GUIDE TO MODELING AND MANUFACTURING COMPOSITE WIND TURBINE BLADES

CONTENTS

INTRODUCTION

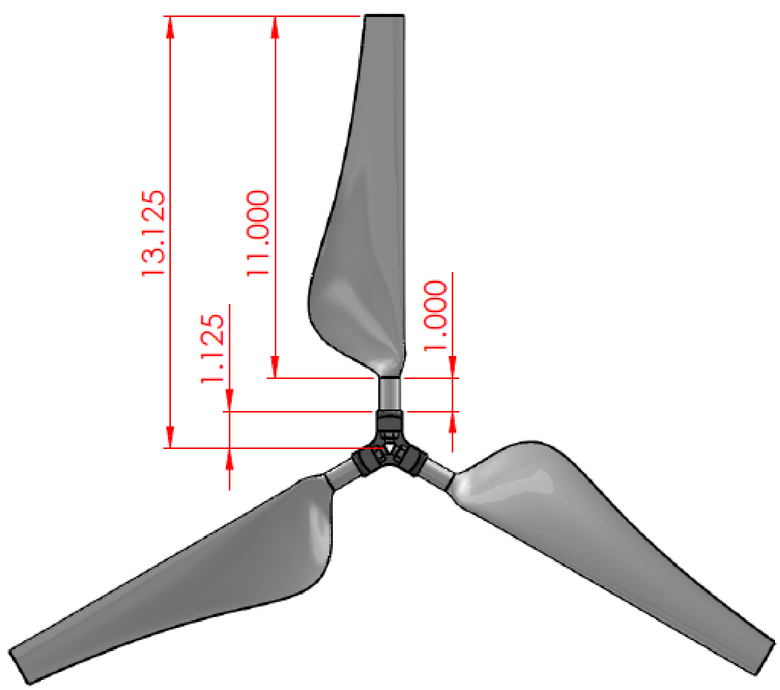
This guide is intended to walk you through the process of modeling your wind turbine blades using Solidworks, producing G-code using the demo of MecSoft VisualMill, casting wax blocks for the blade molds, machining your blade molds using the MaxNC CNC router located in the Emerson Lab, and using your molds to produce fiberglass blades. This guide assumes basic familiarity with Solidworks and machining terminology. Program and hardware specific terms have been **bolded** to aid clarity.

MODELING THE BLADE

BLADE DIMENSIONS

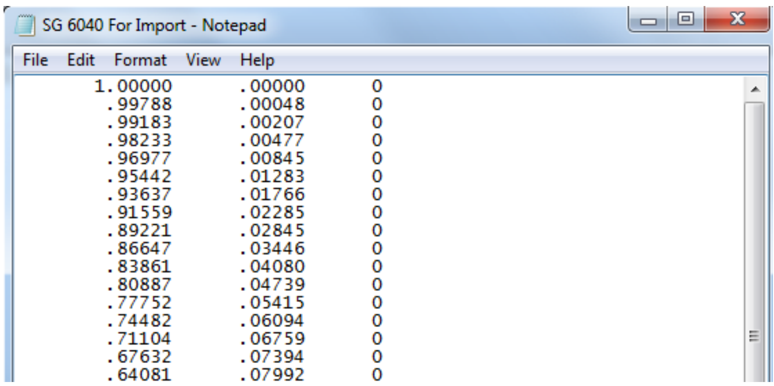
The diameter of the assembled rotor should be 26.25 inches. The rotor hub has a radius of 1.125 inches. A 1.5 inch long 0.5 inch diameter cylindrical aluminum insert will be bonded into the base of each blade to allow it to be attached to the blade hub. When assembled, a 0.5 inch long exposed section of an aluminum blade insert will protrude from your blades to allow the blades to be attached to the hub for testing. Each blade must incorporate a 1 inch long, 0.675 inch diameter cylindrical section of the blade root to allow bonding to the aluminum blade inserts. It is recommended that you leave 0.25 inch between the cylindrical blade root and your first defined airfoil to allow for a smooth transition between the cylindrical root and the first airfoil section. With a 0.25 inch transition, the aerodynamic surfaces of your blade would be 10.75 inches long.

Note: Be sure to account the fact that the aerodynamic surfaces do not begin at a radius of 0 inches and that the blade tip is located at a radius of 13.125 inches from the rotor center when simulating your blades in Matlab.

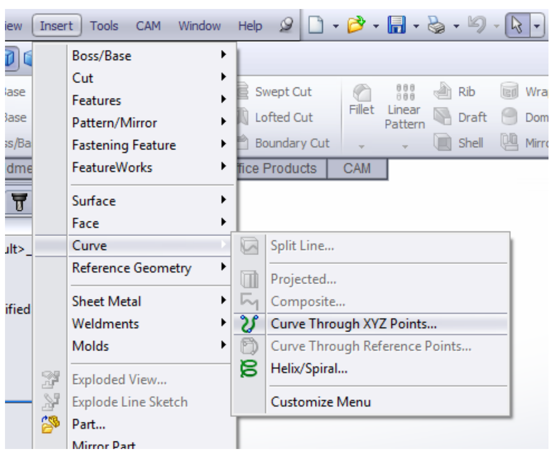


IMPORTING AIRFOIL COORDINATES

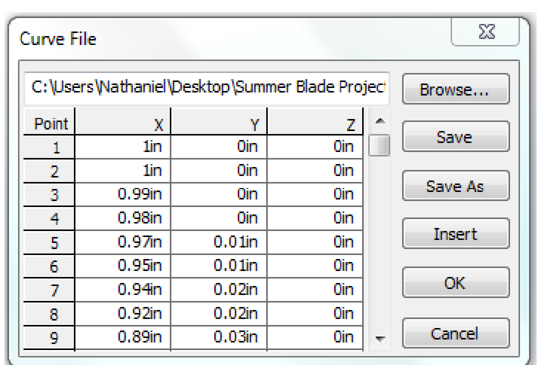
Create a **.txt** file containing the coordinates of your desired airfoil. The file must be a 3-column, tab or space delimited list containing X, Y, and Z coordinates (set all Z coordinates to "0"). The file cannot contain column headings or any other extra information. It is recommended that you scale your airfoil so that it has a chord length of 1 and position it so that the leading edge lies on (0,0,0). This will simplify later steps.



Once you have created the necessary .txt file of coordinates, create a new part in Solidworks and click **Insert>Curve>Curve Through XYZ Points…** to import the coordinates.



Click **Browse** and select your **.txt** file. Click **Save As** to save the coordinates as a **.sldcrv** file. Click **OK**.

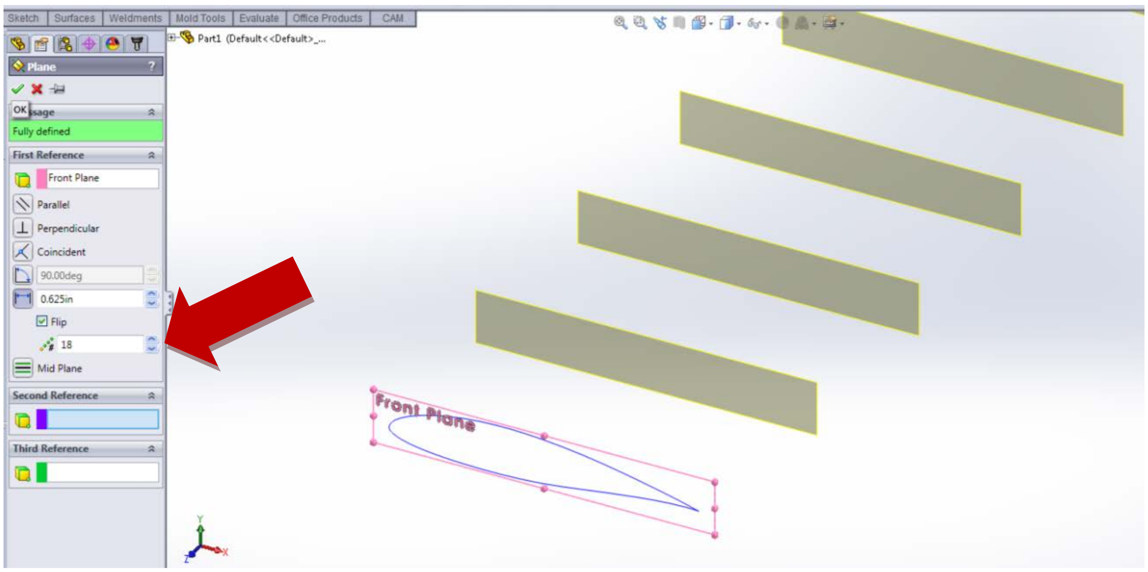


DEFINING BLADE GEOMETRY

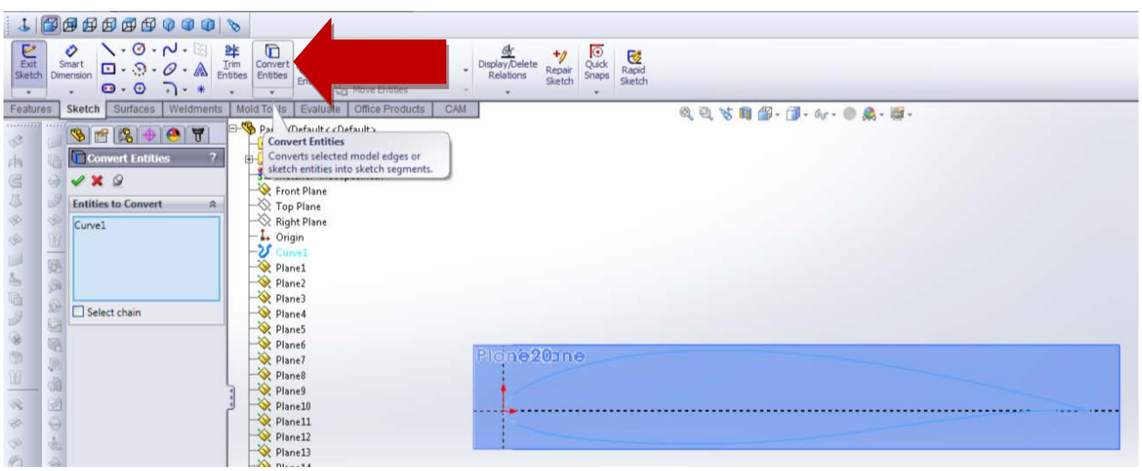
Solidworks will insert a **Curve** containing your airfoil into the part document. Assuming that you defined your coordinates so that the airfoil lies on the X-Y plane, the curve will be located on the **Front Plane**. Next, create a series of **Planes** on which you will define the cross section of the blade.

The spacing and number of these planes is up to you. However, the total length of your blade must be 12 inches. This includes a 1 inch long cylindrical blade root. It is recommended that you leave about 0.25 inches between the cylindrical blade root and your first defined airfoil to allow for a smooth transition between the root and the blade.

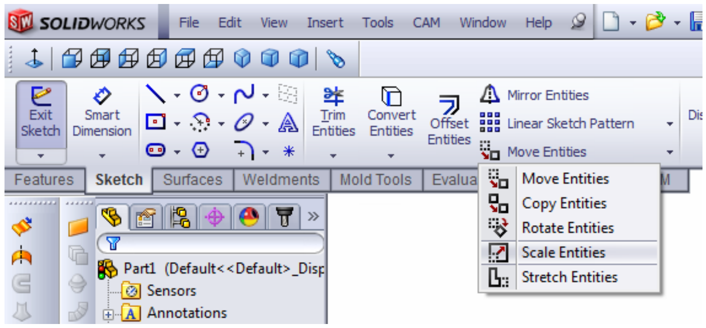
To create the **Planes**, on the **Features Toolbar** click **Reference Geometry>Plane**. Define **Planes** a set distance away from the **Front Plane**. If the Planes are evenly spaced apart, you can increase the **Number of Planes to Create** to automatically create a series of evenly spaced **Planes**.



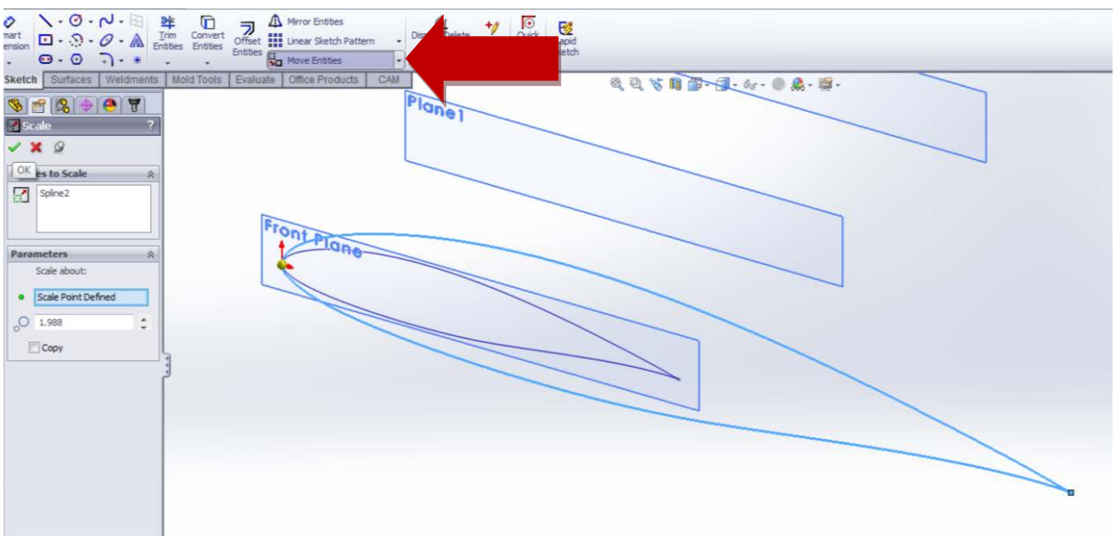
Create a **Sketch** on the **Front Plane**. Use the **Convert Entities** tool to project the airfoil **Curve** onto the **Front Plane**.



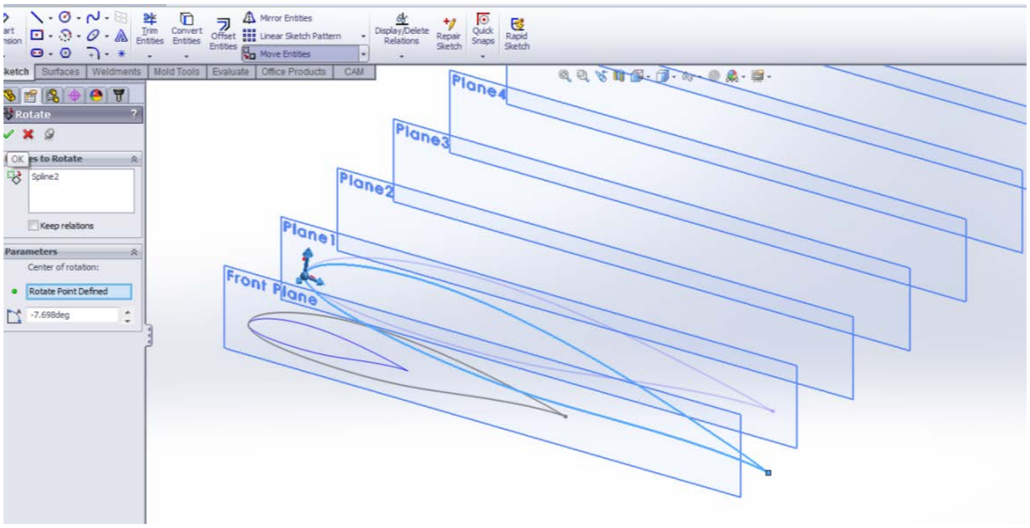
The **Sketch** now contains the airfoil, but the angle and size of the airfoil needs to be adjusted. In the **Sketch Toolbar**, click **Move Entities> Scale Entities**.



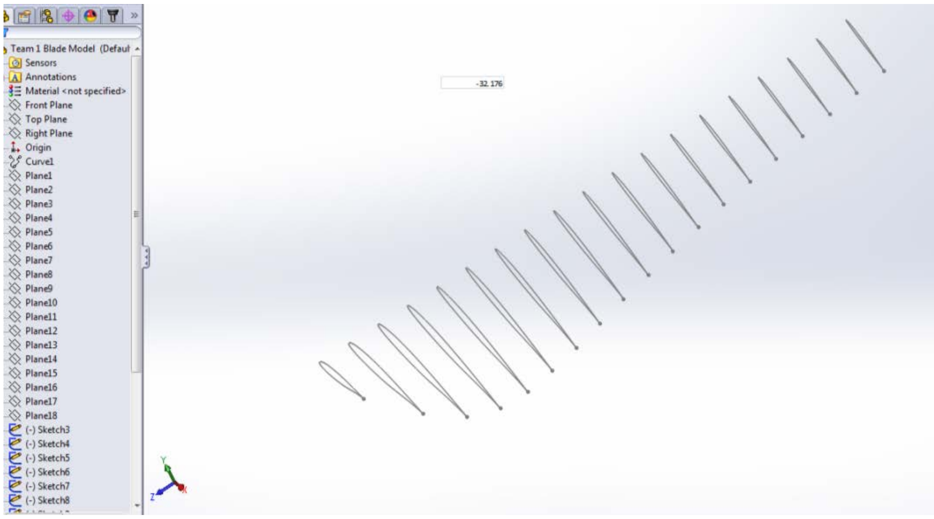
Select the **Origin** as the **Scale Point**. If your original coordinates positioned the leading edge of the airfoil at the **Origin**, this will **Scale** the airfoil around the leading edge. This will appropriately **Scale** the airfoil, assuming that you desire that your blade have a linear leading edge. Adjust the **Scale** to produce the desired airfoil chord length at this point.



Repeat the process for the next **Plane**. Create a **Sketch** on that **Plane**, use **Convert Entities** to project the **Curve** onto the **Plane**, and use the **Scale** tool to **Scale** the airfoil. Now in the **Sketch Toolbar**, click **Move Entities> Rotate Entities**. Select the **Origin** as the **Rotate Point**. Adjust the angle of the airfoil to position it relative to the first airfoil on the **Front Plane**.

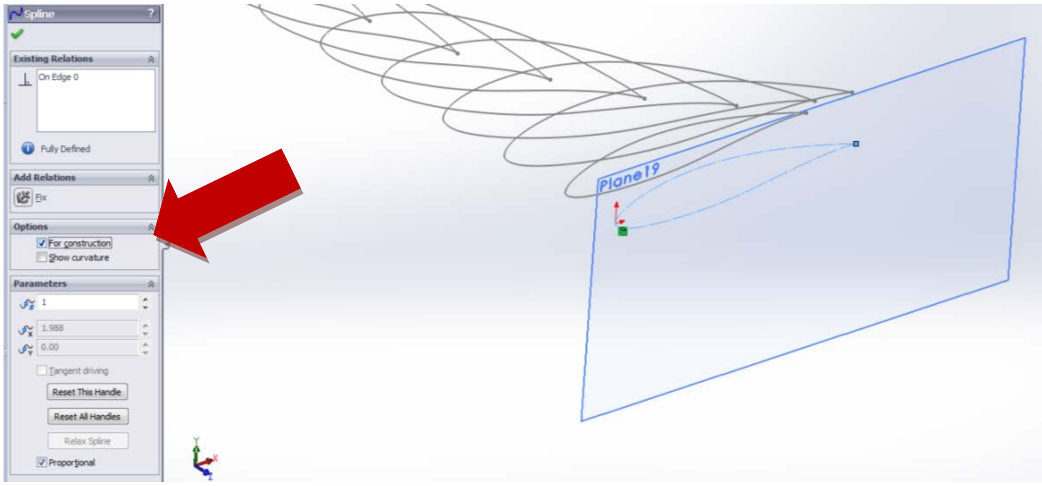


Repeat this process for the remaining Planes to fully define the geometry of your blade. You can select the **Planes** in the **Design Tree**, right click them, and click the sunglasses icon to hide the **Planes** if desired.

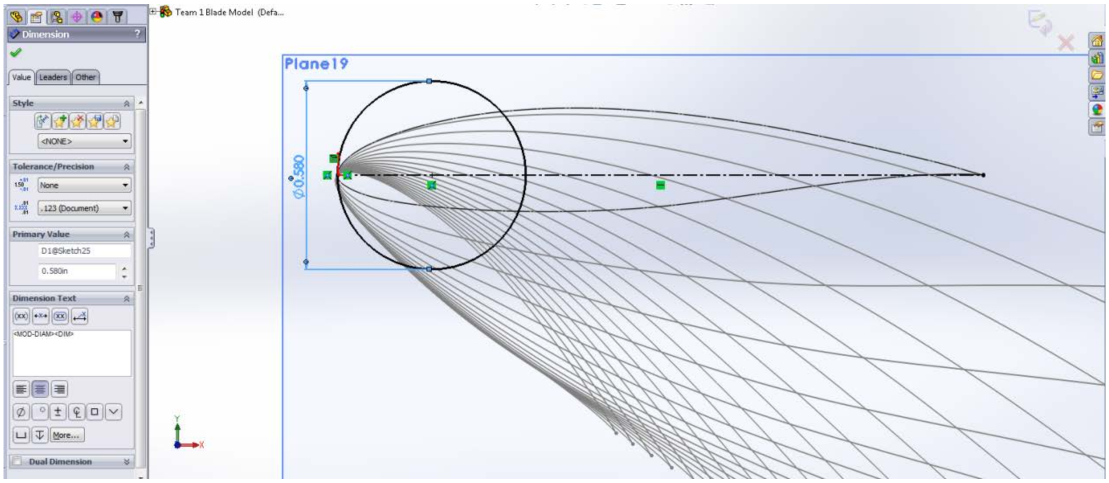


DEFINING ROOT GEOMETRY

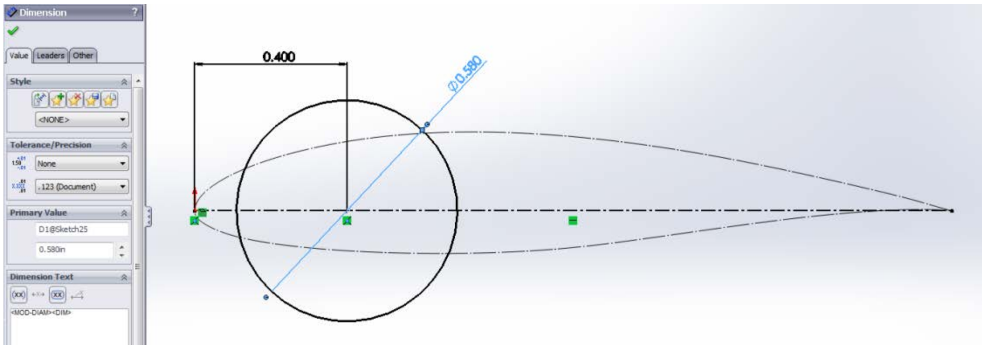
To define the geometry of the blade root, insert a **Plane** 0.25 inches before the first airfoil. Create a **Sketch** on this **Plane**. You may find it helpful to use **Convert Entities** to project the **Sketch** of the first airfoil into your current **Sketch** as a reference. If you do so, select it and check the box to make it **Construction Geometry**. Setting the airfoil as Construction Geometry ensures that while it can be referenced within the **Sketch**, it will be ignored when using the **Sketch** to create **Features** or **Surfaces**.



Create a 0.675 inch diameter circle in the **Sketch**. This circle will be used to **Extrude** the blade root. This diameter is slightly larger than the insert that will be embedded in the root so as to provide space for the insert to be wrapped in fiberglass. There is no "correct" position for the blade root. You can choose to position it so that it is tangent with the leading edge (as shown below) or set it back so that it is closer to where the airfoil is thickest.



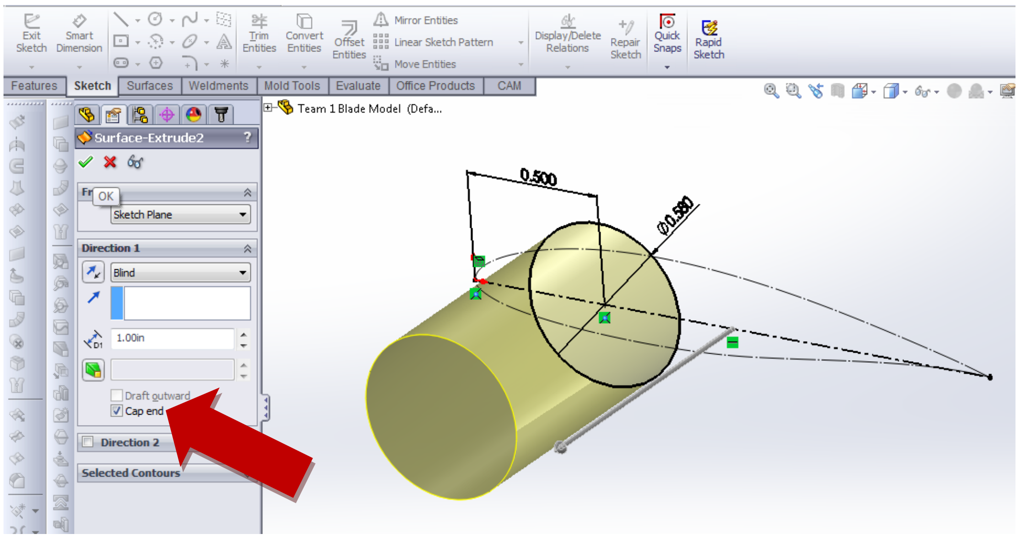
You may find it helpful to define **Construction Geometry** to position the circle (as shown below). You can always go back and adjust the position of this circle later.



CREATING ROOT SURFACES

Select the **Sketch** and then on the **Surfaces Toolbar**, select **Extruded Surface**. Set a length of 1 inch and check the box for **Cap End** to create a surface across the far face of the cylinder.

