Aluminum Anodization

Introduction

When anodizing aluminum, the surface is electrochemically altered to form an abrasive and corrosion-resistive Al_2O_3 film.

It has been reported (Ref. 1) that the electrode kinetics during the Al anodization undergo only minor changes as the oxide layer grows. As a result of this, a stationary analysis of the current distribution is sufficient to determine the thickness uniformity of the resulting anodized layer thickness.

In this tutorial, experimental polarization data is used to model the current distribution on a number of extruded aluminum profiles in an anodization cell.

Model Definition

Figure 1 shows the model geometry, consisting of five L-shaped extruded aluminum anodes placed in an electrolyte bath. The cathode is represented by the rectangular boundary along the *xz*-plane, located at y=0.

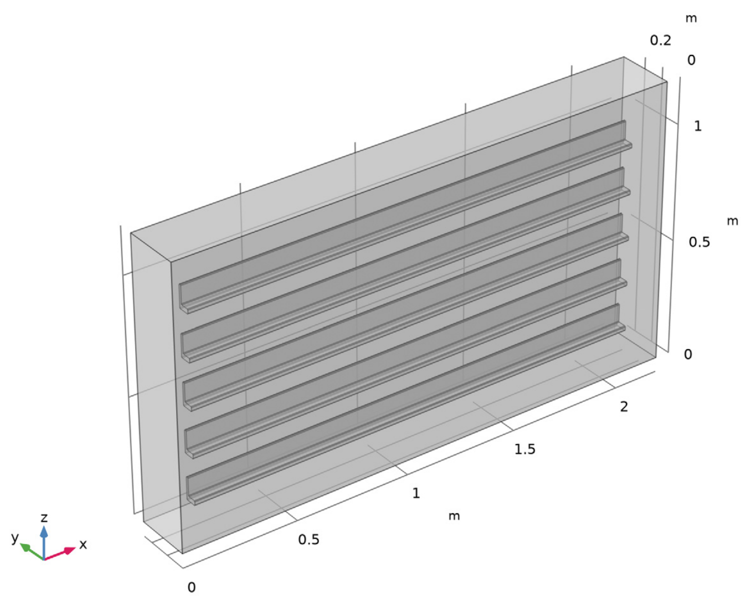


Figure 1: Model geometry. 5 L-shaped aluminum bars in an electrolyte bath.

The model is created using the Secondary Current Distribution interface, using a constant electrolyte conductivity of 0.55 S/cm. The anode kinetics are defined using experimental polarization data, depending both on the electrode potential and the temperature as shown in Figure 2. An average current density of 100 A/m^2 is used for the anodes. The cathode kinetics (hydrogen evolution) is assumed to be very fast so that a primary current condition can be used. The cathode potential is set to 0 V.

The problem is solved using a Stationary study with an auxiliary sweep, solving for the temperatures 15°C, 20°C, and 25°C.

