Journal of Electrostatics 68 (2010) 91–95

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Electrostatic force acting on conductive ball between electrodes

K.P. Disna Jayampathi Karunanayake*, Yasushi Hoshino

Hoshino Laboratory, Department of Systems Engineering, Nippon Institute of Technology, 4-1 Gakuendai, Miyashiro-machi, Minamisaitama-gun, Saitama pref., P.B. 345-8501, Japan

ARTICLE INFO

Article history:
Received 19 June 2009
Received in revised form
6 August 2009
Accepted 21 November 2009
Available online 4 December 2009

Keywords:
Electrostatic force
Electric field
Conductive toner
Particle conductivity
Induce charge

ABSTRACT

To advance electrostatic applications such as novel printing technologies and solder ball control for LSI bumping, the electrostatic force acting on a conductive ball between two electrodes is calculated. The electrostatic force increases as the ratio of the ball diameter to the electrode separation increases. The electrostatic force is also calculated for the case when a charge pattern is formed on the insulating layer on the upper electrode. In this case, the electrostatic force initially varies as the square of the charge pattern area but eventually plateaus to a constant value as the area increases. Experiments investigating the force acting on the ball are performed. The force estimated from these experiments agrees with the value obtained by electric field analysis.

1. Introduction

Electrostatic force is widely used to control particles. Electrostatic force is greatly influenced by the particle conductivity [1]. Insulating particles (known as toner particles) play an important role in electrophotography, which is widely used in electronic printing technologies. Controlling the motion of the toner particles by electrostatic force is essential in the developing and transfer processes of printing [2].

A printing mechanism based on conductive toner control has been proposed. This mechanism, known as the "toner cloud beam", has the potential of producing novel printing technologies for realizing compact and simple printing [3]. Conductive toner moves up and down between the electrodes when a voltage exceeding a certain threshold value is applied to the electrodes and the toner is confined around an indented area on the electrodes [4,5]. The toner becomes cloud-like in this indented area. The printing mechanism is as follows. A toner cloud is generated and toner is extracted from the cloud by applying a pulsed voltage between the two electrodes. The toner travels to the paper and forms dots on the paper.

The challenge of controlling solder ball by electrostatic force has recently been achieved. In all of the above-mentioned applications involving control of a conductive particle by electrostatic force, it is important to understand the electrostatic force acting on a conductive ball between two electrodes.

Concerning the analysis of a conductive ball in the electric field generated by two electrodes, the induced charge on the conductive ball has been reported to be 1.65 ($S \times E \times \varepsilon$), where S is the surface area of the sphere, E is the electric field strength and ε is the dielectric constant of air [6] However, the induced charge on the ball cannot be estimated using this formula when the diameter of the ball is not negligible compared with the distance between the electrodes; the force acting on the ball for this case has not yet been derived.

In this present study, the induced charge on the ball and the electrostatic force acting on the ball are analyzed by using electric field analysis software. The analysis is carried out for ratios of the ball diameter to the electrode separation in the range 0.01–0.95. Analysis is also conducted for the case where one side of one electrode is covered with an insulating layer and a charge pattern is formed on the insulating layer. The calculated force acting on the ball is confirmed by conducting experiments for several values of the above ratio.

2. Electric field analysis

When a conducting ball is on the lower electrode of two electrodes, the electric charge induced on the ball and the force acting on the ball are analyzed numerically by using software (Elfin: ELF Corp., Japan). The two cases shown in Fig. 1 are analyzed. In one case (Fig. 1(a)), the ball lies between the two electrodes and a voltage is applied to the upper electrode, while in the other case (Fig. 1(b)), the lower side of the upper electrode is covered with

* Corresponding author. Tel.: +81 480 33 7721; fax: +81 480 33 7745.
E-mail addresses: disnakarunanayake@yahoo.com (K.P. Disna Jayampathi Karunanayake), hoshino@nit.ac.jp (Y. Hoshino).

0304-3886/$ – see front matter
doi:10.1016/j.elstat.2009.11.004

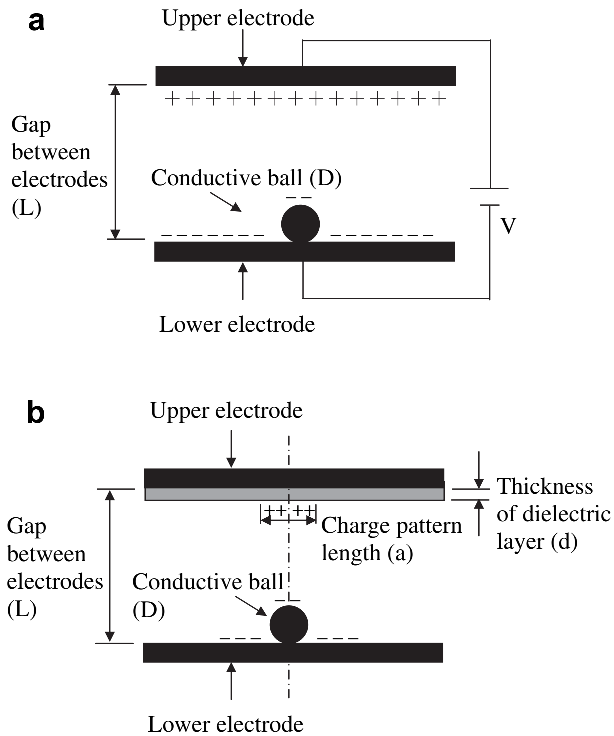

Fig. 1. Models for electric field analysis: (a) ball between two electrodes, (b) dielectric layer on the upper electrode.

a dielectric layer and an electrostatic charge pattern is formed on this dielectric layer.

