

# Electrocoating of a Car Door

## Introduction

Electrocoating (also known as E-coating) is an electrophoretical method for depositing paint onto electrically conducting objects. The method is widely used in various industries (for instance, in the automotive industry), where electrocoating is broadly used to apply the first priming paint layer on car bodies. A salient feature of the electrocoating process is that the deposited paint layer is highly resistive. Due to this feature, it is possible to achieve fairly uniform paint layers, even for complex body shapes, since the local deposition rate decreases with increasing paint thickness.

This example models electrocoating of a car door where the electrolyte is a dispersion of colloidal paint particles and the paint particles are deposited on the cathode surface.

## Model Definition

Figure 1 shows the model geometry. The geometry consists of one single electrolyte domain, with the electrodes being represented as boundaries. The quarter and semicylinder surfaces represent the anodes. The car door cathode is completely immersed in the electrolyte.



Figure 1: Model geometry. Car door (cathode) and three cylindrical anodes.

The car door geometry used in the model is a surface geometry (that is, a geometry with zero though-plane thickness), and the car door electrode surface is modeled using the Thin Electrode Surface node (see below).

#### ELECTROLYTE CHARGE TRANSPORT

Ohm's law is used in the electrolyte domain:

$$\mathbf{i}_l = -\sigma_l \nabla \phi_l$$
$$\nabla \cdot \mathbf{i}_l = 0$$

where  $\phi_l$  (V) is the electrolyte potential,  $\mathbf{i}_l$  is the electrolyte current density vector (A/m<sup>2</sup>) and  $\sigma_l$  (S/m) is the electrolyte conductivity. An uniform composition of the electrolyte is assumed, with an electrolyte conductivity of 0.28 S/m.

#### ELECTRODE REACTIONS

The applied cell voltage results in water electrolysis. Oxygen is evolved on the anodes according to:

$$2H_2O \Leftrightarrow 4H^+ + 4e^- + O_2$$

The equilibrium potential,  $E_{eq,O2}$  (V), for this reaction is 1.23 V versus SHE.

On the cathodes, hydrogen is evolved according to:

$$2H^+ + 2e^- \Leftrightarrow H_2$$

The equilibrium voltage for this reaction is  $E_{eq,H2} = 0$  V versus SHE.

Activation overpotentials are assumed to be negligible at both electrodes. The electrode kinetics expression of type Primary condition (thermodynamic equilibrium) is used in the model, to implement that assumption.

#### FILM THICKNESS AND RESISTANCE

The consumption of protons at the cathode results in a locally increased pH. This in turn results in reduced solubility and deposition rate of the colloidal paint particles on the electrode. This model assumes a linear relation between the paint film formation rate and the local current density:

$$\frac{ds_i}{dt} = -\frac{i_{\text{loc},i}C_{\text{cap}}}{\rho}$$

where s (m) is the thickness of the film,  $C_{\text{cap}}$  (kg/C) is the coulombic efficiency of the paint process and  $\rho$  (kg/m<sup>3</sup>) the density of the film. The index *i* represents the upside and downside of the cathode surface.  $C_{\text{cap}}$  is a lumped empirical parameter that needs to be measured for each processing bath. In the present model, a value of 60 g/C is used.

The depositing film results in a lowered electrolyte conductivity at the cathode. This is incorporated in the model by adding a potential drop at the cathode according to:

$$\Delta \phi_{\text{film},i} = s_i R_{\text{film}} i_{\text{loc},i}$$

where  $R_{\text{film}}(\Omega \cdot m)$  is the film resistivity, set to 5 M $\Omega \cdot m$  in this model.

#### ELECTRODE BOUNDARY CONDITIONS

The cathode is grounded in the model. The following condition is used for the electrolyte potential at the car door cathode boundary

$$\phi_{l,i} = -(E_{\text{eq, H}_2} + \Delta \phi_{\text{film},i})$$

For the anodes the electrolyte voltage is set to

$$\phi_l = E_{\text{cell}} - E_{\text{eq, O}_2}$$

where  $E_{\text{cell}}$  (250 V) is the cell potential. The potential drop due to the ion-exchange membrane that covers the membrane-electrode anode cells is not included in the model.

The local current density of the charge transfer reactions,  $i_{loc}$  (A/m<sup>2</sup>), which is used in the film thickness and resistance equations, is evaluated such that the above electrolyte potential conditions are satisfied at the cathode and anode boundaries, respectively.