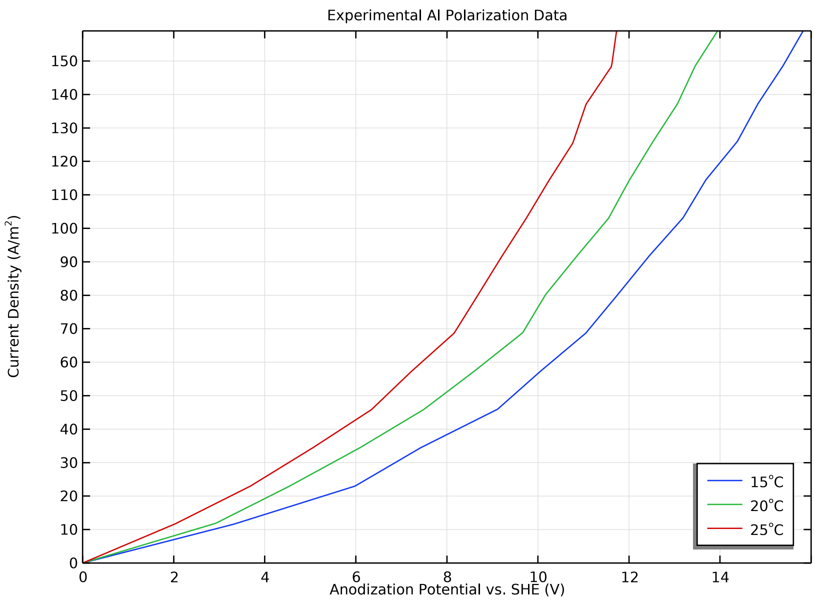


Figure 2: Al anodization polarization data for different temperatures (Ref. 1).

Results and Discussion

Figure 3 shows the electrolyte potential at 25°C. The electrolyte potential drop is in the range of 450 mV. This should be compared to the electrode potential shown in Figure 4, which is in the range of 9.5 V to 9.75 V for the same temperature, resulting in a cell potential of around 10 V.

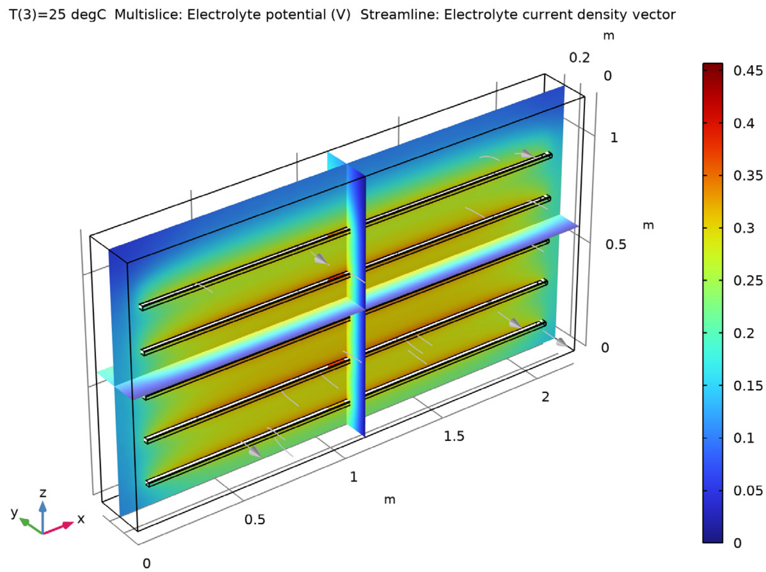


Figure 3: Electrolyte potential.

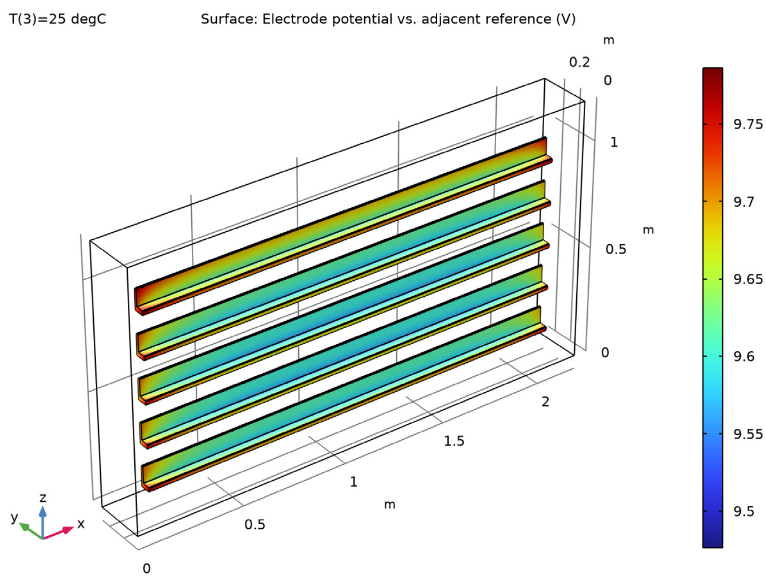


Figure 4: Electrode potential versus SHE.

