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Numerical study of particle deposition in electrostatic painting near a protrusion or indentation on a planar surface

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A B S T R A C T

The edge effect and the Faraday cage effect are two major problems that occur when the target surface contains sharp corners and recessed areas. This can significantly affect the electric field and degrade the deposition uniformity of paint, which is important in electrostatic painting. A numerical study is presented in this paper to investigate the methods to minimize these problems. A 2D axisymmetric numerical model is proposed to analyze the electric field distribution in the electrostatic painting system, assuming a grounded target with a small surface perturbation at the center using COMSOL. Simulations have been performed for different configurations on the target, different values of the corner radius and the space charge. Also, simulations of paint particle trajectories and deposition have been obtained using ANSYS to examine the effect of the particle size and the charge-to-mass ratio on the coating buildup rate of a flat target and a target with an indentation or a protrusion. The injections of mono- and poly-dispersed uncharged and charged particles were considered. The results suggest that preliminary analysis of the electric field distribution on a target having a perturbation provides a simple design tool for predicting coating uniformity.

1. Introduction

In electrostatic painting it is desirable to improve the uniformity and finish quality of the coating. Perturbations in the shape of the target to be coated can significantly affect the electric field distribution along its surface and deteriorate coating quality. When the target surface contains some sharp edges and recessed areas, two major problems may occur: the edge effect and the Faraday cage effect. The electric field in close vicinity to the target surface is composed of two components: one created by the high voltage supplied to the atomizer and another, generated by the space charge of the charged paint droplets. As the electric field concentrates at the edges and sharp corners, the deposition of particles will be greatly enhanced in these areas, which may result in uneven distribution and lack of uniformity of paint. In the paint industry this is known as the window-paning or edge effect [1]. However, in powder coating the back corona effect can also occur near the sharp edges leading to reduced deposition thickness.

The Faraday cage effect is a result of the fact that the electric field lines are shielded and restricted from penetration into indentations. Because the charged particle trajectories tend to follow the electric field lines, fewer particles may enter the area of indentation and this leads to the possibility of less coating. Numerical modeling of the electrostatic spraying process has been used by a number of researchers, but few have investigated these particular phenomena and suggested some approaches to minimize them.

Adamiak et al. [2] studied numerically the electrical conditions in tribo-powder coating of 2D cylindrical objects using the Charge Simulation Method. They investigated the problem of quick corrosion of car wheel edges and confirmed that pin holes in the paint coating resulting from back corona discharge was responsible for this. It has been suggested that the charge-to-mass ratio of the powder should be reduced, as the space charge is the only source of the electric field in this configuration. Chen et al. [3] studied the transfer efficiency models for the electrostatic powder coating process. They considered air with a relatively high velocity containing coarser paint particles to provide a better Faraday cage penetration, if the particle charge and electric field are well-controlled. Adamiak [4,5] investigated uniformity of the powder deposition in the tribo-charging powder coating system along different targets assuming mono- and poly-dispersed powder

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particles, and tracing their trajectories. He found that for large particle diameters and small charge-to-mass ratio, more particles penetrated and were deposited inside the cavity, whereas smaller particles were attracted to the corners, as the charge-to-mass ratio increased. Biris et al. [6] developed a novel charger to charge two kinds of powder particles bipolarily such that the net charge-to-mass ratio is close to zero. They concluded that to overcome the Faraday cage effect and to have a uniform deposition thickness, the charge-to-mass ratio must be reduced. Also, Biris et al. discussed in Ref. [7] how the Faraday cage shielding affects the uniformity and hence the corrosion resistance of the powder coating using a corona gun. Takeuchi [8] investigated the charging characteristics of an electrostatic powder coating system. His measurements showed that the charge-to-mass ratio of coating powders deposited on the target was larger than that of undeposited particles for both corona and tribocharging spray guns. The charge-to-mass ratio of the coating powders was increased by adding a pair of auxiliary electrodes in the space between the corona spray gun and the Faraday cage. Free ions from the corona charging spray gun, which caused the back ionization and spoil the coating quality, were decreased by applying a magnetic field in the spraying space.