All other surfaces use insulating boundary conditions.

#### REGARDING THE USAGE OF THE THIN ELECTRODE SURFACE NODE

The Thin Electrode Surface node is used to model the car door cathode surface in this tutorial. The Thin Electrode Surface node introduces "slitting" of the electrolyte potential and surface concentration dependent variables on the interior boundary, which means that they have different values on each side of the car door boundary. Alternatively, one could have modeled the car door geometry with a nonzero thickness in the geometry, removed the volume occupied by the car door domain from the physics selection, and used the Electrode Surface node on the resulting car door external boundaries. However, that approach would have resulted in far more mesh elements and a longer computation time.

## Results and Discussion

Figure 2 shows the paint thickness at the upside of the door after 120 s. The layer is around 21  $\mu$ m thick. The thickness variation is less than 5%.



Time=120 s Surface Slit: Total film thickness change, up (µm) Total film thickness change, up (µm)

Figure 2: Paint thickness at the upside of the car door after 120 s.

Figure 3 shows the paint thickness after 120 s on the downside of the door. Here the thickness variation is significant. Inside the window frame, the lowest thickness of  $6.2 \,\mu m$  is much lower than on the more exposed parts, which have thicknesses close to  $21 \,\mu m$ .



Time=120 s Surface Slit: Total film thickness change, down ( $\mu$ m) Total film thickness change, down ( $\mu$ m)

Figure 3: Paint thickness at the inside of the car door after 120 s.

Finally, Figure 4 shows a thickness versus time comparison between the upside and downside of the window frame at a particular point.



Figure 4: Paint thickness comparison between the upside and downside of the window frame at a particular point.

A more elaborate model would include a more detailed description of the electrode reaction activation overpotentials. A further modification would be the inclusion of the transport of paint particles in the electrolyte solution and the paint deposition rate dependence on the local chemistry. Including these modifications would yield a Tertiary Current Distribution model.

## Reference

1. F. Hess and U. Gonzales, "Automotive E-Coat Paint Process Simulation Using FEA", paper presented at the NAFEMS Ninth International Conference in Orlando, Florida, USA. May 29 2003.

Application Library path: Electrodeposition\_Module/Tutorials/car\_door

## Modeling Instructions

From the File menu, choose New.

#### NEW

In the New window, click 🔗 Model Wizard.

#### MODEL WIZARD

- I In the Model Wizard window, click 间 3D.
- 2 In the Select Physics tree, select Electrochemistry> Primary and Secondary Current Distribution>Primary Current Distribution (cd).
- 3 Click Add.
- 4 Click 🔿 Study.
- 5 In the Select Study tree, select General Studies>Time Dependent.
- 6 Click 🗹 Done.

#### GEOMETRY I

The geometry sequence for this model takes some time to set up. To skip these steps you can instead import the geometry sequence from the saved model file in the application library.

To skip setting up the geometry sequence manually: Right click the **Geometry** node and choose **Insert Sequence**. Then choose the Electrodeposition\_Module -> Tutorials -> car\_door.mph file from the application library.

#### Import I (imp1)

If you inserted the whole geometry sequence you can now move on directly to the Global Definitions section below. Otherwise start setting up the geometry by importing the car\_door\_geom.mphbin CAD file as follows:

- I In the **Home** toolbar, click **Import**.
- 2 In the Settings window for Import, locate the Import section.
- 3 Click 📂 Browse.
- **4** Browse to the model's Application Libraries folder and double-click the file car\_door.mphbin.
- 5 Click ा Import.

Block I (blk1)

I In the **Geometry** toolbar, click 🗍 Block.

- 2 In the Settings window for Block, locate the Size and Shape section.
- 3 In the **Height** text field, type 0.7.
- **4** Locate the **Position** section. In the **x** text field, type -0.1.
- 5 In the y text field, type -0.03.
- 6 Click 틤 Build Selected.

#### Cylinder I (cyl1)

- I In the Geometry toolbar, click 问 Cylinder.
- 2 In the Settings window for Cylinder, locate the Size and Shape section.
- **3** In the **Radius** text field, type **0.05**.
- 4 Locate the **Position** section. In the **x** text field, type -0.1.
- **5** In the **y** text field, type -0.03.
- 6 In the z text field, type 0.7.
- 7 Locate the Axis section. From the Axis type list, choose y-axis.
- 8 Click 틤 Build Selected.

