Model created in COMSOL Multiphysics 6.4

Electroplating of Multiple Components in a Rack

Introduction

When several components are to be electroplated they are typically mounted on a rack in the electroplating bath. An important aspect is then achieving a uniform thickness of the plated layer for all components mounted on the rack. Numerical modeling allows to investigate the effect of several geometrical and operational parameters on electroplating uniformity in order to optimize the electroplating process.

In this tutorial model, electroplating of an array of oil pump covers mounted on a rack is considered. Within the array, one oil pump cover is displaced toward the anode in order to demonstrate the effect geometrical effect on the current distribution in the bath. A secondary current distribution with full Butler–Volmer kinetics for both anode and cathode is used here to compute the thickness of the deposited layer at the cathode surface.

The example is based on a scientific paper (Ref. 1).

Model Definition

The model geometry is shown in Figure 1. The anode is a planar dissolving anode. The cathode consists of an array of oil pump covers to be decorated by metal plating.

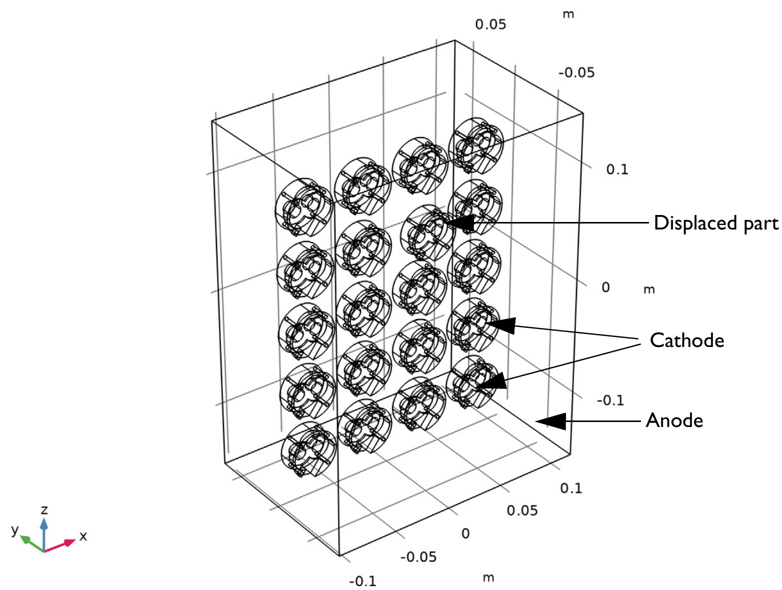


Figure 1: The model geometry.

The model geometry is parameterized so that any oil pump cover can be displaced toward or away from the anode surface. In the results shown below, one oil pump cover is displaced toward the anode surface, as indicated in Figure 1.

ELECTROLYTE CHARGE TRANSPORT

Use the Secondary Current Distribution interface to solve for the electrolyte potential, ϕ_l (SI unit: V), according to

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

where $\mathbf{i}_l$ (SI unit: A/m^2) is the electrolyte current density vector and σ_l (SI unit: S/m) is the electrolyte conductivity, which is assumed to be a constant.

Use the default Insulation condition for all boundaries except the anode and cathode surfaces:

$$\mathbf{n} \cdot \mathbf{i}_l = 0$$

where $\mathbf{n}$ is the normal vector, pointing out of the domain.

The main electrode reaction on both the anode and the cathode surfaces is the nickel dissolution/deposition reaction according to

$$\mathrm{Ni}^{2+} + 2e^- \Leftrightarrow \mathrm{Ni(s)}$$

Use a Butler–Volmer expression to model this reaction; this sets the local current density to

$$i_{\mathrm{loc,\,Ni}} = i_{0,\,\mathrm{Ni}}\left(\exp\left(\frac{\alpha_{\mathrm{a}} F \eta_{\mathrm{Ni}}}{RT}\right) - \exp\left(-\frac{\alpha_{\mathrm{c}} F \eta_{\mathrm{Ni}}}{RT}\right)\right)$$

where $i_{0,\mathrm{Ni}}$ is the exchange current density, α_a is the anodic transfer coefficient, α_c is the cathodic transfer coefficient, and η_{Ni} is the overpotential.

