

Particle Adhesion Force Measurements by Electric Field Detachment Method

Masashi Nagayama, Manabu Takeuchi
Department of Electrical and Electronic Engineering, Ibaraki University
Nakanarusawa, Hitachi, 316-8511 Japan

Abstract

The adhesion forces of polymer particles to aluminum substrates were measured by the electric field detachment method. Conductive polymer particles were used for the measurements. When measuring the adhesion forces, some particles were spattered over on one of a pair of parallel aluminum electrodes. The DC voltage applied to the electrode was increased at a constant rate, and the occurrence of the particle detachment was observed by measuring the current flowing between the electrodes. The adhesion forces of measured particles were estimated from the voltage at the occurrence of the particle detachment. The numbers of particles, which have a certain adhesion force, were estimated from the voltage and current. The influence of particle size, surface roughness of aluminum substrate, etc. on the particle adhesion forces was examined. The adhesion force of polymer particle increased with an increase in particle size and time elapsed after adhesion. The surface roughness of the substrate strongly influences on the particle adhesion force. The mechanism of particle adhesion will be discussed.

Introduction

Adhesion force of toners to carrier beads, photoreceptors and papers play an important role in electrophotographic performance. Toner adhesion forces are affected by many factors such as toner size, toner shape, toner charge, substrate morphology, environmental conditions, etc. Several studies have been made on the adhesion of toners to various substrates, and their adhesion mechanism has been discussed. Although most of those studies have discussed only average adhesion force of toners to several kinds of substrate, adhesion force distributions are also important.

Adhesion force of toner particles consists mainly of electrostatic force, van der Waals force, and surface tension of adsorbed water. Usually, the former one is used in electrophotographic development process, but the latter two disturb the developing process. It is not easy to distinguish contributions of each force to the total adhesion force.

Adhesion force distributions of polymer particles to an aluminum substrate were measured by electric field detachment method in this study [1]. Influence of particle size, surface roughness of aluminum substrate, etc. on the adhesion force distribution was studied. Conductive polymer powders were used for the measurements. Therefor, it is not necessary to consider a contribution of electrostatic force in this study. The adhesion force includes van der Waals force, surface tension of water but excludes electrostatic force in this paper. First, experimental procedures including the principle of electric field detachment method are described in this paper. Then, experimental results are given. Finally factors affecting particle adhesion forces will briefly be discussed.

Experimental

Electric field detachment method

The experimental set up for the electric field detachment method is shown in Figure 1. The system consisted of the following parts: potential sweeper for ramp voltage source, high voltage amplifier for applying voltage to an electrode, whose gain was –10 and maximum voltage –1500 V, power supply unit (Takasago, HV 1.5-03) for high voltage amplifier, electrometer for current measurement, and an X-Y chart recorder. A pair of parallel electrodes that had an air gap of 500 μm were fabricated.

Some sample conductive particles were spattered over the lower aluminum electrode without charging, and its adhesion force to the aluminum electrode was measured. The upper electrode surface had an insulation resin coating of 25 μm in thickness for avoiding charge exchange between the conductive particles and the upper electrode. In other words, the resin coating prevented the removing of particles deposited on the upper electrode to the lower electrode again. An appropriate resistivity and relative dielectric constant for the coating resin were 8.3×10^{11} Ω·cm and 3.4, respectively. The DC voltage applied to the electrode was increased at a constant rate from the initial voltage $V_{initial}$ to a preset voltage V_{max}, and the occurrence of the particle detachment was observed by measuring the current flowing between the electrodes. When the applied voltage reached the preset value (V_{max}), it was returned to the initial value ($V_{initial}$) automatically. This step was repeated increasing the preset voltage (V_{max}), and the adhesion force distributions were obtained. The voltage increasing rate was kept to be 500 mV/s in this measurement [2].

It should be noted that the obtainable maximum value of adhesion force was limited by the breakdown of air in this method. A few particles usually remained on the lower electrode after the final step in this measurement.

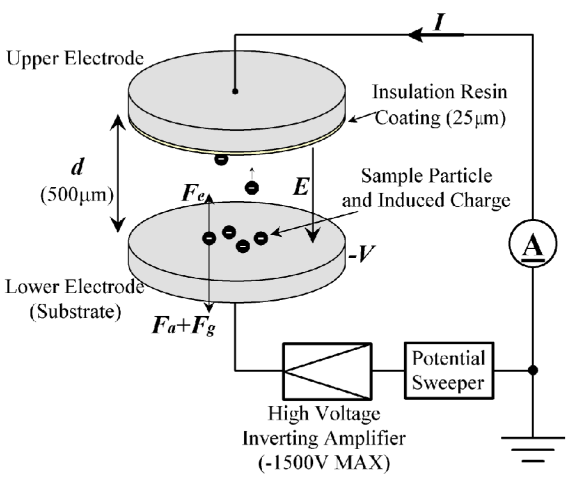


Figure 1. Particle adhesion force measuring system by electric field detachment method.