Figure 5 and Figure 6 show the normalized current distribution at 15°C and 25°C, respectively. At 15°C, the current distribution becomes more uniform (the difference between the minimum and maximum values is smaller). The reason for this is the slower kinetics at the lower temperature (Figure 2), resulting in a dampening effect on local variations in current density. To achieve a more homogeneous thickness of the anodized Al layer it could therefore be beneficial to lower the process temperature. The lower temperature will, however, result in a higher cell potential, thus increasing the electrical energy demands of the process.

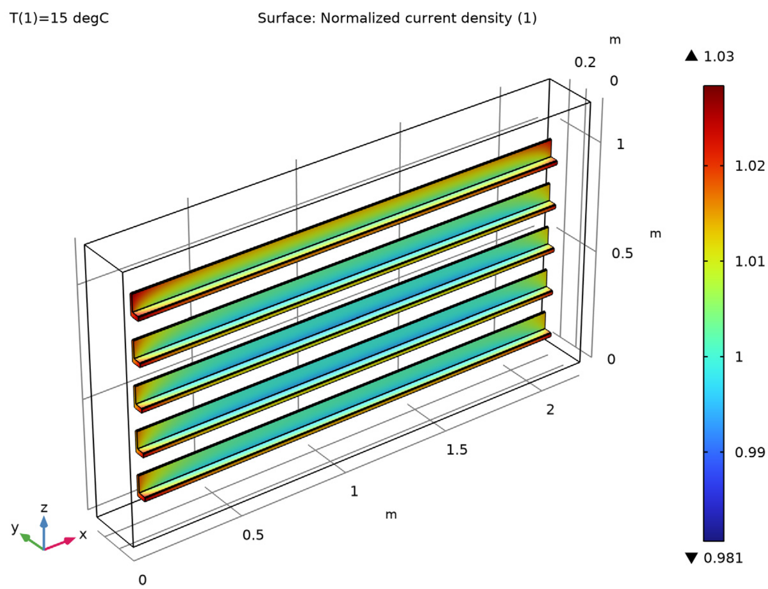


Figure 5: Normalized anode current distribution at 15°C.

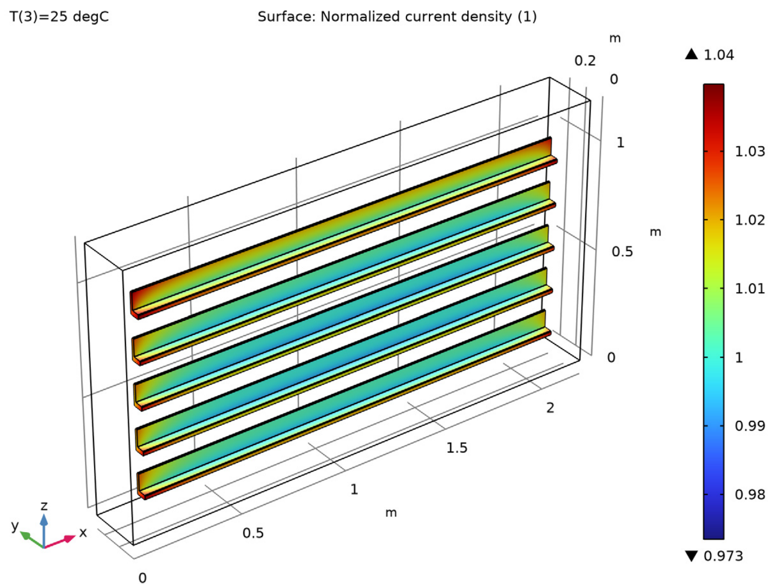


Figure 6: Normalized anode current distribution at 25°C.