2.1. Ball lies between two electrodes

The ball is in electrical contact with the lower electrode. The electrostatic potential around the ball is analyzed. Fig. 2 shows the equipotential lines and the partial forces acting on a radial segment of the ball. The partial force increases as the angle t from the top the ball increases. This increase is due to the increase in the radial surface ($=2\pi \sin t\, dt$). The total charge induced on the ball is also calculated when the voltage on the upper electrode is 1000 V. Fig. 3 shows the dependence of total charge on the ratio between the ball diameter D and the electrode separation L. The dependence of the electrostatic force on this ratio was also analyzed and is shown in Fig. 4.

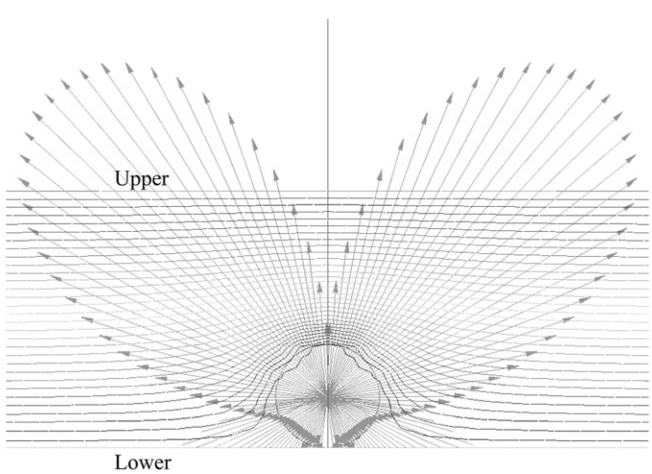

Fig. 2. Equipotential lines and partial forces acting on ball.

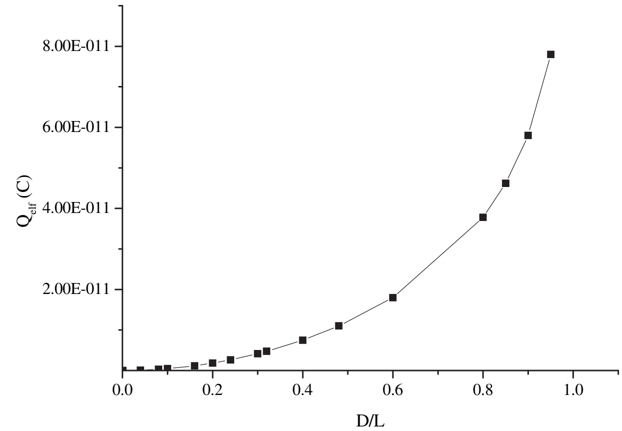

Fig. 3. Dependence of the charge induced on the ball on the ratio of the ball diameter to the electrode separation.

2.2. Upper electrode is covered by a dielectric layer

Electric field analysis is also carried out for the case when the upper electrode is covered by a dielectric layer so that an electrostatic image is formed on this layer. Equipotential lines and partial forces acting on a radial segment of the ball are shown in Fig. 5 for two cases: the charge size is smaller than the ball (Fig. 5(a)) and the charge size is far larger than the ball (Fig. 5(b)). The force acting on the ball is calculated numerically for various thicknesses of the dielectric layer and electrostatic image sizes. Fig. 6 shows the dependence of the electrostatic force on the electrostatic image size for several cases for three cases: the relative dielectric constant of the insulating layer is 1.0 and the diameter of the ball is far smaller than the electrode separation (Fig. 6(a)), the dielectric constant is 2.0 and the ball diameter is far smaller than the electrode separation (Fig. 6(b)), and the dielectric constant is 2.0 and the ball diameter is approximately half the electrode separation (Fig. 6(c)).

3. Results and discussion

3.1. Ball lies between two electrodes

Fig. 3 shows that the induced charge on the ball increases abruptly with an increase in the ball size. The ratio of the calculated

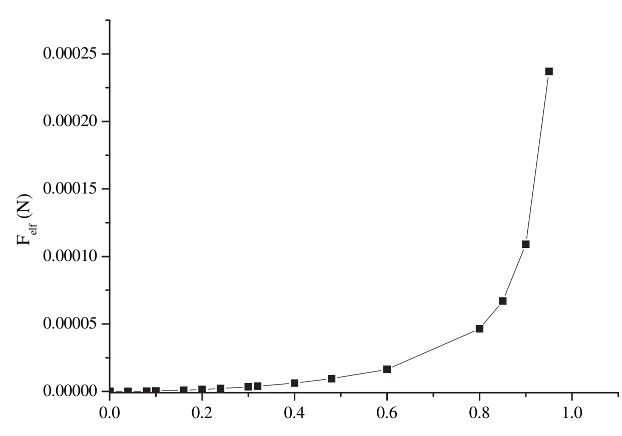

Fig. 4. Dependence of the electrostatic force on the ratio of the ball diameter to the electrode separation.