Journal of Electrostatics 67 (2009) 663–671

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Influences of different powders on the characteristics of particle charging and deposition in powder coating processes

Xiangbo Meng, Jingxu (Jesse) Zhu*, Hui Zhang

Department of Chemical and Biochemical Engineering, The University of Western Ontario, 1151 Richmond Street, London, ON N6A 5B8, Canada

ARTICLE INFO

Article history:
Received 20 October 2008
Received in revised form
20 January 2009
Accepted 26 January 2009
Available online 11 February 2009

Keywords:
Powder coating
Corona charging
Particle charging and deposition
Charge-to-mass ratio
Mass-to-surface ratio
Back corona
Corona quenching
Particle size
Electrostatics

ABSTRACT

This experimental study investigated the influences of two different powder systems (coarse and ultrafine) on particle charging and deposition characteristics during electrostatic powder coating processes. Results disclosed that, despite their differences in particle sizes, the two powders behave similarly in deposition process, commonly resulting in a cone-shaped deposited pattern in the inner portion of the substrate and an increase of deposited particles in the fringe region. However, their different properties lead to the discrepancies in their deposition efficiencies, which account for a higher efficiency with the coarse powder. The study further revealed that the coarse powder is superior to the ultrafine powder in charging in-flight particles, which directly contributes to its higher deposition efficiencies. Furthermore, it was disclosed that the two powders exhibit distinct characteristics in charging deposited particles. Compared to the coarse powder, the ultrafine powder is more uniform in charging deposited particles, mainly owing to its greater particle number and higher specific surface area but less mass. In particular, the charging efficiency of overall deposited particles decreases for the ultrafine powder but increases for the coarse powder with increased charging voltage, closely related to their particle properties. However, both powders decrease in charging efficiency of deposited particles with extended spraying duration due to back corona intensifying with spraying.

1. Introduction

Of three routine mechanisms for charging materials (i.e., induction, tribo, and corona), only corona charging is applicable for both electrically conductive and non-conductive materials in a defined and controllable way [1,2]. Thus corona charging is extensively applied in electrostatic processes such as electrophotography, precipitation of dusts, electrostatic separation, and electrostatic powder coating [3–8]. Electrostatic powder coating has rapidly expanded to more markets since it emerged in the 1950s in finishing industries providing economic and energy savings, resistance to corrosion and chipping, and protection of the environment [8–10].

The typical powder coating system is a point-to-plane configuration supplied with a negative high voltage, in which a spray gun and a grounded metallic substrate serve as the corona electrode (point) and the collecting electrode (plane), respectively. The powder coating process incorporates both a charging and deposition phase in which the particles of high resistivity are first charged by gaseous ions from corona discharges in the vicinity of the corona electrode and then deposit on the substrate in the same electric field [3]. For particles larger than approximately 0.5 μm, electric-field charging of particles dominates, i.e., the gaseous ions collide with and attach onto the particles [11]. The ion identities depend on the polarity of corona discharge and characteristics of the gas mixture, specifically on the electron-attaching species [12]. Due to the accumulation of unipolar ions and charged particles in the inter-electrode space, the corona discharge is usually space-charge limited and requires higher voltages to drive the ions in order to increase the current [12]. Several empirical formulae were developed to describe the current–voltage characteristics of corona discharge [13–15], and Warburg's law has been experimentally proven for predicting the current density distribution on the substrate [16–18].

Theoretically the maximum charge (saturation charge) imparted to a particle by ionized-field charging is proportional to the square of its radius and the electric field in charging zone, as described by Pauthenier limit [1,8]:

$$Q_{max} = 12\pi\varepsilon_0\varepsilon_r r^2 E/(\varepsilon_r + 2) \quad (1)$$

where E is the electric field, r the particle radius, ε_0 the permittivity of free space, ε_r the relative permittivity of the particle, and Q_{max} the

* Corresponding author. Tel.: +1 519 661 3807; fax: +1 519 850 2441.
E-mail address: jzhu@uwo.ca (J. Zhu).

0304-3886/$ – see front matter
doi:10.1016/j.elstat.2009.01.044

saturation charge. For a given electric field, however, the corona current can influence the time to reach the saturation charge [1,8]:

$$\tau = 4\varepsilon_0 E/J \qquad (2)$$

where τ is the time taken for the particle to reach half the saturation charge, and J the current density. Usually the charging efficiency of a particle is described by its charge-to-mass ratio (Q/M) and its maximum Q/M is given by [11]:

$$Q_{max}/M = 9\varepsilon_0\varepsilon_r E/(\varepsilon_r + 2)r\rho \qquad (3)$$

where ρ is the true mass density of the particle. Thus the Q_{max}/M is inversely proportional to the particle radius.