Array I (arr1)

- I In the Geometry toolbar, click 💭 Transforms and choose Array.
- 2 Select the object cyll only.
- 3 In the Settings window for Array, locate the Size section.
- 4 In the x size text field, type 3.
- 5 Locate the **Displacement** section. In the **x** text field, type 0.5.
- 6 Click 틤 Build Selected.

Union I (uni I)

- I In the Geometry toolbar, click 🔲 Booleans and Partitions and choose Union.
- 2 Select the objects arr1(1,1,1), arr1(2,1,1), arr1(3,1,1), and blk1 only.
- 3 In the Settings window for Union, click 틤 Build Selected.

Delete Entities I (dell)

- I In the Model Builder window, right-click Geometry I and choose Delete Entities.
- 2 In the Settings window for Delete Entities, locate the Entities or Objects to Delete section.
- 3 From the Geometric entity level list, choose Domain.
- **4** On the object **unil**, select Domains 1 and 3–7 only.
- 5 Click 틤 Build Selected.

Rotate | (rot |)

- I In the Geometry toolbar, click 💭 Transforms and choose Rotate.
- 2 Click in the Graphics window and then press Ctrl+A to select all objects.
- 3 In the Settings window for Rotate, locate the Rotation section.
- 4 In the Angle text field, type 90.
- 5 From the Axis type list, choose x-axis.

Form Union (fin)

- I In the Model Builder window, click Form Union (fin).
- 2 In the Settings window for Form Union/Assembly, locate the Form Union/Assembly section.
- 3 From the Repair tolerance list, choose Relative.
- 4 In the Geometry toolbar, click 🟢 Build All.
- **5** Click the  $\leftrightarrow$  **Zoom Extents** button in the **Graphics** toolbar.
- 6 Click the Transparency button in the Graphics toolbar.

Your finished geometry should now look like this:



#### **GLOBAL DEFINITIONS**

Note: Start from this point if you chose to import the geometry sequence..

Load some model parameters from a text file.

#### Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- 3 Click **b** Load from File.
- **4** Browse to the model's Application Libraries folder and double-click the file car\_door\_parameters.txt.

#### DEFINITIONS

Add some selections to the model.

#### Anodes

- I In the **Definitions** toolbar, click 🗞 **Explicit**.
- 2 In the Settings window for Explicit, locate the Input Entities section.
- **3** From the **Geometric entity level** list, choose **Boundary**.
- 4 Select Boundaries 2, 33, 34, and 84 only.
- 5 In the Label text field, type Anodes.

#### Cathode

- I In the Definitions toolbar, click 堶 Explicit.
- 2 In the Settings window for Explicit, locate the Input Entities section.
- **3** From the Geometric entity level list, choose Boundary.
- **4** Select Boundaries 7–26, 29–32, 36–39, 41–77, and 79–83 only. (All boundaries of the car door).
- **5** In the **Label** text field, type **Cathode**.

#### PRIMARY CURRENT DISTRIBUTION (CD)

#### Electrolyte I

- In the Model Builder window, under Component I (compl)>
  Primary Current Distribution (cd) click Electrolyte I.
- 2 In the Settings window for Electrolyte, locate the Electrolyte section.
- **3** From the  $\sigma_l$  list, choose **User defined**. In the associated text field, type sigma.

#### Electrode Surface 1

Set up the anodes.

- I In the Physics toolbar, click 🔚 Boundaries and choose Electrode Surface.
- 2 In the Settings window for Electrode Surface, locate the Boundary Selection section.

- **3** From the Selection list, choose Anodes.
- 4 Locate the Electrode Phase Potential Condition section. In the  $\phi_{s,ext}$  text field, type E\_cell.

#### Electrode Reaction 1

- I In the Model Builder window, click Electrode Reaction I.
- 2 In the Settings window for Electrode Reaction, locate the Equilibrium Potential section.
- **3** In the  $E_{eq}$  text field, type Eeq\_02.

#### Thin Electrode Surface 1

Now set up the cathode, which is the car door in this model.