Basic theory

When one of the particles begins flying from the lower electrode to the upper electrode, the following relationship is valid,

$$F_e = F_a + F_g \tag{1}$$

where

F_e = *electrostatic force*

= QE

Q = *induced particle charge*

E = *magnitude of electric field*

F_a = *adhesion force*

F_g = *gravitational force*

The induced particle charge Q can be calculated as follows,

$$Q = 1.65 \times 4\pi\varepsilon_0 r^2 E \tag{2}$$

where r is the radius of the particle and ε_0 is dielectric constant of the free space [3]. Therefore the adhesion force of a particle is given by

$$F_a = F_e - F_g$$

$$= 1.65 \times 4\pi\varepsilon_0 r^2 E^2 - (4/3)\, \pi r^3 \rho g \tag{3}$$

where ρ is specific gravity of measured particle and g is acceleration of gravity. According to Hoshino and his co-workers [1], the current $I_{particle}$ due to particle flying can be written as follows:

$$I = CdV/dt + I_{particle} \tag{4}$$

where

I = *total current*

C = *capacitance of measuring cell*

dV/dt = *rate of voltage increment, 500mV/s*

Because dV/dt is constant, $I_{particle}$ can be measured. Here, if we assume that n particles fly in a unit time, the following equation will be obtained,

$$I_{particle}(t) = Q(t) \cdot n(t) \tag{5}$$

This equation can be written as follows,

$$n(t) = I_{particle}(t)/Q(t) \tag{6}$$

Then, the number of particles flying in a definite time can be calculated by integrating Eq. (6).

Samples

Spherical and conductive powders were used in this study. The powders were made from PMMA. Fundamental properties of the conductive polymer powders were measured before the adhesion force measurements. The results are given in Table 1. Particle size distributions are shown in Figure 2.

Some conductive particles were spattered over on the lower electrode. Five kinds of substrates were used. These substrates were made of aluminum and different with each other in the surface roughness. The surface roughness and optical microscope images of substrate surface are shown in Table 2. The surface roughness of substrate increases in the order of A to E.

Table 1 Fundamental properties of conductive polymer powders used in this study.

Powder	Average particle size [μm]	Specific gravity [g/cm³]	Resin	Shape
A	7.4	1.0	PMMA	Spherical
B	32			
C	50			

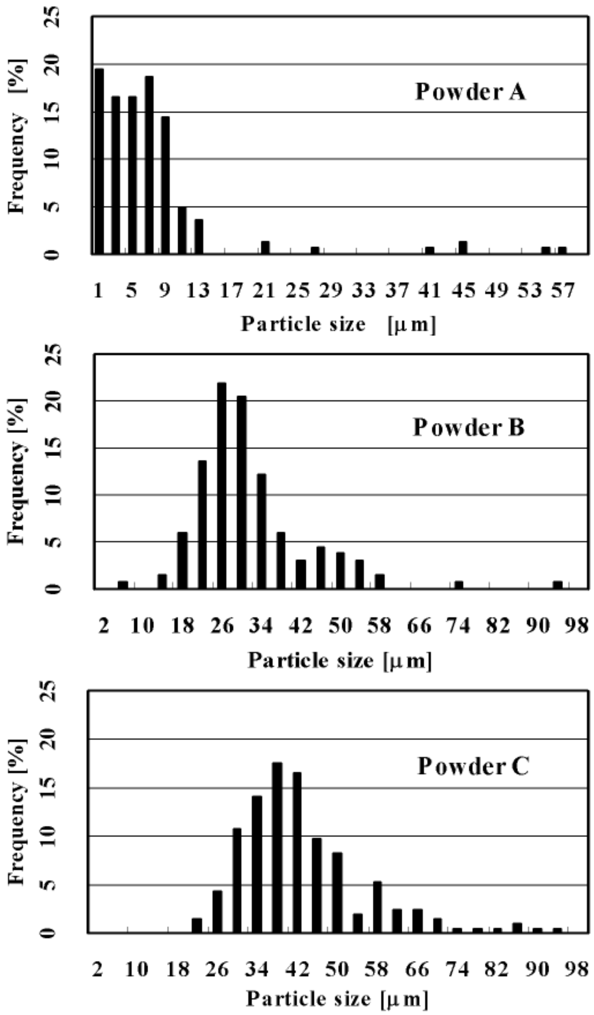
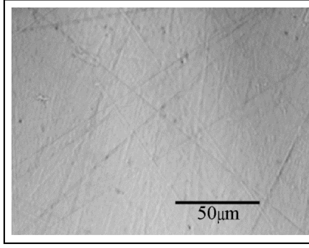
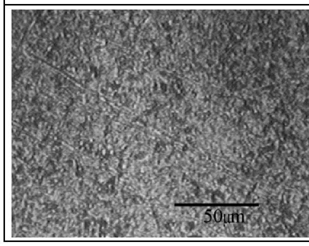
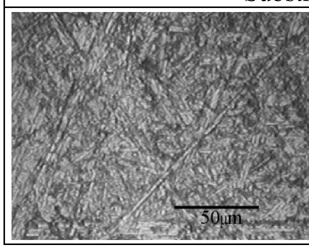