Reference

1. R Akolkar, U. Landau, H. Kuo, and Y. Wang, "Modeling of the current distribution in aluminum anodization," *Journal of Applied Electrochemistry*, vol. 34, pp 807–813, 2004.

Application Library path: `Electrodeposition_Module/Tutorials/al_anodization`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Electrochemistry>Primary and Secondary Current Distribution>Secondary Current Distribution (cd)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Stationary**.
6 Click **Done**.

GLOBAL DEFINITIONS

Load the model parameters from a text file.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `al_anodization_parameters.txt`.

GEOMETRY 1

Now create the model geometry. First draw the aluminum profiles in a work plane, and then extrude the work plane.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click **Work Plane**.
2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
3 From the **Plane** list, choose **yz-plane**.

Work Plane 1 (wp1)>Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane 1 (wp1)>Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3 In the **Width** text field, type `5[cm]`.
4 In the **Height** text field, type `1[dm]`.

Work Plane 1 (wp1)>Rectangle 2 (r2)

1 In the **Work Plane** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `4[cm]`.

4 In the **Height** text field, type `8[cm]`.

5 Locate the **Position** section. In the **yw** text field, type `2[cm]`.

6 Click **Build Selected**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.

Work Plane 1 (wp1)>Difference 1 (dif1)

1 In the **Work Plane** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **r1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **r2** only.

6 Click **Build Selected**.

Work Plane 1 (wp1)>Fillet 1 (fil1)

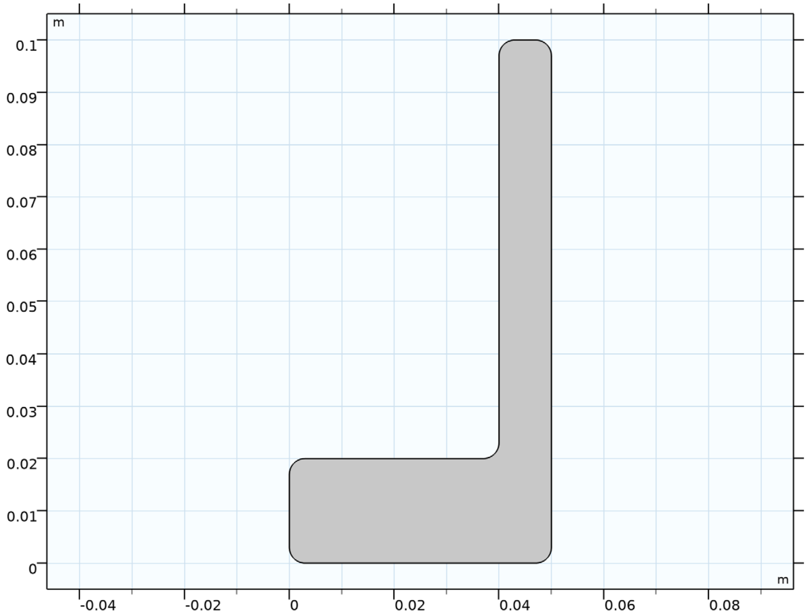
1 In the **Work Plane** toolbar, click **Fillet**.

2 Click the **Select All** button in the **Graphics** toolbar.

3 In the **Settings** window for **Fillet**, locate the **Radius** section.

4 In the **Radius** text field, type `3[mm]`.

5 Click **Build Selected**.



Work Plane 1 (wp1)>Array 1 (arr1)