Note: *While **Extruded Surface** and **Extruded Boss/Base** are similar tools, they are not equivalent. **Surface** tools produce zero-thickness geometries. The tools and methods of manipulating **Surfaces** in Solidworks are different than those used to manipulate **Features**. While it is possible to model your blade using **Features**, it would be extremely difficult to split your blade into molds without using the **Surface Tools**. This guide will use the **Surface** tools throughout.*



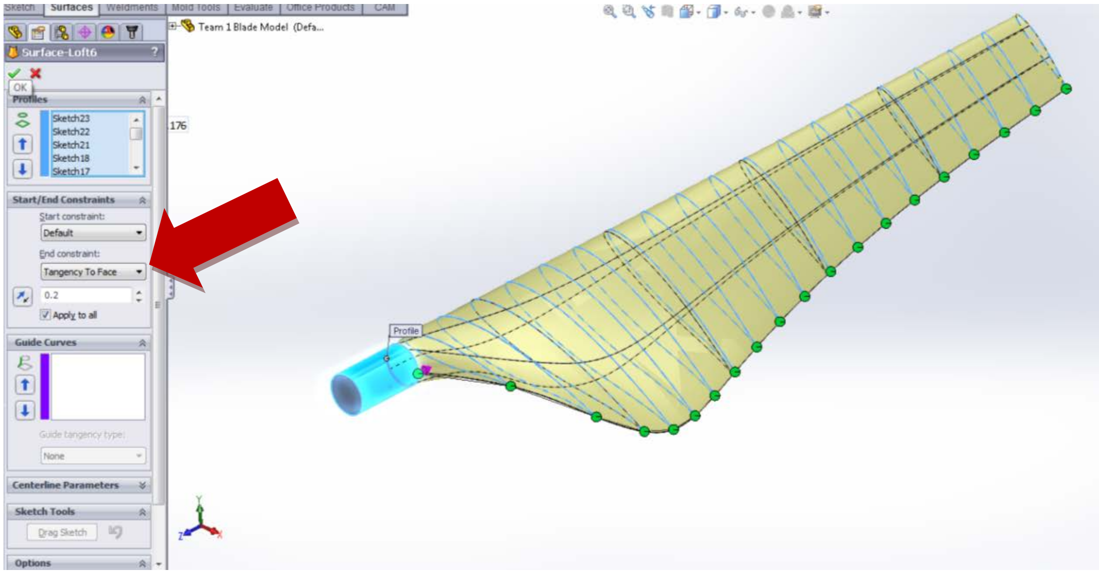
CREATING BLADE SURFACES

Select **Lofted Surface** on the **Surfaces Toolbar**. Add each airfoil sketch in order to **Profiles**. **Lofts** use **Connectors** (indicated by the green dots) as a guide. If the **Connectors** are not aligned, the **Loft** will be twisted and/or self-intersecting. The easiest way to ensure the **Connectors** are aligned is to align the **Connectors** along the trailing edge of the blade. If you click the point representing the trailing edge of each Sketch when selecting each Sketch, Soldworks should automatically place the **Connectors** on the trailing edge.

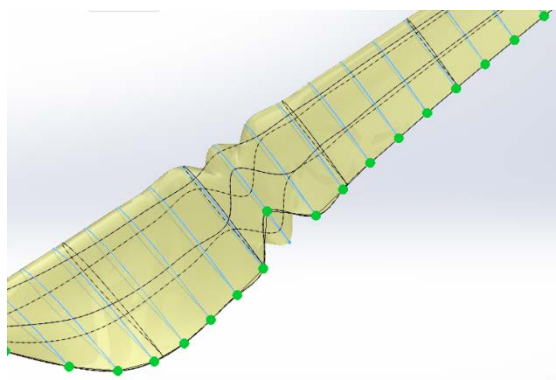
If at any point, Solidworks ceases to display a preview of the **Loft**, there is likely a problem with the **Connectors** and Solidworks will be unable to generate a **Loft**. Try deleting the last profile you added (**right click>delete**) and try selecting it again. You can also drag the **Connectors** to reposition them.

Switch the **Start Constraint** or **End Constraint** (depending on the order in which you selected the profiles) to **Tangency to Face** so that the loft is tangent to the extruded surface. You can adjust the **Tangency Length** to produce the look you want.

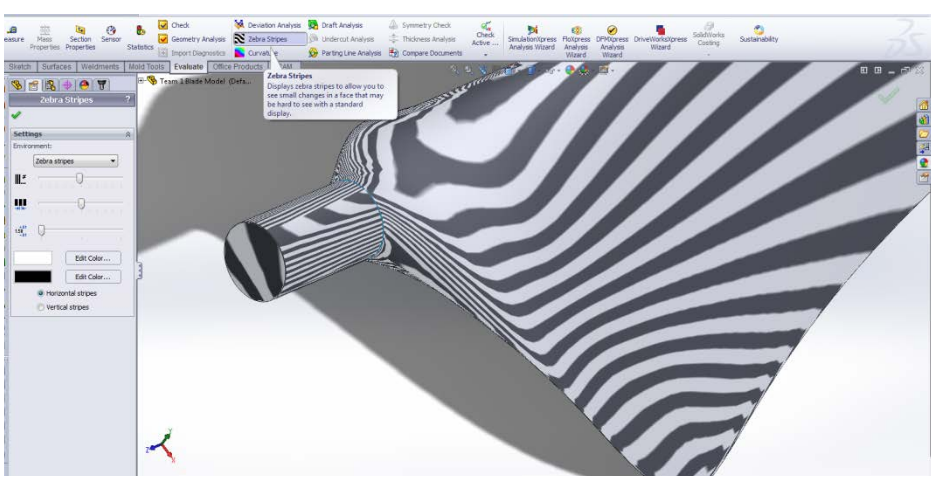
Note: *The blade root was **Extruded** separately, instead of being included in the **Loft**, to ensure that the root is perfectly cylindrical. This is not ensured when using the **Loft** tool.*



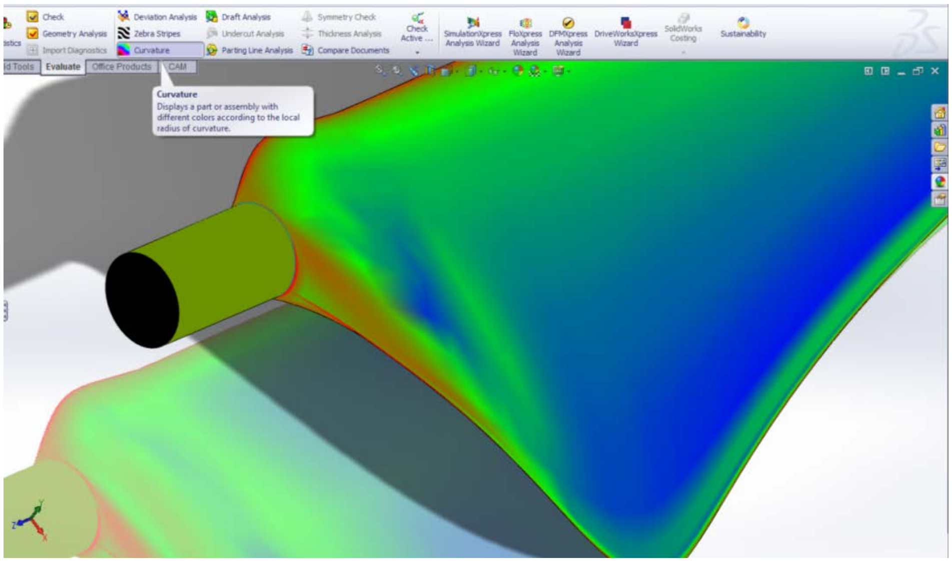
Once you have created the **Loft**, it is important to look for twist or other smaller inconsistencies in the **Loft**. As shown below, these can be glaringly obvious, but they can also be smaller and harder to see.



There are two visualization tools available on the **Evaluate Toolbar** that can be helpful. The aptly named **Zebra Stripes** button will temporarily display stripes that can help show small inconsistencies. Click the button a second time to disable the effect.

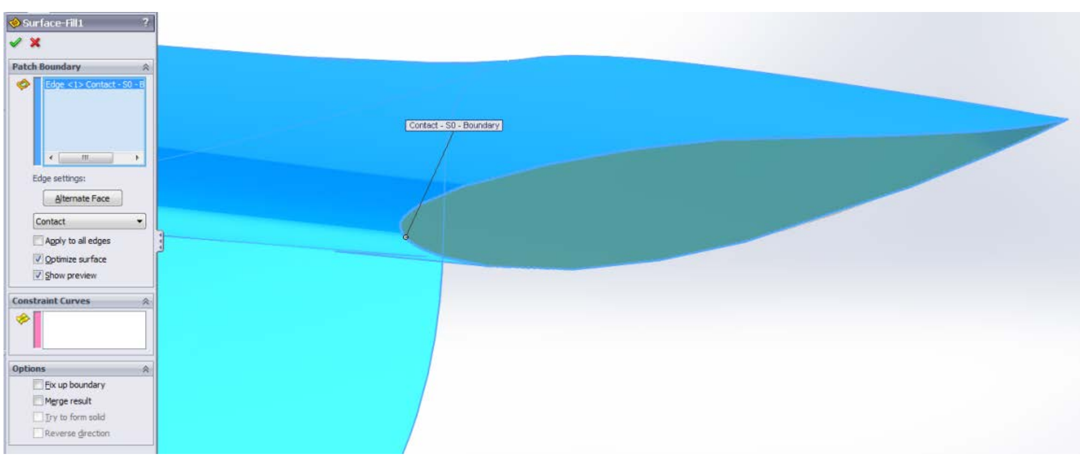


Similarly, the **Curvature** button colors the part according to the local radius of curvature. This can sometimes also show inconsistencies.

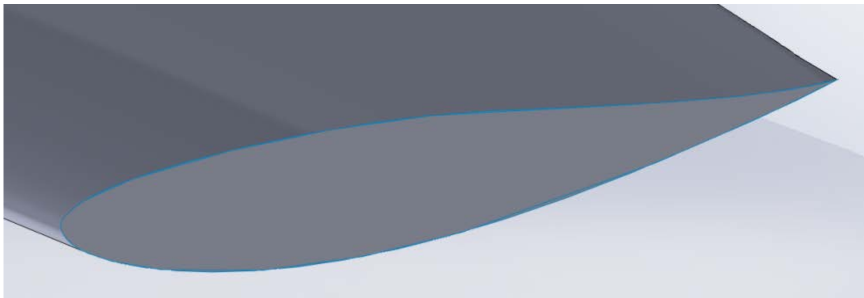


The tip of the blade is still unenclosed. Use the **Filled Surface** tool to create a flat patch across the end of the blade. Use the edge of the tip as the **Patch Boundary**.

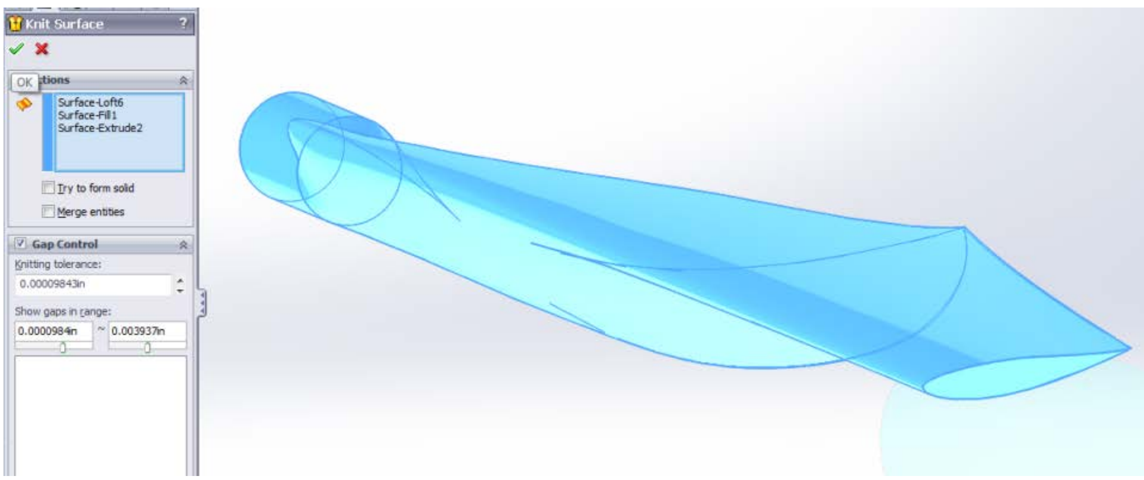
Note: *Ideally the tip would be modeled with rounded edge, however in practice there tends not to be a simple way to do this in Solidworks. Because the blade molds will be machined with a ball-endmill, the edges of the tip will be naturally rounded during the machining process. It is therefore simpler not to model these edges as rounded.*



A shown below, the a blue line will be displayed along the edge of the **Fill**. The same is true where the **Extrude** meets the **Loft**. Blue lines signify edges where **Surfaces** are not actually connected. Were you to zoom in close enough, you would begin to see small gaps between the surfaces along these lines.



The **Knit** tool is used to merge **Surfaces**. This tool is capable of automatically identifying and "knitting" together small gaps. To use it, click the **Knit Surface** tool on **Surfaces Toolbar** and then select all three **Surfaces** you have created. There should be no need to adjust the **Knitting Tolerance** or other settings. If any larger gaps are identified, they will appear under **Gap Control**. If this occurs, check the box(es) to close these gaps.



MODELING MOLD SURFACES

The next step is to divide the blade into two separate halves which will represent the two halves of the mold.

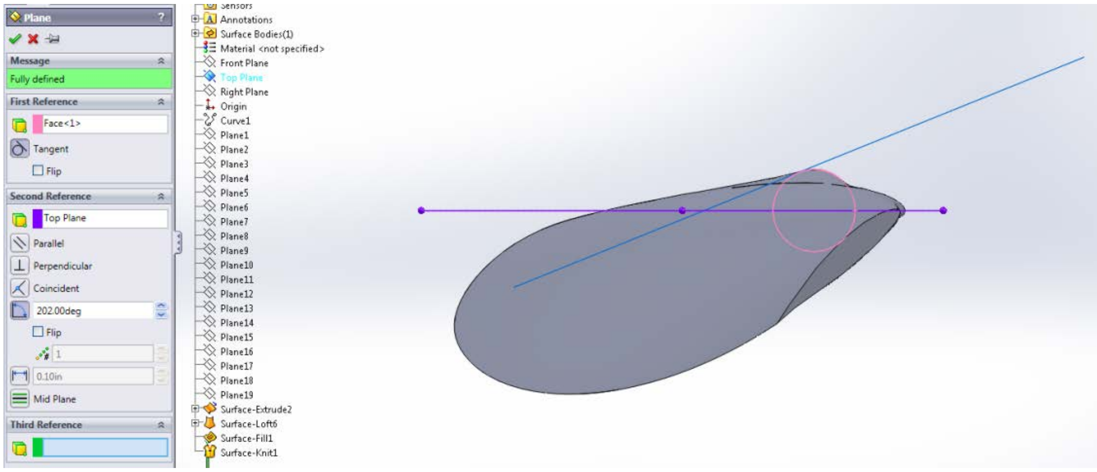
Note: *Solidworks incorporates a collection of **Mold Tools** designed to automate this process. However, due to the complexity of the shape of wind turbine blades, you will likely need to manually complete some of the steps using **Surface Tools** in order to complete the process.*

DRAFT ANALYSIS

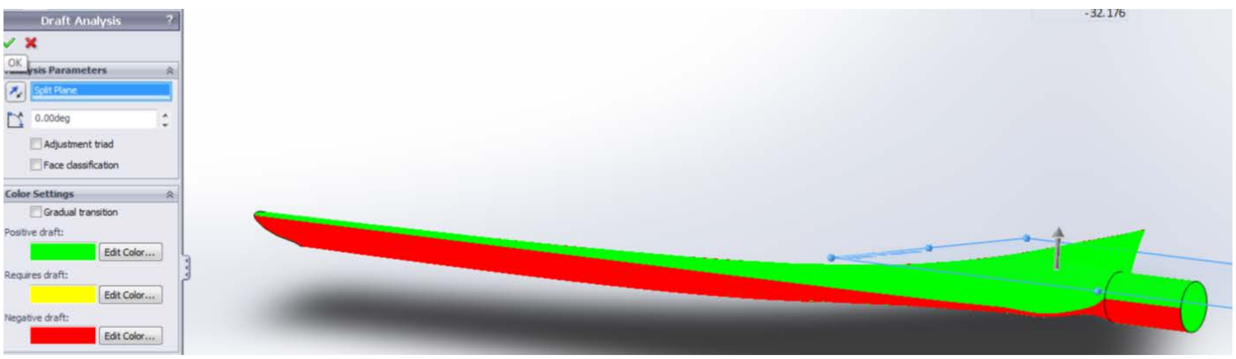
The first step is to define the direction in which the mold will be split. This is known as the **Direction of Pull**. Twisted wind turbine blades will not have a specific direction in which the mold should be split. It generally makes sense to split the mold in a direction that is normal to the cylinder of the blade root.

Insert a **Plane**. It normally simplest to define this plane so that it is tangent to the cylindrical surface and a set angle away from one of the coordinate **Planes**. Adjust the angle of this **Plane** so that it roughly divides the blade. You can adjust this angle later if needed. It is suggested that you rename this **Plane** "Split Plane" so that it is easily identifiable.

Note: *The goal is to choose an* ***Direction of Pull*** *where neither half of the mold with have* ***Undercut*** *or* ***Negative Draft****. The existence of* ***Undercut*** *would likely make the mold impossible to machine with a 3-axis router and would also likely make the final blade impossible to remove from a 2-part mold.*

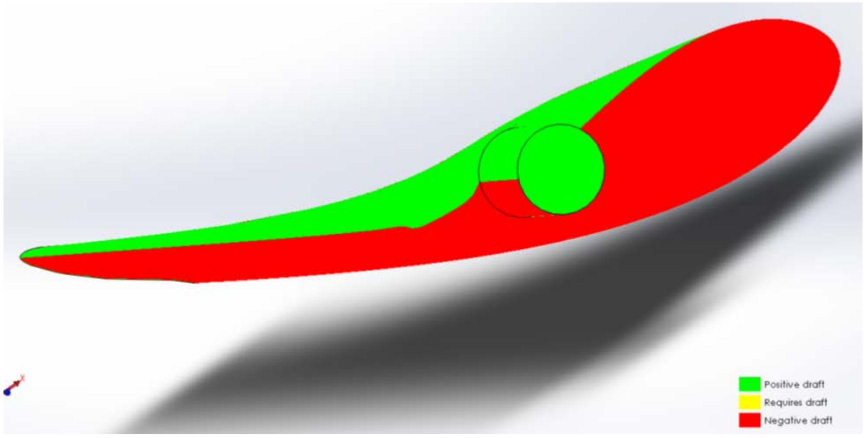


In the **Mold Toolbar**, select **Draft Analysis**. Use the Plane you just created as the **Split Plane**. Set the **Draft Angle** to zero degrees. The blade will be colored to show areas of **Positive** and **Negative Draft**. Because the **Draft Angle** is set to zero, there will be no areas of **Neutral Draft**. Click the checkmark; the coloration will remain.



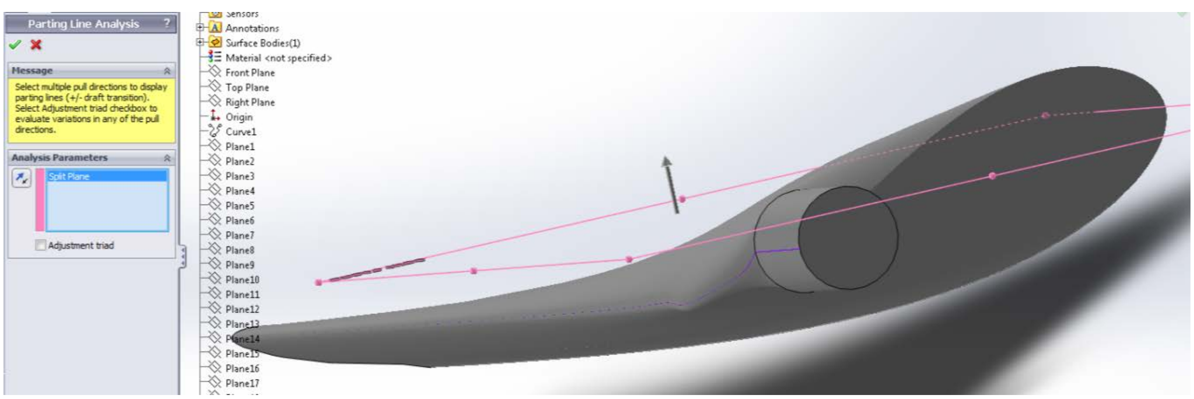
The diameter of the endmill will limit the minimum radius that the CNC router will be able to machine. To allow for the sharp trailing edge of your blade to be machined, the trailing edge of the blade must divide the areas of positive and negative draft. If the blade does not smoothly divide into areas of **Positive** and **Negative Draft** divided by the trailing edge, you will need to adjust the angle of the **Split Plane** so that it does.

Note: *The blade tip and end of the blade root may appear as having either* ***Positive*** *or* ***Negative Draft****; either is acceptable.*

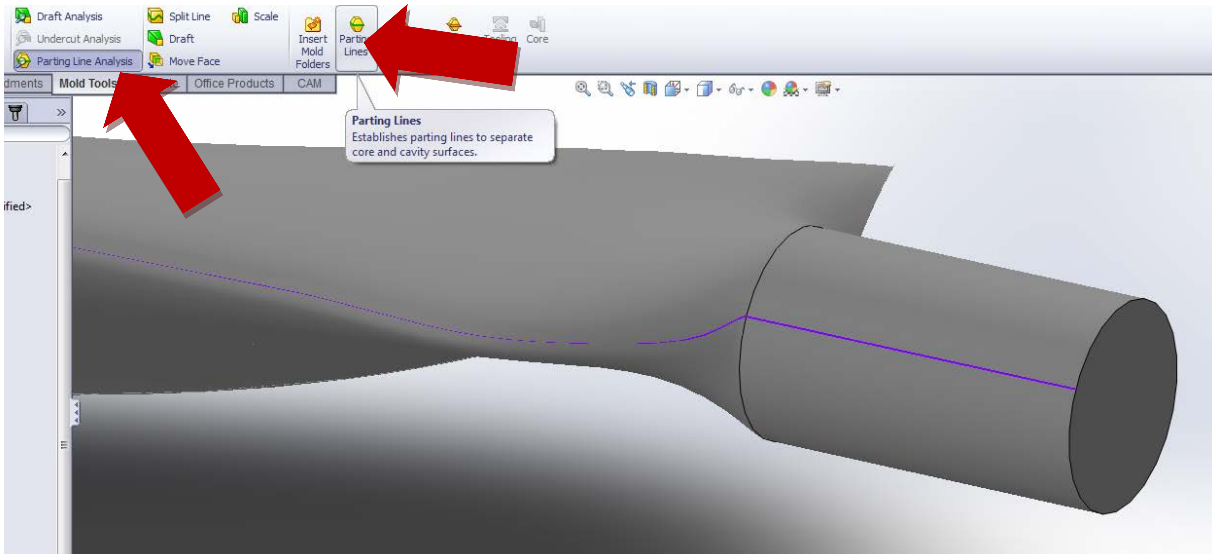


CREATING PARTING LINES

The next step is to create **Parting Lines**. The **Parting Lines** will mark the divide between the two mold halves. To do see where the **Parting Lines** will be located, click **Parting Line Analysis** on the **Mold Toolbar**. Select your split plane to set the **Pull Direction**. Purple **Parting Lines** will appear on your part.

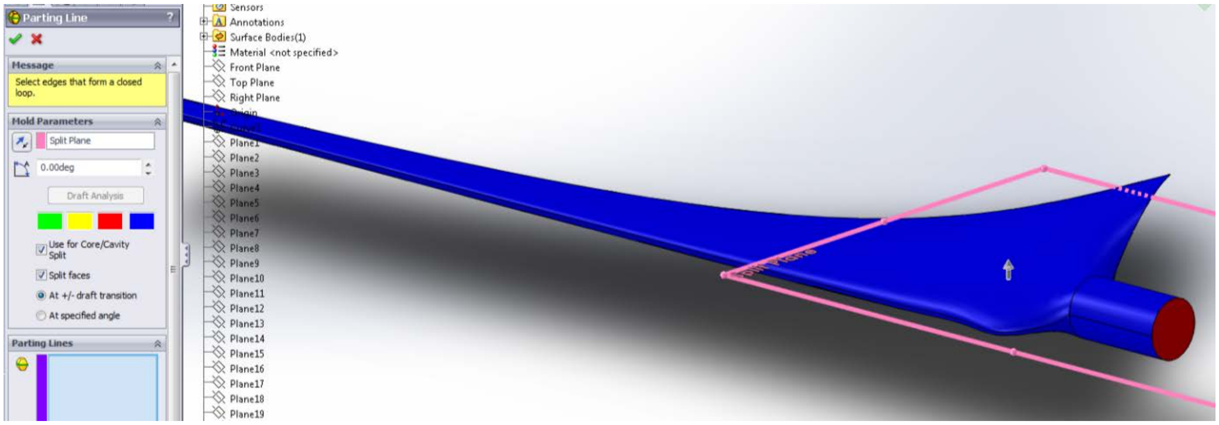


Click the checkmark. The **Parting Lines** will remain visible until the **Parting Line Analysis** button is clicked again. Next, click the **Parting Lines** button to create the parting lines.



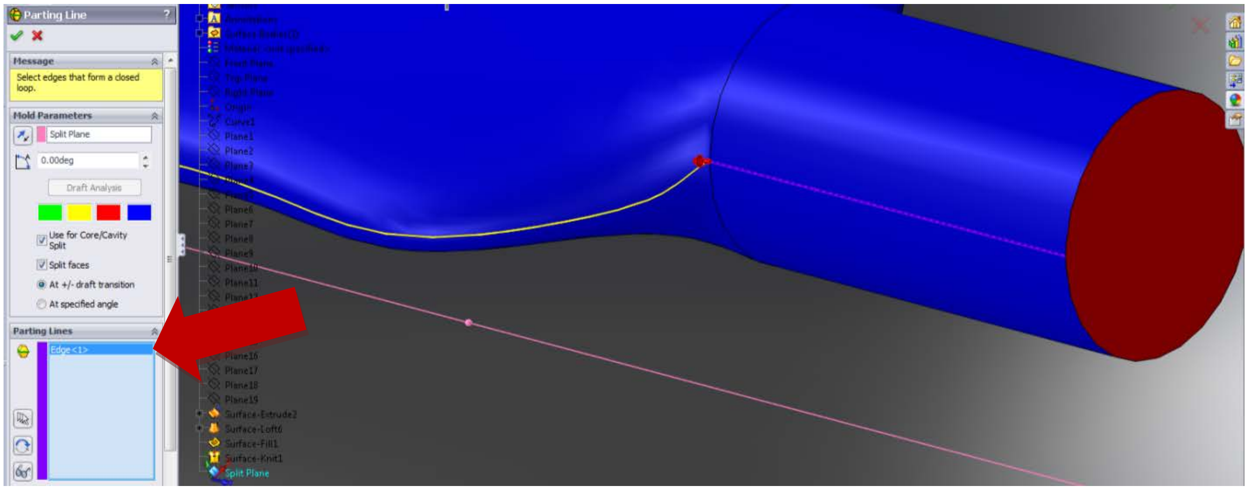
Select your split plane as the **Direction of Pull**. Set the **Draft Angle** to zero and then click **Draft Analysis**. Check the boxes for **Use For Core/Cavity Split** and **Split Faces**. Select **At +/- Draft Transition**.

