

Development of a Full Vehicle Electrocoat Paint Simulation Tool

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ABSTRACT

The primary coating layer that inhibits salt spray induced corrosion on vehicle bodies is electrocoat. The application of electrocoat involves the electrodeposition of a polymer film on all metallic components of the vehicle body after body construction. Particularly challenging in the electrocoat process is the deposition of the coating in recessed areas of the vehicle due to material and electrical current access constraints to those regions. Currently the verification of correct electrocoat coverage requires the use of costly tear-down prototypes. A simulation tool, called EPD, has been developed that predicts the electrocoat coverage on the full vehicle body. The tool allows engineers to identify areas where there may be issues with electrocoat coverage and to see the effect of vehicle design or process modifications on coverage.

A challenge in the development of any simulation tool is computational speed. Because the electrocoat process can be simulated as a DC electric field problem, boundary element methods can be used, resulting in a significant reduction in the computational intensity of the simulation. In the paper, details of the physics-based tool – EPD – will be given as well as examples of practical use of the tool on vehicle parts, vehicle programs, and for electrocoat tank design. Benefits from

the tool such as improved vehicle quality, paint usage reduction, energy reduction, and environmental savings will also be discussed.

INTRODUCTION

Automotive coatings serve to protect the underlying substrate and to provide a final aesthetic finish for vehicles. A typical automotive surface can have as many as seven layers of material comprising the final finish. To provide good corrosion protection, the first organic layer of the coating is a highly crosslinked polymer barrier to the migration of ions known as electrocoat (or E-coat). Typically, the E-coat film is applied to the surface of the vehicle by a cathodic electrodeposition process, wherein a grounded vehicle is submerged in a tank of water-borne polymeric resin and a (positive) voltage is applied to a series of anodes. Subsequently, the resulting film that is electrodeposited is cured by baking after rinsing off excess uncoagulated material in a number of rinse stages.

The chemistry involved during the processing of E-coat has been extensively studied in the literature and summarized by Beck[1, 2]. The collected works in Gould [3] and Yeates [4] also provide a good summary, historical background, and practical issues relevant to

the E-coat process and its evolution. Campbell and Brown [5, 6] performed early studies on E-coat deposition and modeling bulk properties by examining the kinetics of anodic polymer electrodeposition with emphasis on heating effects within the diffusion layer. Bauer and Qaderi [7] and Pierce [8] performed similar experiments and modeling for cathodic electrodeposition of water-borne polymers. Kinetic parameters were determined based on oxide film growth kinetics in which the resistance of the growing film was considered to be non-Ohmic. However, factors such as the influence of geometrically complex surfaces could not be considered using bulk data. Thus, the thrust of this report is to lay out a mathematical view of the E-coat process as a whole, providing the foundation of an overall process simulator. The film deposition rate is considered to be a distributed quantity influenced by local electric field strength, local current history, and geometry, as well as global material properties.

FORMULATION

The formulation of the equations necessary to describe the electrodeposition of nonconductive materials from a suspension can be segregated into several distinct steps. The first of these steps is to relate the local deposition rate of material from suspension onto the appropriate surfaces to the local variables, such as current density. A great deal of research has been conducted in the development of local deposition models[6, 8]. The second step in the development of an electrodeposition tool would be the efficient implementation for the behavior of the bulk electric potential in the tank. This DC electric problem is coupled to the film deposition physics at the film interface, which implicitly incorporates local geometrical influences on electric field strength.

LOCAL FILM DEPOSITION MODEL

The rate of material being deposited on the cathode surface can be related to the current density, assuming that the specific charge transferred to the substrate surface results from the charge on the depositing ions. Performing a mass balance on a differential surface patch of the cathode results in the following balance equation for the local mass flux, M [kg/M²],

$$\frac{\partial M}{\partial t} = c_M j. \quad (1)$$

Here, j [A/M²] is the local current density and c_M [kg/C] is the mass basis coulombic efficiency. Considering the possibility of back dissolution (or lack of coagulation) of the deposited material, Equation 1 becomes,

$$\frac{\partial M}{\partial t} = c_M (j - j_d), \quad (2)$$

where j_d is the dissolution current density.

A basic assumption applied at this point is that deposition of material onto the cathode surface is irreversible as long as the localized pH exceeds the value needed to coagulate the dispersion; that is, mass is not lost from the cathode for cases where $j < j_d$. Equation 2 can be expressed in terms of local film thickness (after baking), h [M], by noting that, $M = \rho_f h$, where ρ_f [kg/M³] is the density of the cured deposited material. Substitution yields the following equation governing film growth,

$$\frac{\partial h}{\partial t} + h \frac{\partial \ln \rho_f}{\partial t} = \frac{c_M}{\rho_f} (j - j_d). \quad (3)$$

Assuming the density of the cured film to be constant yields,

$$\frac{\partial h}{\partial t} = c(j - j_d), \quad (4)$$

where c [M³/C] is volume basis coulombic efficiency.