1 In the **Work Plane** toolbar, click **Transforms** and choose **Array**.

2 Select the object **fil1** only.

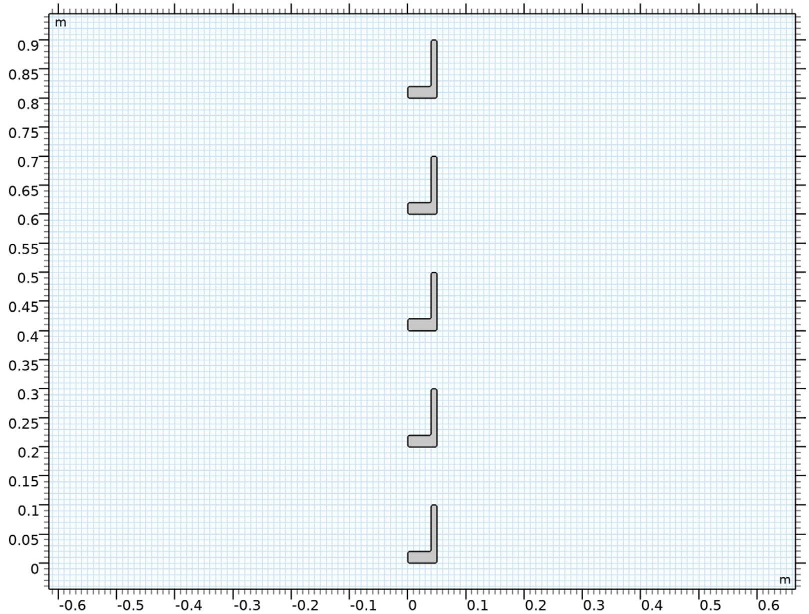
3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **yw size** text field, type `5`.

5 Locate the **Displacement** section. In the **yw** text field, type `2[dm]`.

6 Click **Build Selected**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.



Extrude 1 (ext1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
`2[m]`

4 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

5 In the **New Cumulative Selection** dialog box, type `Anodes` in the **Name** text field.

6 Click **OK**.

7 In the **Settings** window for **Extrude**, click **Build Selected**.

8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Move 1 (mov1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Move**.

2 Click the **Select All** button in the **Graphics** toolbar.

3 In the **Settings** window for **Move**, locate the **Displacement** section.

4 In the **x** text field, type `1.25[dm]`.

5 In the **y** text field, type `1[dm]`.

6 In the **z** text field, type `1[dm]`.

7 Click **Build Selected**.

Block 1 (blk1)

1 In the **Geometry** toolbar, click **Block**.

2 In the **Settings** window for **Block**, locate the **Size and Shape** section.

3 In the **Width** text field, type `2.2[m]`.

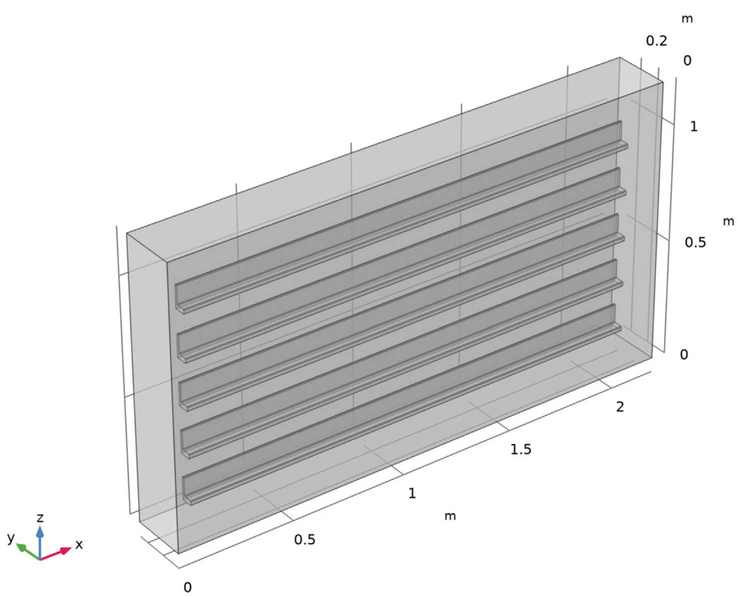
4 In the **Depth** text field, type `0.25[m]`.