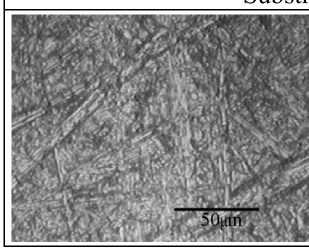
Figure 2 Particle size distributions of conductive powders used in this study.

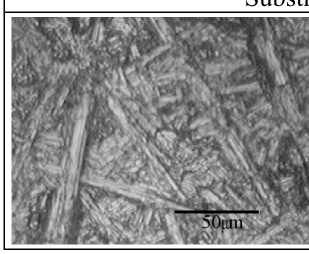
Table 2 Substrates used in this study.

Substrate A		
	Ra	0.0920
	Ry	2.03
	Rz	0.941
	Sm	469
	S	1200
	Surface Treatment	Metal polishing compound

Substrate B		
	Ra	0.206
	Ry	3.23
	Rz	2.23
	Sm	129
	S	171
	Surface Treatment	Carrier (KBN100)

Substrate C		
	Ra	0.517
	Ry	5.25
	Rz	3.95
	Sm	298
	S	147
	Surface Treatment	Sandpaper (#1200)

Substrate D		
	Ra	0.820
	Ry	6.59
	Rz	5.67
	Sm	180
	S	95.9
	Surface Treatment	Sandpaper (#600)

Substrate E		
	Ra	1.33
	Ry	11.5
	Rz	9.77
	Sm	150
	S	86.2
	Surface Treatment	Sandpaper (#240)

Results and Discussions

Dependence of adhesion force distribution on particle size

First, dependence of adhesion force distribution of the conductive powders on their particle size was measured. Three kinds of powders A, B and C were used in the measurements. All the measurements were carried out at 30 °C and 35 % relative humidity (RH). Therefore, the adhesion forces of particles consist mostly of van der Waals force in this case, i.e. contribution of surface tension of water can be considered to be very small because of low RH. Results of adhesion force distributions are shown in Figure 3. The average adhesion forces of three powders are given in Table 3. It was confirmed that the adhesion force of particles decreased with a decrease in particle size. Since the contact area of a particle with the substrate decreases with a decrease in particle size, the results in Figure 3 are not inconsistent with the estimation that the adhesion force consists mostly of van der Waals force in this case.

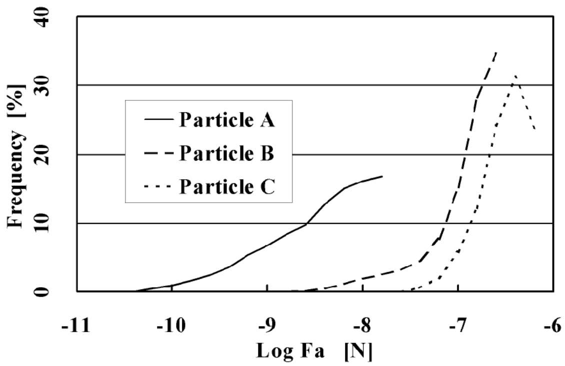


Figure 3 Adhesion force distributions for three kinds of powders with different mean particle sizes.

Table 3 Average adhesion forces of powders A, B and C.

	Powder A	Powder B	Powder C
Average adhesion force [N]	7.09×10^{-9}	1.55×10^{-7}	3.62×10^{-7}

Dependence of adhesion force distribution on surface roughness of substrates

Next, dependence of adhesion force distributions of a polymer powder on the surface roughness of aluminum substrates was examined. Only the powder A and the substrates A to E were used in this experiment. The measurements were made at 15 °C and 40 %RH.