FILM CONDUCTIVITY

In order to describe the electrodeposition process, a relationship between the current density, j , and the electric field intensity, E , within the deposited film must be established. In principal, this relationship is more structural or constitutive in nature, but some theoretical basis exists, which gives rise to particular mathematical forms [9]. The simplest structural relationship is to assume that the deposited film is Ohmic, that is, it obeys Ohms law. This would result in the total film resistance, R , being proportional to its local film thickness, h . However, it is well known that these films are, in general, non-Ohmic in nature[8].

Pierce [8] reports that modern latex-based electrocoat materials can grow as a series of porous channels that become more tortuous or narrow as the deposited film grows. An example of such wet film morphology for electrodeposition is shown in Figure 1. This particular system displays webbing with open pores. Therefore, as time goes on, the apparent conductivity of the deposited film would decrease as material diffuses into and deposits in the channels.

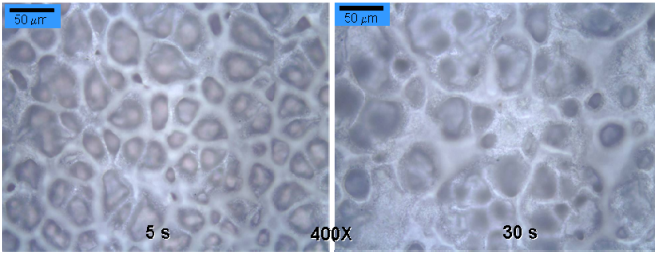


Figure 1: Microscopy for wet electrocoat film on electrogalvanized steel.

An approach to modeling such changing conductivity would be to define an "equivalent" surface area that migrating ions have access to during deposition. An auxiliary equation is required to predict the rate of closure or rate of increase in tortuosity, of surface pores. Pierce proposed a model equation which assumes that tortuosity changes are controlled by the same driving force responsible for film growth,

$$\frac{d\theta}{dt} = k(j - j_d), \quad (5)$$

where, θ , is the fraction of closed surface area and, k [M^2/C], is the pore closure rate. The concept of a pore current density, j_p , must then be introduced and related to the mean surface current density, j . The pores would represent a path of least resistance for the migration of ions; thus, are sites for charge transfer. A charge balance on such a surface leads to the following description of the mean surface charge density,

$$j = j_p(1 - \theta). \quad (6)$$

At this point, an apparent film conductivity, σ_a , can be defined based on the empirically defined pore model and its fractional area available for conduction. This relation is defined as,

$$c_a = c_p(1 - \theta), \quad (7)$$

where σ_p is a pore conductivity. This view of the film conductivity is that the electrical behavior within a pore is Ohmic with an apparent non-Ohmic behavior due to changing film morphology. This view may not be correct for all deposition cases but it, at a minimum, provides an empirical description for the non-Ohmic film growth of E-Coat materials.

Further complications arise in describing the film conductivity during electrodeposition. Energy is irreversibly lost in the form of Joule heating in the growing film. The magnitude of the energy loss is given by[9],

$$Q_{Joule} = J \cdot E = \sigma_a \left| \frac{V_s}{h} \right|^2, \quad (8)$$

and should be taken into account. The reason for this is the fact that the film conductivity will change due to changing temperatures in the film[10].

Film Current Density

Closure to the above relations requires a description of the electric field, E , inside the deposited film. The electric field inside the film must be expressed in terms of a local voltage gradient; however, several simplifying assumptions can be made. Referring to Figure 2, the following assumptions are made:

- The film thickness, h , is much smaller than the length scale of the field problem outside the film. This allows the film thickness to be viewed as a surface property; that is, the only contribution of the deposited film is to the surface conductivity.
- The time scale for charge transfer through the film to the grounded substrate is small compared to the time scale of the growing film, hence, a pseudo-steady state assumption may be applied.

These assumptions allow,

$$E = \frac{V_s}{h}, \quad (9)$$

where V_s , is the potential at the surface of the deposited film.

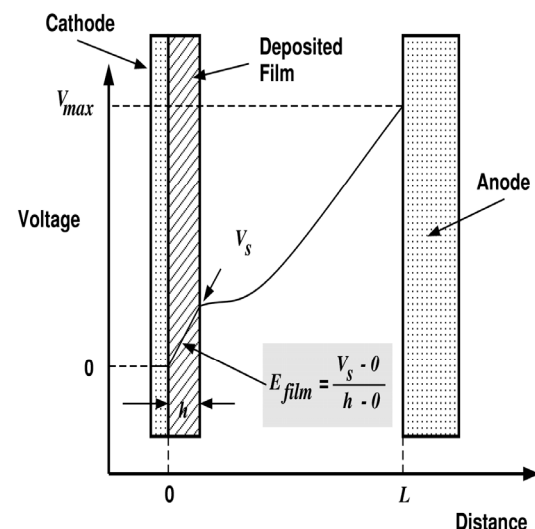


Figure 2: Definition of film electric field.