5 In the **Height** text field, type `1.2[m]`.

6 Click **Build Selected**.

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

8 Click the **Zoom Extents** button in the **Graphics** toolbar.



Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **blk1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **mov1** only.

6 Click **Build Selected**.

SECONDARY CURRENT DISTRIBUTION (CD)

Now start setting up the physics. Start with the conductivity of the Electrolyte node, which has already been added by default.

Electrolyte 1

1 In the **Model Builder** window, under **Component 1 (comp1)>** **Secondary Current Distribution (cd)** click **Electrolyte 1**.

2 In the **Settings** window for **Electrolyte**, locate the **Electrolyte** section.

3 From the σ_l list, choose **User defined**. In the associated text field, type `sigma`.

DEFINITIONS

The kinetics of the anodes make use of experimental polarization curves. Use an interpolation function to import the experimental data.

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `al_polarization_data.csv`.

6 Click **Import**.

7 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
iloc_Al	1

8 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
Column 1	V
Column 2	degC

9 In the **Function** table, enter the following settings:

Function	Unit
iloc_Al	A/m^2

Integration 1 (intop1)

Also add a nonlocal integration coupling for the anode boundaries. It will be used later when normalizing the current density distribution.

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, locate the **Source Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Anodes**.

SECONDARY CURRENT DISTRIBUTION (CD)

Electrode Surface - Anodes

1 In the **Physics** toolbar, click **Boundaries** and choose **Electrode Surface**.

2 In the **Settings** window for **Electrode Surface**, type `Electrode Surface - Anodes` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Anodes**.

4 Locate the **Electrode Phase Potential Condition** section. From the **Electrode phase potential condition** list, choose **Average current density**.

5 In the $i_{l,\mathrm{average}}$ text field, type `i_avg`.

6 In the $\phi_{s,\mathrm{ext,init}}$ text field, type `E_cell_init`.

Electrode Reaction 1

1 In the **Model Builder** window, click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, locate the **Electrode Kinetics** section.

3 From the $i_{\mathrm{loc,expr}}$ list, choose **User defined**. In the associated text field, type `iloc_Al(cd.Evsref,T)`.

Electrode Surface - Cathode

Now set up the cathode surface. The cathode reaction, hydrogen evolution, is very fast. Assume a negligible activation potential (a primary current distribution) for this electrode surface.

1. In the **Physics** toolbar, click **Boundaries** and choose **Electrode Surface**.
2. In the **Settings** window for **Electrode Surface**, type `Electrode Surface - Cathode` in the **Label** text field.
3. Select Boundary 2 only.

Electrode Reaction 1

1. In the **Model Builder** window, click **Electrode Reaction 1**.
2. In the **Settings** window for **Electrode Reaction**, locate the **Electrode Kinetics** section.
3. From the **Kinetics expression type** list, choose **Primary condition (thermodynamic equilibrium)**.

MESH 1

Now set up the mesh.

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Edit Physics-Induced Sequence**.