Note: *This will differ from the **Draft Analysis** you previously ran, because Solidworks will analyze your part by **Face**. **Faces** which contain areas of both **Positive** and **Negative Draft** will be classified as blue **Straddle Faces** that must be split.*

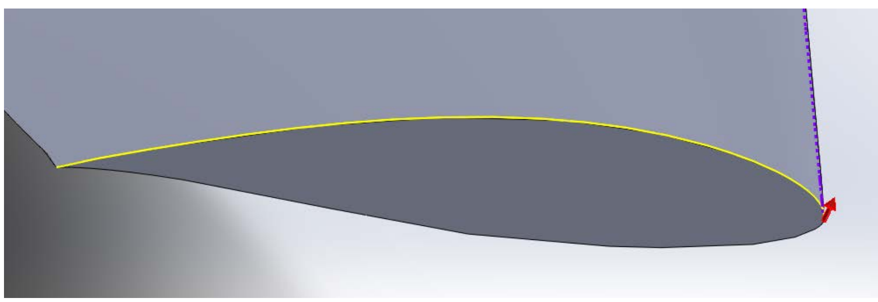


Select an appropriate edge as a **Parting Line**. Solidworks will attempt to identify the next contiguous segment. Solidwork's guess will be highlighted yellow and a red arrow will point toward it. If the guess is incorrect, click the red arrow to switch between the possible edges until the proper edge is identified. Then, select that edge.

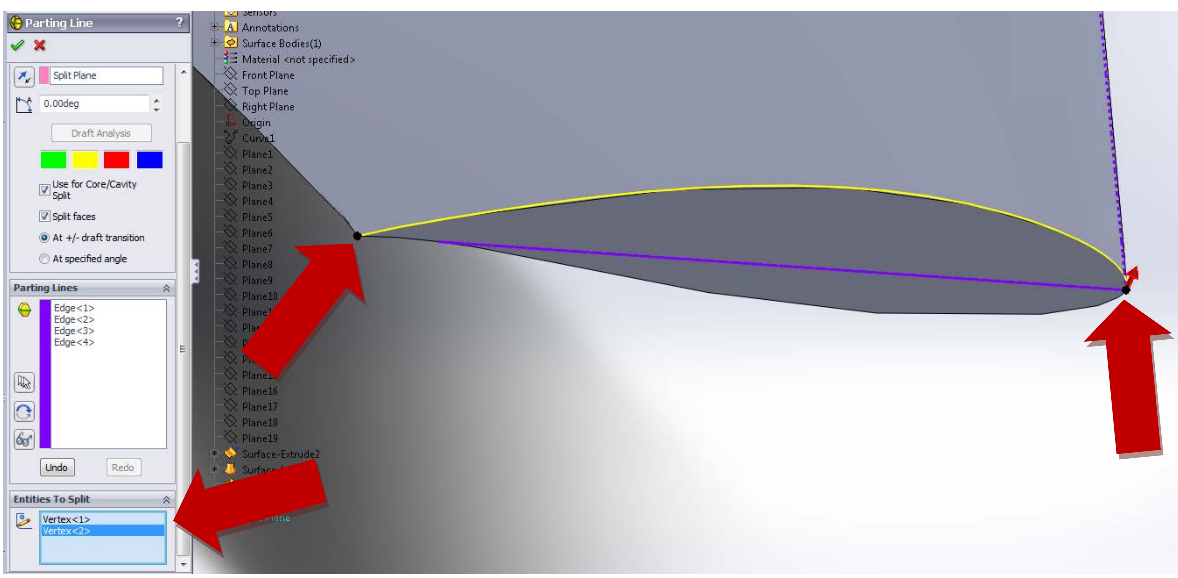
Note: *Alternatively you can ignore the red arrow and simply click segments to select them. However, by doing so, you risk missing tiny segments that may exist on your blade. If you miss a segment, Solidworks will be unable to complete the **Parting Line**.*



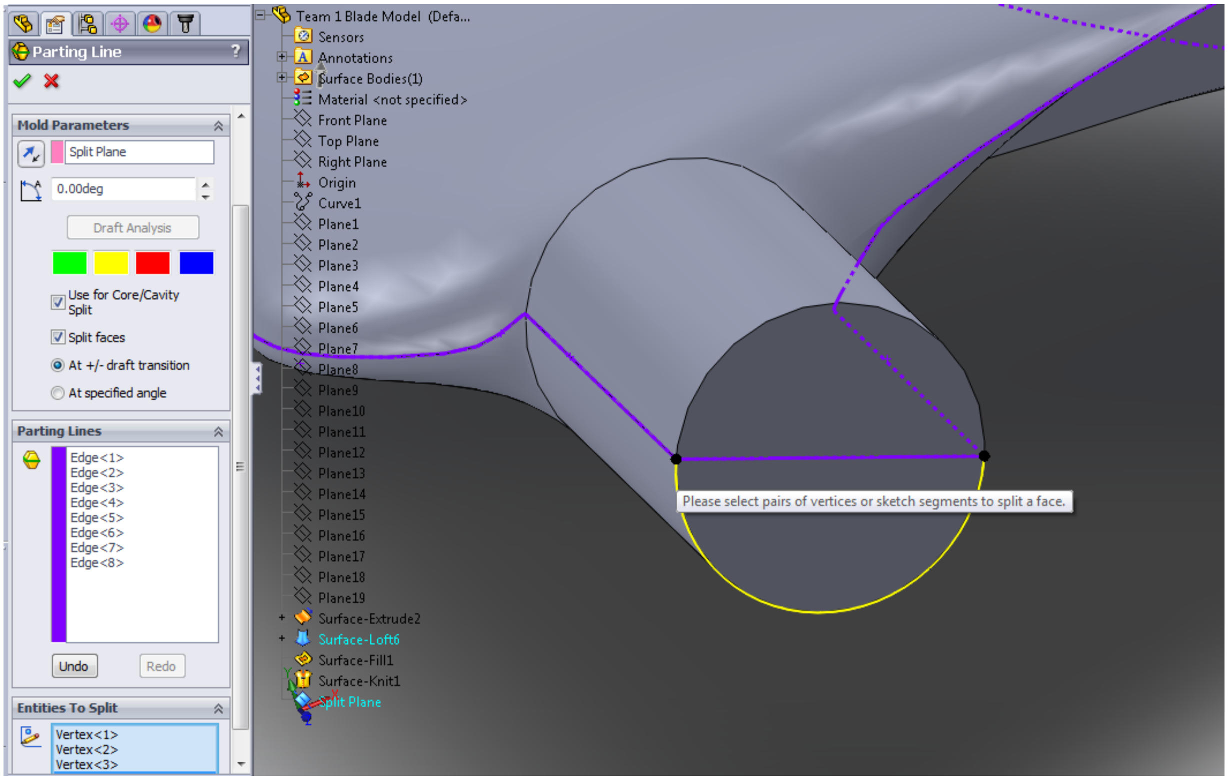
Any flat Faces with zero **Draft** will need to be **Split**. Assuming that your split plane is perpendicular to the ends of your blade, you will need to **Split** both ends.



When you reach the first of these faces, select the **Entities to Split** box and then select the appropriate points on either side of the face. This will **Split** the face.



Repeat the process when you reach the other end of the blade.

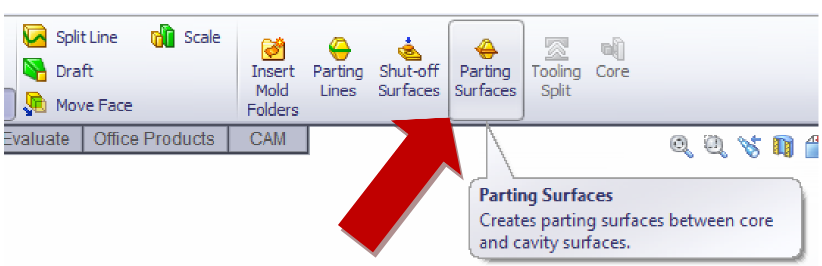


Once you have closed the loop of **Parting Line** segments, click the checkmark to create the **Parting Lines**.

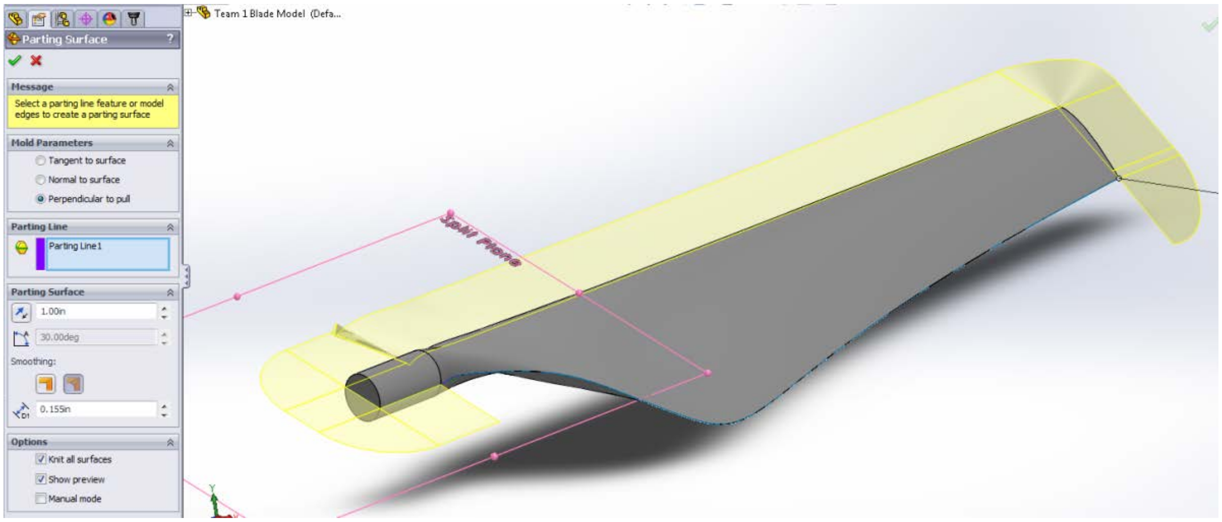
CREATING PARTING SURFACES

The next step is to create **Parting Surfaces** extending out from the **Parting Lines**. The **Parting Surfaces** will be incorporated into both halves of the mold and will serve to produce matching faces around the edges of the part. The exact shape and size of the Parting Surfaces is not critical in this case. In general, you want to create **Parting Surfaces** that extend about 1 inch from the edge of the part and are reasonably smooth. The **Parting Surfaces** should have a high **Draft Angle** and cannot have **Negative Draft**.

Click the **Parting Surfaces** button on the **Mold Toolbar** to have Solidworks attempt to automatically generate **Parting Surfaces**.



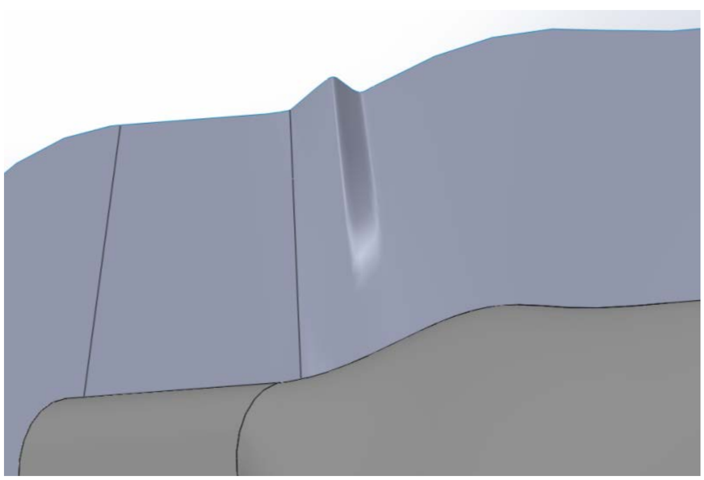
Select **Perpendicular to Pull**. Select the your **Parting Line** as the **Parting Line**. Set the length of the **Parting Surface** as 1 inch. Check the boxes next to **Knit all Surfaces** and **Show Preview**. It is likely that Solidworks will be unable to create smooth **Parting Surfaces** around your entire blade. If so, you will have to manually correct this later. Click the check to accept the **Parting Surfaces**.



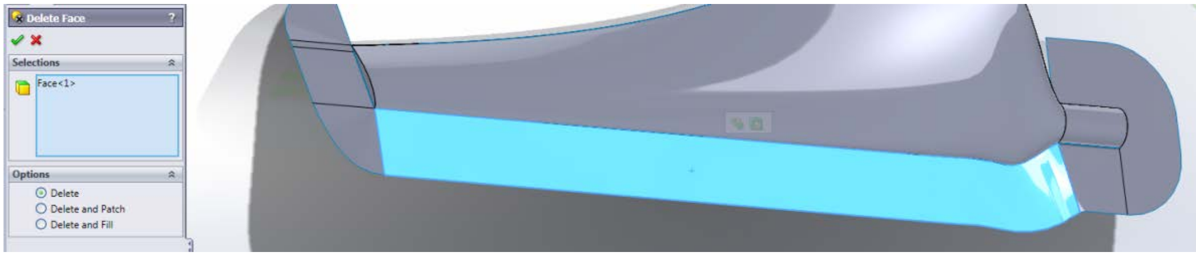
CORRECTING PARTING SURFACES

There are likely problems with the **Parting Surfaces** that you just created. Every blade will have different issues and will require different fixes. The following instructions may not directly apply to your blade, but should demonstrate useful methods of completing the **Parting Surfaces**.

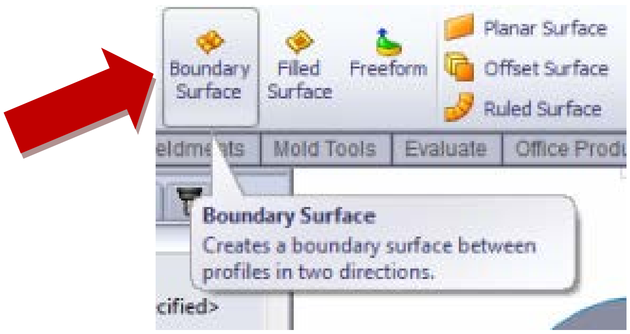
There may be wrinkles or other unnecessarily convoluted sections of the automatically generated **Parting Surfaces**. If so, these areas should be manually replaced.



Use the **Delete Face** tool on the **Surfaces Toolbar** to delete the problem face.

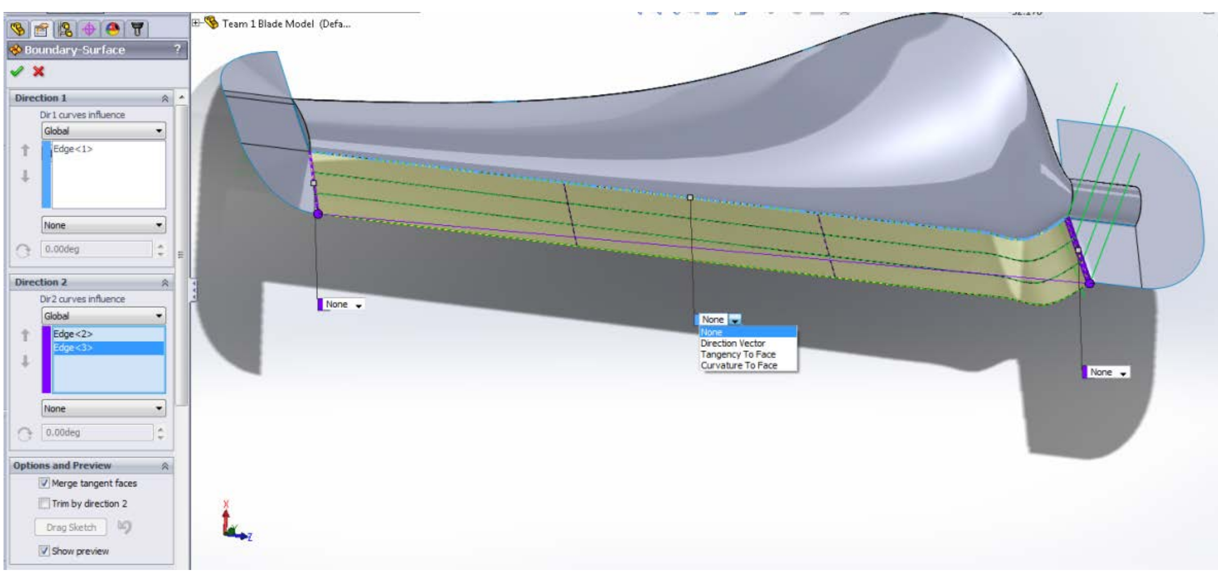


Replace the face using a **Boundary Surface**. Boundary Surfaces are defined by two or more edges or **Sketches** that form the boundary of the **Surface**.

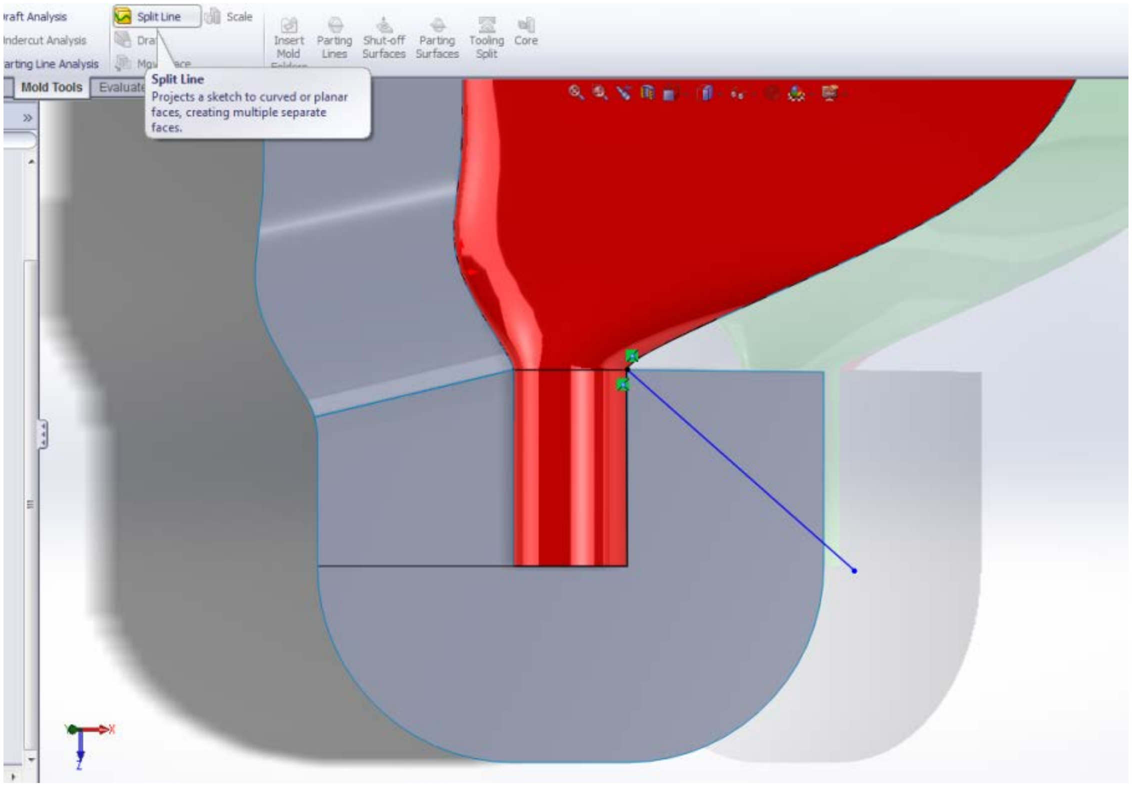


Select the edge of the blade as the **Direction 1 Curve**. Select the two bordering edges of the existing **Parting Surfaces** as the **Direction 2 Curves**. A preview of your **Boundary Surface** should appear. If so, click the check mark.

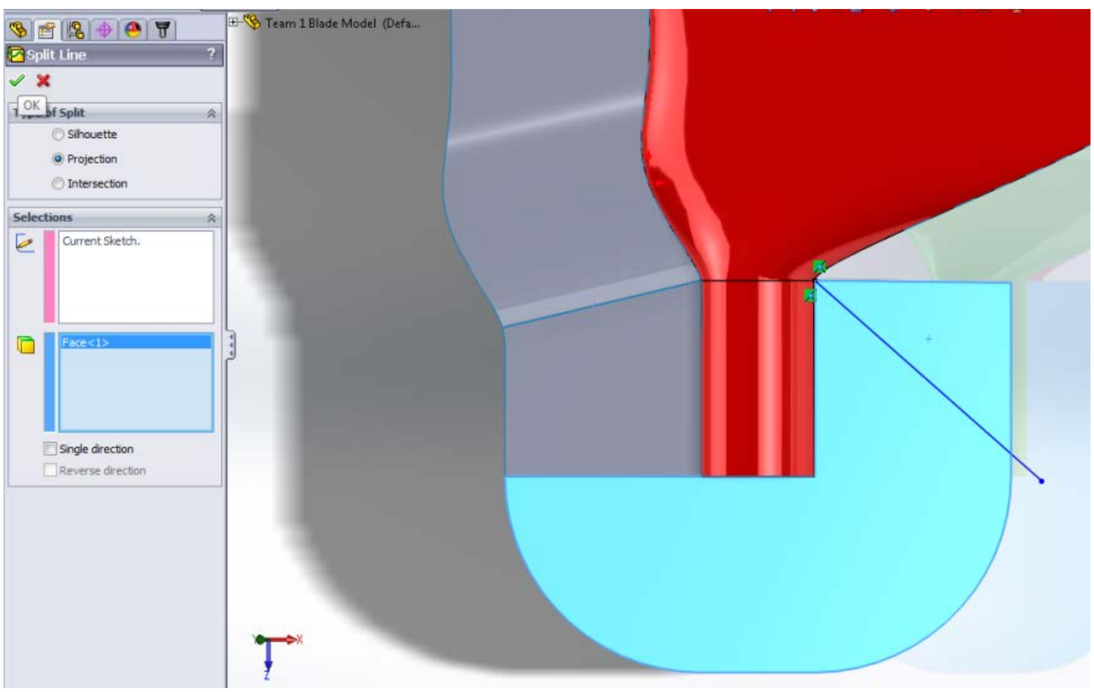
Note: ***Direction 1*** *and* ***Direction 2*** *are interchangeable, however opposite edges must be included in the same* ***Direction****. The* ***Curves*** *in* ***Direction 1*** *and* ***Direction 2*** *must share endpoints.*



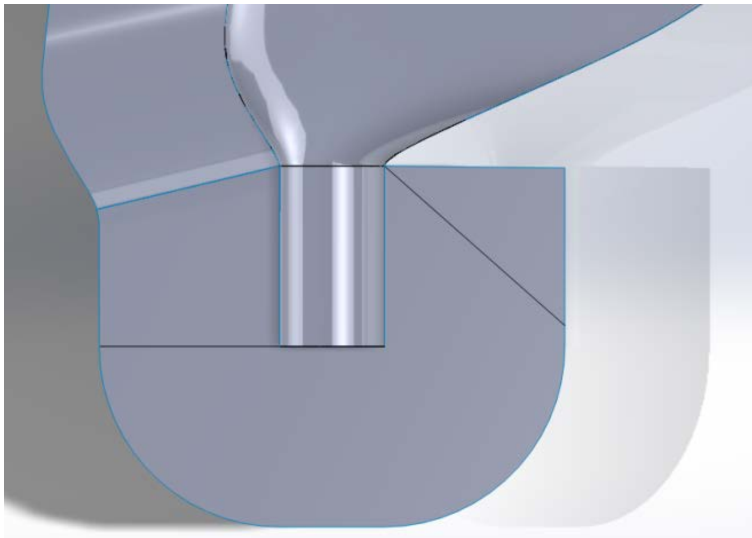
Sections of the **Parting Surface** may be missing. It may be necessary to trim existing sections to allow for a smooth transition. To do so, create a **Sketch** on one of the existing **Planes** to mark where to trim the **Surface**. On the **Mold Toolbar**, select **Split Line**.



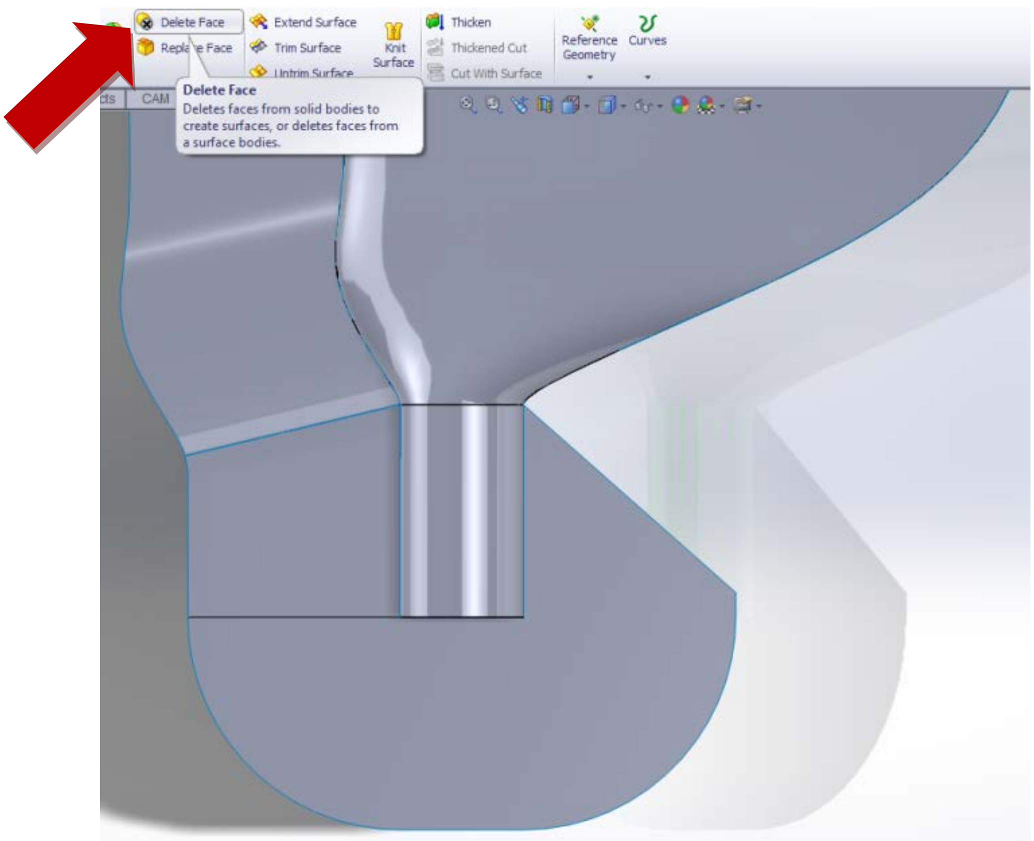
Selection **Projection**, use the **Sketch** you just created as the **Sketch to Project**, and select the relevant face as the **Face to Split**.