- I In the Physics toolbar, click 🔚 Boundaries and choose Thin Electrode Surface.
- 2 In the Settings window for Thin Electrode Surface, locate the Boundary Selection section.
- **3** From the **Selection** list, choose **Cathode**.
- 4 Click to expand the Dissolving-Depositing Species section. Click + Add.
- **5** In the table, enter the following settings:

Species	Density (kg/m^3)	Molar mass (kg/mol)
s1	rho	Meff

- 6 Click to expand the Film Resistance section. From the Film resistance list, choose Thickness and conductivity.
- 7 In the  $s_0$  text field, type 0.1[um].
- 8 In the  $\sigma_{film}$  text field, type 1/R\_film.
- **9** From the  $\Delta s$  list, choose Total film thickness change, up (cd/tesl).
- IO From the  $\Delta s$  list, choose Total film thickness change, down (cd/tes I).
- II From the Boundary condition formulation list, choose Current density.

#### Electrode Reaction I

- I In the Model Builder window, click Electrode Reaction I.
- **2** In the **Settings** window for **Electrode Reaction**, locate the **Stoichiometric Coefficients** section.
- **3** In the **Stoichiometric coefficients for dissolving-depositing species:** table, enter the following settings:

Species	Stoichiometric coefficient (I)
sl	1

#### MESH I

Now set up the mesh.

- I In the Model Builder window, under Component I (compl) click Mesh I.
- 2 In the Settings window for Mesh, locate the Sequence Type section.
- 3 From the list, choose User-controlled mesh.

#### Size

- I In the Model Builder window, under Component I (compl)>Mesh I click Size.
- 2 In the Settings window for Size, locate the Element Size section.
- 3 From the **Predefined** list, choose Fine.

#### Size 1

- I In the Model Builder window, right-click Free Tetrahedral I and choose Size.
- 2 In the Settings window for Size, locate the Geometric Entity Selection section.
- **3** From the Geometric entity level list, choose Boundary.
- 4 Click **Paste Selection**.
- 5 In the Paste Selection dialog box, type 7 in the Selection text field.
- 6 Click OK.
- 7 In the Settings window for Size, locate the Element Size section.
- 8 From the **Predefined** list, choose Finer.

#### 9 Click 📗 Build All.

Your finished mesh should now look like this:



**IO** Click the **Transparency** button in the **Graphics** toolbar.

#### STUDY I

#### Step 1: Time Dependent

The problem is now ready for solving. Set up to the study to simulate the coating process during 2 minutes.

- I In the Model Builder window, under Study I click Step I: Time Dependent.
- 2 In the Settings window for Time Dependent, locate the Study Settings section.
- 3 In the **Output times** text field, type range(0,5,120).
- **4** In the **Home** toolbar, click **= Compute**.

#### RESULTS

A number of plots have been added by default. Now, create separate plots of the electrode potential versus adjacent reference plot for the upside and downside of the car door geometry.

Electrode Potential vs. Adjacent Reference, All Electrodes

I In the Model Builder window, under Results click

Electrode Potential vs. Adjacent Reference (cd).

2 In the Settings window for 3D Plot Group, type Electrode Potential vs. Adjacent Reference, All Electrodes in the Label text field.

Electrode Potential vs. Adjacent Reference, Cathode Upside

- I Right-click Electrode Potential vs. Adjacent Reference, All Electrodes and choose Duplicate.
- 2 In the Settings window for 3D Plot Group, type Electrode Potential vs. Adjacent Reference, Cathode Upside in the Label text field.

Surface Slit 1

- In the Model Builder window, expand the Electrode Potential vs. Adjacent Reference, Cathode Upside node, then click Surface Slit 1.
- 2 In the Settings window for Surface Slit, locate the Expression on the Downside section.
- 3 In the Expression text field, type root.comp1.cd.Evsrefu.
- 4 Click to expand the Inherit Style section. From the Plot list, choose None.

#### Surface 1

- I In the Model Builder window, click Surface I.
- 2 In the Settings window for Surface, click to expand the Inherit Style section.
- 3 Right-click Surface I and choose Disable.

Electrode Potential vs. Adjacent Reference, Cathode Upside

- I In the Model Builder window, click Electrode Potential vs. Adjacent Reference, Cathode Upside.
- 2 In the Electrode Potential vs. Adjacent Reference, Cathode Upside toolbar, click 团 Plot.