Results of adhesion force distributions of powder A are shown in Figure 4. Average adhesion forces are given in Table 4. The adhesion force of the powder decreased in the order of substrates from A up to D. These results can be attributable to a decrease in contact area between a particle and the substrate with an increase in surface roughness of the substrate. However, the adhesion force of particle with substrate E was larger than that with substrate D. Contact area between a particle and the substrate increases again in substrate E because, particles can get into scratches of the rough substrate, resulting in an increase in the adhesion force.

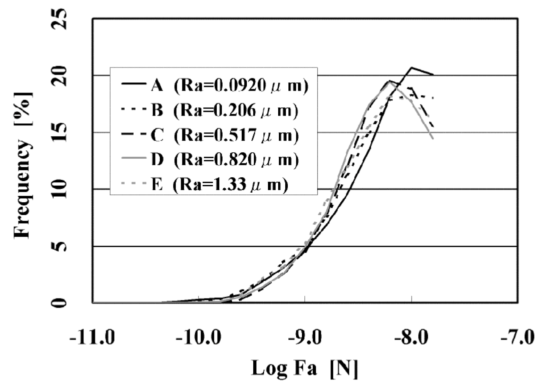


Figure 4 Adhesion force distributions of powder A for five kinds of substrates.

Table 4 Average adhesion forces of powder A for five kinds of substrate.

Substrate	A	B	C	D	E
Average adhesion force [nN]	7.37	6.91	6.77	6.52	6.62

Dependence of adhesion force distribution on elapsed time

Finally, dependence of adhesion force distribution of a powder on elapsed time after spattering over the lower aluminum electrode was studied. The powder A and substrate A were used, and the elapsed times were chosen to be 0, 15, 30 and 60 minutes. The measurements were done at 30 °C, 40 %RH and 80 %RH. The results at 40 %RH and 80 %RH are shown in Figures 5 and 6, respectively. Average adhesion forces are given in Table 5. As a whole, the adhesion forces of powder A was smaller at 40%RH than at 80%RH. This result indicates that surface tension of adsorbed water is larger at higher RH

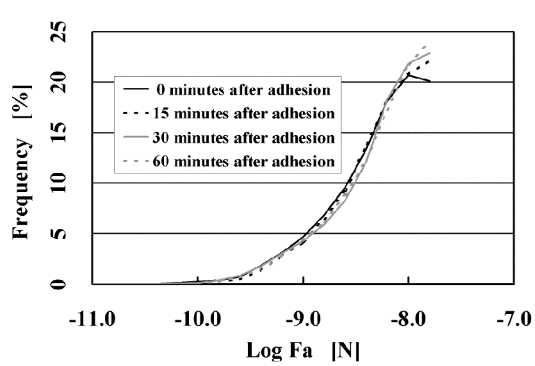


Figure 5 Adhesion force distributions of powder A for five choices of elapsed time after adhesion at 30 °C and 40 % RH.

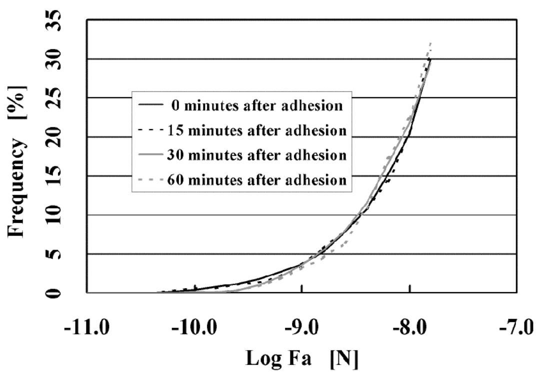


Figure 6 Adhesion force distributions of powder A for five choices of elapsed time after adhesion at 30 ℃ and 80 % RH.

Table 5 Average adhesion forces of powder A as a function of elapsed time after adhesion at 30 °C, 40 % RH and 80 % RH.

Elapsed time [minutes]	0	15	30	60
Average adhesion force at 40 %RH [nN]	7.37	7.70	7.83	7.94
Average adhesion force at 80 %RH [nN]	8.50	8.65	8.69	9.12

Conclusion

Adhesion forces of conductive spherical particles to aluminum substrates were measured by electric field detachment method, and following results were obtained.

1. The adhesion force of larger particle is larger than that of the smaller one.
2. The substrate roughness influences the adhesion force.
3. Long elapsed time after spattering over the substrate increases adhesion force.

References

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Biography

Masashi Nagayama received his B. Eng. in Electrical and Electronic Engineering from Ibaraki University in 1999. He is currently a master course student of the same university. Adhesion forces of particles are the core of his research interest. E-mail: nm9623@hcs.ipc.ibaraki.ac.jp