During powder coating processes, Wu [11] found that particles receive charge by two steps: primary charging and secondary charging. The former is imparted onto in-flight particles mainly in the high-field region near the corona electrode, usually within 50 mm of the electrode; the latter imparted onto deposited particles by free ions which carry 90% of the corona current and constantly bombard the deposited layer [11]. After being primarily charged, the in-flight particles form a powder cloud traveling towards the substrate and are subject to various forces. Besides the gravitational force, the aerodynamic force (i.e. drag force) is due to the supplied gas for transportation, and the electrostatic forces are from the electric fields due to the charging voltage, the space charge, the deposited charge, and the image charge [19]. The aerodynamic force in the region close to the gun dominates whereas Coulombic forces become increasingly important as the charged particles near the substrate [8]. Thus, the precise trajectories of particles depend on a balance between electrostatic and aerodynamic forces, and are particle-size dependent [8]. By numerically investigating powder trajectories in tribo-charging powder coating, Adamiak [20,21] showed that the charge and size of in-flight particles are two important factors influencing their trajectories, and that the powder cloud expands and becomes more dispersed with increasing distance from the gun. While approaching the vicinity of the substrate, especially within about 10 mm of the substrate, the motion of the particles is dominated by electrostatic forces [1,8] and the charged particles mainly depend on their image force to adhere onto the substrate after deposition [8,11].

With the accumulation of charged particles of high resisitivity on the substrate, an abnormal kind of discharge (viz., back corona) may occur if the electric field within the deposited layer exceeds its breakdown strength [22–24]. Masuda and Mizuno [22–24] defined the initiation of back corona as follows:

$$E_d = \rho_d J \geq E_b \qquad (4)$$

where J is the current density through the layer, ρ_d the resistivity of the deposited layer, and E_d, E_b the electrical field across the layer and the breakdown field of the layer, respectively. With increased voltage of negative polarity, back corona evolves from a random breakdown, to an onset-glow, and finally to either a streamer or a steady-glow with increased intensity [22,23]. The fundamental requirements for the formation of back corona can be concluded as a porous layer, a high electric field across the deposited layer, and a supply of incoming ions [25]. Back corona produces gaseous ions of polarity opposite to the corona which move towards the corona electrode and neutralize the charge of deposited and in-flight particles. Back corona consequently causes reduction of particle deposition efficiency [22–25] and self-limits the deposited layer [8]. Tachibana [26] observed that in-flight particles reverse their paths in the vicinity of a substrate undergoing back corona. In practice, due to the difficulties in directly detecting free ions of both polarities, an increase in the overall current density often serves as evidence of back corona [5,27].

Obviously, for better characterizing the powder coating process, the charging and deposition behaviors of applied particles should be studied. Many previous studies investigated particle charge [28–31], and mostly evaluated particle deposition by measuring overall transfer efficiency (TE) [32–35] as the mass ratio of deposited particles to overall sprayed particles. Unfortunately, few studies correlated the primary charging of in-flight particles with their deposition, nor the influence of non-uniform electric field on particle charging and deposition. In particular, particle size was shown to greatly influence the coated film [36]. Coarse powder (with mean particle diameter larger than 30 μm, as defined by Zhu and Zhang [37]) is being widely electrostatically applied in finishing industries using current technology, and incurs many aesthetic problems, especially poor surface quality and excessive film thickness (50–100 μm). As a result, all the applications of coarse powder coating in automotive industries are only applied to the underneath parts and trim components [38]. In contrast ultrafine powder (<25 μm diameter, as defined by Zhu and Zhang [37]) improves the appearance of the coated film, reduces the film thickness to approximately 25 μm, and decreases the VOCs emission from approximately 75 g/m^2 for painted surface to approximately 15 g/m^2 presently [36–38]. Thus, ultrafine is widely considered the next generation of powder coating [3,36–38] and with flow aids the ultrafine powder should improve flowability for powder coating applications [39].

Recently the authors conducted a series of studies [40–43] using two powder systems (coarse and ultrafine) to better understand powder coating processes, especially characterizing the distorted field between electrodes, local behaviors of particle charging and deposition. Experimental results verified that the addition of powder particles incurs quenching in corona current for reasons disclosed by Awad and Castle [44]. However, the effects of corona quenching are distinctive for both powder systems and the current-density distribution is deformed with respect to the Warburg's law [40]. Furthermore, the authors showed the deposited particles to distribute non-uniformly on the substrate with a cone-shaped deposition (as first observed by Ye et al. [45,46]), and that their charging characteristics have a strong dependence on their particle properties and the secondary charging [41,42]. In addition, for both powders the authors investigated the particle-size evolution of the deposited layer and reported the powder coating process to be a size-selective process [43]. In addition to these new findings [40–43] on mechanisms associated with powder coating processes, deeper insight regarding the influences of different powders have on the powder coating processes is crucially needed and is therefore the goal of this paper. Herein the concepts of charge-to-mass ratio (Q/M) and mass-to-surface ratio (M/S) continue to be relied upon to characterize particle charging and deposition, as employed in the preceding efforts [41,42].

2. Experimental

2.1. Apparatus

The experimental setup is illustrated in Fig. 1a. To synchronize the powder feeding, voltage supplying, and current-data collecting, a system controller sent three signals simultaneously to the gun control unit, the screw feeder, and the A/D board, respectively. The powder was accurately fed into a Venturi pump by a Schenck AccuRate® screw feeder at 1.0 g/s, and then pneumatically transported to a Nordson Surecoat™ negative corona gun by a feeding gas of 150 kPa. The powder particles were charged and then coated on a metallic substrate in a Nordson® Model 902 booth. The corona current was measured by an electrometer (Model 6514 Keithley®) and then transferred to a computer for storage via an A/D board (NI