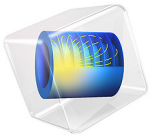

Model created in COMSOL Multiphysics 6.4

Aperture Shape Optimization for Electroplating of a Printed Circuit Board

Introduction

A printed circuit board (PCB) is the heart of almost any electronic product, carrying the components and copper wires supporting its functionality. This tutorial demonstrates how to simulate copper deposition on a PCB using the **Secondary Current Distribution** and **Shape Optimization** interfaces.

An aperture is typically used in the electroplating bath in order to achieve uniform deposition thickness across the PCB. The size and aspect ratio of the aperture are optimized using the **Transformation** feature in the **Shape Optimization** interface.

The PCB pattern in this example is defined by imported ECAD files.

Note: This model requires ECAD Import Module and Optimization Module licenses.

Model Definition

Figure 1 shows the model geometry.

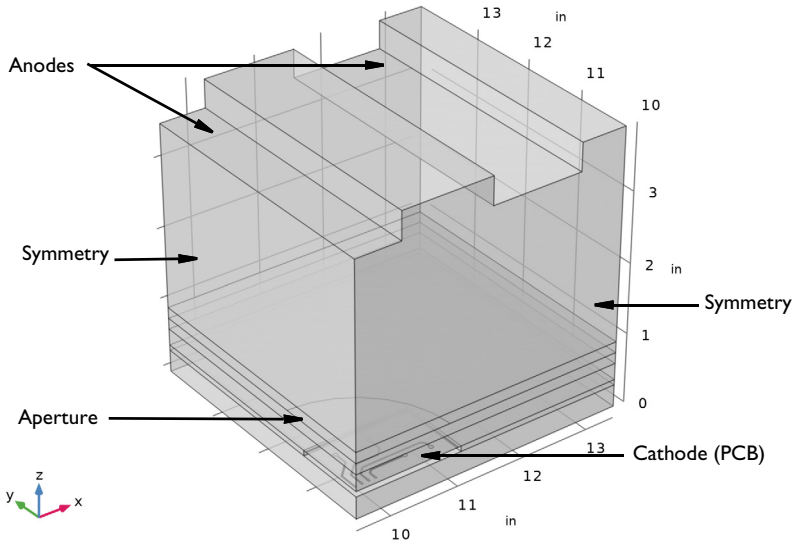

Figure 1: Model geometry.

The anodes are a set of stretched blocks at the top of the geometry. The cathode is the PCB pattern located at the bottom-center of the electroplating bath. An isolating screen with an aperture is placed between the anodes and the cathode to control the current distribution on the PCB. Due to mirror symmetry, only one-fourth of the actual geometry is used in the model.

CHARGE TRANSPORT

The model uses the **Secondary Current Distribution** interface to simulate the current distribution in the electroplating bath. It solves for the electrolyte potential, ϕ_l (V), according to

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

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

The default Insulation condition is used 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 copper deposition/dissolution reaction

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

A **Butler–Volmer** kinetics is used to model copper dissolution and deposition at the anode and cathode surfaces, respectively, which sets the local current density to

$$i_{\mathrm{loc}} = i_0\left(\exp\left(\frac{\alpha_a F\eta}{RT}\right) - \exp\left(-\frac{\alpha_c F\eta}{RT}\right)\right)$$

Note that the local current density is positive at the anode surface and negative at the cathode surfaces, depending on the sign of the overpotential, η (V), defined as

$$\eta = \phi_s - \phi_l - E_{\mathrm{eq}} \tag{1}$$

where E_{eq} (V) is the equilibrium potential of the copper dissolution/deposition reaction and ϕ_s (V) is the potential of the electronic phase of the electrode.

On both the anode and the cathode surfaces, the electrolyte current density is set to the local current density of the copper deposition reaction:

$$\mathbf{n} \cdot \mathbf{i}_l = i_{\text{loc}} \tag{2}$$

The anode is grounded in the model whereas the cathode electric potential is solved for by an additional equation in order to fulfill a total current condition on the boundary according to

$$\int i_{\text{loc}} = I_{\text{total}} = I_{\text{avg}} A_{\text{cathode}} \tag{3}$$

The **Thin Electrolyte Layer** feature is used at the isolating screen. The **Symmetry** boundary condition is set at the appropriate boundaries

The model is solved using a stationary study.