The overpotential η_{Ni} (V) is calculated from:

$$\eta_{\mathrm{Ni}} = \phi_{s,\,\mathrm{ext}} - \phi_l - E_{\mathrm{eq,\,Ni}}$$

On the anode and cathode surfaces, the electrolyte current density is set to the local current density of the nickel dissolution/deposition reaction:

$$\mathbf{n} \cdot \mathbf{i}_l = i_{\mathrm{loc,\,Ni}}$$

The electric potential of the metal is selected as a bootstrap by setting this potential to 0 V at the anode and the average current density of −100 A/m^2 is applied at the cathode surface. This results in positive local current density at the anode surface and negative at the cathode surfaces.

The deposition thickness at the cathode boundary surfaces, d (m), is calculated according to

$$d = \frac{-i_{\mathrm{loc,\,Ni}}}{nF}\frac{M}{\rho}t$$

where M is the mean molar mass (59 g/mol), ρ is the density (8900 kg/m^3) of the nickel atoms, n is the number of participating electrons, and t is the plating time.

The model is solved using a Stationary study.

Results and Discussion

Figure 2 shows a streamline plot of the electrolyte current density and a surface plot of the total current density at the oil pump cover (cathode) surfaces. The current flows from the anode surface to the cathode surface in the electrolyte. The surface plot of the total current density indicates nonuniform current density distribution across the complex shape of the oil pump cover, and between different components in the array. Generally for each individual component, the current density is the highest at the oil pump cover boundaries closest to the anode surface and is the lowest at the boundaries farthest away from the anode surface. In the array, the current density is the highest at the displaced oil pump cover, located more closely to the anode. It is also observed that the oil pump covers mounted along the outer edge of the rack receive higher current than those mounted at the center of the rack. In summary, the nonuniform current distribution, seen in Figure 2, is attributed to both the complex shape of the cover as well as the mounting position on the rack.

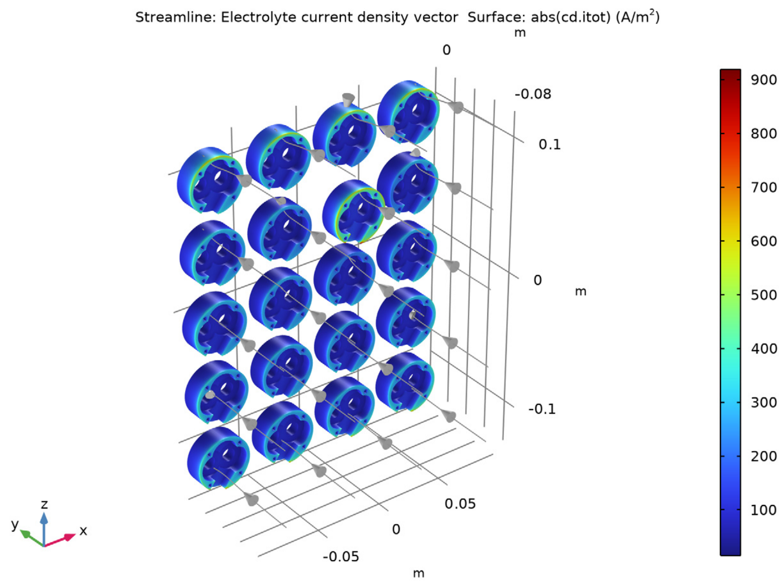


Figure 2: Current density distribution in the rack.

Figure 3 shows the corresponding electroplating thickness over the cathode surfaces. Since the deposition thickness is proportional to the stationary local electrode current density at the cathode surface in this model, the deposition distribution is identical to the current distribution. The lowest deposition thickness is found to be at the bottom surface of the oil pump cover and the highest deposition thickness is found to be at the top surface of the displaced oil pump cover.

The numerical models of this type are useful in optimizing the deposition process by changing design parameters such as plating rack configuration, plating cell geometry, distance between the anode and cathode surface, conductivity of the electrolyte and operational parameters such as applied current or potential.

