag ($\boldsymbol{F}_{drag}$) forces for a particle fully submerged in the linear sublayer in contact with a wall is described in Hein et al. (2002).