When processing the results of the computation, the deposition thickness, s (m), at the PCB is calculated according to

$$s = \frac{i_{\text{loc}}}{I_{\text{avg}}} s_{\text{target}} \tag{4}$$

where s_{target} (m) is the target mean deposition thickness for the whole cathode.

The time needed to achieve this thickness, t_{dep} (m), is related to s_{target} as

$$t_{\text{dep}} = s_{\text{target}} \frac{nF}{I_{\text{avg}}} \frac{\rho}{M} \tag{5}$$

where M is the mean molar mass (63.55 g/mol) and ρ is the density (8960 kg/m^3) of the copper atoms and n (= 2) is the number of participating electrons.

SHAPE OPTIMIZATION

The shape optimization problem is set up using the **Free Shape Domain**, **Symmetry/Roller**, and **Transformation** features. The aperture shape and size optimization is performed over a narrow domain next to the aperture using the **Free Shape Domain** feature. The **Transformation** feature is used at the aperture to allow anisotropic scaling in the x and y directions. The **Symmetry/Roller** feature is set at all boundaries of the **Free Shape Domain** feature except the aperture. The objective function at the **Shape Optimization** study node is set using a **P-norm** feature, which is defined in terms of the normalized current density over the PCB cathode boundaries.

Results and Discussion

Figure 2 shows the initial and shape-optimized aperture along with deposition thickness across the PCB. The deposition is found to be fairly uniform with the shape-optimized aperture. The aperture size is reduced in order to get uniform deposition across the PCB. The aspect ratio of the aperture is changed from circular to ellipsoidal after shape optimization.

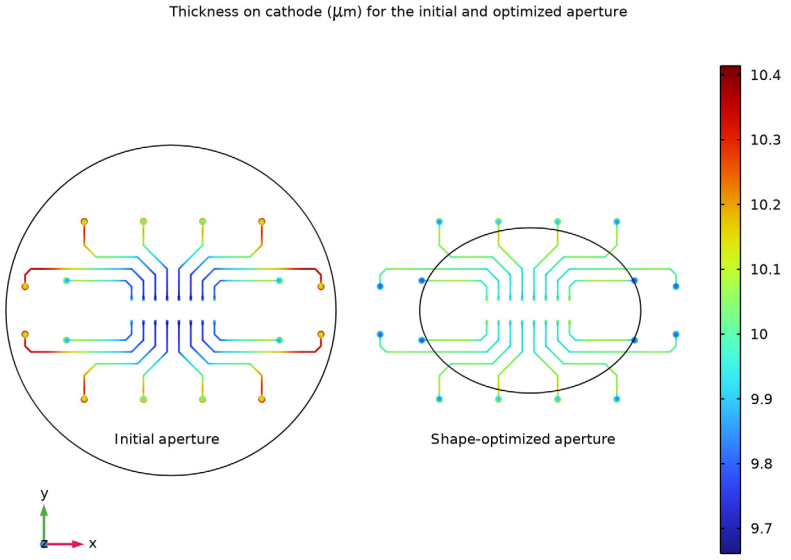

Figure 2: Initial and shape-optimized aperture along with deposition thickness across the PCB.

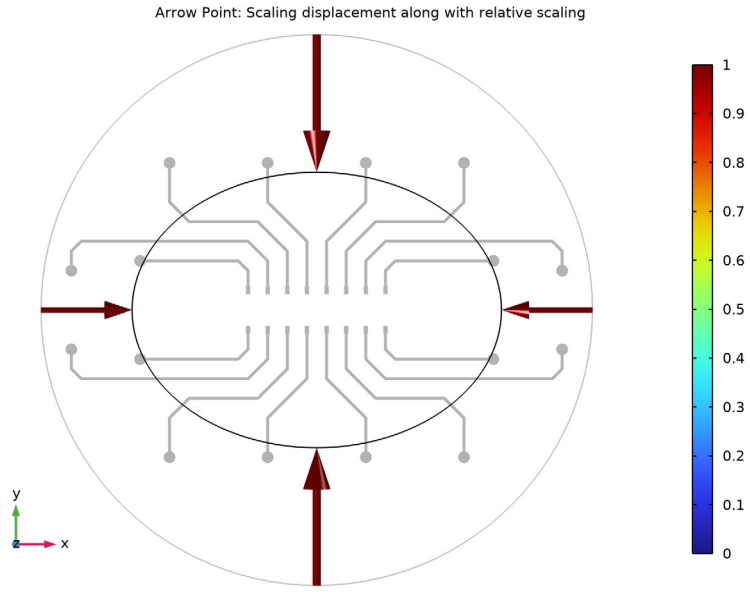

Figure 3: Initial and shape-optimized aperture along with the scaling displacement and relative scaling.