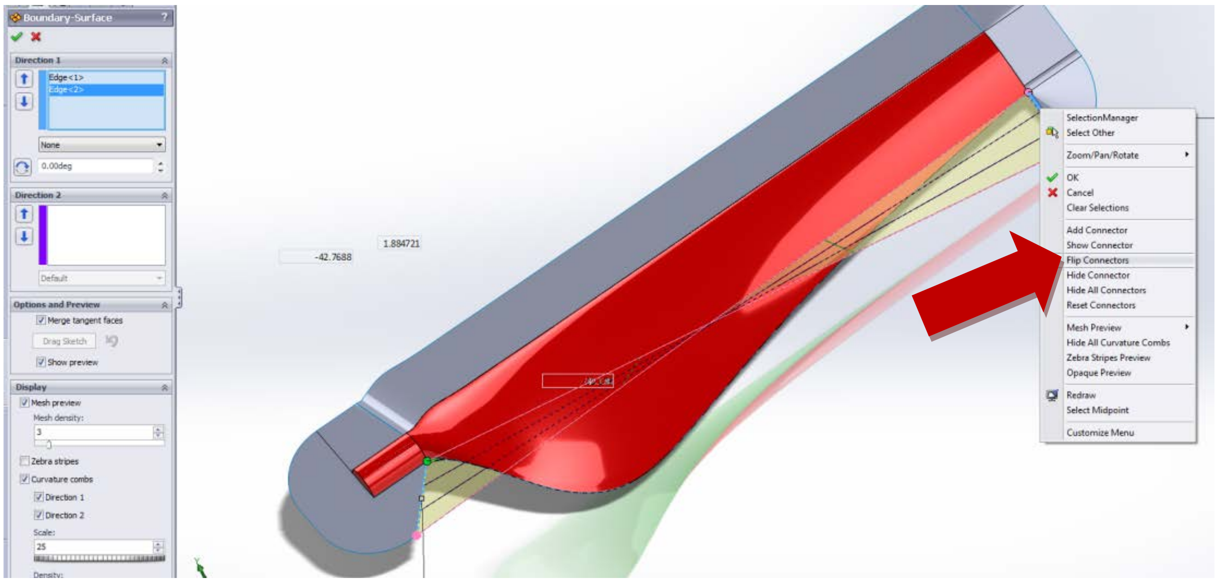
Click the checkmark to split the face using this line.



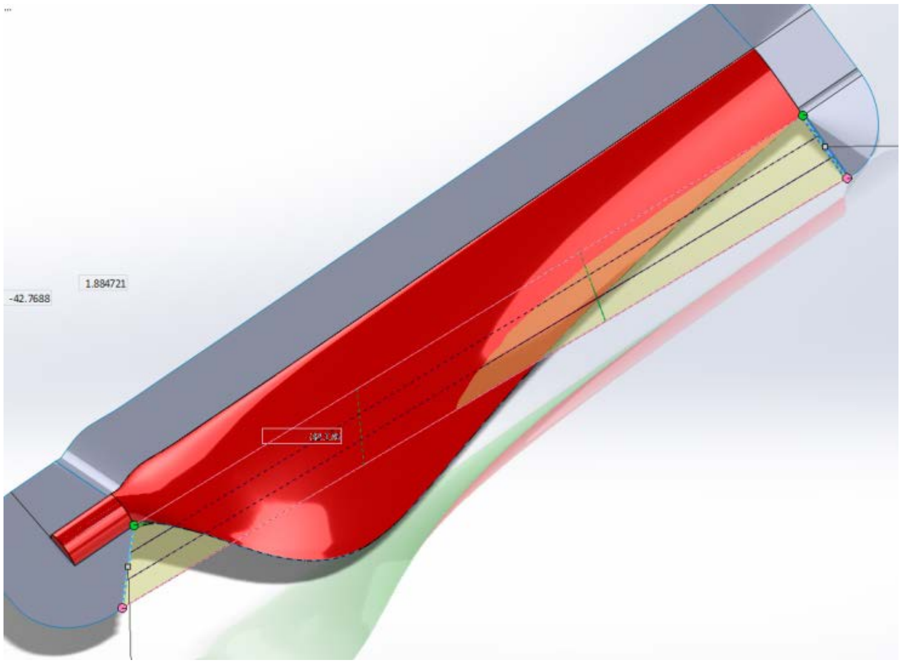
Use the **Delete Face** tool on the **Surfaces Toolbar** to delete the unnecessary face.



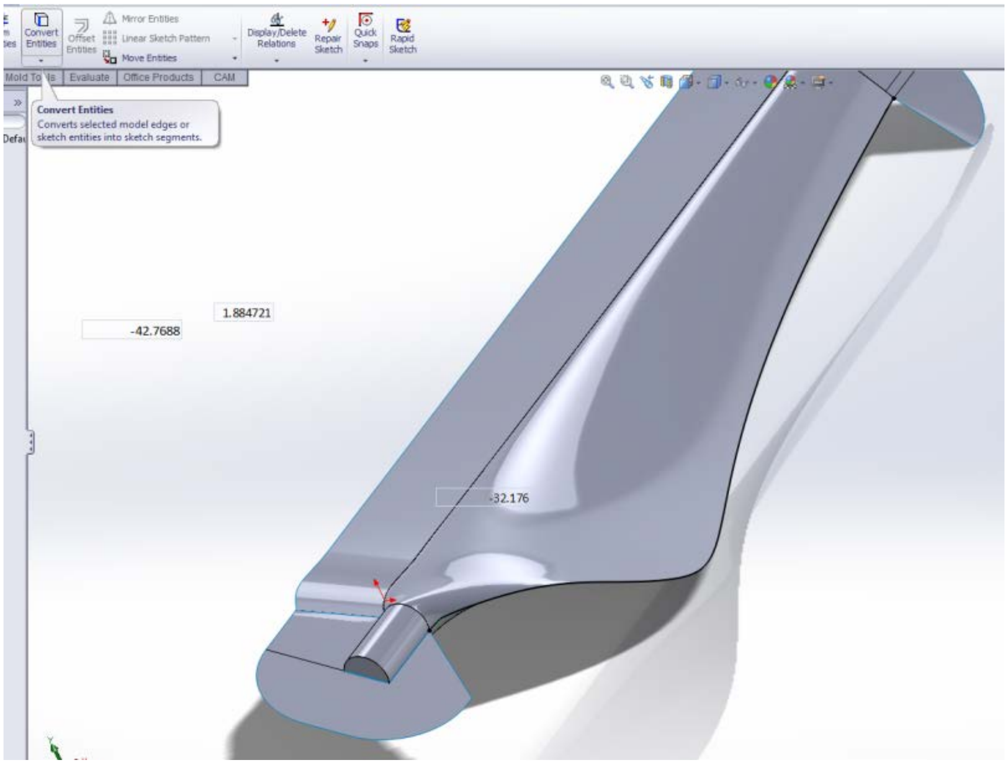
The next step is to attempt to use a **Boundary Surface** to create the missing section of the **Parting Surface**. If you ever attempt to create a **Boundary Surface** and find that it is twisted, right click one of the selected Curves and click **Flip Connectors** to untwist the surface.



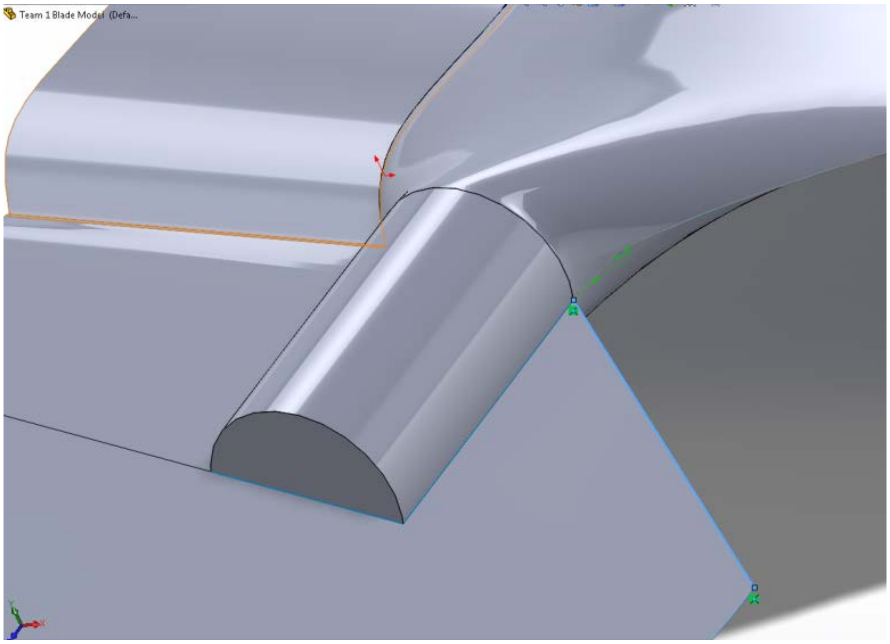
In this case, any attempt to select the trailing edge of the blade resulted in Solidworks crashing. The ends of the edges used to define a boundary surface must meet. In this case, miniscule gaps existed. This is a common reason why boundary surfaces fail.



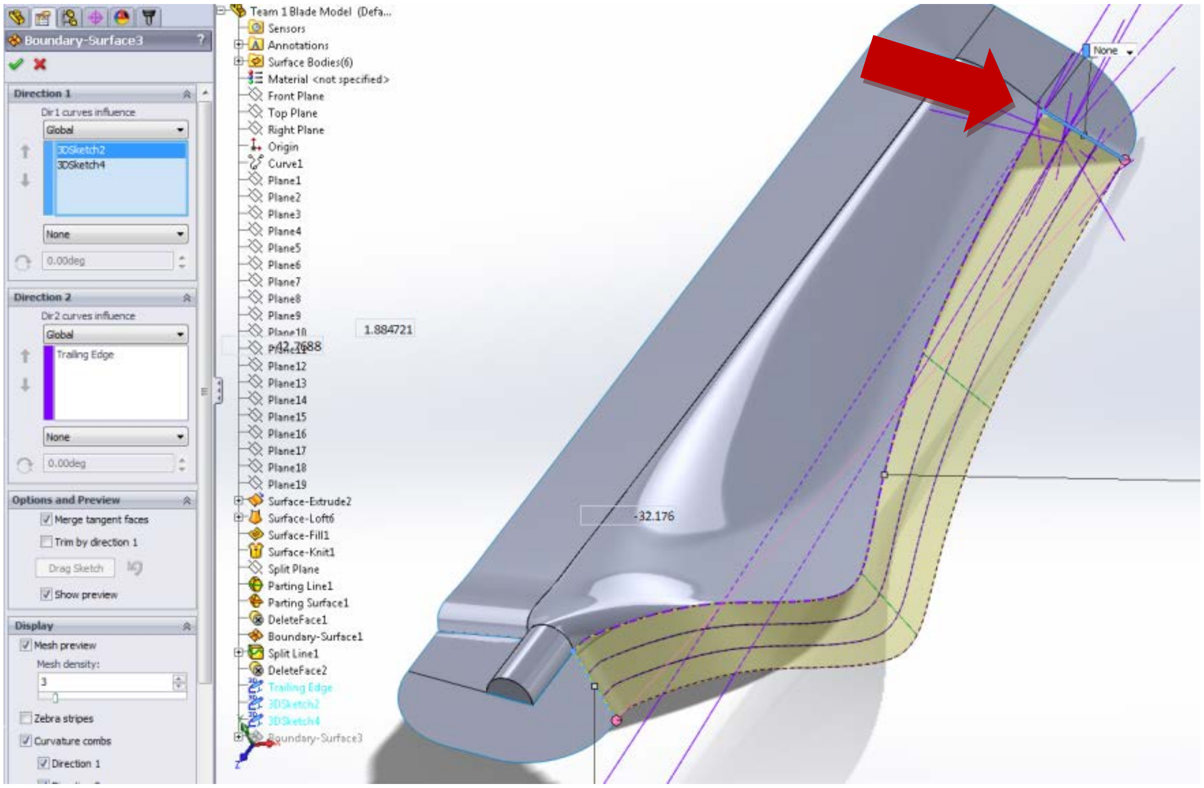
To solve this, three separate **3D Sketches** were created to manually define the three edges of the boundary surface. The **Convert Entities** tool was used to import the trailing edge of the blade into one **3D Sketch**.



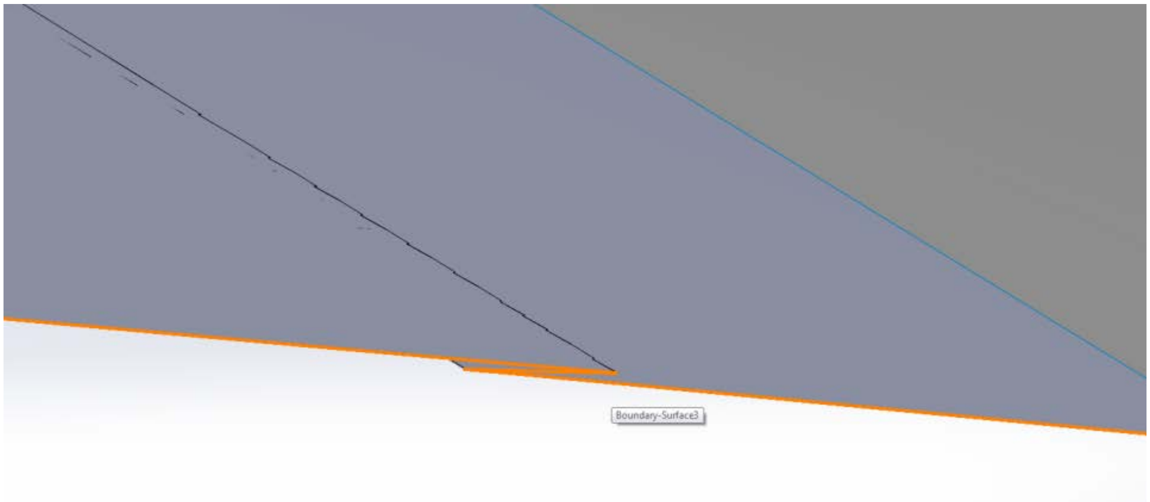
The other two **3D Sketches** were created by drawing **Lines** from the corner of the edge of the adjacent **Parting Surface** to the end point of the **3D Sketch** containing the trailing edge.



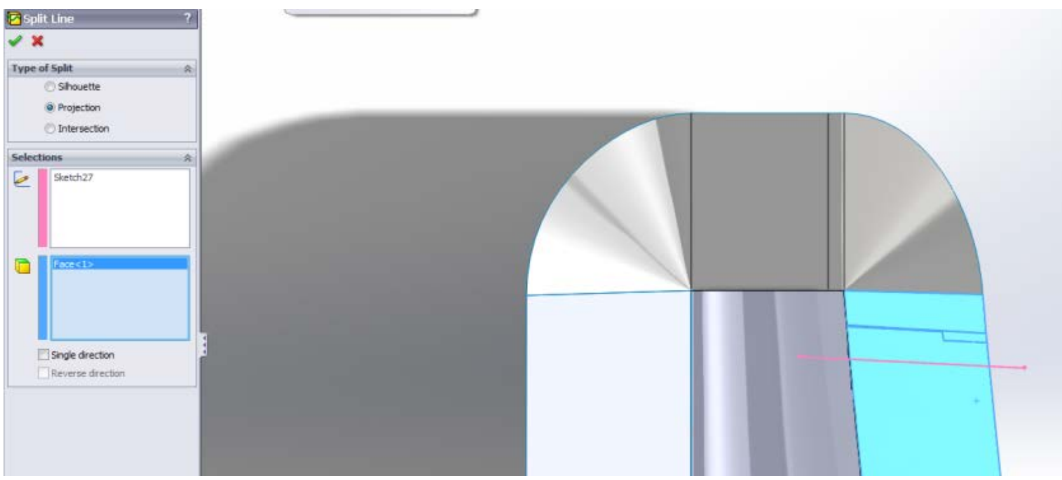
These three **3D Sketches** were then used to define a **Boundary Surface**. The purple **Curvature Comb** is displayed to highlight areas of high curvature. In this case, the **Curvature Comb** indicated a problem area. However, Solidworks was able to produce the **Boundary Surface**.



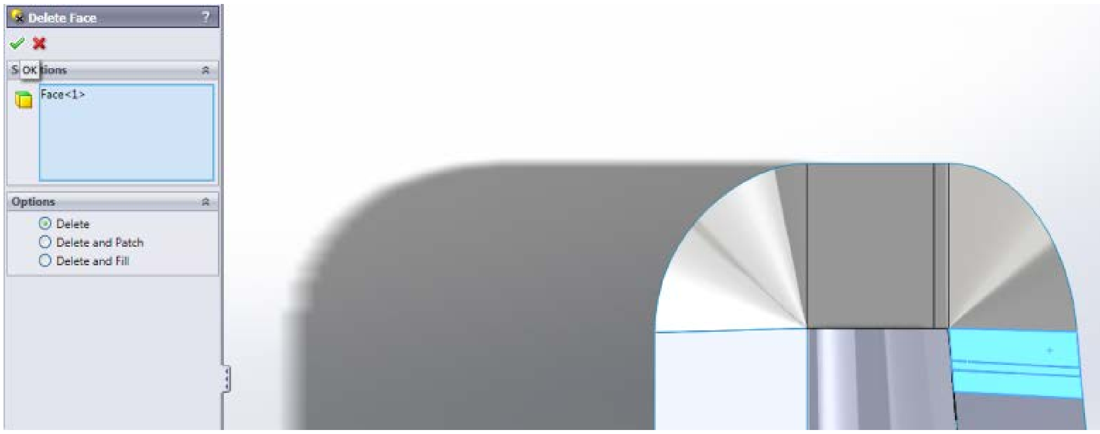
From a distance, the **Boundary Surface** appeared acceptable, however upon closer inspection it became apparent that there was a small wrinkle.



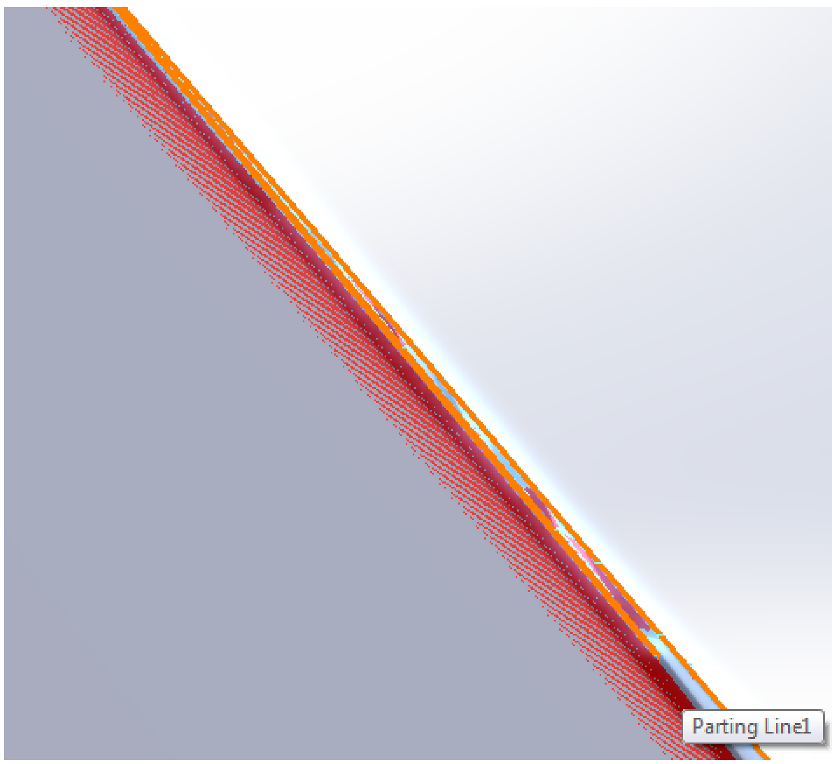
A **Sketch** was created and used to create a **Split Line.**



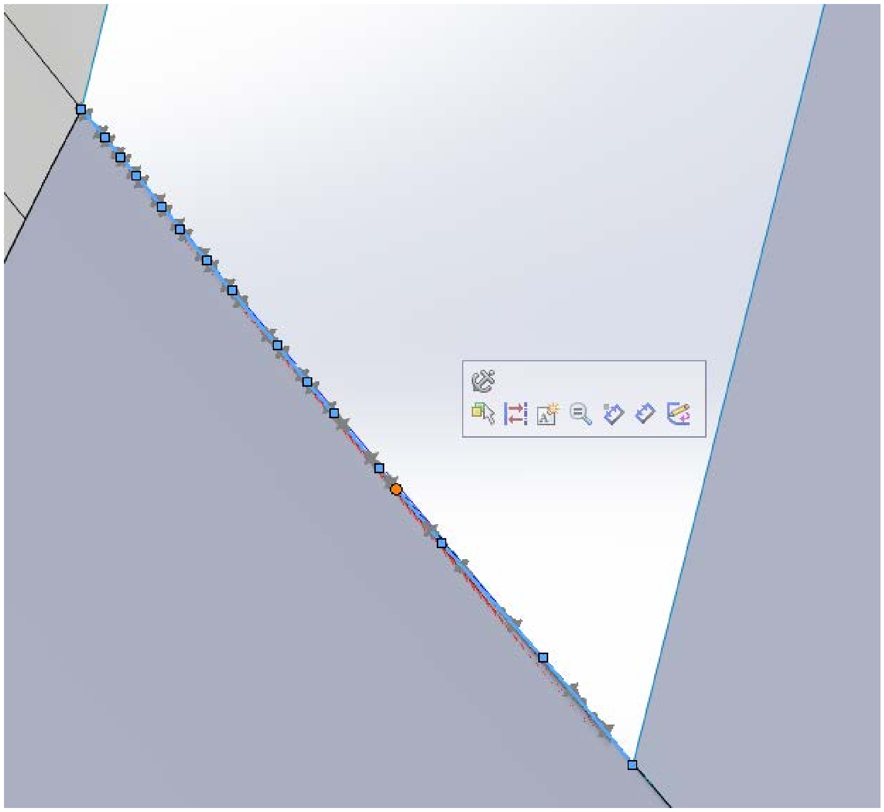
The **Delete Face** tool was used to delete the wrinkled section.



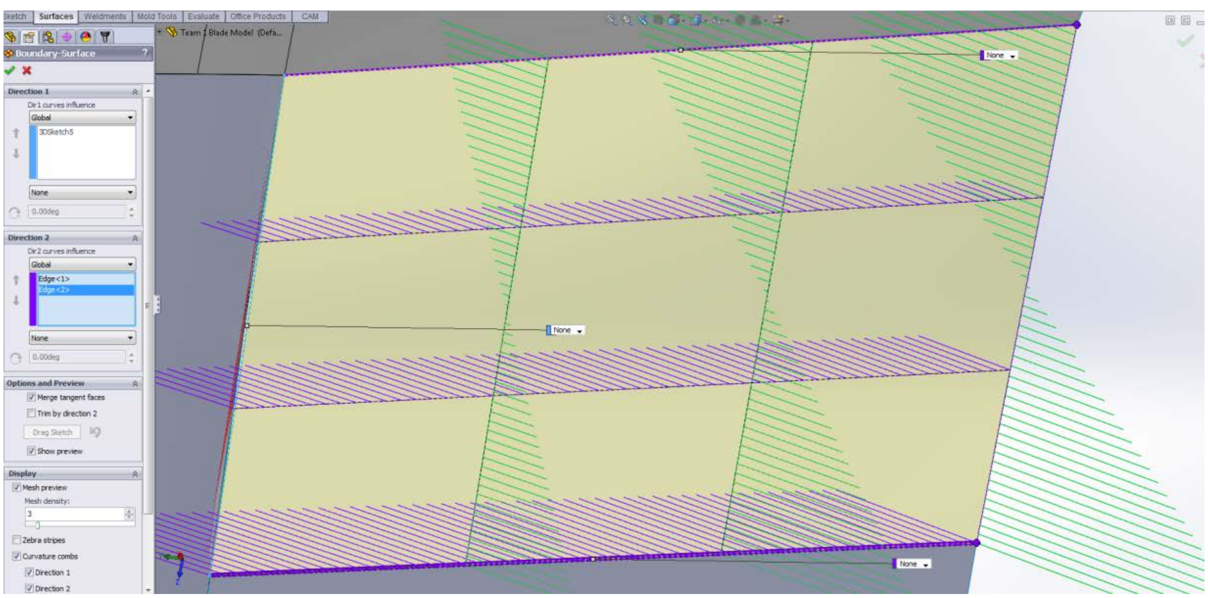
Upon further inspection, it became apparent that the source of the problems was that the **Parting Line** zigzagged slightly.



