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Original Research Paper

Adhesive strength distribution of charged particles on metal substrate in external electric field

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ABSTRACT

An improved airflow method to measure the distribution of adhesive strength between charged particles and a metal substrate in an external electric field is presented. In this study, toner particles were negatively charged with a corona charger and deposited on the substrate. The substrate with the particles on the surface was mounted in a rectangular air channel with parallel electrodes. Air velocity was increased at a constant rate, and entrained particles were detected by a laser particle monitor. By studying the relationships between particle entrainment efficiency and air velocity, the particle–substrate adhesion was analyzed in detail. It was found that particle adhesion increased with the increase in the initial charge of particles. It was also found that the particle adhesion increased in a vertically downward electric field but decreased in the upward electric field. These experimental results cannot be explained by the Coulomb force in the electric field. Therefore, a theoretical model based on charge transfer in the external electric field was proposed. This model explains the variation of the particle–substrate adhesion by considering the image force arising due to the transferred charges.

1. Introduction

Powders and particulate solids are widely used in industrial applications. When handled in air, the surfaces of these particles become electrostatically charged by contact or friction with other solid materials. The charged particles cause problems [1,2] such as adhesion [3–6], segregation [7], as well as fire and explosion hazards [8]. To explain the mechanism of particle charging, several models have been proposed. Some of the proposed models are the condenser model based on contact potential difference [9–11] and the charge relaxation model based on Paschen's law [12–14]. In an electric field, charged particles experience electrostatic forces, making the particles useful in applications such as electrostatic precipitation [15], particle separation [16], powder coating [17], and electrophotography [18]. To achieve an optimum performance in each application, accurate measurement and control of the charge on the particles is crucial [19–23]. In addition, the electrostatic forces acting on the particles need to be measured and analyzed. Several methods, including the centrifuge, electrostatic removal, and micro-cantilever removal have been employed to measure the particle–substrate interaction forces [24–28]; however, simpler and more convenient measurement methods are necessary to enable statistical analysis of the forces.

Theoretical analysis of the charge on particles has been studied for many decades. In a conductive material, the surface charges move until an equilibrium state is attained. In a dielectric material, on the other hand, the charges cannot move freely and remain on the surface; thus, the charges are distributed on the surface according to the charging process. As a typical case, the electrostatic force between a uniformly charged dielectric particle and a conducting plane has been calculated including the effect of higher-order polarizations [29]. The electrostatic force between a partially charged dielectric particle and a conducting particle has also been calculated, showing that the force strongly depends on the charge distribution [30–32]. When a particle with charge concentrated on its bottom surface is placed on a conducting plane, the electrostatic adhesive force is stronger than that for a uniformly charged particle. The effect of electrostatic behavior of non-uniformly charged particles on a planar dielectric solid has also been investigated [33]. Furthermore, by applying an analytical model for a charged dielectric particle, the attachment and detachment of particles in an applied electric field has been analyzed [34]. In these analyses, the effects of the initial charge of the particle and the applied

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electric field on the particle–substrate interaction force was studied but the effect of charge transfer by contact between different materials on the interaction force was not studied.

In the present study, we develop an improved experimental method based on particle entrainment to measure the adhesive strength distribution of charged particles in an external electric field, and investigate the effects of the initial charge of particles and the applied electric field on adhesion. The experimental results are discussed taking into account the charge transfer between the surfaces and the image force as well as the Coulomb force.

2. Experiment

2.1. Particle charging and deposition on metal substrate

Fig. 1 shows a schematic diagram of the experimental setup designed for controlling the initial charge of particles and depositing the charged particles on a metal substrate. A small amount of particles were dispersed into airflow through an ejector and negatively charged with a corona charger (Prima Sprint, Wagner-Hosokawa Micron Ltd.). A stainless steel substrate that is 40 mm long, 15 mm wide, and 1 mm high was placed at the distance of 300 mm from the nozzle of the corona charger. The charged particles were deposited on the substrate in a manner similar to the deposition process used for electrostatic powder coating. The charge on the particles and the amount of particles deposited on the metal substrate were altered by changing the applied voltage and the operation time, respectively. The experimental conditions were as follows: the powder flow rate was 1.0×10^{-5} kg/s and the air flow rate was 1.7×10^{-3} kg/s; thus, the mass flow ratio of the particles to gas was approximately 0.006. The voltage applied to the corona charger was less than 100 kV, and the corona current was less than 120 μA.