Figure 3 shows the initial and shape-optimized aperture along with the PCB scaling displacement, and relative scaling. The arrows in Figure 3 indicate the scaling displacement in the x and y directions along with the magnitude of relative scaling. The scaling displacement is found to be more in alignment with the y direction than with the x direction, which is expected considering the PCB size. The magnitude of the relative scaling is also found to be well within the lower and upper bounds set at the **Transformation** feature.

Application Library path: `Electrodeposition_Module/Tutorials/pcb_aperture_optimization`

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 In the **Select Physics** tree, select **Mathematics** > **Optimization and Sensitivity** > **Shape Optimization**.

5 Click **Add**.

6 Click **Study**.

7 In the **Select Study** tree, select **General Studies** > **Stationary**.

8 Click **Done**.

GLOBAL DEFINITIONS

Load parameters from a 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 `pcb_aperture_optimization_parameters.txt`.

GEOMETRY 1

This model utilizes a premade geometry file containing a PCB pattern imported from an ECAD file. 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 `pcb_aperture_optimization_geom_sequence.mph`.

3 In the **Geometry** toolbar, click **Build All**.

Use the transparency button to see the entire geometry clearly.

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

Disable the analysis of the geometry as the remaining small geometric details are needed.

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

6 In the **Settings** window for **Geometry**, locate the **Cleanup** section.

7 Clear the **Automatic detection of small details** checkbox.

8 In the **Geometry** toolbar, click **Build All**.

DEFINITIONS

Add an integration coupling variable, load variables from a text file and add a P-norm node.

Integration 1 (intop1)

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 **Cathode**.

Variables 1

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

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 `pcb_aperture_optimization_variables.txt`.

P-Norm 1 (pnorm1)

1 In the **Definitions** toolbar, click **Physics Utilities** and choose **P-Norm**.

2 In the **Settings** window for **P-Norm**, locate the **Geometric Entity Selection** section.

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

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

5 Locate the **P-Norm** section. In the a text field, type `cd.itot/i_avg-1`.

6 From the p list, choose **2**.

MATERIALS

Add a material to specify the electrolyte conductivity.

Electrolyte

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Electrolyte` in the **Label** text field.

3 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Electrolyte conductivity	sigmal_iso ; sigmalii = sigmal_iso, sigmalij = 0	50	S/m	Electrolyte conductivity

SECONDARY CURRENT DISTRIBUTION (CD)

Define the physics settings in the Secondary Current Distribution interface.

Electrode Surface 1

1 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 **Cathode**.

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

5 In the $I_{l,total}$ text field, type `-ItotCathode`.

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 **Butler–Volmer**.

4 In the i_0 text field, type `i0`.

5 In the α_a text field, type `alphaa`.

Electrode Surface 2

1 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 **Anode**.

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 **Butler–Volmer**.

4 In the i_0 text field, type `i0`.

5 In the α_a text field, type `alphaa`.

Thin Electrolyte Layer 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Thin Electrolyte Layer**.

2 Select Boundary 46 only.

Symmetry 1

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

2 Select Boundaries 1, 2, 4–6, 9, 10, 15, 30, 39, 40, 42, and 43 only.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the *phil* text field, type `phil_initial`.

SHAPE OPTIMIZATION

The Shape Optimization is solved over a narrow domain next to the aperture. Also, set symmetry and the scaling using the Transformation node.

Free Shape Domain 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Shape Optimization** click **Free Shape Domain 1**.

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

3 From the **Selection** list, choose **Free Shape Domain**.

Symmetry/Roller 1

1 In the **Shape Optimization** toolbar, click **Symmetry/Roller**.

2 In the **Settings** window for **Symmetry/Roller**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **All boundaries**.