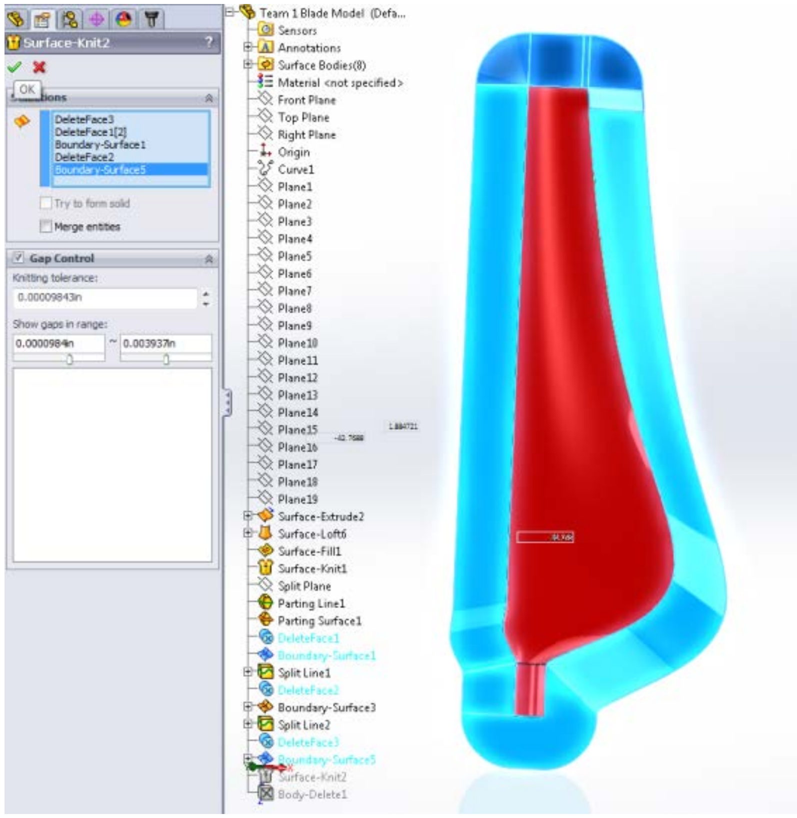
As a workaround, **3D Sketch** was created and a **Spline** was closely fit to the **Parting Line** while omitting the zigzag.



This **3D Sketch**, along with the edges of the existing **Parting Surface**, was used to create a **Boundary Surface** to fill the gap. This left a miniscule gap between the blade and the **Parting Surface**, however the size of this gap was negligible.



The last step is to **Knit** the **Parting Surfaces**. Do not **Knit** the **Surfaces** of the blade.

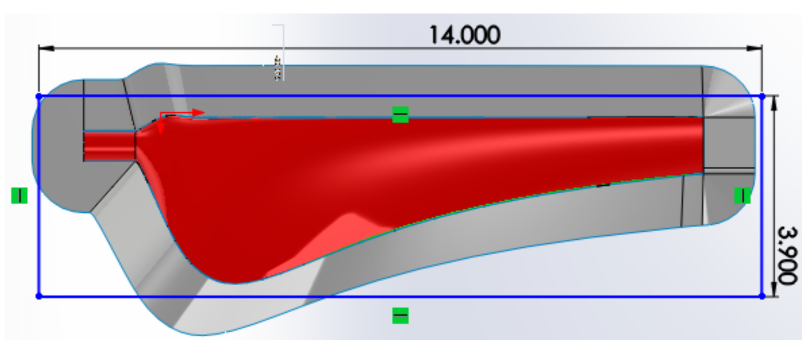


In this case, it is not necessary to model the rest of the molds. Only the mold cavities and **Parting Surfaces** will be machined.

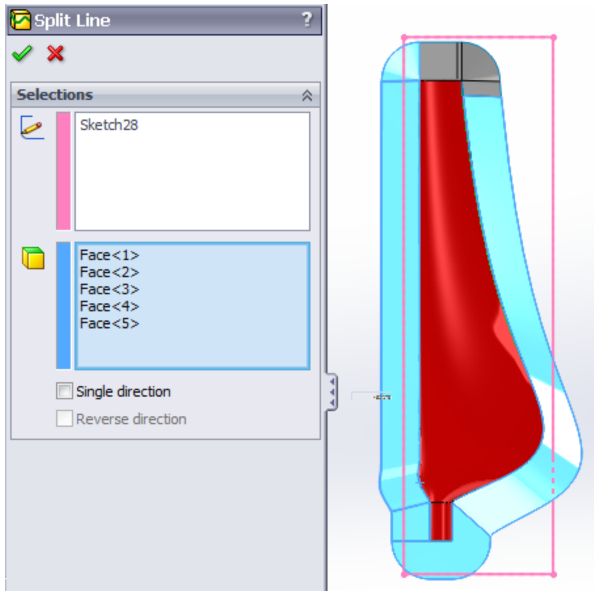
TRIMMING THE PARTING SURFACES

Due to the size of the stock from which the molds can be machined, the machined surfaces of the mold can be no larger than 14x3.9 inches. If your **Parting Surfaces** are larger than this, it will be necessary to trim them.

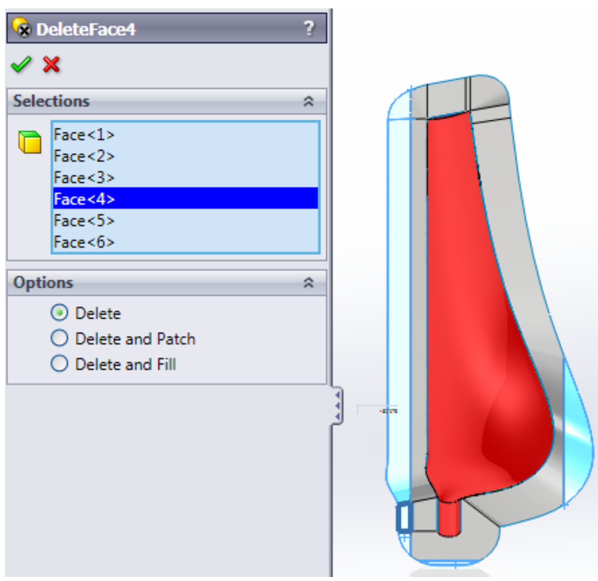
To check the size of the **Parting Surfaces**, create a **Sketch** on the **Split Plane**. Create a rectangle that is 14x3.9 inches. Roughly center this rectangle around the blade. If all of the **Surfaces** fit within the rectangle, you can delete the **Sketch** and skip to the Creating Mold Files section. If the **Surfaces** extend beyond the rectangle, exit the **Sketch** and proceed to trim the necessary surfaces.



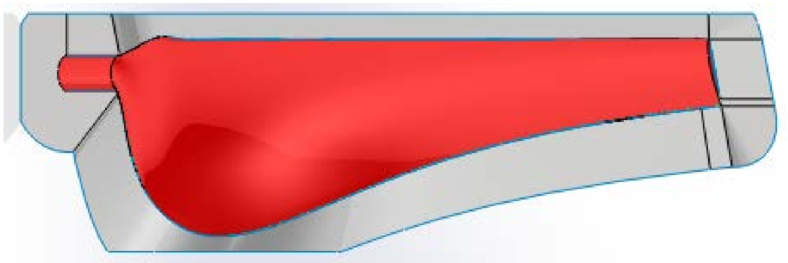
To trim the surfaces, on the **Mold Toolbar**, select **Split Line**. Selection **Projection**, use the **Sketch** you just created as the **Sketch to Project**, and select the faces that the rectangle intersects as the **Face to Split**.



Use the **Delete Face** tool on the **Surfaces Toolbar** to delete the faces that lie outside of the 14x3.9 inch box.

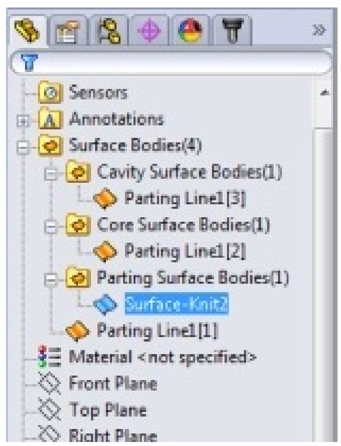


This will ensure that the mold surfaces can be machined.

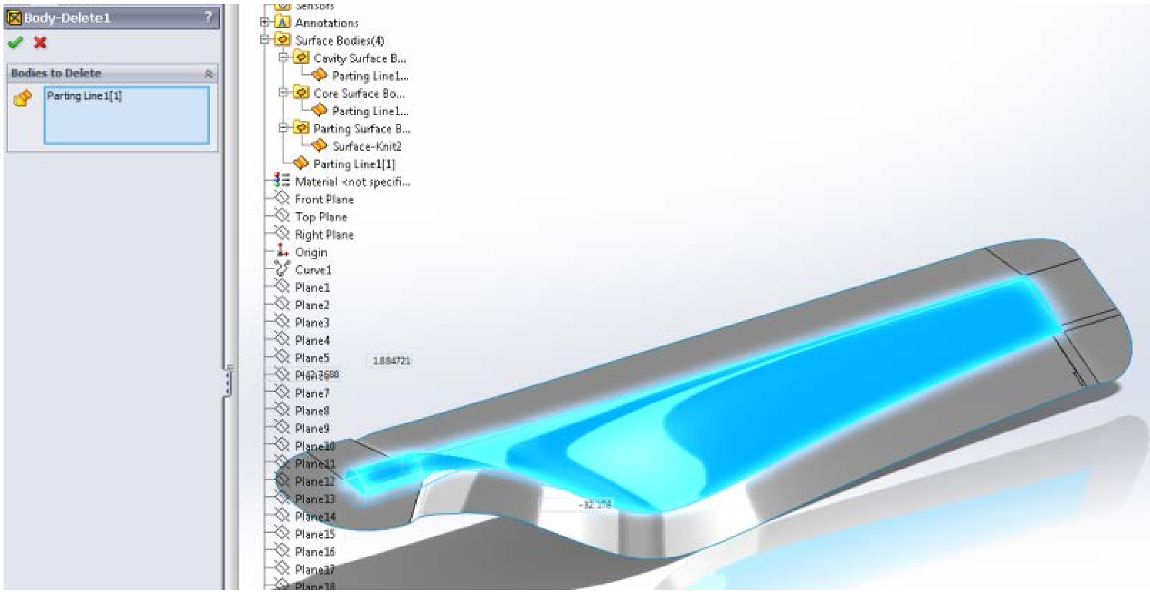


CREATING MOLD FILES

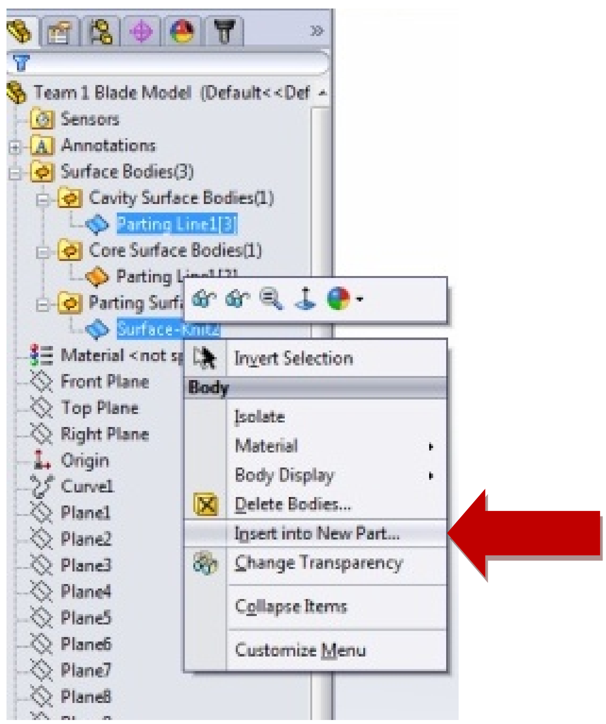
Solidworks will have automatically created three folders in the **Part Tree**. The **Cavity Surface Bodies** and **Core Surface Bodies** folders each represent one half of the mold. The **Parting Surface Bodies** folder is intended to contain the **Parting Surfaces**. Check to ensure that one half of the blade is in the **Cavity Surface Bodies** and **Core Surface Bodies** folders. Confirm that the **Parting Surfaces** are in the **Parting Surface Bodies** folder. If any of these are not in the correct folder, drag them into the right folder.



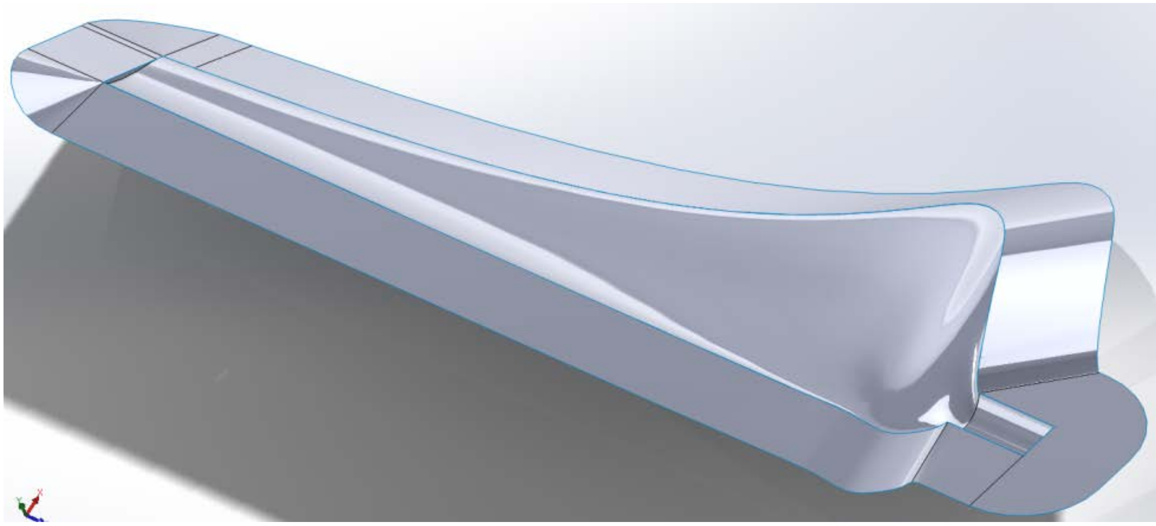
You likely will a redundant **Surface Body** consisting of the entire blade. This is no longer necessary, so right click it and select **Delete Body...** to delete it.



The next step is to create two new files containing each half of the mold. Select both the **Parting Surface Bodies** and the **Cavity Surface Bodies**. Right click and select **Insert into New Part...**

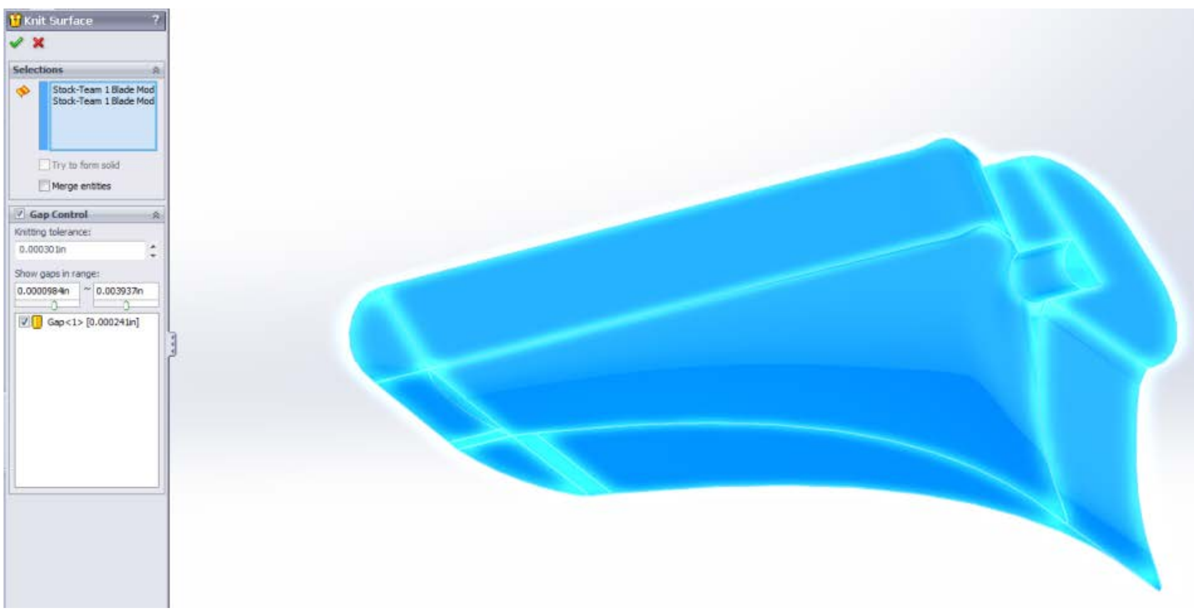


The **Save As** dialogue will open. Name your mold half as either the front (upwind) or rear (downwind) mold half and save it. The file should include the **Parting Surfaces** and only one half of the blade. It will be zero-thickness.

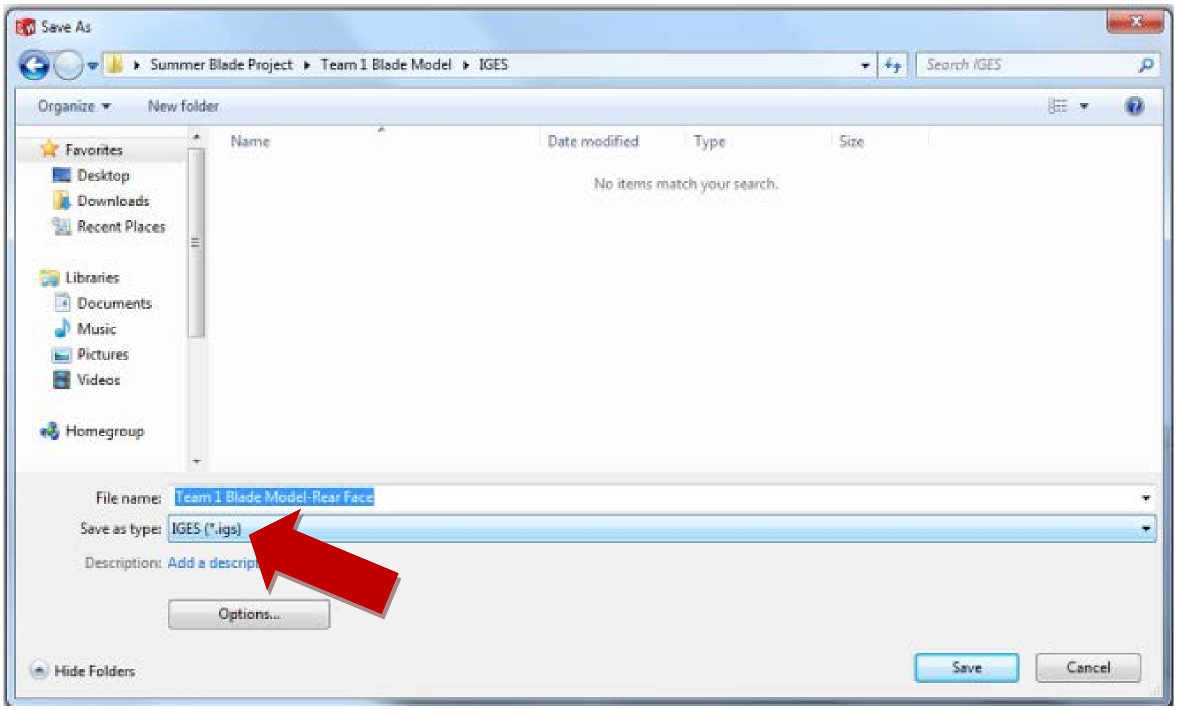


Use the **Knit** tool to **Knit** the **Parting Surfaces** and blade half. If necessary, check the box(es) to close any gaps.

Note: *It is possible that gaps or overlap too large for the **Knit** tool to correct will remain. While not ideal, if small enough, these will not impact the machining of the molds and can be left uncorrected.*



Click **File>Save As** and save the file as a **IGES** (**.igs**) file. **IGES** is a non-proprietary interchange file format for **CAD** data.



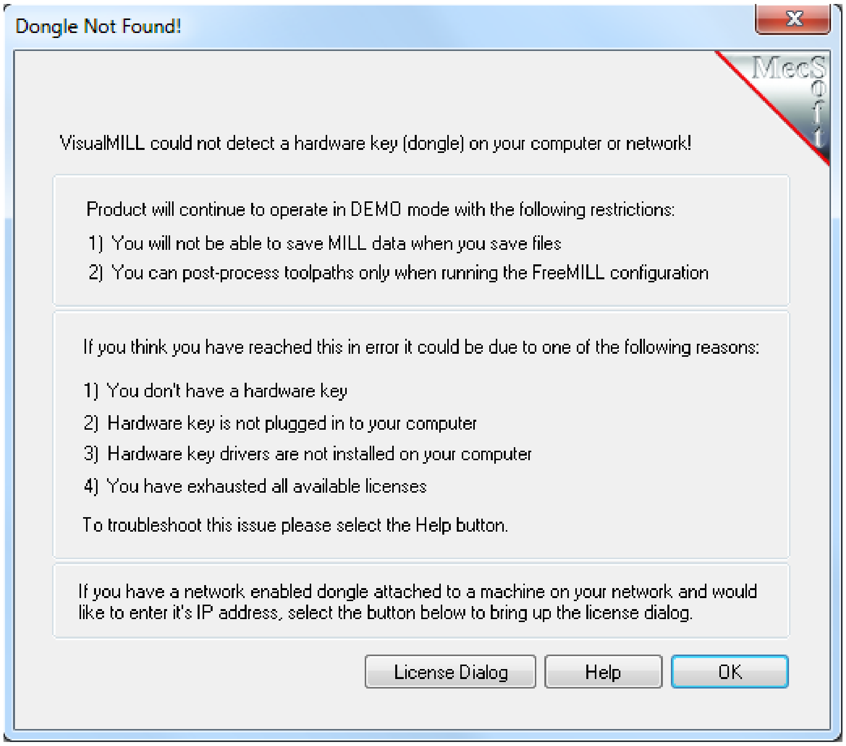
PREPARING THE MOLD FILES FOR MACHINING

To machine the molds, G-code must be generated which will be used to program the CNC router. Solidworks does not have the built in capability to do this. CAM (Computer-Aided Manufacturing) software is used to do this.

VISUALMILL SOFTWARE

There are many CAM programs, but this guide will utilize the demo version of MecSoft VisualMILL. This program is freely available for download. While the demo version has limited capabilities, it does have the necessary features and is comparably intuitive to use. This program can be downloaded from MecSoft's website: http://mecsoft.com/downloadvisualmill/ You will need to provide an email address to download the software.

Once you have downloaded and installed the program, open VisualMILL. You will see the following screen. Click the **OK** button.

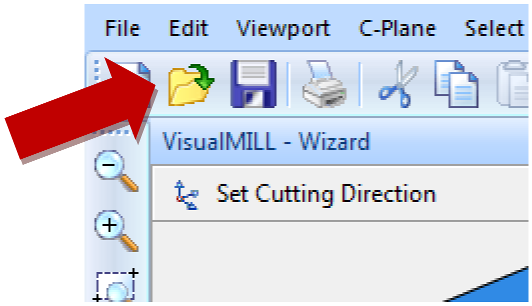


The start screen will appear. Select **FreeMILL** and click **OK**.

PART ORIENTATION

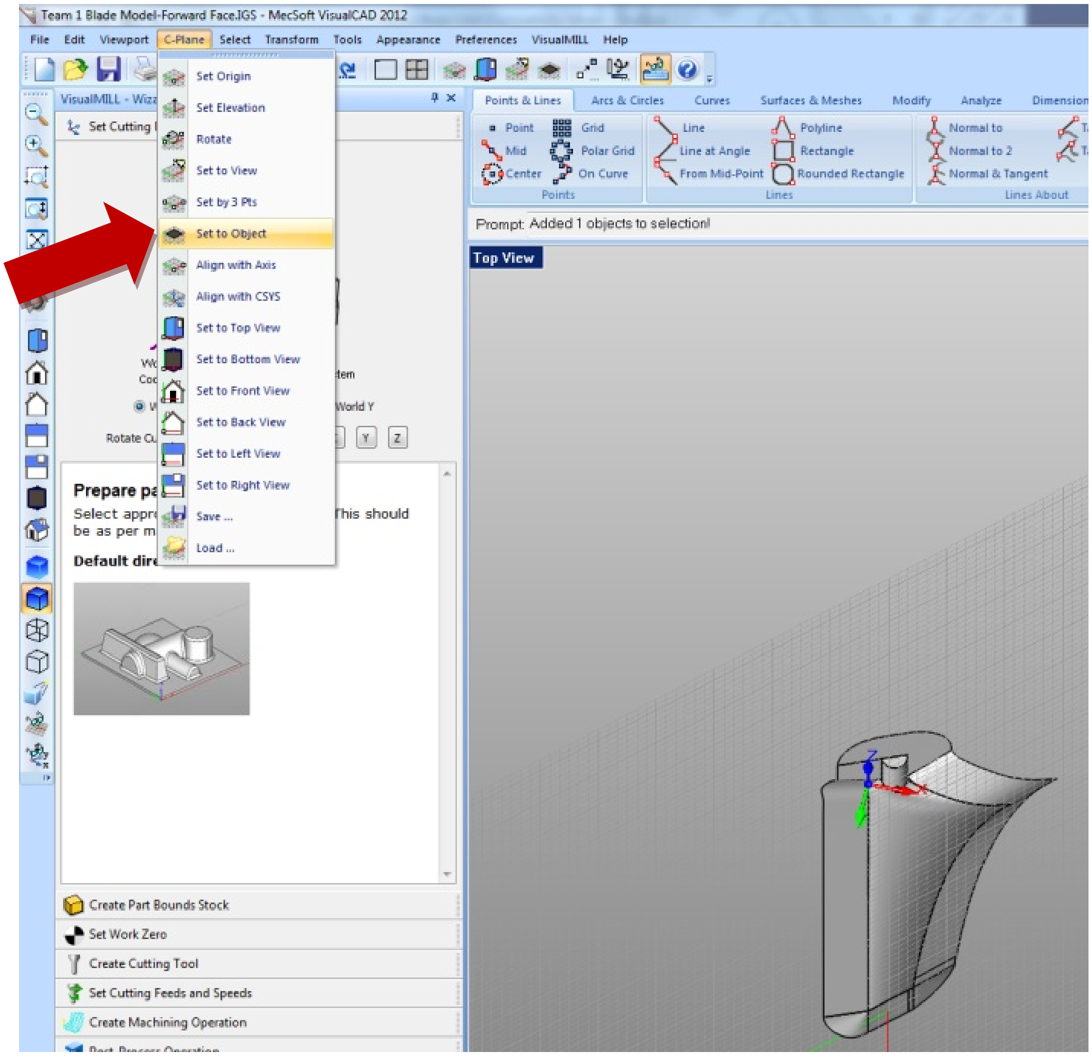
Note: *You will NOT be able to save during this process using the demo version of this software. You must complete the entire process to output G-Code before closing the program.*

Open one of the **IGES** mold files you created in Solidworks.