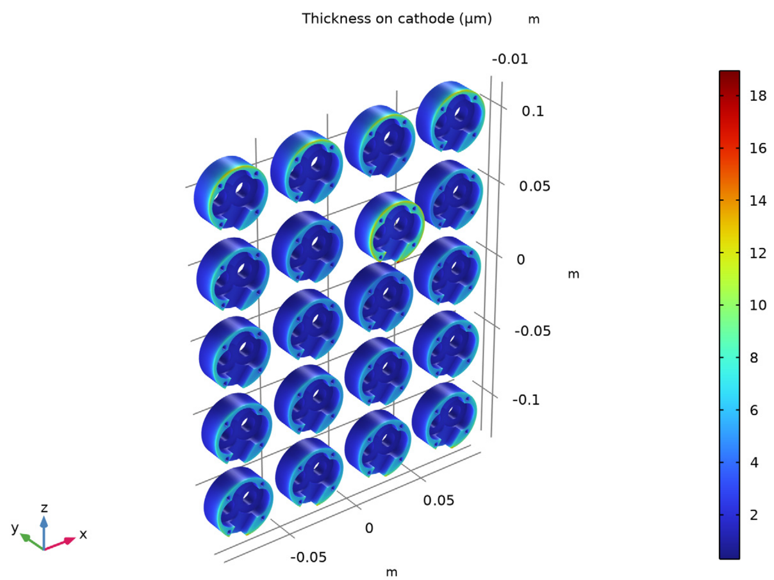


Figure 3: The electroplating thickness at the cathode.

Reference

1. J. Deconinck, G. Floridor, B. Van den Bossche, L. Bortels, and G. Nelissen, "Numerical 3D BEM Simulation of the Chromium Layer Thickness Distribution on Parts in a Rack Plating Configuration," *Simulation of Electrochemical Processes*, vol. 48, p. 173, 2005.

Application Library path: `Electrodeposition_Module/Tutorials/electroplating_rack`

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 **Preset Studies for Selected Physics Interfaces** > **Stationary with Initialization**.
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 `electroplating_rack_parameters.txt`.

GEOMETRY 1

The model geometry is available as a parameterized geometry sequence in a separate MPH file. If you want to build it from scratch, follow the instructions in the section Appendix — Geometry Modeling Instructions. Otherwise load it from file with the following steps.

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
2 Browse to the model's Application Libraries folder and double-click the file `electroplating_rack_geom_sequence.mph`.
3 In the **Insert Sequence** dialog, click **OK**.
4 In the **Geometry** toolbar, click **Build All**.
5 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

SECONDARY CURRENT DISTRIBUTION (CD)

Now start setting up the current distribution model. First, set the domain selection to 1 to solve the current distribution only in the electrolyte domain.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Secondary Current Distribution (cd)**.
2 In the **Settings** window for **Secondary Current Distribution**, locate the **Domain Selection** section.
3 In the list, choose **2**, **3**, **4**, **5**, **6**, **7**, **8**, **9**, **10**, **11**, **12**, **13**, **14**, **15**, **16**, **17**, **18**, **19**, **20**, and **21**.
4 Click **Remove from Selection**.
5 Select Domain 1 only.

Electrolyte 1

Next, set the user defined electrolyte conductivity.

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`.

Electrode Surface - Anode

Now define the nickel dissolution electrode reaction on the anode surface.

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

   Keep the default boundary condition for this surface, setting (grounding) the electric potential to zero.

Electrode Reaction 1

Set the Butler-Volmer electrode kinetics for the nickel dissolution reaction.

1 In the **Model Builder** window, click **Electrode Reaction 1**.
2 In the **Settings** window for **Electrode Reaction**, locate the **Equilibrium Potential** section.
3 In the E_{eq} text field, type `Eeq_Ni`.
4 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Butler–Volmer**.
5 In the i_0 text field, type `i0_Ni`.

Electrode Surface - Anode

Now duplicate this node to define the cathode settings. Set the average current density at the cathode surface.

Electrode Surface - Cathodes

1 In the **Model Builder** window, right-click **Electrode Surface - Anode** and choose **Duplicate**.

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

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Array 1**.