Transformation 1

1 In the **Shape Optimization** toolbar, click **Transformation**.

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

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

4 From the **Selection** list, choose **Transformation Boundary**.

5 Locate the **Translation** section. In the table, select the **Lock** checkbox for **X**.

6 From the **Translation type** list, choose **Fixed**.

7 Locate the **Scaling** section. From the **Scaling type** list, choose **Anisotropic**.

8 In the table, enter the following settings:

	Lock	Lower bound	Upper bound
X		0.5	1.5
Y		0.5	1.5

9 Click to expand the **Center of Scaling and Rotation** section. In the table, enter the following settings:

Coordinates	Center type	Center of scaling and rotation (m)
Xg	Minimum	0
Yg	Minimum	0

MESH 1

Generate the mesh as follows.

Free Triangular 1

In the **Mesh** toolbar, click **More Generators** and choose **Free Triangular**.

Size

1 In the **Model Builder** window, click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Fine**.

Free Triangular 1

1 In the **Model Builder** window, click **Free Triangular 1**.

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

3 From the **Selection** list, choose **Cathode**.

Size 1

1 Right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extra fine**.

Swept 1

1 In the **Mesh** toolbar, click **Swept**.

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

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

4 From the **Selection** list, choose **Electrolyte Swept Mesh Regions**.

5 Click to expand the **Source Faces** section. Click **Paste Selection**.

6 In the **Paste Selection** dialog, type 9 in the **Selection** text field.

7 Click **OK**.

8 In the **Settings** window for **Swept**, locate the **Mesh Generation** section.

9 From the **Elements** list, choose **Prisms**.

Size 1

1 Right-click **Swept 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 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type 9 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**.

Distribution 1

1 In the **Model Builder** window, right-click **Swept 1** and choose **Distribution**.

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

3 In the **Number of elements** text field, type 2.

Distribution 2

1 Right-click **Swept 1** and choose **Distribution**.

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

3 From the **Selection** list, choose **Electrolyte Swept Mesh Region 2**.

Free Triangular 2

1 In the **Mesh** toolbar, click **More Generators** and choose **Free Triangular**.

2 Select Boundary 46 only.

Size 1

1 Right-click **Free Triangular 2** and choose **Size**.

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

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

4 From the **Selection** list, choose **Transformation Edge**.

5 Locate the **Element Size** section. From the **Predefined** list, choose **Extremely fine**.

Swept 2

1 In the **Mesh** toolbar, click **Swept**.

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

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

4 From the **Selection** list, choose **Free Shape Domain**.

Size 1

1 Right-click **Swept 2** 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 Boundaries 44 and 46 only.

5 Locate the **Element Size** section. From the **Predefined** list, choose **Extra fine**.

Distribution 1

In the **Model Builder** window, right-click **Swept 2** and choose **Distribution**.

Free Tetrahedral 1

1 In the **Mesh** toolbar, click **Free Tetrahedral**.

2 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

STUDY 1

Next, add **Shape Optimization** study node.

Shape Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Shape Optimization**.

2 Click **Get Initial Value**.

3 In the **Model Builder** window, click **Shape Optimization**.

4 In the **Settings** window for **Shape Optimization**, locate the **Optimization Solver** section.

5 In the **Move limits** text field, type `0.2`.

6 Locate the **Objective Function** section. In the table, enter the following settings:

Expression	Description
`comp1.pnorm1`	`P-norm`

7 Find the **Objective settings** subsection. From the **Objective scaling** list, choose **Initial solution based**.

8 Click to expand the **Output** section. From the **Keep solutions** list, choose **First and last**.

9 Select the **Plot** checkbox.

10 In the table, enter the following settings:

Plot group	Plot window
Shape Optimization	Graphics

11 Click the **Go to XY View** button in the **Graphics** toolbar.

Step 1: Stationary

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

2 In the **Settings** window for **Stationary**, locate the **Study Settings** section.

3 From the **Tolerance** list, choose **User controlled**.

4 In the **Relative tolerance** text field, type `1e-6`.

Finally, compute the results.

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

RESULTS

First, create mirror data sets and then plot the thickness on the cathode copper layout along with the initial aperture and then with the shape-optimized aperture.