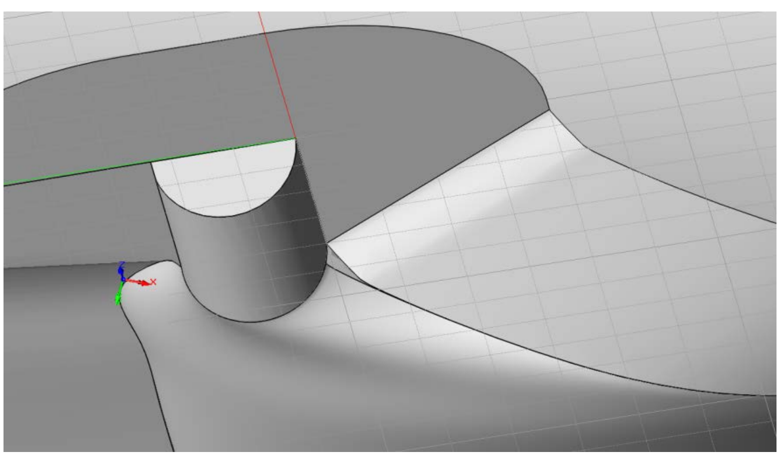


Your mold should appear in the **ViewPoint**. To rotate the part, hold down the right mouse button and drag. To zoom, scroll.

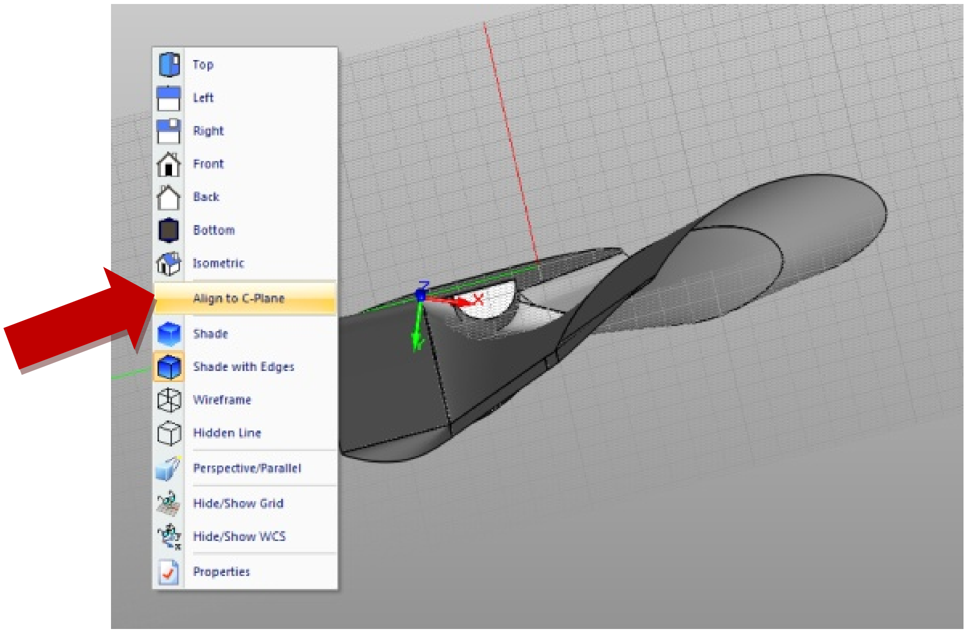
Click **C-Plane>Set to Object** to adjust the position of the **C-Plane** (**Construction Plane**). Clicking a point on the part will make the **C-Plane** tangent with that point. The endmill will be positioned normal to the **C-Plane** during machining. The goal is to position the **C-Plane** so that the depth of the part in the direction normal to the plane is roughly minimized. This will minimize the quantity of material that needs to be removed during the machining process. The **Parting Surfaces** you created surrounding the blade root may provide an adequate point to use.



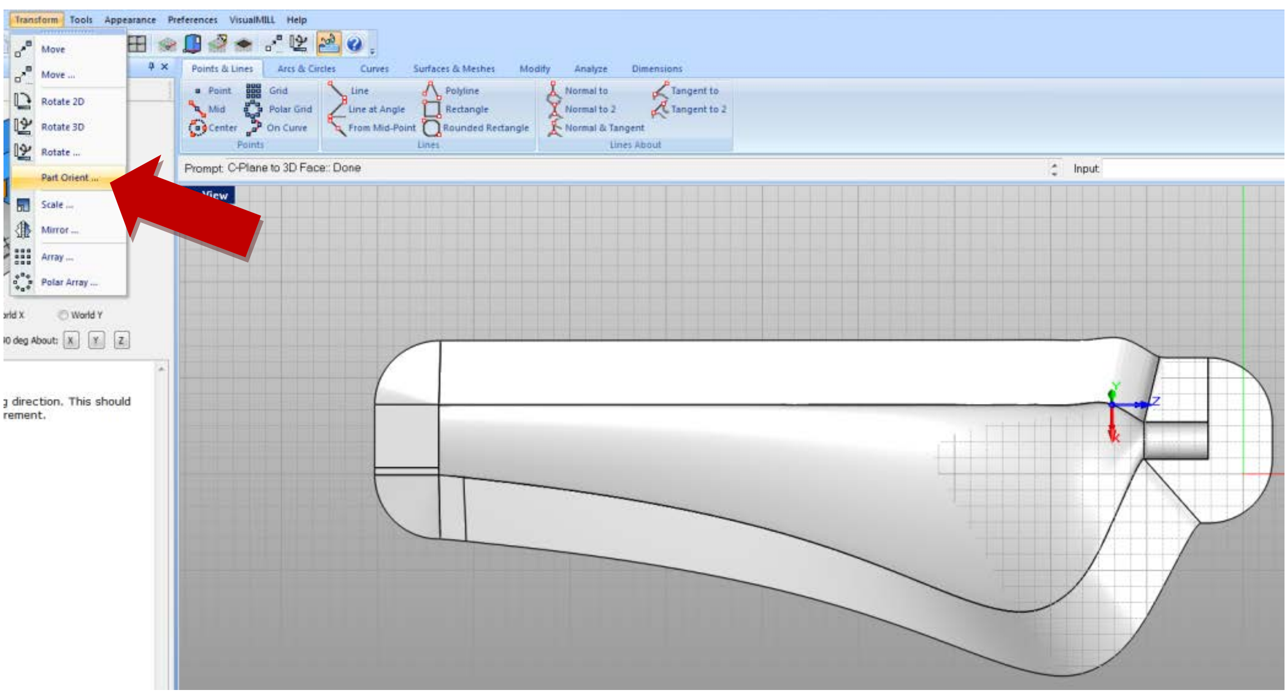
Once you have selected a point, the **C-Plane** will be moved so as to be tangent with this point. This will be visible in the **Viewpoint**.



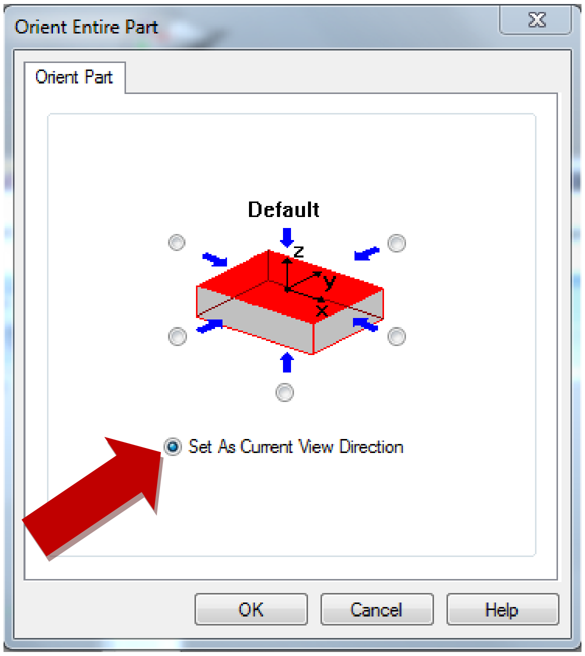
If you need to adjust the **C-Plane**, you can also use the other **C-Plane** tools such as **C-Plane>Set by 3 Pts**. Once the **C-Plane** has been appropriately positioned, right click on the **Viewport** (without selecting a part geometry) and click **Align to C-Plane**.



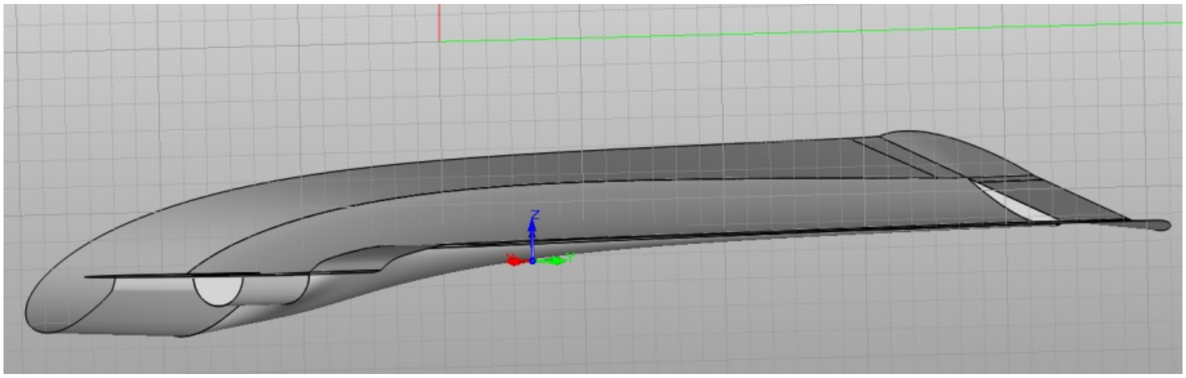
This view will now have moved to face the **C-Plane**. Click **Transform>Part Orient...**



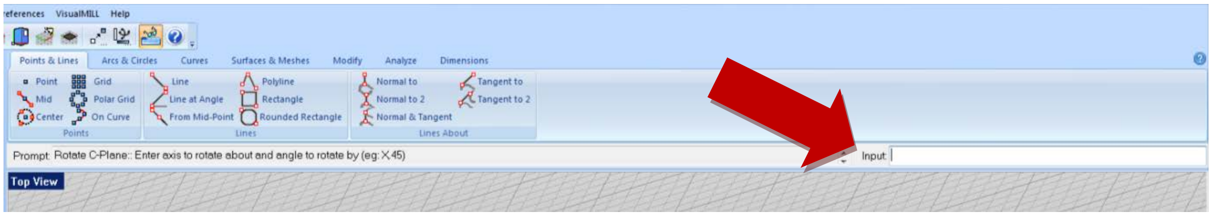
A window will open. Select **Set As Current View Direction**. Click **OK**. This will align the **Coordinate Axes** with the **Viewpoint** and **C-Plane**.



Check that the **Z-Axis** is now normal to the prior location of the **C-Plane**. Because this will be a female mold, the **Z-Axis** should be pointing towards what will become the interior of the blade. If the **Z-Axis** is inverted, again click **Transform>Part Orient...** and, this time, select the arrow facing upwards before clicking **OK**. The **Z-Axis** should now be facing the correct direction.



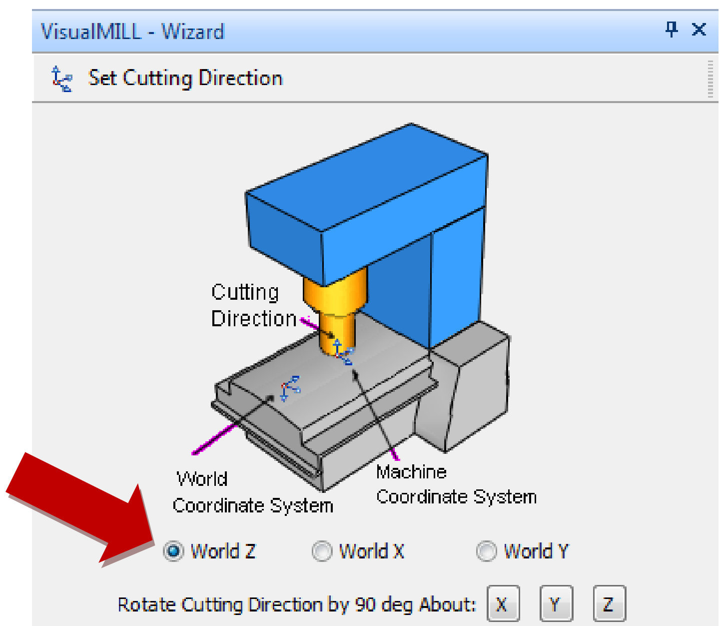
For consistency while machining, the **X-axis** must point along the length of the blade. If it is not already properly positioned, you must use the **Transform** and **C-Plane** tools to correct this. The **C-Plane** will no longer have the same orientation relative to the part. This can be corrected, by clicking **C-Plane>Align with CSYS**. This will align the **C-Plane** with the **Coordinate Axes**. The green line on the **C-Plane** corresponds with the **Y-Axis** and the red line with the **X-Axis** of the **C-Plane**. The **C-Plane>Rotate** tool can be used to rotate the **C-Plane** relative to the **Coordinate Axes**. The rotation can then be entered into the **Dialogue Box** (e.g. X,45) to rotate the **C-Plane**.



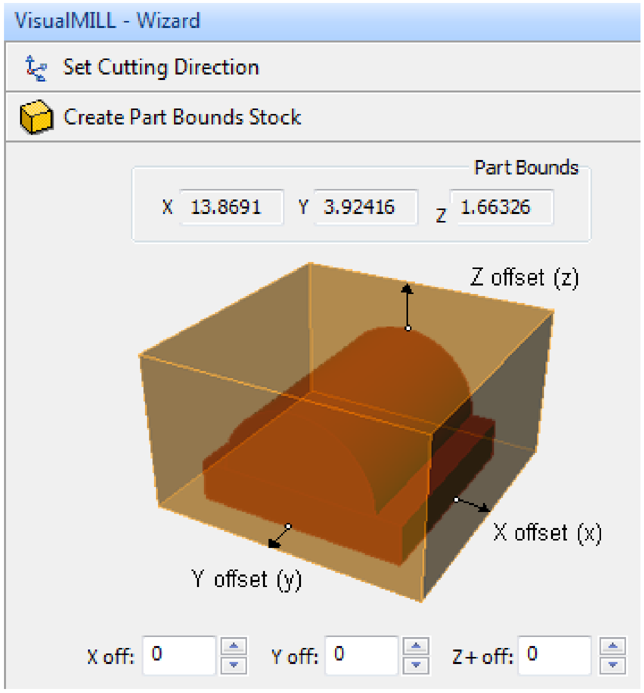
Once the C-Plane is properly orientated, again right click on the **Viewpoint** (without selecting a part geometry) and click **Align to C-Plane**. Click **Transform>Part Orient...** A window will open. Select **Set As Current View Direction**. Click **OK**. Confirm that the **Coordinate Axes** are properly orientated.

VISUALMILL WIZARD

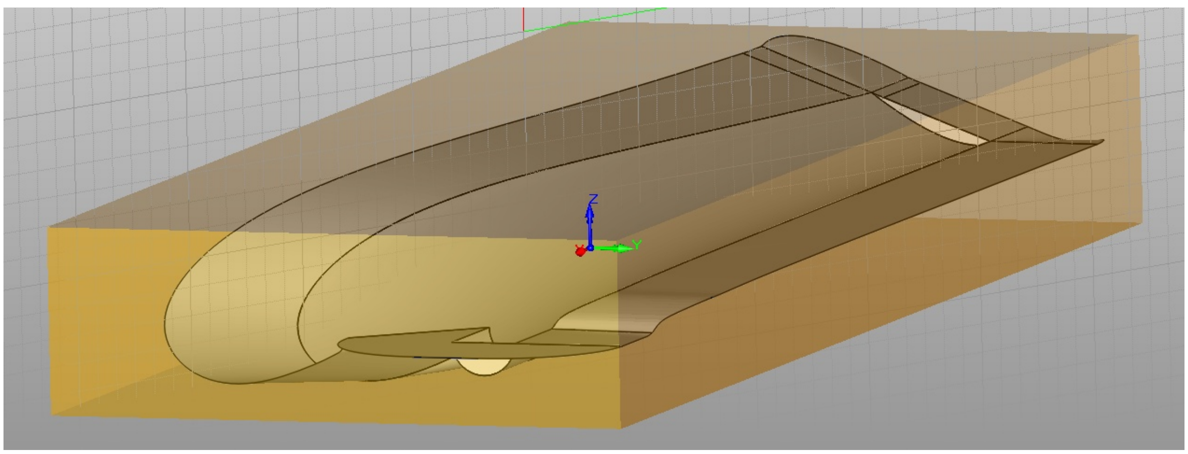
The VisualMill **Wizard** will be located on the left hand of your screen. Now that the mold is properly orientated, you will need to sequentially go through the steps in the **Wizard** to prepare the mold for machining. Under **Set Cutting Direction**, check that **World Z** is selected. This will orient the part so that the endmill will be pointing in the negative-Z direction.



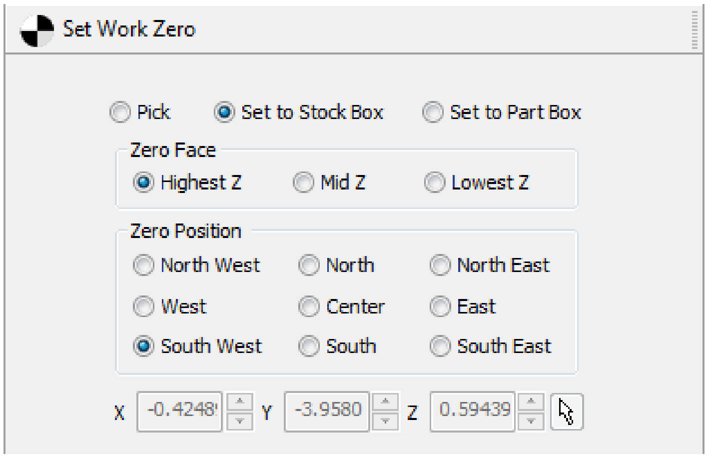
Select **Create Part Bounds Stock** in the **Wizard**. This will allow the size of the initial stock to be machined to be set. VisualMill will automatically define the smallest possible rectangular stock oriented so that the faces are normal to the coordinate axes. Confirm that the stock size is less than 14 inches in the X-direction and 4 inches in the Y-direction. If the thickness is greater than 2 inches, this can be compensated for when casting the wax block that will be machined. There is no need to adjust the size of the stock in the **Wizard**.



The **Stock** will be displayed in the **Viewpoint**.

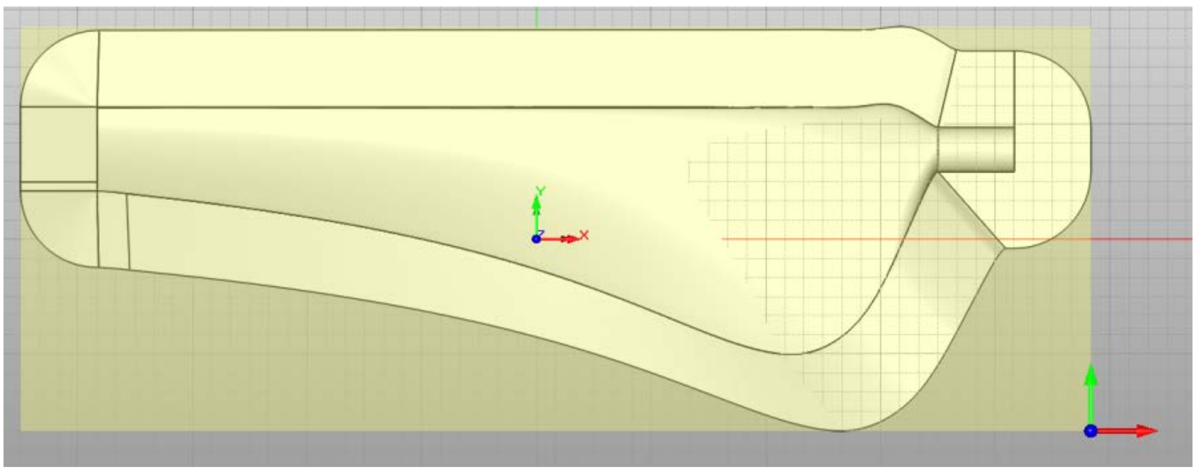


Click **Set Machine Zero** in the **Wizard**. The **Machine Zero** is the point that the CNC router will consider to be (0,0,0,). Select **Set to Stock Box**. The **Stock Box** will appear in the **Viewpoint**. A second set of larger axes will be visible. These represent the **Machine Zero**. Under **Zero Face**, select **Highest Z**. This will locate the **Machine Zero** on the top face of the Stock Box.

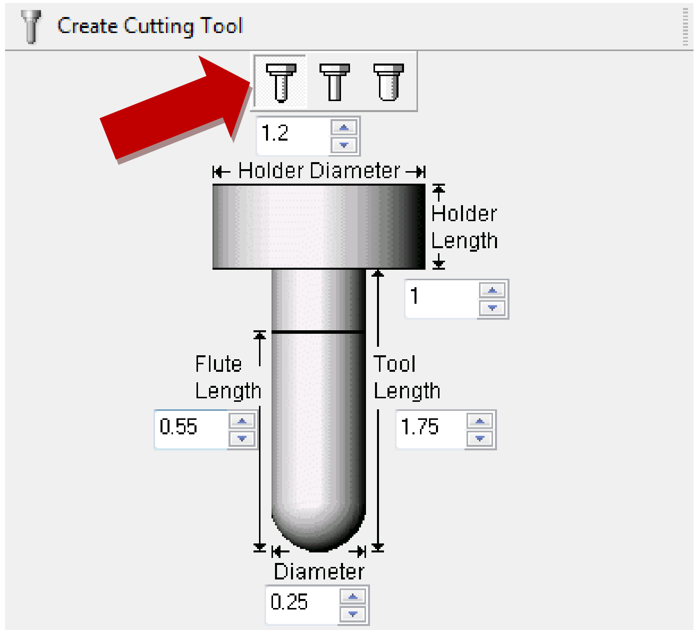


Set the **Zero Position** so that the **Machine Zero** is located on the **South West** corner.

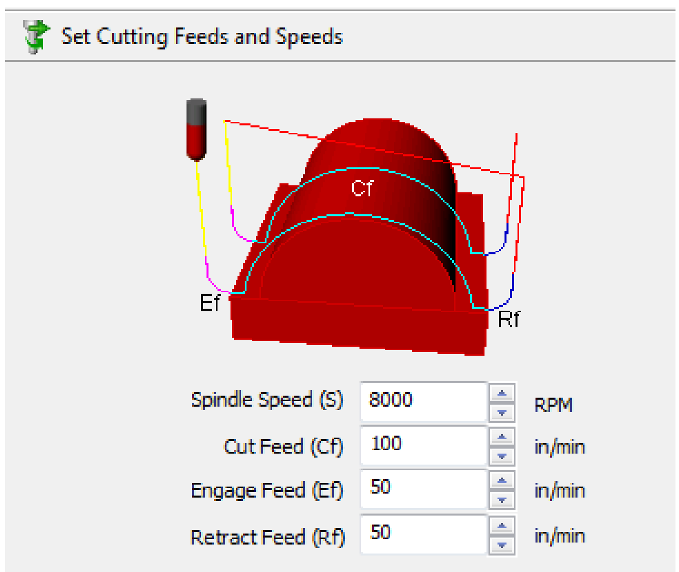
Note: *While any Machine Zero can be used if the CNC Router is set up appropriately, for consistency, it is important that you use the same arrangement described here.*



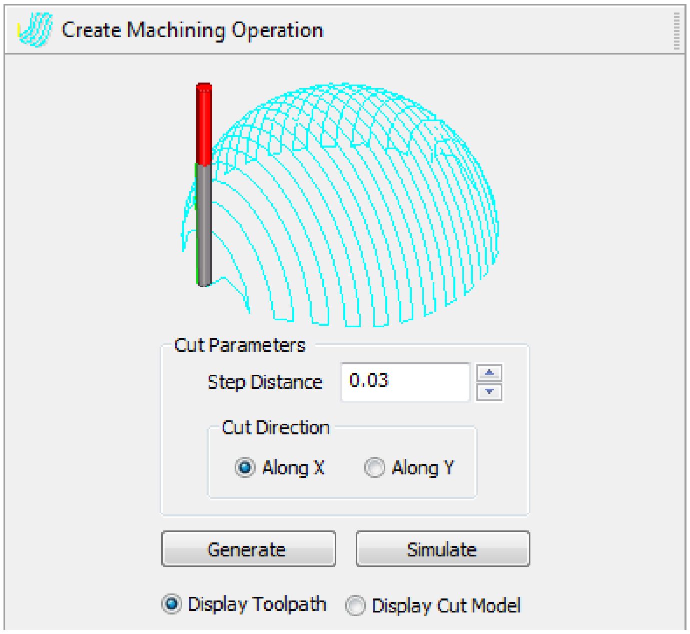
Select **Create Cutting Tool** in the **Wizard**. Select the **Ball End Mill**. Set the **Holder Diameter** to 1.2, the **Holder Length** to 1, the **Flute Length** to .55, the **Tool Length** to 1.75, and the **Diameter** to .25. This will define the dimensions of the cutting tool.



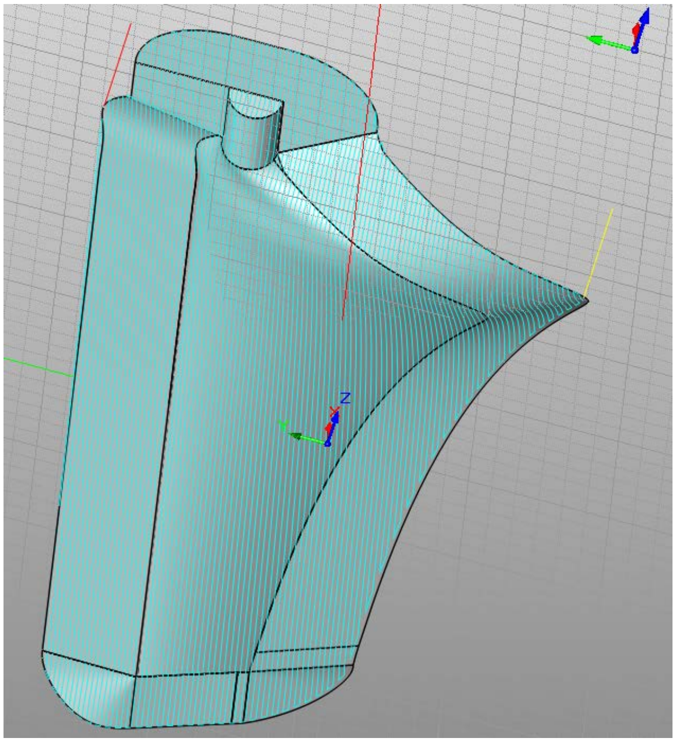
Select **Set Cutting Feeds and Speeds** in the **Wizard**. Set the **Spindle Speed** to 8,000 RPM. Set the **Cut Feed** to 1000 in/min. Set the **Engage Feed**, and **Retract Feed** to 100 in/min.