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 `Iavg`.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

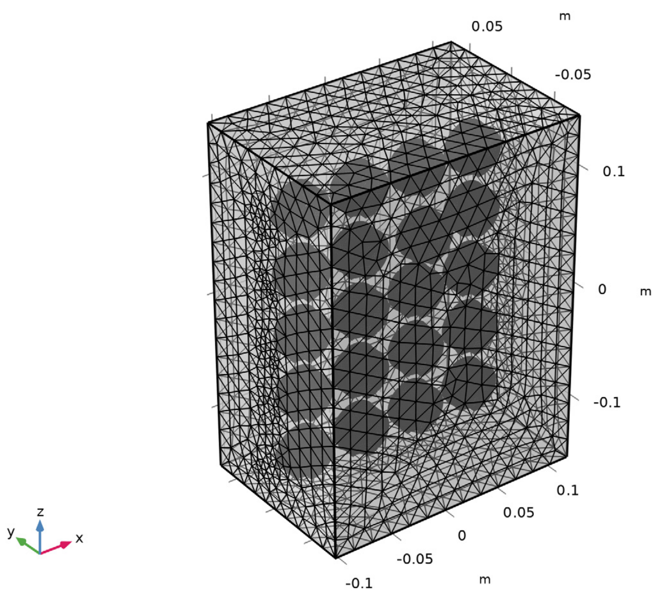
2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Fine**.

4 Click **Build All**.

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

The mesh should look like this:



DEFINITIONS

Before solving, load the definition of a postprocessing variable from a text file.

Variables 1

1 In the **Definitions** toolbar, click **Local Variables**.

The electroplating thickness at the cathode surface, defined in the variable `thickness_cathode`, is evaluated from the local electrode reaction current density together with the reaction stoichiometry, and surface properties such as density and molecular weight and plating time parameters.

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

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `electroplating_rack_variables.txt`.

STUDY 1

The model is now ready to be solved.

1 In the **Study** toolbar, click **Compute**.

RESULTS

Polish the streamlines of the default electrolyte current density plot group, and change the selection of the surface plot to the cathode surface only.

Streamline 1

1 In the **Model Builder** window, expand the **Results** > **Electrolyte Current Density (cd)** node, then click **Streamline 1**.

2 In the **Settings** window for **Streamline**, locate the **Streamline Positioning** section.

3 From the **Positioning** list, choose **On selected entities**.

4 Locate the **Selection** section. Click to select the **Activate Selection** toggle button.

5 Select Boundary 2 only.

Color Expression 1

1 In the **Model Builder** window, expand the **Streamline 1** node.

2 Right-click **Color Expression 1** and choose **Disable**.

Surface 1

In the **Model Builder** window, under **Results** > **Electrolyte Current Density (cd)** click **Surface 1**.

Selection 1

1 In the **Electrolyte Current Density (cd)** toolbar, click **Selection**.

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

3 From the **Selection** list, choose **Array 1**.

Electrolyte Current Density (cd)

1 In the **Model Builder** window, under **Results** click **Electrolyte Current Density (cd)**.

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

3 Clear the **Plot dataset edges** checkbox.

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

5 In the **Electrolyte Current Density (cd)** toolbar, click **Plot**.

The plot should look like Figure 2.

Electroplating Thickness

Next, plot electroplating thickness on the cathode surface.

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Electroplating Thickness` in the **Label** text field.

3 Click to expand the **Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Array 1**.

5 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

Surface 1

1 In the **Electroplating Thickness** toolbar, click **Surface**.

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

3 In the **Expression** text field, type `thickness_cathode`.

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

Electroplating Thickness

1 In the **Model Builder** window, click **Electroplating Thickness**.

2 In the **Electroplating Thickness** toolbar, click **Plot**.

The plot should look like Figure 3.

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 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

First load the geometrical parameters from a text file.

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 `electroplating_rack_geometrical_parameters.txt`.

OIL PUMP COVER

Now, start with creating a geometry part for oil pump cover.

1 In the **Geometry** toolbar, click **Create Part**.

2 In the **Settings** window for **Part**, type `Oil Pump Cover` in the **Label** text field.

Cylinder 1 (cyl1)

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

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

3 In the **Radius** text field, type `D_opc/2`.

4 In the **Height** text field, type `t_opc`.

Cylinder 2 (cyl2)

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

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

3 In the **Radius** text field, type `d_opc/2`.

4 In the **Height** text field, type `t_opc`.

5 Locate the **Position** section. In the **x** text field, type d_opc*4/5.

Mirror 1 (mir1)

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

2 Select the object **cyl2** only.

3 In the **Settings** window for **Mirror**, locate the **Input** section.

4 Select the **Keep input objects** checkbox.

5 Locate the **Normal Vector to Plane of Reflection** section. In the **x** text field, type 1.

6 In the **z** text field, type 0.

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 In the **z-coordinate** text field, type t_opc/2.