Mirror 3D 1

1 In the **Model Builder** window, expand the **Results** > **Datasets** node.

2 Right-click **Results** > **Datasets** and choose **More 3D Datasets** > **Mirror 3D**.

3 In the **Settings** window for **Mirror 3D**, locate the **Plane Data** section.

4 In the **X-coordinate** text field, type `9.5`.

Mirror 3D 2

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 3D**.

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

3 From the **Dataset** list, choose **Mirror 3D 1**.

4 Locate the **Plane Data** section. From the **Plane** list, choose **xz-planes**.

5 In the **y-coordinate** text field, type `10`.

Thickness on Cathode and Aperture Shapes

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

2 In the **Settings** window for **3D Plot Group**, type `Thickness on Cathode and Aperture Shapes` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 3D 2**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Thickness on cathode (\mu m) for the initial and optimized aperture`.

6 Clear the **Parameter indicator** text field.

Surface 1

1 In the **Thickness on Cathode and Aperture Shapes** 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**.

Selection 1

1 In the **Thickness on Cathode and Aperture Shapes** toolbar, click **Selection**.

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

3 From the **Selection** list, choose **Cathode**.

Thickness on Cathode and Aperture Shapes

In the **Model Builder** window, under **Results** click **Thickness on Cathode and Aperture Shapes**.

Line 1

1 In the **Thickness on Cathode and Aperture Shapes** toolbar, click **Line**.

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

3 In the **Expression** text field, type `1`.

4 Select the **Description** checkbox. In the associated text field, type `Optimized Aperture Shape`.

5 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

6 Select the **Radius scale factor** checkbox. In the associated text field, type `0.005`.

7 From the **Coloring** list, choose **Uniform**.

8 From the **Color** list, choose **Black**.

Selection 1

1 In the **Thickness on Cathode and Aperture Shapes** toolbar, click **Selection**.

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

3 From the **Selection** list, choose **Transformation Edge**.

Thickness on Cathode and Aperture Shapes

In the **Model Builder** window, under **Results** click **Thickness on Cathode and Aperture Shapes**.

Annotation 1

1 In the **Thickness on Cathode and Aperture Shapes** toolbar, click **Annotation**.

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

3 In the **Text** text field, type `Shape-optimized aperture`.

4 Locate the **Position** section. In the **x** text field, type `8.6`.

5 In the **y** text field, type `9`.

6 Locate the **Coloring and Style** section. Clear the **Show point** checkbox.

Thickness on Cathode and Aperture Shapes

1 In the **Model Builder** window, click **Thickness on Cathode and Aperture Shapes**.

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

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

Surface 2

1 In the **Model Builder** window, under **Results** > **Thickness on Cathode and Aperture Shapes** right-click **Surface 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Mirror 3D 2**.

4 From the **Optimization solution** list, choose **0**.

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

6 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Transformation 1

1 Right-click **Surface 2** and choose **Transformation**.

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

3 In the **x** text field, type `-3`.

Line 2

1 In the **Model Builder** window, under **Results** > **Thickness on Cathode and Aperture Shapes** right-click **Line 1** and choose **Duplicate**.

2 In the **Settings** window for **Line**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 3D 2**.

4 From the **Optimization solution** list, choose **0**.

5 Locate the **Expression** section. In the **Description** text field, type `Initial Aperture Shape`.

6 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Line 1**.

Transformation 1

1 Right-click **Line 2** and choose **Transformation**.

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

3 In the **x** text field, type `-3`.

Annotation 2

1 In the **Model Builder** window, under **Results** > **Thickness on Cathode and Aperture Shapes** right-click **Annotation 1** and choose **Duplicate**.

2 In the **Settings** window for **Annotation**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 3D 2**.

4 From the **Optimization solution** list, choose **0**.

5 Locate the **Annotation** section. In the **Text** text field, type `Initial aperture`.

6 Locate the **Position** section. In the **x** text field, type `5.9`.

Thickness on Cathode and Aperture Shapes

1 Click the  **Go to XY View** button in the **Graphics** toolbar.

2 Click the  **Show Grid** button in the **Graphics** toolbar.

3 In the **Model Builder** window, click **Thickness on Cathode and Aperture Shapes**.

4 In the **Thickness on Cathode and Aperture Shapes** toolbar, click  **Plot**.

Shape Optimization

Next, edit the default Shape Optimization plot which shows the transformation of the aperture from the initial size to the optimized size.