Electrode Potential vs. Adjacent Reference, Cathode Downside

- I Right-click Electrode Potential vs. Adjacent Reference, Cathode Upside and choose Duplicate.
- 2 In the Settings window for 3D Plot Group, type Electrode Potential vs. Adjacent Reference, Cathode Downside in the Label text field.

Surface Slit I

- I In the Model Builder window, expand the Electrode Potential vs. Adjacent Reference, Cathode Downside node, then click Surface Slit I.
- 2 In the Settings window for Surface Slit, locate the Expression on the Upside section.
- 3 In the Expression text field, type root.comp1.cd.Evsrefd.
- 4 Locate the **Expression on the Downside** section. In the **Expression** text field, type root.compl.cd.Evsrefd.

## 5 In the Electrode Potential vs. Adjacent Reference, Cathode Downside toolbar, click Plot.

#### Total Film Thickness, Cathode

- I In the Model Builder window, under Results click Total Electrode Thickness Change (cd).
- 2 In the Settings window for 3D Plot Group, type Total Film Thickness, Cathode in the Label text field.

The total film thickness at both the sides of the car door was plotted by default. Now create separate upside and downside plots.

Total Film Thickness, Cathode Upside

- I Right-click Total Film Thickness, Cathode and choose Duplicate.
- 2 In the Settings window for 3D Plot Group, type Total Film Thickness, Cathode Upside in the Label text field.

Surface Slit I

- I In the Model Builder window, expand the Total Film Thickness, Cathode Upside node, then click Surface Slit I.
- 2 In the Settings window for Surface Slit, locate the Expression on the Downside section.
- 3 In the **Expression** text field, type root.comp1.cd.sbtotu.
- **4** In the **Total Film Thickness, Cathode Upside** toolbar, click **O** Plot.

#### Total Film Thickness, Cathode Downside

- I In the Model Builder window, right-click Total Film Thickness, Cathode and choose Duplicate.
- 2 In the Settings window for 3D Plot Group, type Total Film Thickness, Cathode Downside in the Label text field.

Surface Slit I

- I In the Model Builder window, expand the Total Film Thickness, Cathode Downside node, then click Surface Slit 1.
- 2 In the Settings window for Surface Slit, locate the Expression on the Upside section.
- 3 In the **Expression** text field, type root.comp1.cd.sbtotd.
- **4** In the **Total Film Thickness, Cathode Downside** toolbar, click **I** Plot.

#### Total Film Thickness Comparison

Finally, compare the total upside and downside film thickness at a specific point on the car door geometry.

- I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Total Film Thickness Comparison in the Label text field.
- 3 Locate the Plot Settings section.
- 4 Select the y-axis label check box. In the associated text field, type Total film thickness (\mu m).

#### Point Graph 1

- I In the Total Film Thickness Comparison toolbar, click 🗠 Point Graph.
- **2** Select Point 139 only.
- 3 In the Settings window for Point Graph, click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (compl)> Primary Current Distribution>Dissolving-depositing species>cd.sbtotu Total film thickness change, up m.
- 4 Click to expand the Legends section. Locate the y-Axis Data section. From the Unit list, choose μm.
- 5 Locate the Legends section. Select the Show legends check box.
- 6 From the Legends list, choose Manual.
- 7 In the table, enter the following settings:

#### Legends

Upside

#### Point Graph 2

- I Right-click Point Graph I and choose Duplicate.
- 2 In the Settings window for Point Graph, locate the Selection section.
- **3** Click to select the **Delta Activate Selection** toggle button.
- 4 Click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (compl)>Primary Current Distribution>Dissolving-depositing species>cd.sbtotd Total film thickness change, down m.
- 5 Locate the Legends section. In the table, enter the following settings:

## Legends

Downside

#### Total Film Thickness Comparison

I In the Model Builder window, click Total Film Thickness Comparison.

- 2 In the Settings window for ID Plot Group, locate the Legend section.
- 3 From the **Position** list, choose **Upper left**.
- **4** In the **Total Film Thickness Comparison** toolbar, click **O Plot**.

Animation I

- I In the **Results** toolbar, click **Animation** and choose **File**.
- 2 In the Settings window for Animation, locate the Target section.
- 3 From the Target list, choose Player.
- 4 Locate the Scene section. From the Subject list, choose Total Film Thickness, Cathode Downside.
- **5** Click the **Play** button in the **Graphics** toolbar.