2.2. Measurement of adhesive strength distribution of charged particles

Fig. 2 shows a schematic diagram of the experimental setup used for measuring the adhesive strength distribution of charged particles on the metal substrate. The design of this setup is based on the airflow method [35–38]. To analyze the electrostatic forces between particles and the metal substrate in an external electric field, we modified a commercially available airflow system (ASD-01, IMP Co., Ltd.) by adding parallel electrodes. The substrate with the particles prepared in Section 2.1 was manually placed in this system to be mounted flush with the inside surface of a rectangular air channel, which is 1.0 mm high, 8.0 mm wide, and 140 mm long, with an entrance length of 100 mm. A vertical dc electric field was applied in the channel with a high-voltage power supply. The strength and direction of the electric field was controlled in the range of ±500 kV/m.

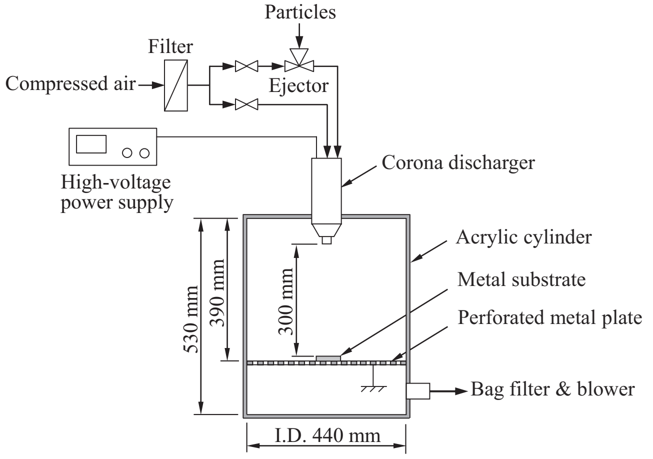

Fig. 1. Experimental setup for controlling the initial charge of particles and depositing the charged particles on a metal substrate.

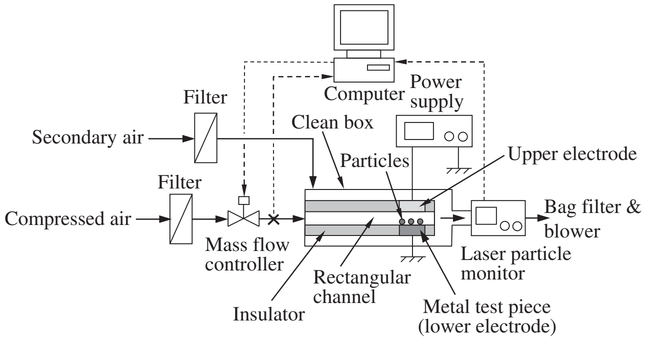

Fig. 2. Experimental setup for measuring particle–substrate adhesion.

Clean compressed dry air was supplied to entrain the particles from the metal substrate. The air velocity in the channel was controlled by a computer and increased at a constant rate. When the separation force caused by aerodynamic drag exceeded the adhesive force, the particles were entrained from the substrate into the airflow. These entrained particles were detected by a laser particle monitor, in which the airflow rate was kept constant by supplying secondary air. The air flow rate and the output electric signal of the laser particle monitor corresponding to the entrainment flux of particles were automatically recorded into the computer. The measurement time was 10 min, and the data sampling interval was 0.1 s. All the experiments were conducted under room conditions (temperature: 23 ± 5 °C, relative humidity: 28 ± 8%).

2.3. Toner particles

Toner particles made of polyester were used in this experiment. Toner A was free of external additives, whereas toner B was modified with external additives; i.e. polyester particles were coated with silica nanoparticles to decrease the adhesive forces. This is because the nanoroughness created by the silica nanoparticles on the surface of the polyester particles decrease the adhesive forces. Fig. 3 shows the SEM images of these toner particles. It is found that the shape of the particles is irregular, and the two types of toner particles are similar to each other in shape and size. Fig. 4 shows count-based particle size distributions. There was no notable difference between the two types of particles. The values of the count median diameter, D_{p50}, and the geometric standard deviation, σ_g, were 5.6 μm and 1.3, respectively. Table 1 summarizes the properties of these toner particles.

2.4. Analysis method of particle–substrate adhesion

As the particle–substrate adhesion depends on each contact state, the adhesive force is not constant; thus, the air velocity for particle entrainment is distributed. The distribution function can be analyzed by the particle entrainment efficiency, η, which is defined as the number ratio of entrained particles to total particles [36,37], i.e.:

$$\eta = \frac{\int_0^u n' du}{\int_0^\infty n' du}, \qquad (1)$$

where n' is the differential coefficient of the number of entrained particles with respect to the cross-sectional average air velocity, u.