Work Plane 1 (wp1) > Plane Geometry

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

Work Plane 1 (wp1) > Circle 1 (c1)

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

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

3 In the **Radius** text field, type d_opc.

4 Locate the **Position** section. In the **xw** text field, type d_opc*4/5.

Work Plane 1 (wp1) > Mirror 1 (mir1)

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

2 Select the object **c1** only.

3 In the **Settings** window for **Mirror**, locate the **Input** section.

4 Select the **Keep input objects** checkbox.

Work Plane 1 (wp1) > Union 1 (uni1)

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

2 Click in the **Graphics** window and then press Ctrl+A to select both objects.

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

4 Clear the **Keep interior boundaries** checkbox.

Extrude 1 (ext1)

1 In the **Model Builder** window, under **Global Definitions** > **Geometry Parts** > **Oil Pump Cover** right-click **Work Plane 1 (wp1)** and choose **Extrude**.

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

3 In the table, enter the following settings:

Distances (m)
t_opc/2

Cylinder 3 (cyl3)

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

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

3 In the **Radius** text field, type `d_opc`.

4 In the **Height** text field, type `t_opc/2`.

5 Locate the **Position** section. In the **y** text field, type `d_opc*4/5`.

6 In the **z** text field, type `t_opc*3/5`.

Work Plane 2 (wp2)

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

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

3 In the **z-coordinate** text field, type `t_opc*3/5`.

Work Plane 2 (wp2) > Plane Geometry

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

Work Plane 2 (wp2) > Polygon 1 (pol1)

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

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

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

4 In the **xw** text field, type `d_opc*4/5 0 0 -d_opc*8/5 -d_opc*8/5 -d_opc*4/5 -d_opc*4/5 -d_opc*4/5 -d_opc*4/5 -d_opc*4/5`.

5 In the **yw** text field, type `-d_opc -D_opc/2 -D_opc/2 -D_opc/2 -D_opc/2 -d_opc -d_opc 0 0 0`.

Extrude 2 (ext2)

1 In the **Model Builder** window, under **Global Definitions** > **Geometry Parts** > **Oil Pump Cover** right-click **Work Plane 2 (wp2)** and choose **Extrude**.

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

3 From the **Specify** list, choose **Vertices to extrude to**.

4 On the object **cyl3**, select Point 6 only.

Cylinder 4 (cyl4)

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

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

3 In the **Radius** text field, type `0.3*d_opc/2`.

4 In the **Height** text field, type `t_opc`.

5 Locate the **Position** section. In the **x** text field, type `0.43*D_opc/sqrt(2)`.

6 In the **y** text field, type `0.43*D_opc/sqrt(2)`.

Rotate 1 (rot1)

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

2 Select the object **cyl4** only.

3 In the **Settings** window for **Rotate**, locate the **Input** section.

4 Select the **Keep input objects** checkbox.

5 Locate the **Rotation** section. In the **Angle** text field, type `90,180,270`.

Difference 1 (dif1)

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

2 Select the object **cyl1** only.

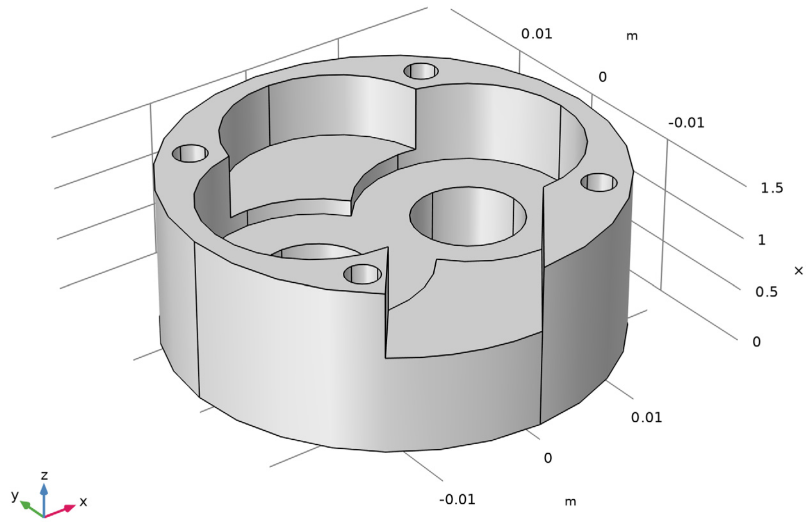
3 In the **Settings** window for **Difference**, locate the **Difference** section.