1 In the **Model Builder** window, click **Shape Optimization**.

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

3 From the **Dataset** list, choose **Mirror 3D 2**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Arrow Point: Scaling displacement along with relative scaling`.

6 Click the  **Go to Default View** button in the **Graphics** toolbar.

7 Click the **Go to XY View** button in the **Graphics** toolbar.

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

Selection 1

1 In the **Model Builder** window, expand the **Shape Optimization** node.

2 Right-click **Line 1** and choose **Selection**.

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

4 From the **Selection** list, choose **Transformation Edge**.

Surface 1

1 In the **Model Builder** window, right-click **Shape Optimization** and choose **Surface**.

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

3 In the **Expression** text field, type 1.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Cathode**.

Line 2

1 In the **Model Builder** window, under **Results** > **Shape Optimization** right-click **Line 1** and choose **Duplicate**.

2 In the **Model Builder** window, click **Line 2**.

3 In the **Settings** window for **Line**, locate the **Data** section.

4 From the **Dataset** list, choose **Mirror 3D 2**.

5 From the **Optimization solution** list, choose **0**.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Gray**.

Shape Optimization

1 In the **Model Builder** window, click **Shape Optimization**.

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

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

4 In the **Shape Optimization** toolbar, click **Plot**.

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

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 `pcb_aperture_optimization_geom_sequence_parameters.txt`.

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **in**.

PCB

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

2 In the **Settings** window for **Block**, type `PCB` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `PCBWidth+2*PCBMargin`.

4 In the **Depth** text field, type `PCBHeight+2*PCBMargin`.

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

6 Locate the **Position** section. In the **x** text field, type `PCBxMin-PCBMargin`.

7 In the **y** text field, type `PCByMin-PCBMargin`.

8 In the **z** text field, type `PCBOffset-PCBThickness`.

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

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

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 `PCBOffset`.

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

5 In the **New Cumulative Selection** dialog, type `PCB copper layout` in the **Name** text field.

6 Click **OK**.

7 In the **Settings** window for **Work Plane**, click **Go to Plane Geometry**.

Work Plane 1 (wp1) > Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.

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

3 Click **Browse**.

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

5 Click **Import**.

6 Locate the **Layers** section. In the table, clear the **Import** checkbox for **Dielectric**.

GEOMETRY 1

Work Plane 1 (wp1)

In the **Model Builder** window, collapse the **Component 1 (comp1)** > **Geometry 1** > **Work Plane 1 (wp1)** node.

Rim

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Selections** > **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Rim` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

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

5 On the object **wp1**, select Boundary 1 only.

6 Click **Build Selected**.

Cathode

1 In the **Geometry** toolbar, click **Selections** and choose **Difference Selection**.

2 In the **Settings** window for **Difference Selection**, locate the **Geometric Entity Level** section.

3 From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click the **Add** button for **Selections to add**.

5 In the **Add** dialog, select **PCB copper layout** in the **Selections to add** list.

6 Click **OK**.

7 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.

8 Click the **Add** button for **Selections to subtract**.

9 In the **Add** dialog, select **Rim** in the **Selections to subtract** list.

10 Click **OK**.

11 In the **Settings** window for **Difference Selection**, type `Cathode` in the **Label** text field.

12 Click **Build Selected**.

Bath

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

2 In the **Settings** window for **Block**, type `Bath` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `BathWidth`.

4 In the **Depth** text field, type `BathHeight`.

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

6 Locate the **Position** section. In the **x** text field, type `PCBxMin-(BathWidth-PCBWidth)/2`.

7 In the **y** text field, type `PCByMin-(BathHeight-PCBHeight)/2`.

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

Electrolyte Swept Mesh Region 1

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

2 In the **Settings** window for **Block**, type `Electrolyte Swept Mesh Region 1` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `BathWidth`.

4 In the **Depth** text field, type `BathHeight`.

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

6 Locate the **Position** section. In the **x** text field, type `PCBxMin-(BathWidth-PCBWidth)/2`.

7 In the **y** text field, type `PCByMin-(BathHeight-PCBHeight)/2`.

8 In the **z** text field, type `PCBOffset-PCBThickness`.

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

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 From the **Plane type** list, choose **Face parallel**.