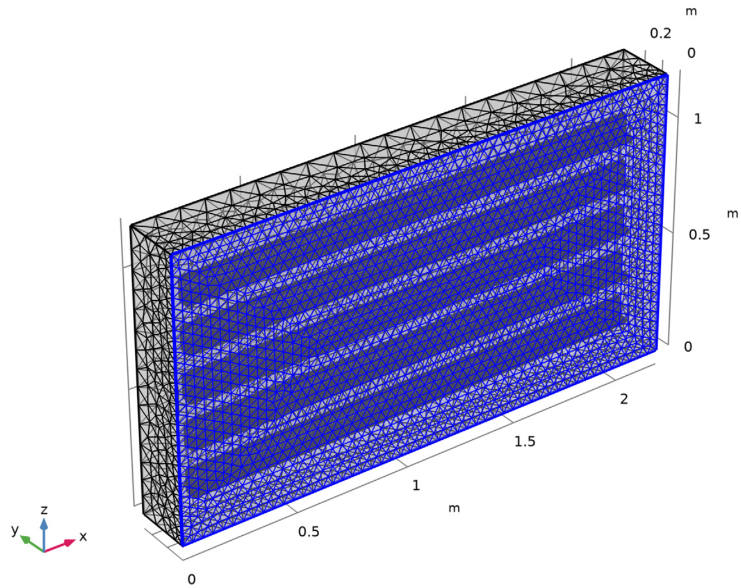
Size

1. In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Finer**.

Size 1

1. In the **Model Builder** window, right-click **Free Tetrahedral 1** 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. Select Boundary 2 only.
5. Locate the **Element Size** section. From the **Predefined** list, choose **Extremely fine**.

6 Click **Build All**.



STUDY 1

Step 1: Stationary

The model is now ready for solving. Use an auxiliary sweep to solve the problem for three different temperatures.

1 In the **Model Builder** window, under **Study 1** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
T (Temperature)	15 20 25	degC

6 In the **Home** toolbar, click **Compute**.

RESULTS

Electrolyte Potential (cd)

A number of default plots have been created automatically. Switch off the transparency mode to view the hidden selections.

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

Electrode Potential vs. Adjacent Reference (cd)

Modify the Electrode Potential versus Adjacent Reference plot to plot the potential on the anodes only.

1 In the **Model Builder** window, click **Electrode Potential vs. Adjacent Reference (cd)**.
2 In the **Settings** window for **3D Plot Group**, click to expand the **Selection** section.
3 From the **Geometric entity level** list, choose **Boundary**.
4 From the **Selection** list, choose **Anodes**.

Streamline 1

1 In the **Model Builder** window, expand the **Electrode Potential vs. Adjacent Reference (cd)** node.
2 Right-click **Streamline 1** and choose **Delete**.

Normalized Current Distribution

Proceed as follows to create a plot of the normalized current distribution.

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2 In the **Settings** window for **3D Plot Group**, type `Normalized Current Distribution` in the **Label** text field.
3 Locate the **Selection** section. From the **Geometric entity level** list, choose **Boundary**.
4 From the **Selection** list, choose **Anodes**.
5 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

Surface 1

1 Right-click **Normalized Current Distribution** and choose **Surface**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `cd.itot/i_avg`.
4 Select the **Description** check box. In the associated text field, type `Normalized current density`.

5 In the **Normalized Current Distribution** toolbar, click **Plot**.

Normalized Current Distribution

You can now use the same plot group to plot for the different temperature parameter values.

1 In the **Model Builder** window, click **Normalized Current Distribution**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Parameter value (T (degC))** list, choose **20**.

4 In the **Normalized Current Distribution** toolbar, click **Plot**.

5 From the **Parameter value (T (degC))** list, choose **15**.

6 In the **Normalized Current Distribution** toolbar, click **Plot**.

7 From the **Parameter value (T (degC))** list, choose **25**.

8 In the **Normalized Current Distribution** toolbar, click **Plot**.

Finally, since the current density is proportional to the thickness of the deposited oxide layer, you can create a plot of the oxide layer thickness after 25 minutes of deposition time as follows:

9 Right-click **Normalized Current Distribution** and choose **Duplicate**.

Deposited Layer Thickness after 25 min

1 In the **Model Builder** window, under **Results** click **Normalized Current Distribution 1**.

2 In the **Settings** window for **3D Plot Group**, type `Deposited Layer Thickness after 25 min` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Deposited Layer Thickness after 25 min** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `cd.itot*25[min]*M*eff/(6*F_const*rho*(1-por))`.

This expression is based on Faraday's law of electrolysis, where the number 6 corresponds to the number of electrons passed per deposited molecule of aluminum oxide.

4 From the **Unit** list, choose **µm**.

5 In the **Description** text field, type `Oxide layer thickness after 25 min`.

6 In the **Deposited Layer Thickness after 25 min** toolbar, click **Plot**.