Considering an industrial electrostatic liquid painting system, Toljic et al. [9] succeeded in creating a full 3D numerical model of the electrostatic coating process for a moving target using the commercial CFD program FLUENT. They assumed a conduction mechanism for particle charging and the simulated target plate took the shape of a car door, assuming a specified hole on the surface of the plate for the handle. They considered motion of the target in two directions following a zig-zag pattern. Their numerical results showed some improvements in the thickness uniformity compared with the stationary target, but the deposition around the door handle was at higher level due to the edge effect. Domnick et al. [10] also presented a numerical model of the electrostatic spray painting system using a rotary bell atomizer with six external corona needles, which were arranged symmetrically around the atomizer body. They chose the target geometry as a rear part of a car body. They compared their numerical and experimental results of the deposition thickness at the edges of the target and above the inclined panel. Their simulation results were in a good agreement with the measured ones except at the positions very close to the edges, where the simulated deposition thickness was overestimated.

Although the commercial programs to solve the mechanical and electrical parts of the electrostatic coating process have been developed, the understanding of the phenomena of the edge effect and the Faraday cage effect for complicated target geometries has not been modeled extensively and warrants more investigation. In the first part of this paper, we discuss a numerical model using COMSOL commercial software to simulate the electric field distribution on a grounded target plate, which includes either a small protrusion or indentation at the center. The electric field for different values of the radius and the height of the protrusion (or the depth of the indentation), the radius of the corner and the space charge existing between the high voltage and ground electrodes was calculated. The second part of the paper presents another numerical model using ANSYS commercial software to investigate the effect of the particle size and the charge-to-mass ratio on the uniformity of the coating buildup rate on a flat target and a target with an indentation or a protrusion. Several different model parameters, such as the size of the particles, the charge-to-mass ratio, the size of the surface perturbation and the radius of the corner, were considered in this study and the relationship between the electric field patterns and coating thickness are discussed.

2. Mathematical model

The electric field, generated by the applied voltage and the space charge formed by the charged particles and ions, is governed by Poisson's equation

$$\nabla^2\phi = -\frac{\rho}{\varepsilon} \tag{1}$$

where ϕ is the scalar electric potential, ρ is the total space charge density and ε is the electric permittivity. The Finite Element Method is used to solve the Poisson's equation to obtain the electric potential in the whole computational domain, and then the vectors of the electric field can be determined as the gradient of the electric potential.

$$E = -\nabla\phi \tag{2}$$

The target is assumed to be a conductive grounded electrode so that its surface remains equipotential. The total current density $\boldsymbol{J}$ in the steady state must satisfy the continuity equation

$$\nabla \cdot J = 0 \tag{3}$$

The injected particles move with an initial velocity, which is equal to the velocity of the assisting air. They begin to diverge after leaving the gun due to the different forces, which will affect their trajectories, including the electrical, drag, gravitational and inertial forces. The particle trajectories can be found by solving the equations of motion, which results from a balance of all considered forces

$$m\frac{dv}{dt} + F_{\boldsymbol{d}} + F_{\boldsymbol{g}} + F_{\boldsymbol{e}} = 0 \tag{4}$$

where v is the particle velocity, $F_{\boldsymbol{d}}$ is the drag force, $F_{\boldsymbol{g}}$ is the gravitational force and $F_{\boldsymbol{e}}$ is the electrostatic force defined as

$$F_{\boldsymbol{e}} = qE \tag{5}$$

For the particle sizes of interest the gravitational force may be neglected. Hence, the drag force as well as both the particle charge and local electric field strength are the important factors that control and determine the particle trajectory and the resulting deposition thickness.

3. Numerical model

COMSOL, a Finite Element commercial software [11], was employed to determine the electric field in a 2D model of the problem. The stationary model, as depicted in Fig. 1a, consists of a grounded electrode having a circular disc shape located 25 cm from a circular high voltage electrode, supplied with a voltage equal to 90 kV. Both electrodes were assumed to have equal radii of 50 cm. A small circular perturbation of radius r_p and height h exists at the center. A positive value of h represents a protrusion and a negative value an indentation. A very fine mesh was generated near the corners of radius r_c. The electric field over the entire grounded electrode was simulated for different sizes of the perturbations and corner radii. The space charge between the two electrodes was also considered in the simulation by assuming three different charge densities of 0, 1 and 10 $\mu C/m^3$.

For the deposition study, ANSYS, a Computational Fluid Dynamic (CFD) commercial software [12], was employed to simulate the particle trajectories and estimate the coating buildup rate on a stationary flat target and a target with a surface perturbation. The model was also used to investigate the effect of the particle size as