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

5 On the object **blk2**, select Boundary 4 only.

6 Click  **Go to Plane Geometry**.

Work Plane 2 (wp2) > 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 `BathWidth/6`.

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

5 Locate the **Position** section. In the **xw** text field, type `-BathWidth/2+BathWidth/6/2`.

6 In the **yw** text field, type `-BathHeight/2`.

Work Plane 2 (wp2) > Array 1 (arr1)

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

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

3 Select the object **r1** only.

4 In the **Model Builder** window, click **Array 1 (arr1)**.

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

6 In the **xw size** text field, type `3`.

7 Locate the **Displacement** section. In the **xw** text field, type `BathWidth/3`.

GEOMETRY 1

Work Plane 2 (wp2)

In the **Model Builder** window, collapse the **Component 1 (comp1)** > **Geometry 1** > **Work Plane 2 (wp2)** node.

Anode

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

2 In the **Settings** window for **Extrude**, type `Anode` in the **Label** text field.

3 Locate the **Distances** section. In the table, enter the following settings:

Distances (in)
`AnodeThickness`

4 Select the **Reverse direction** checkbox.

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

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

Difference 1 (dif1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Booleans and Partitions** > **Difference**.

2 Select the objects **blk2** and **blk3** 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 From the **Objects to subtract** list, choose **PCB**.

6 Select the objects **blk1** and **ext1** only.

Work Plane 3 (wp3)

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 `ApertureOffset+PCBOffset-4*ApertureThickness`.

4 Click **Go to Plane Geometry**.

Work Plane 3 (wp3) > Cross Section 1 (cro1)

1 In the **Work Plane** toolbar, click **Cross Section**.

2 In the **Settings** window for **Cross Section**, locate the **Cross Section** section.

3 From the **Intersect** list, choose **Selected objects**.

4 From the **Objects to intersect** list, choose **Bath**.

GEOMETRY 1

Work Plane 3 (wp3)

1 In the **Model Builder** window, collapse the **Component 1 (comp1)** > **Geometry 1** > **Work Plane 3 (wp3)** node.

2 In the **Model Builder** window, click **Work Plane 3 (wp3)**.

3 In the **Settings** window for **Work Plane**, click **Build Selected**.

Extrude 2 (ext2)

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 (in)
`8*ApertureThickness`

4 Click **Build Selected**.

Aperture Source

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

2 In the **Settings** window for **Work Plane**, type `Aperture Source` in the **Label** text field.

3 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `ApertureOffset+PCBOffset`.

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

5 Click **Go to Plane Geometry**.

Aperture Source (wp4) > 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 `BathWidth`.

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

5 Locate the **Position** section. In the **xw** text field, type `PCBxMin-(BathWidth-PCBWidth)/2`.

6 In the **yw** text field, type `PCByMin-(BathHeight-PCBHeight)/2`.

Aperture Source (wp4) > 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 `ApertureRadius`.

4 Locate the **Position** section. In the **xw** text field, type `9.5`.

5 In the **yw** text field, type `10`.

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

Edges Adjacent to Circle

1 In the **Work Plane** toolbar, click **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, type `Edges Adjacent to Circle` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Add**.

4 In the **Add** dialog, select **Circle 1** in the **Input selections** list.

5 Click **OK**.

Aperture Source (wp4)

1 In the **Model Builder** window, collapse the **Component 1 (comp1)** > **Geometry 1** > **Aperture Source (wp4)** node.

2 In the **Model Builder** window, click **Aperture Source (wp4)**.

3 In the **Settings** window for **Work Plane**, click **Build Selected**.

Difference 2 (dif2)

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

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

3 Click the **Paste Selection** button for **Objects to add**.

4 In the **Paste Selection** dialog, type `dif1,wp1` in the **Selection** text field.

5 Click **OK**.

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

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

8 Click the **Paste Selection** button for **Objects to subtract**.

9 In the **Paste Selection** dialog, type `ext2,wp4` in the **Selection** text field.

10 Click **OK**.

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

12 Select the **Keep objects to subtract** checkbox.

Union 1 (uni1)

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

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

3 Click the  **Paste Selection** button for **Input objects**.

4 In the **Paste Selection** dialog, type `ext2,wp4` in the **Selection** text field.

5 Click **OK**.

Work Plane 5 (wp5)

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**.