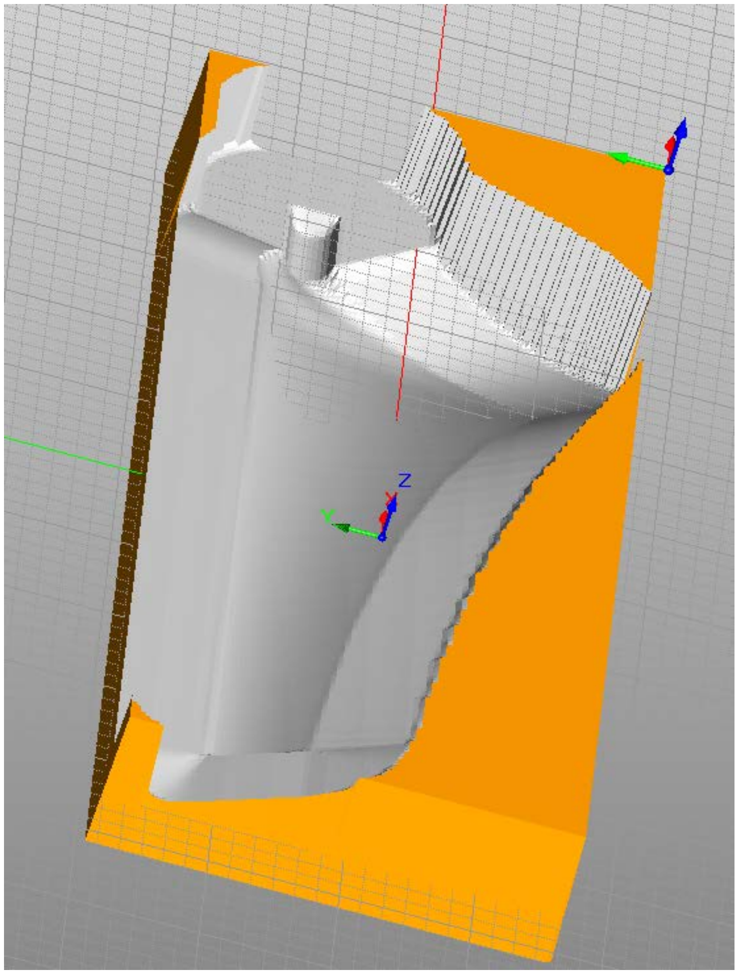
Select **Create Machining Operation** in the **Wizard**. Set the **Step Distance** to 0.03. Select **Along X** as the **Cut Direction**. Select **Display Toolpath**. Click the **Generate** button.



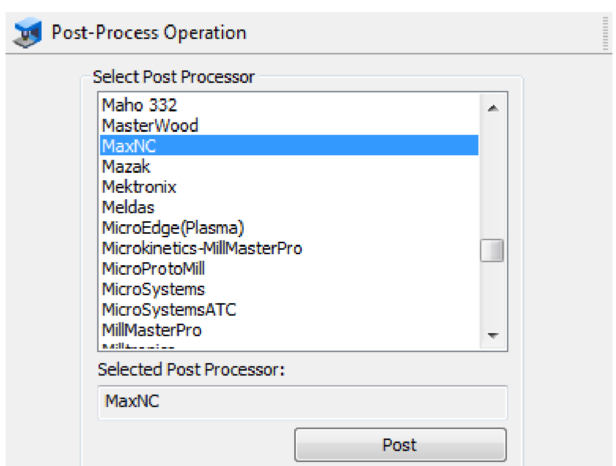
A toolpath will be displayed with blue lines. These should be orientated so as to run along the length of the blade. The **Engage** and **Retract Feeds** will be shown in red and yellow.



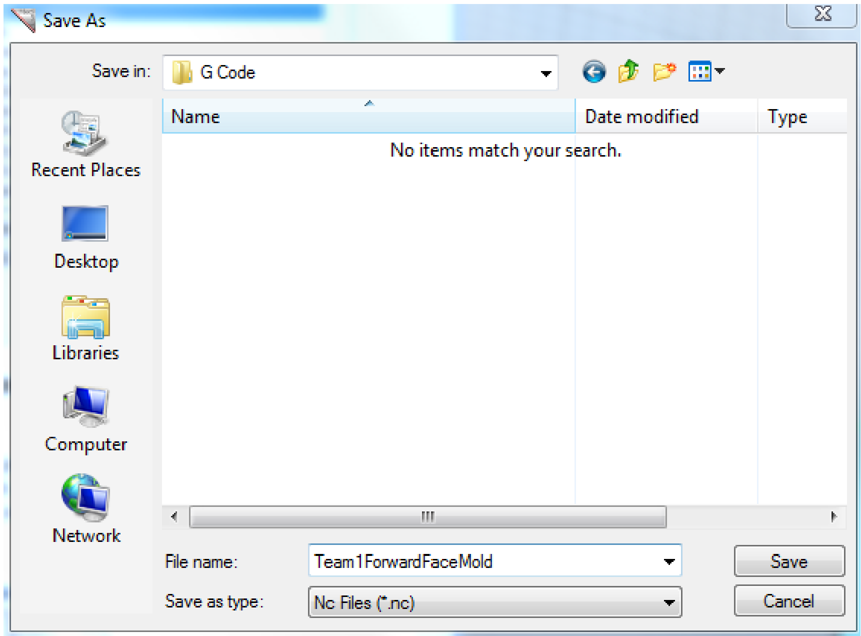
If you select **Display Cut Model** and then click the **Simulate** button, a model of the machined part will appear.



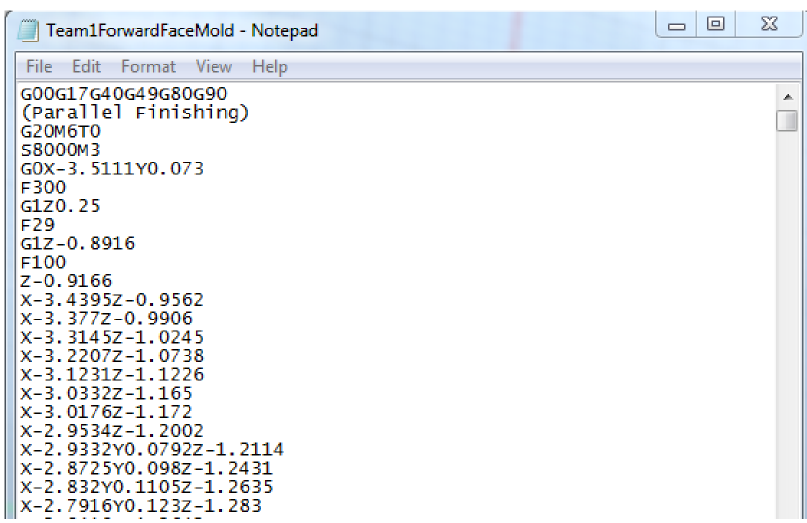
Select **Post-Process Operation** in the **Wizard**. This will output the toolpath as G-Code that can be used by the CNC router. Select **MaxNC** as the **Post Processor**. Click the **Post** button.



The **Save As** window will open. Save your G-code. Make sure to use a filename that fully identifies the file. The **MaxNC** software will display only the first six characters of your filename. It is therefore suggested that you ensure that the first six characters of your filename will be enough to identify your file.



G-Code can be opened using any text editor.




```
G00G17G40G49G80G90
(Parallel Finishing)
G20M6T0
S8000M3
G0X-3.5111Y0.073
F300
G1Z0.25
F29
G1Z-0.8916
F100
Z-0.9166
X-3.4395Z-0.9562
X-3.377Z-0.9906
X-3.3145Z-1.0245
X-3.2207Z-1.0738
X-3.1231Z-1.1226
X-3.0332Z-1.165
X-3.0176Z-1.172
X-2.9534Z-1.2002
X-2.9332Y0.0792Z-1.2114
X-2.8725Y0.098Z-1.2431
X-2.832Y0.1105Z-1.2635
X-2.7916Y0.123Z-1.283
```

CASTING WAX BLOCKS FOR MACHINING

Each half of the mold will be machined from a block of machining wax. Machining wax is easily machined, dimensionally stable, non-porous, non-abrasive, and self-lubricating. As a result, it has ideal machining properties and epoxy will not adhere to it. Unlike molds made of most other materials, a smooth-surfaced mold made of machining wax requires no additional finishing processes. Machining wax can be melted and poured into a mold to produce a desired shape. This means that machining wax can be easily recycled and reused. Machining wax is comparatively expensive and soft, so it is not a suitable material for large-scale or production tooling. However, in this case, it provides an ideal mold material.

Note: The color of m*achining wax can vary. The blue and purple waxes are otherwise identical products from different manufacturers.*

MELTING THE WAX

It will be necessary to cast an appropriately sized block of machining wax for each mold halve. A slow cooker will be provided to melt the wax and loaf pans will be provided to serve as molds for the wax. Use the provided slow cooker to melt the wax. To create a 2 inch high block, roughly 3.5 lb will need to be melted. If you require a thinner or thicker block for your molds, you can adjust the quantity of wax accordingly. Turn the slow cooker to **High**, cover it, and wait. Melting the wax will take 5-6 hours. You can stir the wax once or twice to mix it and break up any chunks. Resist the urge to stir it more frequently; repeatedly opening the slow cooker will only delay the process.

Note: *If you are melting wax shavings, you may need to melt a batch and then add more shavings once the first batch has melted in order to fit an adequate quantity of shavings in the slow cooker.*

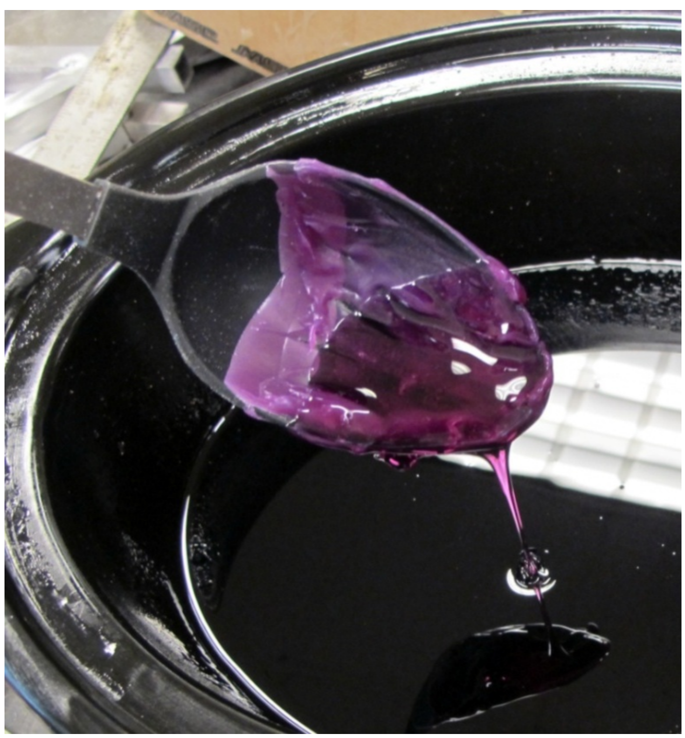
Note: *Machining wax has a melting temperature of around 226° F. To fully melt the wax, it will need to be heated to 270-290° F. If it is heated above 300° F it may begin to burn. These numbers are given as a reference; you should not need to measure the temperature of the wax.*

INSULATING THE WAX MOLD

The wax must cool slowly and evenly or it will crack and/or warp after it has been poured. To ensure that the wax cools properly, the loaf pan must be placed in a cardboard box or other insulating container. Your insulating box does not need to be anything fancy, however it is particularly important that the pan be insulated from whatever surface it is resting on. Ensure that the loaf pan is level.

POURING THE WAX

Once the wax has fully melted and has the consistency of maple syrup, it is ready to be poured.



CAUTION: Take extreme care when pouring the wax to ensure that you do not come in contact with the wax or any other hot items. Use oven mitts and safety glasses.

Do not stir the wax immediately prior to pouring. That way, any metal shavings or other heavy contaminants will remain at the bottom of the slow cooker. If the wax you were melting contained metal shavings or other contaminants, you should pour the wax through a kitchen strainer. To pour the wax, pick up the ceramic liner of the slow cooker using a pair of oven mitts. Slowly pour the wax into the loaf pan. If there is debris at the bottom of the ceramic liner, stop pouring before reaching the debris. Wipe the rim of the ceramic liner with a paper towel before returning the liner to the slow cooker. If you used the kitchen strainer, use paper towels to wipe off as much of the wax as possible from the strainer before the wax hardens. If there is debris at the bottom of the slow cooker, carefully use paper towels to remove it while the wax is still hot. Remember to shut off the slow cooker.

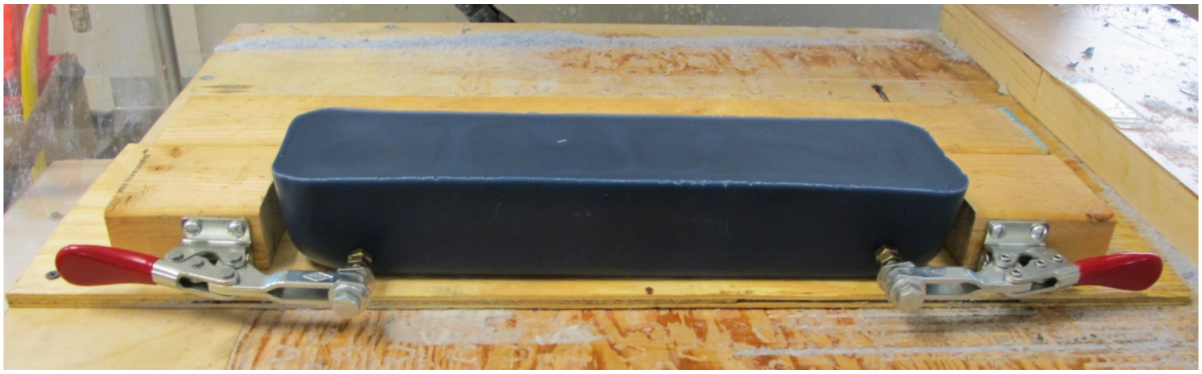
Cover the loaf pan. Leave it to cool for 12 hours. Once it has cooled, you can remove the wax from the loaf pan. Machining wax shrinks approximately 7% when cooling. As a result, it should be relatively easy to remove from the pan.

MACHINING MOLDS

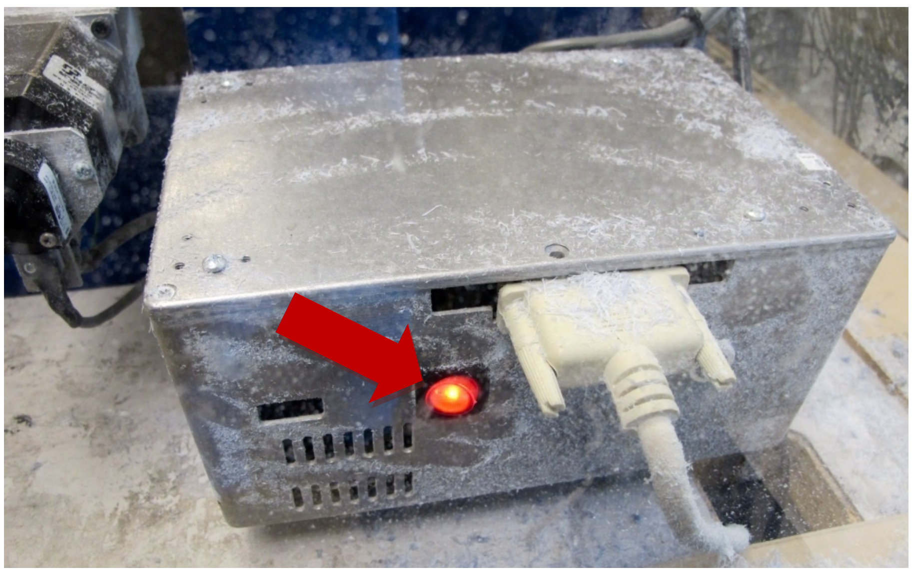
The MaxNC CNC router located in Emerson Lab will be used to machine the molds. Once setup, machining a mold should take one to two hours. Budget at least this much time when machining a mold.

TURNING ON AND HOMING THE ROUTER

Secure the wax block to the router using the toggle clamps on the provided clamping jig.



Turn on the attached computer. Load your G-code files onto the computer. These files must be placed in the **C:\MAXPATH** folder and must be renamed with a **.T** file extension. Turn on the router control box using the red switch.



Open the **Maxpath** program. This software is used to control the router and load your **G-code**. The software is entirely controlled using key-commands. Press **A** to continue. Press the **Caps Lock** key.

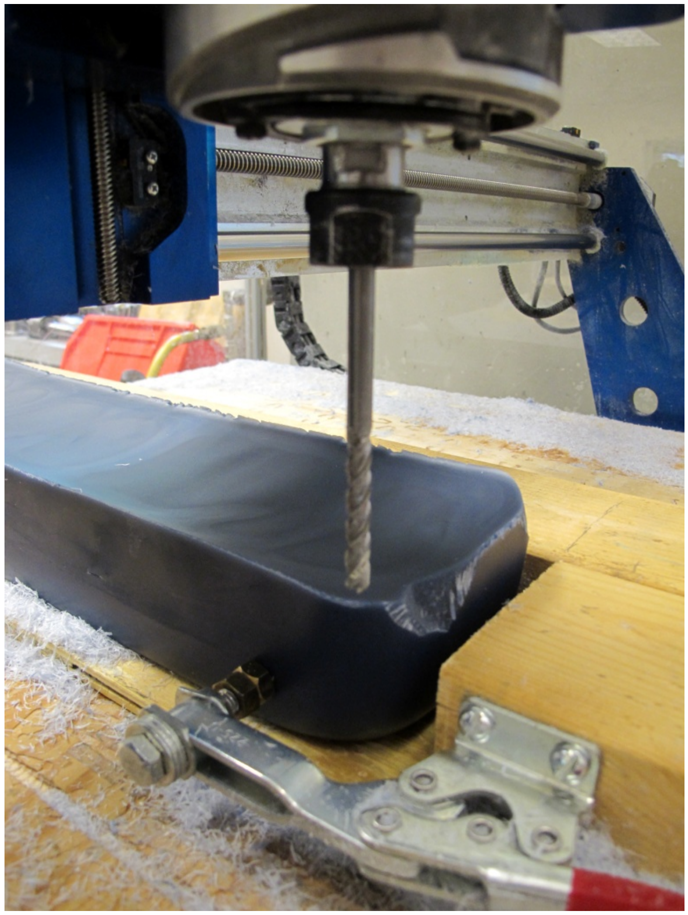
The next step is to **Home** the router. When **Homed**, the router will move in the positive Z direction (up), then the positive Y direction (back), followed by the positive X direction (right) until it reaches the limit switch limiting the motion of each axis. Before **Homing** the machine, check that the machine is clear of obstructions. Press **H** to **Home** the machine. Wait for the router to check all axes and cease moving.

JOGGING AND ZEROING THE ROUTER

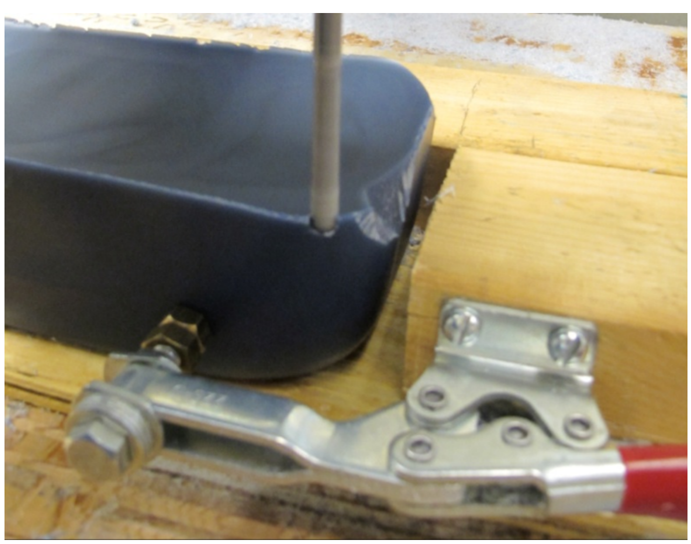
Once the router has been **Homed**, press **C** to continue. Press **5** to **jog** the machine. This will allow you to manually control the movement of the router spindle.

Press **X**, **Y**, or **Z** and then the left or right-hand **Shift** keys to **jog** the machine. The right-hand **Shift** key will move the router in the selected positive direction while the left-hand **Shift** key will move the router in the selected negative direction.

The next step is to position the router where you would like your **Zero** to be. Position the router so that the tip of the end mill lies just over the **South West** corner of the wax block.



Turn on the router spindle using the black switch located on top of the router. Shut the Plexiglas door. Using the **Jog** commands, lower the router so that the tip of the end mill plunges roughly 1/8 inch. into the wax block. This will ensure that the machined surfaces will not extend beyond the top surface of the wax block. Open the Plexiglas door and shut off the router spindle.

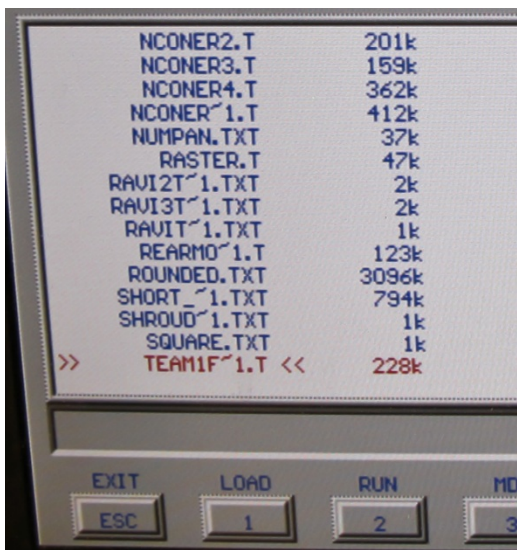


Press **M** to return to the **Main Menu**. Press **6** and then **0** to zero all axes. Press **M** to return to the **Main Menu**.

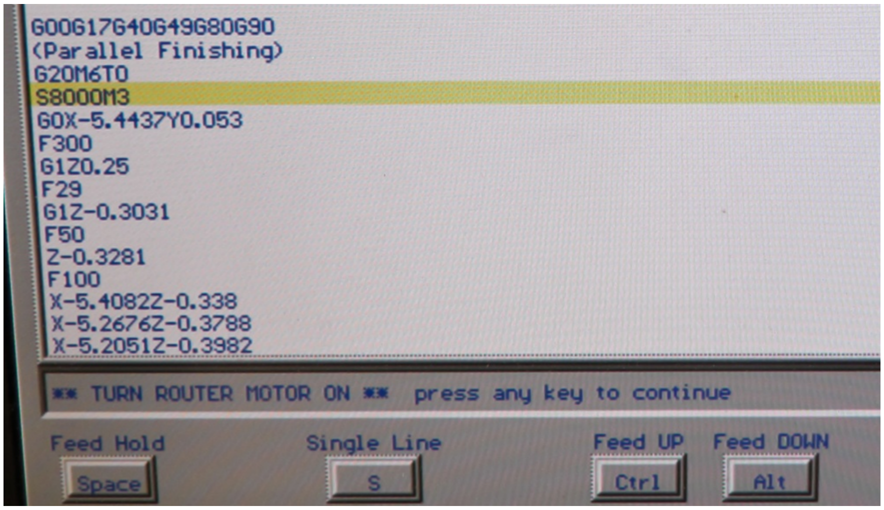
LOADING AND TESTING THE G-CODE

Press **1** and then **Enter** to load your **G-code**.

The files contained within the **C:\MAXPATH** folder will be displayed. Use the **Up** and **Down** arrow keys to locate your file. Press **Enter** to select it.



It is a good idea to check that the machine is properly configured and will behave as intended before machining the wax block. To do so, remove the wax block. Then, press **2** to **Run** the file. Check for any obstructions and then press any key to continue. If at any point you need to stop the motion of the machine, press the **Space Bar**. Watch the movement of the machine for several minutes to confirm that the programming appears correct and the end mill will not come in contact with the clamping jig. Stop the router using the **Space Bar.** Press **M** to return to the **Main Menu**.



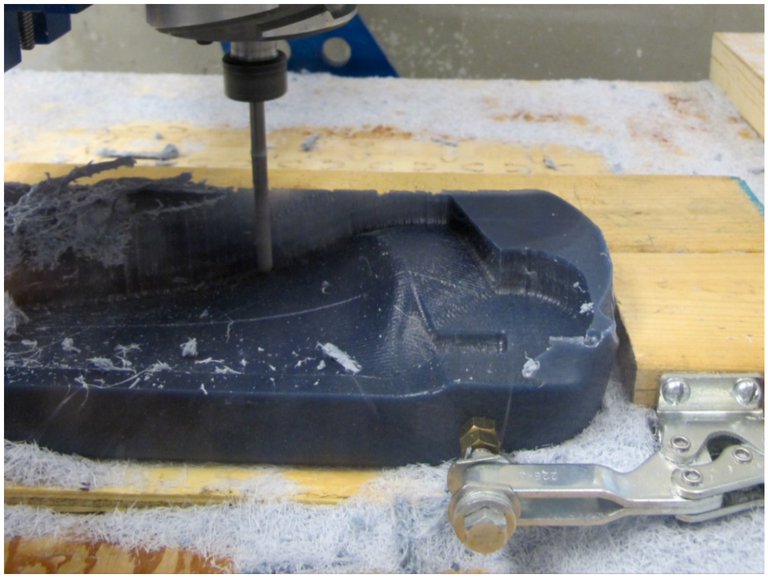
Note: *Pressing the **Space Bar** will pause the movement of the axes. It will not, however, stop the spindle. The program can be continued if paused, so do not hesitate to press the **Space Bar** if you have concerns about the operation of the machine or need to leave it unattended.*

MACHINING THE MOLD

Press **3** to enter **MDI** mode to return to your zero. Enter **0X0Y0Z** and press **Enter** to move the router to the point that was previously set as zero. Reposition the wax block and clamp it in place.