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

5 Select the objects **cyl2**, **cyl3**, **cyl4**, **ext1**, **ext2**, **mir1**, **rot1(1)**, **rot1(2)**, and **rot1(3)** only.

6 Click **Build Selected**.

The geometry of oil pump cover should look like this:



GEOMETRY PARTS

Now, create a geometry part for plating tank.

PLATING TANK

1 In the **Geometry** toolbar, click **Create Part**.

2 In the **Settings** window for **Part**, type `Plating Tank` in the **Label** text field.

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 `n_x*D_opc+(n_x+1)*dist_x`.

4 In the **Depth** text field, type `n_y*D_opc+(n_y+1)*dist_y`.

5 In the **Height** text field, type `H_tank`.

6 Locate the **Position** section. From the **Base** list, choose **Center**.

7 In the **z** text field, type `H_tank/2`.

GEOMETRY 1

Now, assemble an array of oil pump covers in the electroplating tank.

Oil Pump Cover 1 (pi1)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Oil Pump Cover**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Displacement** subsection. In the **xwi** text field, type `((D_opc+dist_x)*(1-n_x))/2`.

4 In the **ywi** text field, type `((D_opc+dist_y)*(1-n_y))/2`.

Plating Tank 1 (pi2)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Plating Tank**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Displacement** subsection. In the **zwi** text field, type `-z_out*6`.

Array 1 (arr1)

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

2 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

3 Select the object **pi1** only.

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

5 In the **x size** text field, type `n_x`.

6 In the **y size** text field, type `n_y`.

7 Locate the **Displacement** section. In the **x** text field, type `D_opc+dist_x`.

8 In the **y** text field, type `D_opc+dist_x`.

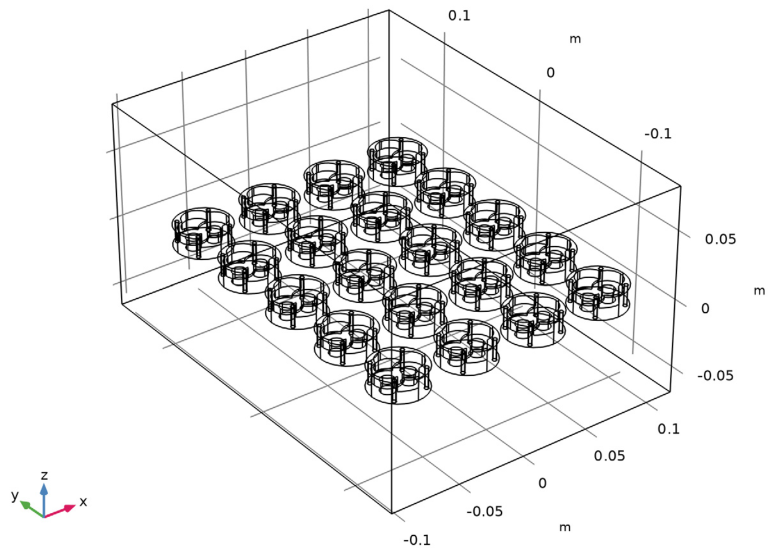
9 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

10 From the **Show in physics** list, choose **Boundary selection**.

11 Click **Build Selected**.

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

The geometry of an array of oil pump covers should look like this:



Cylinder Selection 1 (cylsel1)

One can displace a particular oil pump cover making use of cylinder selection.