4 In the **x-coordinate** text field, type `PCBxMin-(BathWidth-PCBWidth)/2+BathWidth/2`.

5 In the **Model Builder** window, collapse the **Work Plane 5 (wp5)** node.

Work Plane 6 (wp6)

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 **zx-plane**.

4 In the **y-coordinate** text field, type `PCByMin-(BathHeight-PCBHeight)/2+BathHeight/2`.

5 In the **Model Builder** window, collapse the **Work Plane 6 (wp6)** node.

Partition Domains 1 (pard1)

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

2 In the **Settings** window for **Partition Domains**, locate the **Partition Domains** section.

3 From the **Work plane** list, choose **Work Plane 5 (wp5)**.

4 On the object **dif2**, select Domains 1–4 only.

5 On the object **uni1**, select Domains 1 and 2 only.

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

7 Click  **Build Selected**.

Partition Domains 2 (pard2)

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

2 On the object **pard1(1)**, select Domains 1–8 only.

3 On the object **pard1(2)**, select Domains 1–4 only.

4 In the **Settings** window for **Partition Domains**, locate the **Selections of Resulting Entities** section.

5 Select the **Resulting objects selection** checkbox.

6 Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **PCB copper layout**.

7 Click **Build Selected**.

Delete Entities 1 (del1)

1 In the **Model Builder** window, right-click **Geometry 1** 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 Click the **Go to Default View** button in the **Graphics** toolbar.

5 On the object **pard2(1)**, select Domain 8 only.

6 Click the **Zoom Box** button in the **Graphics** toolbar.

7 On the object **pard2(1)**, select Domains 5–8 only.

8 On the object **pard2(2)**, select Domains 3 and 4 only.

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

10 On the object **pard2(1)**, select Domains 4–8 only.

11 On the object **pard2(2)**, select Domains 3 and 4 only.

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

13 On the object **pard2(1)**, select Domains 1–8 only.

14 On the object **pard2(2)**, select Domains 1–4 only.

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

16 On the object **pard2(1)**, select Domains 1–8 and 12 only.

17 On the object **pard2(2)**, select Domains 1–4 only.

18 Click the **Zoom Box** button in the **Graphics** toolbar.

19 On the object **pard2(1)**, select Domains 1–12 only.

20 On the object **pard2(2)**, select Domains 1–6 only.

21 Click **Build Selected**.

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

Form Union (fin)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.

3 From the **Action** list, choose **Form an assembly**.

4 In the **Geometry** toolbar, click **Build All**.

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

Create some selections for use when setting up the model.

Electrolyte Swept Mesh Region 2

1 In the **Geometry** toolbar, click **Selections** and choose **Box Selection**.

2 In the **Settings** window for **Box Selection**, type `Electrolyte Swept Mesh Region 2` in the **Label** text field.

3 Locate the **Box Limits** section. In the **z minimum** text field, type `0`.

4 In the **z maximum** text field, type `0`.

Electrolyte Swept Mesh Regions

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Electrolyte Swept Mesh Regions` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Add**.

4 In the **Add** dialog, in the **Selections to add** list, choose **Electrolyte Swept Mesh Region 1** and **Electrolyte Swept Mesh Region 2**.

5 Click **OK**.

6 In the **Settings** window for **Union Selection**, click **Build Selected**.

Free Shape Domain

1 In the **Geometry** toolbar, click **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, type `Free Shape Domain` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Click **Add**.

5 In the **Add** dialog, select **Circle 1 (Aperture Source)** in the **Input selections** list.

6 Click **OK**.

7 In the **Settings** window for **Adjacent Selection**, locate the **Output Entities** section.

8 From the **Geometric entity level** list, choose **Adjacent domains**.

Transformation Boundary

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Transformation Boundary` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog, select **Circle 1 (Aperture Source)** in the **Selections to add** list.

6 Click **OK**.

Transformation Edge

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Transformation Edge` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Edge**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog, select **Edges Adjacent to Circle (Aperture Source)** in the **Selections to add** list.

6 Click **OK**.

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