Return to the **Main Menu** and reload your **G-code** by pressing **1** and then **Enter**. Use the **Up** and **Down** arrow keys to locate your file. Press **Enter** to select it. Turn on the spindle using the black switch. Shut the Plexiglas door. Then, press **2** to run the file. Check for any obstructions and then press any key to continue.

The machining process should take one to two hours. The router will need to be supervised to ensure that nothing unexpected occurs. Once the machining process is complete, return to the **Main Menu**. Raise the router by pressing **5** to **jog** the machine. Then press **Z** and hold down the right-hand **Shift** key to raise the end mill clear of the mold. Unplug the router spindle and allow the spindle to come to a stop and the dust to settle. Carefully open the Plexiglass door. Remove the mold. Sweep as much of the wax shavings as possible into the clean wax collection box. Avoid contaminating the wax with metal shavings, wood shavings, or other contaminants. This wax will be melted down for reuse.



Repeat the process for the second mold. When complete, shut off the router using the red switch on the control box. Close **Maxpath** by returning to the **Main Menu** and pressing **ESC** followed by **Y**. Shut down the computer.

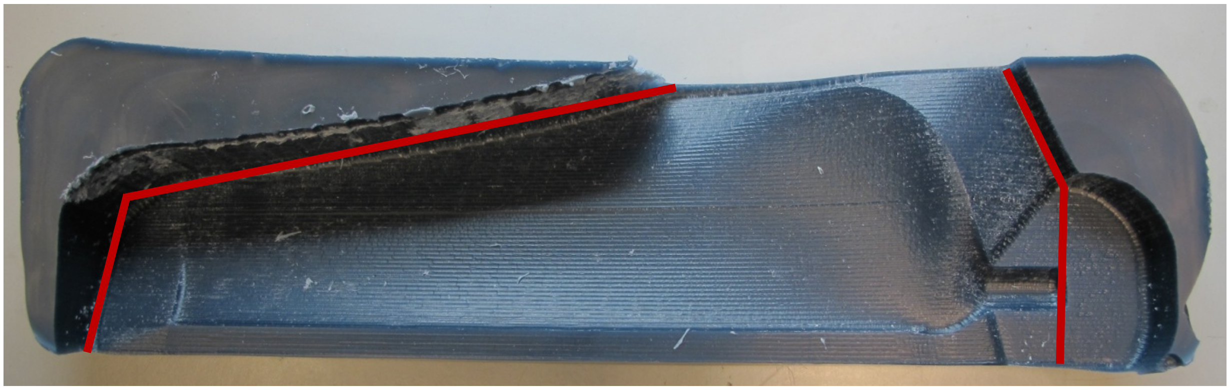
PREPARING MOLDS

Before the mold is ready for use, it must be trimmed with a bandsaw and polished with steel wool.

TRIMMING THE MOLD

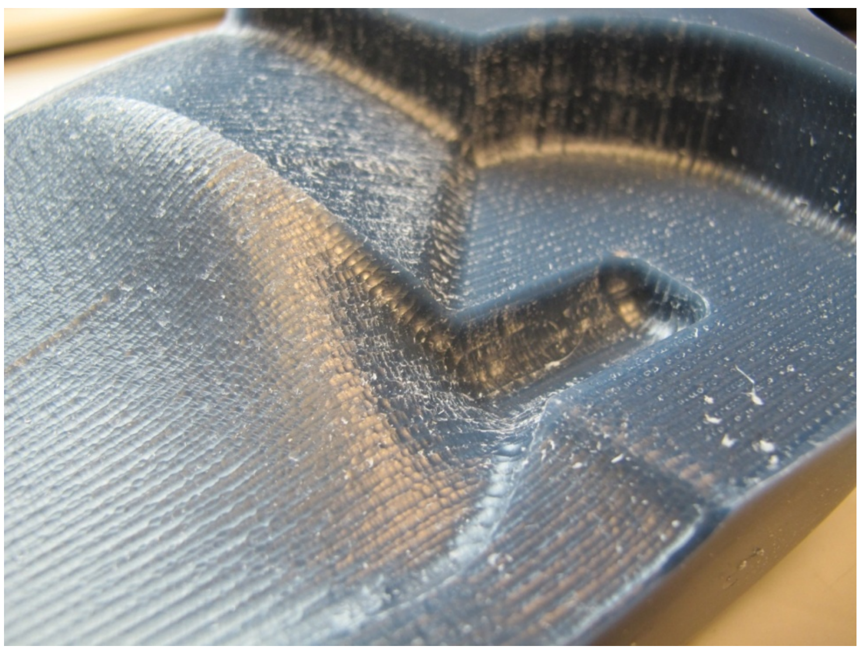
Some sections of the wax block surrounding your blade and parting surfaces will not have been machined. These sections can get in the way when using the mold to layup the fiberglass parts. Remove these sections with a bandsaw, leaving the blade and parting surfaces. In addition, cut along the back edge of the blade root. This will make it easier to make the fiberglass conform to the shape of the blade root.

Before using the bandsaw, ensure that the bandsaw table and blade are free of metal shavings and other debris. Ultimately, your mold will be melted down so that the wax can be reused, so it is important that metallic particles do not become imbedded in you mold. Put the wax pieces you cut from the mold in the clean wax collection box.



POLISHING THE MOLD

The machining process will leave ridges on the surface of the surface of the mold. Before the mold is ready for use, it must be polished to remove these ridges and create a smooth surface. Surface imperfections on the mold will be transferred to the fiberglass parts and may make it difficult to remove the fiberglass parts from the mold once cured.



It is important to take the time to completely smooth the surface of the mold. To do so, use 000 grade steel wool to polish the mold. You want to completely remove the ridges and any other imperfections, however you do not want to remove so much material that you alter the geometry of your blade. Take care not to round any corners or edges on the surface of the mold while polishing it. When finished, no ridges or imperfections should be visible. You only need to polish the surfaces that were machined. The other faces of the mold can be left unfinished. When finished, wash off the mold to clean it.

MANUFACTURING THE BLADES

To manufacture each half of blade, fiberglass and epoxy must be applied to each of the molds and allowed to cure. This process will need to be repeated three times to produce the components for the three blades. Laying up both halves of a blade should take two people one hour. The halves must then cure for at least twelve hours before being removed from the molds. The process can then be repeated to produce the remainder of the blade halves. Once all of the halves have cured and been trimmed, the blades can be assembled. This process should take one hour. Once the blades have been assembled, they will need to cure for at least 12 hours. The blades must then be sanded and any imperfections must be filled before the blades will be ready for testing.

CUTTING THE FIBERGLASS

Each half of the blade will use four layers of 8.5 oz. twill-weave E fiberglass. Since fiberglass is an anisotropic material, half of the layers will be orientated in a 0/90° direction and the other half will be orientated in a +/-45° direction. Half of the layers will be cut and positioned so that the fibers run along the length of the blade and across the blade. The other half of the layers will be orientated so that the fibers run diagonally across the blade.

Note: *Fiberglass is frequently listed as having a weight given in ounces. This specifies the oz./yd.^{2} and the relative weight of the fabric. "Twill" specifies the weave of the fabric. There are two common types of fiberglass: E-glass and S-2 glass. S-2 glass has greater strength and superior properties, however it is more expensive.*

Cut out a paper template to use to mark out the pieces of fiberglass you will use. The template should cover the entire top surface of the mold, including the parting surfaces. It does not need to be exact; it will not matter if the pieces of fiberglass are slightly oversize. It is, however, important that the entirety of the blade surface be covered by the fiberglass.

Note: *Throughout this process avoid distorting the weave or fraying the edges of the fiberglass.*

Use a permanent marker to mark out the eight pieces of fiberglass. Try to closely pack these pieces to avoid waste. Four of these pieces must be orientated in a 0/90° direction and four must be orientated in a +/-45° direction with respect to the weave of the fiberglass. It is recommended that the pieces be marked so that their orientation can be more easily identified. Use scissors to cut out the pieces. Small scraps of fiberglass can be thrown out.

The pieces will be laid on the mold in the following order:

1. 0/90°
2. +/-45°
3. 0/90°
4. +/-45°

It is suggested that you stack the pieces in order in two piles so that the first piece (0/90°) is on top. This will make it easier to keep track of the pieces when laying up the molds.

LAYING UP THE BLADES

Caution: Uncured epoxy is a sensitizer. Wear nitrile gloves when working with epoxy and avoid skin contact.

Raka #127 low viscosity resin and #350 non-blush hardener will be used. This epoxy uses a 2:1 ratio of resin to hardener. The pumps on the bottles are calibrated to disburse a set amount. Squirt two complete pumps of resin and one complete pump of hardener into a mixing cup. Mix the epoxy thoroughly for a minute with a mixing stick. This will provide enough epoxy to lay up both halves of a blade. Once the epoxy has been mixed, it will begin to cure. The epoxy will be usable for around 30-60 minutes until it begins to "gel."

It is recommended that one person work to layup each half of the blade to ensure that the process is completed before the epoxy gels. The ultimate goal is to fully saturate all of the fiberglass with epoxy and eliminate any bubbles, without using more epoxy than is needed. While the portion of the fiberglass covering the blade must be fully saturated and bubble-free, it is not essential that this be true for the fiberglass extending beyond the blade surfaces.

Using gloved hands, cover the surface of the mold with epoxy. Lay down the first layer of fiberglass. Press this layer down. If more epoxy in needed to saturate the fiberglass, add some on top of the fiberglass and massage it into the fiberglass. Try to eliminate any bubbles. Most likely, bubbles will form at the tip and root of the blade where the fiberglass will not easily conform to the mold. It likely will not be possible to fully eliminate these bubbles until the third or fourth layer of fiberglass has been applied to the mold. When the first layer has been fully saturated, lay down the next layer of fiberglass and repeat the process.

Note: *The pieces of fiberglass will stretch. This will likely be particularly apparent when working with the +/-45° pieces. If care is not taken to avoid stretching the pieces, the pieces may stretch until they no longer fully cover the mold.*

Once the fourth layer has been applied and is fully saturated, work to eliminate any remaining bubbles. If any excess epoxy can be easily squeezed out from between the layers, do so. Once the pieces are bubble free, the blade halves are complete. Clean any spilled epoxy before it cures. Allow the fiberglass to cure for twelve hours.

TRIMMING AND SANDING THE BLADE HALVES

Caution: The edges of the hardened fiberglass will be sharp. Be careful not to cut yourself or give yourself fiberglass splinters.

After twelve hours, the blade halves can be removed from the molds. The epoxy will not have reached full strength until 24-48 hours after it has been mixed, so take care to avoid bending the blades or they may be damaged. It should be possible to 'peel' the parts from the molds.

The outer surface of the blade (the surface that was against the mold) should be smooth and largely free of imperfections. The pieces will still need to be trimmed.

Carefully use a permanent marker to mark the edges of the blade. The edge may be difficult or even impossible to see in some areas, particularly along the trailing edge. It may help to first roughly trim the blade halves and then align the opposing halves so that the opposite side can be used as a reference.

Use a diamond grit band saw to trim the blade halves. Ensure that the water reservoir has been partly filled before using the saw. Remember that while you can always trim more material, including after the blade has been assembled, you cannot replace material that you have trimmed. Err on the side of caution when choosing where to cut. Wipe off the saw when finished.

Caution: Wear safety glasses when operating the saw. It is suggested that you wear nitrile gloves because fiberglass powder is itchy and abrasive. Avoid twisting or deflecting the blade or it may snap. Diamond grit blades should not cut your skin if you come in contact with the blade, but avoid testing this.

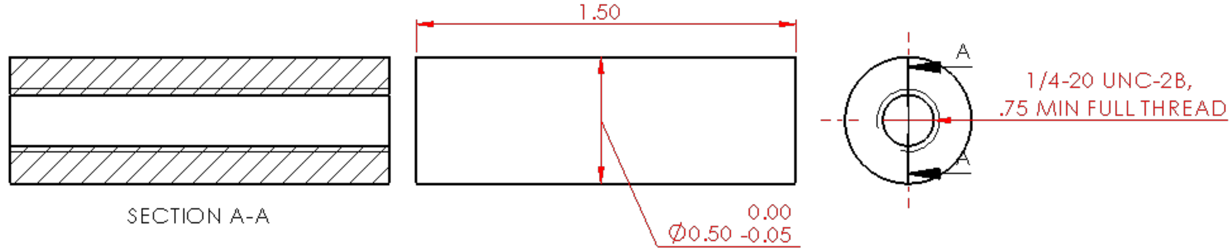
After being trimmed, the blade halves should fit together with minimal gaps.

The pieces will need to be sanded to ensure adhesion and improve the fit of the pieces. Use 100 grit or rougher sandpaper. Rough up the interior sides of the pieces along the edges of the piece. Rough up both the interior and exterior sides of the blade root areas. It may be helpful to bevel the edges of the pieces to allow the pieces to fit more closely together.

Caution: Avoid inhaling fiberglass dust. Fiberglass dust is abrasive and itchy. You may wish to wear nitrile gloves while sanding.

PREPARING FOR ASSEMBLY

One aluminum blade root will be required for each blade. 1/2 inch of the blade root will protrude from the blade when assembled.



The protruding 1/2 inch of each blade root must be masked off using the provided blue polyester **Flash Tape**. If the blade roots have not been entirely tapped, the end of the root that has been tapped must be masked. The portions of the aluminum blade roots that remain exposed must be roughed up with 100 grit or rougher sandpaper.

The root area of the blade will be wrapped using basalt 3K **tow**. Use a pair of scissors to cut a 3 ft. long piece of **tow** from the spool for each blade.

Note: ***Tow** is an continuous untwisted bundle of fibers that comes in spools. The "3K" signifies that each bundle contains 3,000 fibers.*

Note: *Basalt is a less commonly used composite material produced from volcanic rock. Basalt has strength properties that are superior to that of E-glass and comparable to that of S-2 glass. In this case, basalt tow is being used because it is available for purchase in small quantities.*

Heat shrink tube will be used to compress the basalt **tow** around the root of the blade and hold the blade together as the epoxy cures. Cut a 1.5 inch long piece for each blade. This piece will be shrunk around the root of each blade. If the tubing will fit around the tip of the blade, cut a roughly 1/2 inch long piece for each blade. This piece will be used to hold the tip of the blade together as it cures. If the tips of the blades are larger than the tubing, cut a section of **flash tape** to wrap around the tip of each blade.

Note: *While similar to the heat shrink tubing used for electrical applications, this tubing has been chemically treated for use with composites.*

ASSEMBLING THE BLADES

It is suggested that the entire set of three blades be assembled simultaneously. At a bare minimum, two people will be required to do this, though having additional hands is extremely helpful.

Raka #127 low viscosity resin and #350 non-blush hardener will again be used. This epoxy uses a 2:1 ratio of resin to hardener. Squirt two complete pumps of resin and one complete pump of hardener into a mixing cup. Mix the epoxy thoroughly for a minute with a mixing stick.

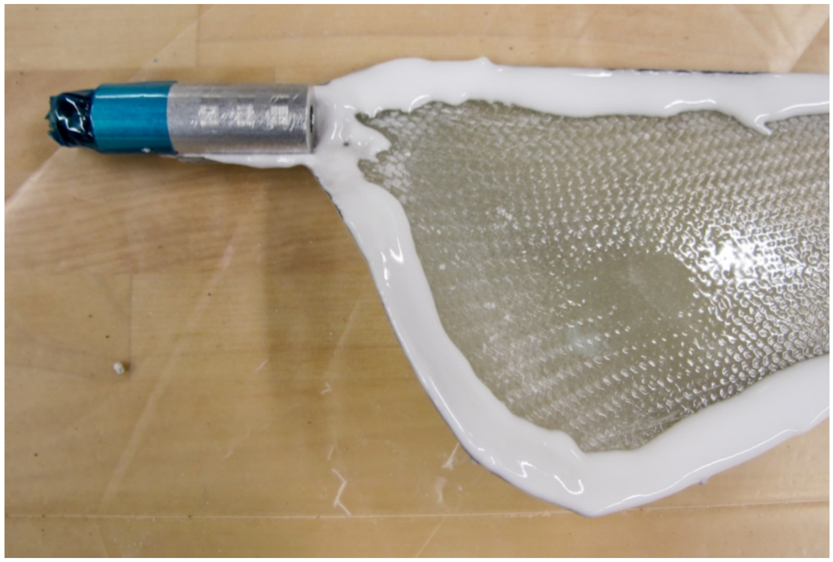
Pour 1/2 of the epoxy into a second mixing cup. This epoxy will be thickened using glass bubbles. Add and mix glass bubbles into one of the mixing cups. Stop adding glass bubbles when the epoxy reaches the consistency of Marshmallow Fluff.

Caution: Avoid inhaling glass bubbles. Glass bubbles are extremely low density. Avoid gusts of air or other disturbances that will aerosolize the bubbles. Wear nitrile gloves when handling epoxy.

Note: *Glass bubbles can be used as an additive for epoxy. Glass bubbles thicken epoxy, reduce its density, and make the hardened epoxy easier to sand.*

Use a finger to spread the thickened epoxy along the edges and blade root of one half of a blade. Spread thickened epoxy along the root and leading edge of the other half of the blade.

Press an aluminum blade root into place on one of the blade halves. The blade root should be positioned so that **flash tape** wrapped section extends beyond the fiberglass blade half.



Press the two halves of the blade together. If there are any areas where the gap between the two halves have not been filled with epoxy, add epoxy to fill the gap. Wipe off any excess epoxy with paper towels. If heat shrink tube is being used to secure the blade tip, slide a 1/2 inch. section of heat shrink tube over the tip of the blade.

Use a heat gun to shrink the tubing so that it tightly compresses around the blade. Heat all sides of the tubing so that it shrinks evenly. Do not get epoxy on the heat gun. If heat shrink tubing is not being used for the blade tip, use flash tape to tightly tape the blade tip together.

Caution: Heat guns can reach over 1000° F. Be extremely careful what you point the heat gun at. The gun and anything that has been heated will remain hot for some time after being turned off.

Note: *As uncured epoxy is heated, its viscosity will decrease. The areas that are heated may begin to drip. Heating the epoxy will also speed the curing process in these areas.*

Wipe up any excess thickened epoxy on the root-area of the blade. Apply a layer of un-thickened epoxy around the root area. Take a length of basalt **tow** and wrap it tightly and evenly around the root of the blade. Overlap the first wrap of basalt **tow** so that can be pulled tight. While wrapping the **tow**, apply additional un-thickened epoxy as needed to ensure that the **tow** is fully saturated.

Slide a 1.5 inch long section of heat shrink tube over the blade root.

Use a heat gun to shrink the tubing so that it tightly compresses around the blade root. Heat all sides of the tubing so that it shrinks evenly. Do not get epoxy on the heat gun. Wipe off any excess epoxy that has been squeezed out by the heat shrink tube.

Check if any gaps have formed along the edges of the blade. If so, add thickened epoxy to fill these gaps. Wipe up any excess epoxy. Allow the blade to cure for at least 12 hours.

FINISHING THE BLADES

Once the blades have cured, use a knife to carefully slice the heat shrink tubing and peel it off. Leave the **flash tape** in place to protect the exposed aluminum while sanding.

The edges of the blades will need to be sanded to round the edges and remove excess material. Use 60 grit sandpaper to shape the edges. Smooth the blade root area, but do not sand completely through the basalt.

When done, the edges should be rounded and smooth.

If there are any gaps or voids in the outer surface of the blade, these areas will need to be filled with Bondo and sanded.

Note: *Bondo is a two-part polyester resin based automotive filler. Bondo hardens quickly and is easily sanded.*

Caution: Bondo is toxic and generates significant fumes. Use only in a well ventilated area and avoid breathing the fumes. Wear gloves when handling.

Mix an appropriate quantity of Bondo. Bondo requires a very small quantity of the red filler to be mixed with a much larger quantity of the grey resin. Look at the relative size of the hardener and resin containers to get a sense of a ratio. The ratio does not be exact. Mix the Bondo in a mixing cup or on a scrap of cardboard or similar material. The mixed Bondo should be slightly pink. Bondo hardens rapidly and will only be usable for a few minutes after being mixed. Apply the Bondo to the necessary areas of the Blade. Wipe or scrape off the excess. When the Bondo starts to become lumpy, stop applying it and mix a new batch. Allow the Bondo to dry for an hour before continuing sanding.

Sand off the excess Bondo using 100 grit sandpaper. When the blade has been properly shaped and all gaps have been filled, sand the entire blade with 220 grit sandpaper to smooth the entire surface. Remove the **flash tape** around the blade root. If any epoxy, fiberglass, and/or basalt extends beyond 1/2 inch. from the end of the blade root, use a knife to carefully trim and remove it. Wash off the blades to clean them, while making sure than water does not enter the blades through the tapped hole in the blade root.

Apply Loctite thread-locking compound to half of a 1 inch long 1/4-20 threaded steel stud. Screw the end of the stud that has been coated with Loctite into the aluminum blade root until 1/2 inch of the stud remains protruding. Allow the Loctite to harden. The blades are now complete and ready for testing.

PAINTING THE BLADES

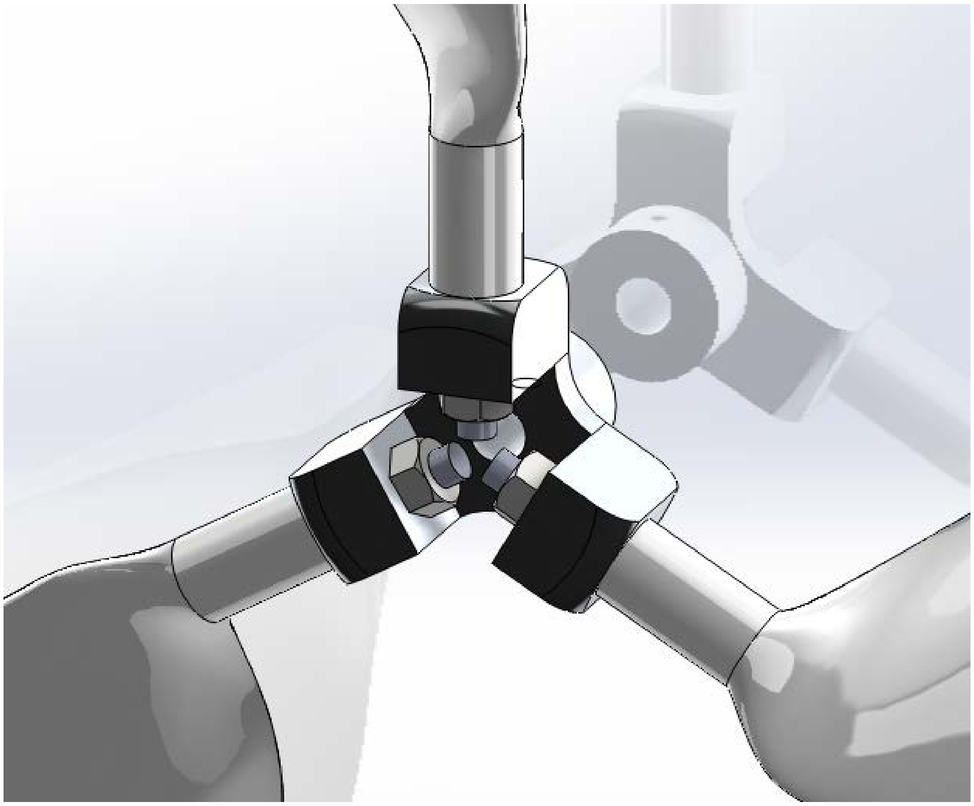
If desired, the blades can be painted with spray-paint. A wooden block with 1/2 inch diameter holes serves as an effective stand for the blades when painting and also serves to mask the exposed aluminum blade roots.

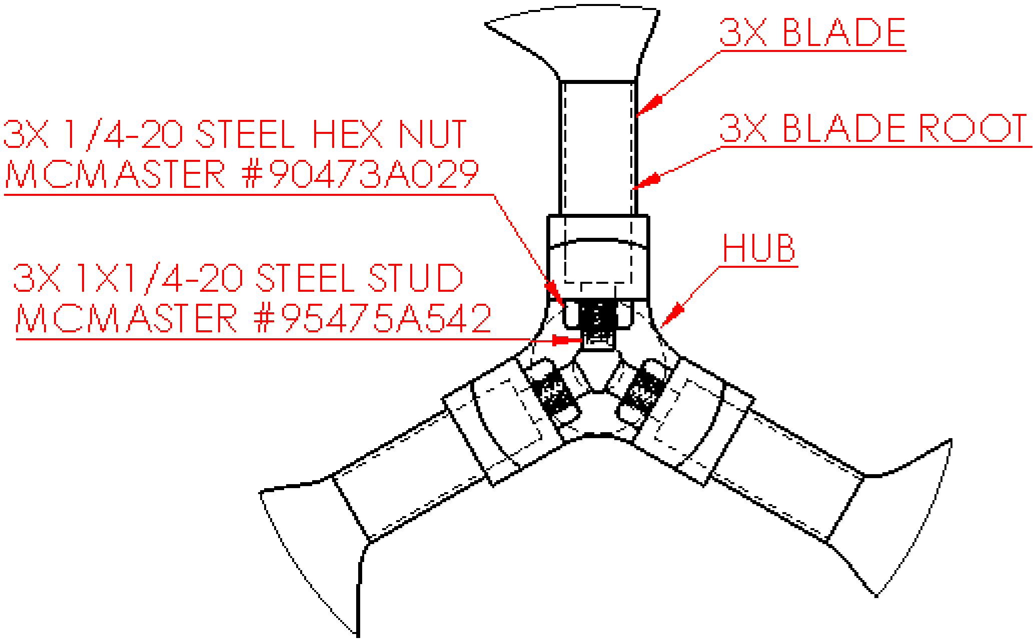
Caution: Paint outside or in the paint booth. Take precautions to avoid breathing the fumes.

When spray painting, it is recommended that you use even passes along the length of the blade. Start and end each pass before and after passing over the blade. Do not attempt to paint the blade with a single coat; use multiple lighter coats for best results. If there are bare spots, do not attempt to fix these with short bursts of paint; do an another entire pass from one end of the blade to the other. It generally takes about an hour for the paint to be dry to the touch, but the paint will not have reached full strength until several hours after that. Allow the blades to dry in a well ventilated location.

ROTOR ASSEMBLY

Assemble the rotor as shown below. The hub and required hardware will be provided. Your rotor is now ready for testing.




3X BLADE
3X BLADE ROOT
3X 1/4-20 STEEL HEX NUT
MCMASTER #90473A029
HUB
3X 1X1/4-20 STEEL STUD
MCMASTER #95475A542