1 In the **Geometry** toolbar, click **Selections** and choose **Cylinder Selection**.
2 In the **Settings** window for **Cylinder Selection**, locate the **Geometric Entity Level** section.
3 From the **Level** list, choose **Object**.
4 Locate the **Input Entities** section. From the **Entities** list, choose **From selections**.
5 Click **Add**.
6 In the **Add** dialog, select **Array 1** in the **Selections** list.
7 Click **OK**.
8 In the **Settings** window for **Cylinder Selection**, locate the **Size and Shape** section.
9 In the **Outer radius** text field, type `D_opc/2`.
10 Locate the **Position** section. In the **x** text field, type `-(n_x*D_opc+(n_x+1)*dist_x)/2+floor(part_in)*(dist_x+D_opc)-D_opc/2`.
11 In the **y** text field, type `-(n_y*D_opc+(n_y+1)*dist_y)/2+((part_in-floor(part_in))*10)*(dist_y+D_opc)-D_opc/1.25`.

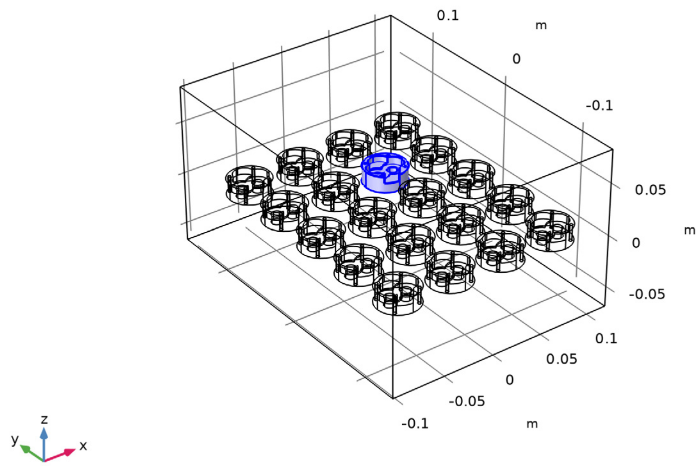
Move 1 (mov1)

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

2 In the **Settings** window for **Move**, locate the **Input** section.

3 From the **Input objects** list, choose **Cylinder Selection 1**.

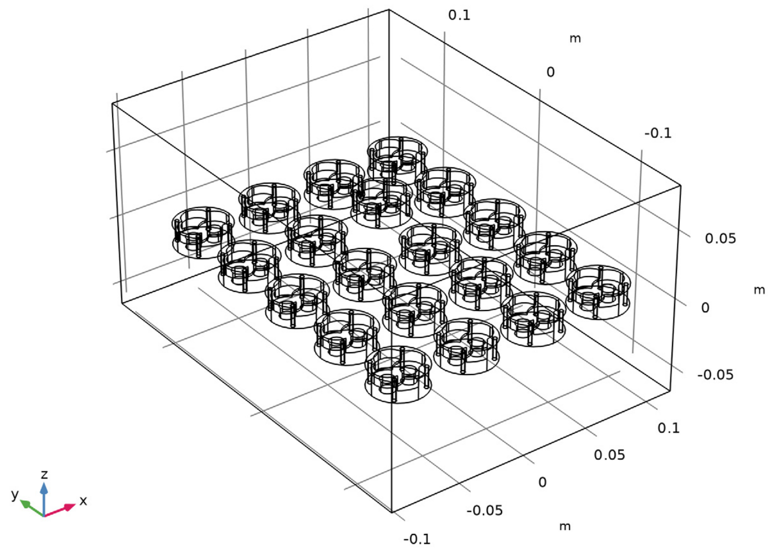
The oil pump cover to be displaced is highlighted below:



4 Locate the **Displacement** section. In the **z** text field, type `z_out`.

5 Click **Build Selected**.

The geometry of an array of oil pump covers should look like this:



Rotate 1 (rot1)

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

2 In the **Settings** window for **Rotate**, locate the **Input** section.

3 From the **Input objects** list, choose **Array 1**.

4 Click in the **Graphics** window and then press Ctrl+A to select all objects.

5 Locate the **Rotation** section. From the **Axis type** list, choose **x-axis**.

6 In the **Angle** text field, type `90`.

7 Click **Build Selected**.

The final geometry should look like this: