

# Automated Drill Design Software

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## Abstract

This section of the report discusses a tool which can create automated 3D CAD drill models based on geometric as well as manufacturing parameters. This tool is a required component of numerical/FE-models of FRP drilling. The tool outputs the drill in a variety of solid geometry formats which can then be meshed and used in different FE analysis packages.

## 1 Introduction

This section of the report discusses the development of an automated drill modeling tool in Solidworks. The tool uses Solidworks to generate a 3D model of a drill based on manufacturing parameters of the drill supplied by the user. The need to use manufacturing parameters to model drills will be established. The applet uses a GUI to accept these parameters from the user and generates the model “on-the-fly”. The applet allows the user to save the model in a variety of formats which can be them imported into a meshing program or into the meshing module of an FEA package for subsequent use in FE-based simulations. The applet was written using Visual Basic APIs in SolidWorks 2003 and is forward-compatible with SolidWorks 2005. The current version of the applet is restricted to designing two-flute twist drills.

The subsequent section discusses the geometry of conventional two-flute drills and their design and manufacturing. This is followed by a discussion of the 3D analytical formulation of drill geometry. After this, an algorithm to model drills using commercial CAD tools is discussed. Finally, an implementation of this algorithm in Solidworks to create an automatic drill geometry modeling tool is presented.

## 2 Design and Manufacturing of Drills

### 2.1 Description of Drill Geometry

The geometry of two-flute twist drills is shown in Figure 1. For more information on the standard description of features and geometry of drills, the reader is referred to Galloway [1] and the ASM Handbooks [2].

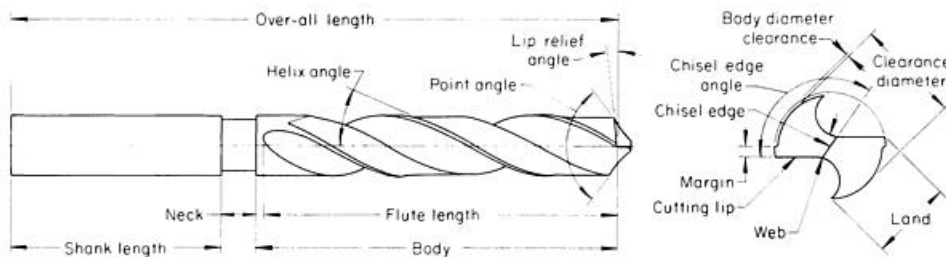


Figure 1: Standard Geometry of Two-Flute Twist Drill [2]

## 2.2 Manufacturing - Two-Flute Drills

The geometric parameters of conventional two-flute twist drills are determined by their manufacturing parameters. Drill manufacturing consists primarily of two grinding steps, namely grinding the flute faces and grinding the flank faces. The parameters of these grinding operations determines the geometric parameters of the drill. Parameters such as point angle and web thickness are implicit functions of the drill's manufacturing parameters.

Let us first take a look at how a two-flute twist drill is manufactured. The starting material is a cylindrical rod (or bar-stock) that is the of same diameter as required in the drill. During flute grinding (see Figure 2), the grinding wheel rotates in-place with the drill simultaneously rotating about and moving down its axis. The dual motion of the drill controls the helix angle of the flute and the position and profile of the grinding wheel controls the cross-section of the drill flute. In a two-flute drill, this is performed twice at orthogonal positions to generate both flutes.

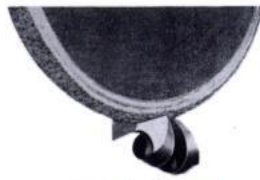


Figure 2: Flute Grinding [3]

During flank grinding, the grinding wheel rotates about a fixed axis to form a “grinding cone” of cone-angle  $\theta$  (see Figure 3) and the dill rotates “in-place”. This grinding is also performed twice from symmetric positions to generate both flank surfaces. These flank surfaces can be considered as sections of the grinding cones.

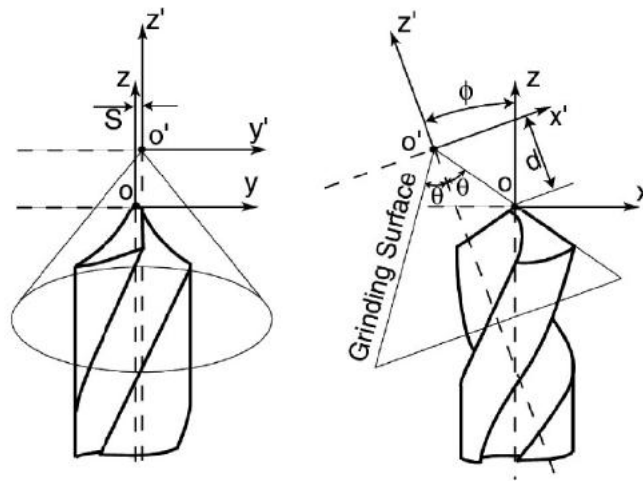


Figure 3: Flank Grinding [4]

Figure 3 also shows some of the control parameters during flank grinding. The coordinate system of the grinding cone is rotated angle  $\phi$  CCW in the  $x - z$  plane with respect to the drill's coordinate system. The grinding cone's vertex is located a fixed distance  $d$  from the tip of the drill, as measured along this rotated coordinate system. Finally, the vertex is shifted a distance  $S$  in the  $y$  axis. The figure shows the position of a grinding cone that will generate the right-flank surface of a drill. A similar grinding cone is symmetrically positioned to grind the right cone surface.

The next section will discuss how the manufacturing parameters such as grinding wheel cross-section and axis of rotation determine the geometric parameters of the drill. We will also see that the same design features can be generated with multiple sets of manufacturing parameters. Before we take a look at an analytical formulation of the drill geometry, past work in characterizing the drill geometry - based on which much of the work in this report has been developed - is discussed.

### 3 Literature Review

Galloway [1] initiated a formal study of drill geometry in his seminal ASME paper where he discussed several aspects of the drilling process. Subsequent researchers built on his basic framework and extended his analytical equations to develop computer-based models. Fujii et al [5, 6] developed algorithms to develop drill models using a computer. The drill geometry was analyzed by considering the “slicing” of the drill by arbitrary planes. A computer model was also developed to design a twist drill. Tsai and Wu [7] also presented explicit mathematical equations to describe the drill point geometry. These equations covered the conventional conical drills as well as the ellipsoidal and hyperboloidal drills. The effect of grinding parameters on various cutting angles was also discussed.

As regards to developing meshed drills for FE-applications, Hsu [8] performed the first FEM simulations for drilling. He developed a drill-mesher that produced a mesh of a two-flute twist drill based on user supplied parameters. The drill was designed using similar manufacturing-based techniques as discussed in the previous section. The mesher could output a surface mesh as well as a hexahedral volume mesh in different formats for use in various packages. Choi [9] used analytically defined flank sections and twisted them down a helical path to fully define the drill geometry. He developed an applet to generate a 3D FE-mesh based on this technique for processing in Abaqus. This applet was capable of generating  $n$ -flute geometry.

### 4 Overview of Modeling Procedure

Existing drill design methods rely extensively on discretized analytical equations. Errors and approximations from the discretization can affect the quality of the final drill design. A modeling technique that closely mimics the manufacturing process will be of use here as this will offer the maximum reduction of discretization errors. Also, as solid modeling software get more powerful, it make sense to use the powerful geometric modeling capabilities of these packages instead on relying on manually written equations and algorithms. Also, as we would like use these drill models in various different FEM packages, its cumbersome to generate meshes specific to each package. As modern software packages can import open-source standard solid models (eg., ACIS-SAT, STL), it is very convenient to design the drill using standard CAD techniques so that it is in a format that can be converted/viewed in a variety of platforms.

The drill modeling procedure discussed in this report tries to address these issues, and provides an easy way to generate arbitrary two-flute drill geometry using commercial CAD packages in a portable format. The modeling algorithm mimics the manufacturing process by performing boolean subtraction operations corresponding to the grinding steps preserving the order in which these steps are performed. The following section discusses the analytical formulation of the model upon which the algorithm is developed.

### 5 Analytical Formulation

#### 5.1 Basics

It is useful to first define a coordinate system that will serve through the analysis. The same coordinate system from previous studies [5, 6, 7] is used to allow easy comparison. The axes of the system,  $x, y, z$ , are described as follows:

- $x$ -axis - Parallel to the secondary cutting edge of the drill flank
- $z$ -axis - Parallel to the axis of the drill

- y-axis - Orthogonal to the  $x$  and  $z$  axes

## 5.2 Flute Shape

The cross-section the flute is dependent on the shape of the grinding wheel used for grinding it. The cross-section of the drill has to be designed such that it generates a straight secondary cutting edge when the flanks are ground. Hence, the shape of the flute grinding wheel is dependent on the specifications of the drill that is being ground. Instead of describing the grinding wheels, we can directly consider the cross sectional profile of the flute. The cross-section of the flute can be divided into 8 sections as shown in Figure 4. Sections 1, 2, 3, 4 are unground parts of the drill-blank and are arcs which make up a circle. Sections 5 and 6 can be described by the following polar equation:

$$\psi = \sin^{-1} \frac{W}{2r} + \frac{\sqrt{r^2 - \left(\frac{W}{2}\right)^2}}{r} \tan h \cot p$$

where,  $W$  is the web thickness,  $r$  is the radius of the drill,  $h$  is the helix angle and  $p$  is the half-point angle.

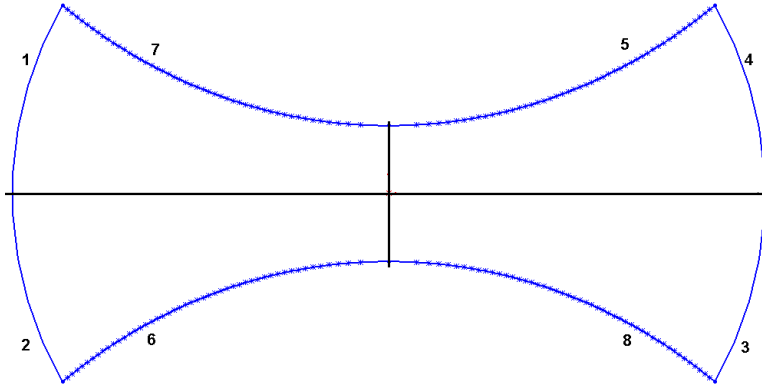


Figure 4: Flute Cross-Section

Here,  $r$  is varied from  $\frac{W}{2}$  to  $R$ . This polar equation makes sure that the flank section produces a drill with a straight cutting edge. Sections 7 and 8 do not contribute much to the cutting performance of the drill and only need to be optimized to provide rigidity. For simplicity, they can be modeled as symmetric to sections 5 and 6 respectively.

To convert the flute profile from 2D to a 3D boundary surface, a  $z$ -component term can be appended to the equation to capture the helical profile. The  $z$ -component term is as follows (for a drill of radius  $r$ ):

$$z_{flute} = \frac{\tan h}{r} z$$

Here,  $h$  is the peripheral helix angle, and is (for a drill of length  $l$ ):

$$h = \tan^{-1} \frac{2\pi r}{l}$$

## 5.3 Flank Shape

Figure 3 showed the coordinate system of the grinding cone. Let us define the axes of this system as  $\{x^*, y^*, z^*\}$ . The relationship between this coordinate system and the drill's coordinate system  $\{x, y, z\}$  is given as follows:

$$\begin{bmatrix} 1 \\ x^* \\ y^* \\ z^* \end{bmatrix} = T \begin{bmatrix} 1 \\ x \\ y \\ z \end{bmatrix} \quad (1)$$

where,  $T$  is the transformation matrix:

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\sqrt{d^2 \tan^2 \theta - S^2} & \cos \phi & 0 & \sin \phi \\ -S & 0 & 1 & 0 \\ d & -\sin \phi & 0 & \cos \phi \end{bmatrix} \quad (2)$$

From the figure, we can see that the cone vertices are defined at  $(0, 0, 0)$  of the cone-coordinate system. This position in the drill coordinate system is given by:

$$\begin{bmatrix} 1 \\ x_v \\ y_v \\ z_v \end{bmatrix} = T^{-1} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (3)$$

Thus, the vertices of the grinding cone are as follows:

Right Cone:

$$\begin{aligned} x_v &= -(\sqrt{d^2 \tan^2 \theta - S^2} \cos \phi + d \sin \phi) \\ y_v &= S \\ z_v &= d \cos \phi - \sqrt{d^2 \tan^2 \theta - S^2} \sin \phi \end{aligned}$$

Left Cone:

$$\begin{aligned} x_v &= \sqrt{d^2 \tan^2 \theta - S^2} \cos \phi + d \sin \phi \\ y_v &= -S \\ z_v &= d \cos \phi - \sqrt{d^2 \tan^2 \theta - S^2} \sin \phi \end{aligned}$$

## 5.4 Required Parameters

From the above analysis, we can see that the following parameters (geometric and manufacturing) are needed to completely describe a drill:

**Geometric -**

- $R$  Radius of drill
- $w$  Web thickness
- $h$  Helix angle
- $p$  Half-point angle

**Manufacturing -**

- $d$  x-shift of cone (in cone-coordinate system)
- $S$  y-shift of cone (in cone-coordinate system)
- $\theta$  Cone angle

It may make more intuitive sense to describe a drill using additional geometric parameters such as the relief angle or the chisel edge angle (and not the manufacturing parameters), but the objective of this report is to present a modeling algorithm that closely follows the manufacturing process. Hence, the algorithm uses these (non-intuitive) manufacturing parameters instead of the additional geometric parameters. In

most cases, when a drill is specified, it is described using these additional geometric parameters. But these parameters are implicit functions of the parameters discussed above. For example, the chisel edge angle ( $\xi$ ) is expressed as:

$$\xi = \pi - \tan^{-1} \left( \frac{\sqrt{\tan^2 \theta d^2 - S^2} \cos \phi - \tan^2 \theta d \sin \phi}{S} \right) \quad (4)$$

Hence we can see that for a given chisel edge angle, there are multiple sets of possible manufacturing parameters.

## 6 Algorithm Development

Based on the above analytical formulation, an algorithm is presented in this section to realize the drill in a given CAD program. The actual implementation of the algorithm is dependent on the specific features of the individual CAD program in which it is applied.

The general algorithm to develop the geometry of the drill is as follows:

1. Obtain the geometric and manufacturing parameters from the user. Calculate the derived variables from these parameters.
2. Draw the cross-section of the flute and create the solid flute by helical-extrusion
3. Locate the cone vertices
4. Draw the cone axes at these vertices and create a “virtual” cone
5. Use the cones to perform a boolean-subtract cut to generate the flank surfaces of the drill
6. Draw the cross-sections of the drill margin
7. Use helical-extrusion to create the 3D margin volume
8. Perform a boolean-cut operation to remove margin volume

## 7 Algorithm Implementation using Solidworks APIs

### 7.1 Solidworks

Solidworks is a popular 3D modeling CAD package. Solidworks uses a feature-based parametric approach for 3D drawings. Features are defined to create volume and modifications to sketches and these features can be rolled-back or modified to create multiple configurations of the same part. The program uses a feature hierarchy to determine “child” and “parent” features. Solidworks allows models to be saved in many different graphical formats and is hence very useful in ensuring that the model is portable.

Solidworks is also integrated with an API (Application Programming Interface) which contains many functions that can be called from programming languages such as Visual Basic and C++. These functions provide access to Solidworks’ graphical engine and can be used to create solid models. Programs can also be written in these programming languages that can accept input to generate user-defined solid models.

### 7.2 Applying Algorithm to Solidworks

The algorithm is applied in SolidWorks as follows.

#### 7.2.1 Coordinate Axis

The same coordinate axis as the analytical formulation is retained in SolidWorks for easy portability.

### 7.2.2 Flute Cross Section

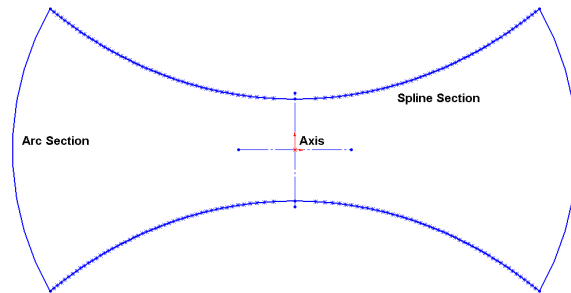


Figure 5: Flute Cross Section

As described earlier, the flute cross-section is symmetric about both the  $x$  and the  $y$  axes. Hence, it suffices to just draw one quadrant of the flute and mirror it about both axes. The arc part of the quadrant (Figure 5) is generated with the `CreateArcVB` function. A set of points are then generated using the polar function to describe the other part of the cross-section in the quadrant. To create the curve, these points can either be connected with lines or by drawing an interpolated spline function through them. A spline function is more efficient as fewer points need to be sampled to generate a high-quality “fit”. Significant performance improvement was noticed when a spline-fit was used instead of a line-fit. The spline was created using the `SketchSpline` function. After one quadrant is completely sketched, “mirror” lines were drawn to denote the  $X$  and  $Y$  axes using the `CreateLine2` function with the `ConstructionGeometry` option set to `True`. Using these mirror lines, the quadrant was mirrored about both axes and the full flute-cross section was realized. SolidWorks automatically connects the spline functions when they are mirrored to ensure that the profile is closed sketch.

### 7.2.3 Creating the Solid Flute Body

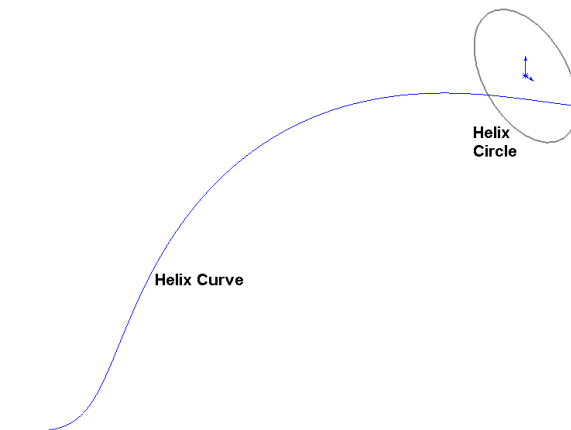


Figure 6: Helix Circle and Helix

To create the solid flute body, the 2D section is swept-extruded about a helical path. In order to define the helical path, a circle denoting the diameter of the helix is first needed. A circle centered at  $X = 0, Y = 0$  is generated with the same radius as that of the drill flute using the `CreateCircle` function. The `InsertHelix` command is then used to create the 3D helix using height and number of helical revolutions as parameters. The helix height is the same as the length of the drill flute, and for one revolution this can be calculated

based on the drill radius ( $R$ ) and the helix angle ( $h$ ) as:

$$l_{flute} = \frac{2\pi R}{\tan h} \quad (5)$$

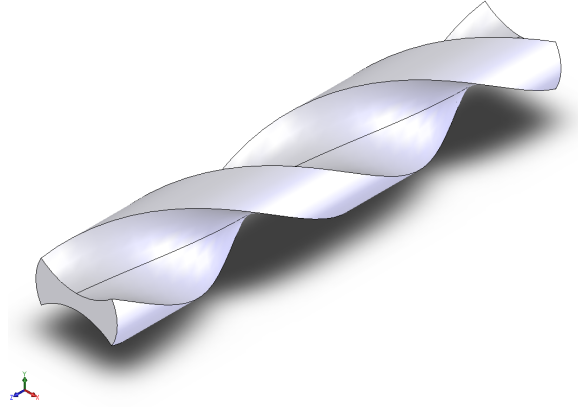


Figure 7: Solid Flute Body

The sweep-extrusion is performed using the `Part.Extension` routine and this generates the solid flute body.

#### 7.2.4 Generating the Flank Surfaces

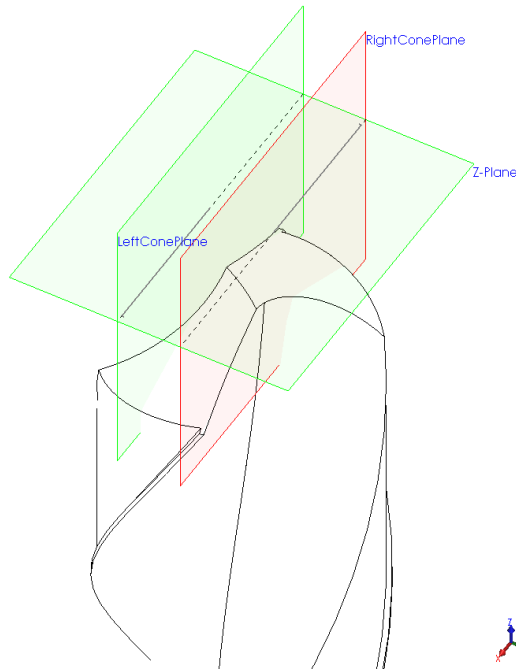


Figure 8: Planes to Generate Flank Surfaces

The flanks are generated by taking a swept-cut of a conical section around a specifically defined axis. From the analytical formulation, we know that the grinding cone's axis is located on a plane parallel to the  $x - z$



plane. Two separate planes have to be defined as we are considering two flank grinding operations and hence two grinding cones. We also know that the vertex of both grinding cones is located in a plane parallel to the  $x - y$  plane. As we know the offset distance, the plane Z-Plane is created using the `CreatePlaneAtOffset3` function. Using straight lines drawn on this plane, the orthogonal planes parallel to the  $x - z$  planes can be defined (using a line and a plane an orthogonal plane can be defined). The two planes are created using the `CreatePlaneAtAngle3` function.

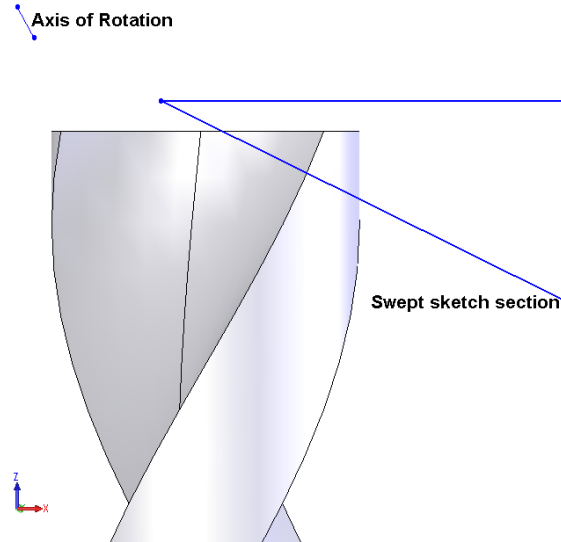


Figure 9: Sketch to Cut the Flank

Following this, the cone axis and cone profile are sketched on these planes and a swept-cut is taken. SolidWorks’ swept-cut operation works by first generating a volume by sweeping a 2D cross-section about an axis. A boolean operation is then performed and the intersection regions between the swept volume and the volume of a given solid object in the design space is removed from the solid object. In the grinding operation, the cone removes all the material from the drill outside of the cone. Hence the cone profile sketch is designed such that it effectively removes material outside the grinding cone.

This operation is performed twice, once for each set of cone grinding axes and the solid drill geometry is realized after this step.

### 7.2.5 Drill Margin and Relief

Existing literature does not extensively cover the modeling of the drill margin and relief, hence these features are only approximately drawn. In order to generate these features, we need to know the margin length and the relief width. Using this, a 2D cross-section is drawn on the same plane where the flute was generated, as shown in Figure 11 . The same helix which was used to generate the flute is redrawn and the profile is swept-extruded along this helical path. A boolean cut is performed and the 3D volume described by the swept-extrusion is removed from the solid body of the drill.

## 8 User Interface Development

Visual Basics APIs was used to design an ergonomic and accessible user interface. The interface accepts inputs from the user regarding the geometric and manufacturing specifications of the drill in SI units. A schematic of a drill with all the dimensions marked is also shown alongside for ease-of-use. After entering the data, the user can click the “Generate Drill” in order to invoke the necessary Solidworks commands to execute the program. Following a brief wait, the drill is generated in Solidworks. The user now has the option

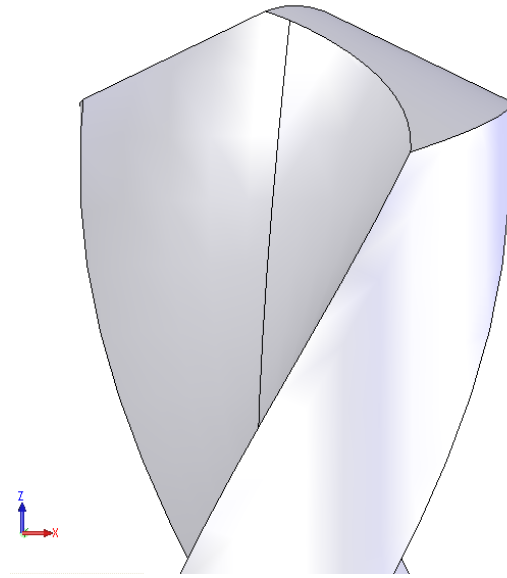


Figure 10: Solid Drill with both Flanks cut

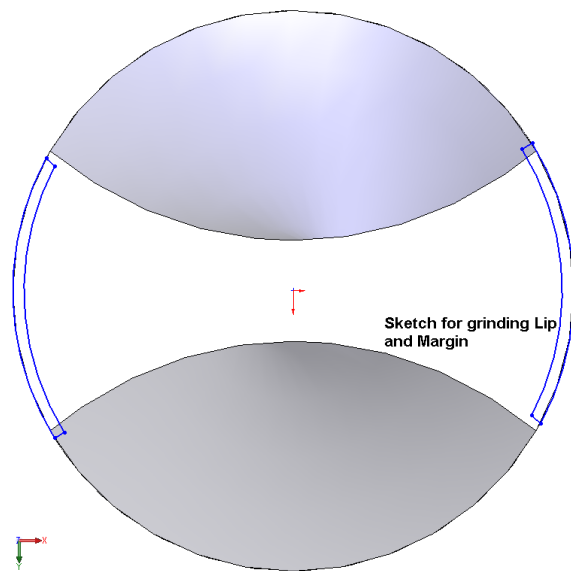


Figure 11: Drawing the Cross-section of the Margin and Lip Relief Cut

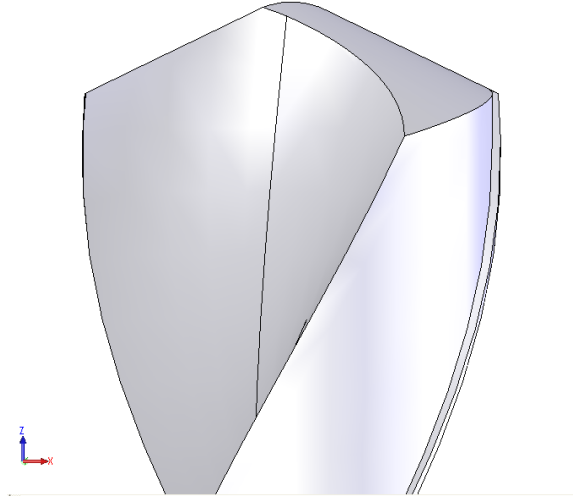


Figure 12: Fully Designed Drill

of saving the drill in a variety of formats, which can then be imported into either a Finite Element program for subsequent analysis. Currently, the software supports saving the drill in the .SLDPRT (Solidworks), .SAT (ACIS) and .IGS (International Graphics Exchange) formats. The user interface is shown in Figure 13.

## 9 Results

Using the capability of the software to save in different formats, a drill was generated and exported into Abaqus and DEFORM using the SAT and STL formats, respectively. The drills were then meshed using the meshing module of these two packages. The resultant meshes along with the original solid model can be seen in Figure 14.

## 10 Future Work

Future work includes expanding the package to model different drill types. A module that permits the description of arbitrary ground geometries can also be included. Physical prototypes of the drill also have to be created and compared with regular drills to validate the accuracy of the modeling technique.

## References

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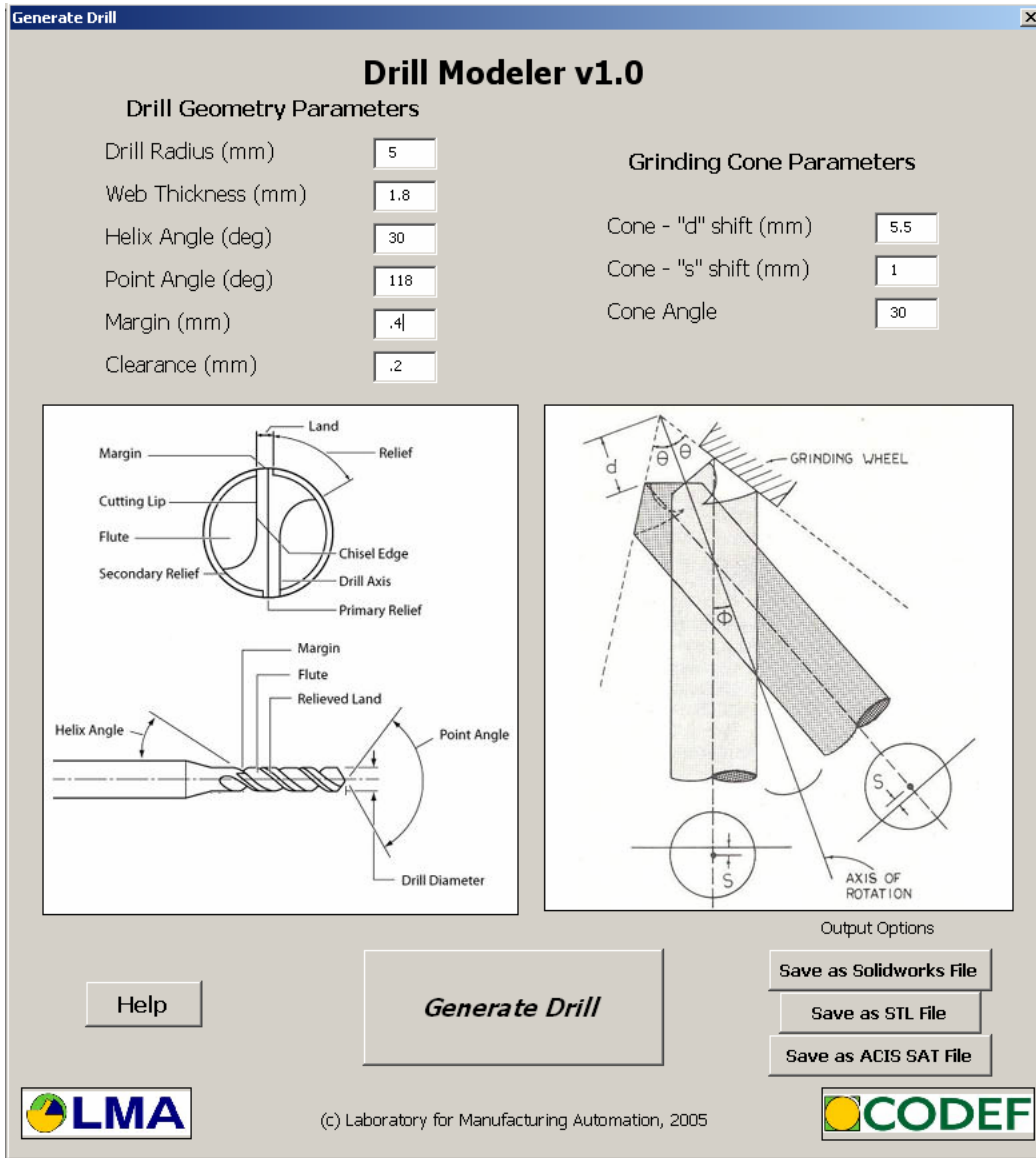


Figure 13: Drill Modeler, GUI

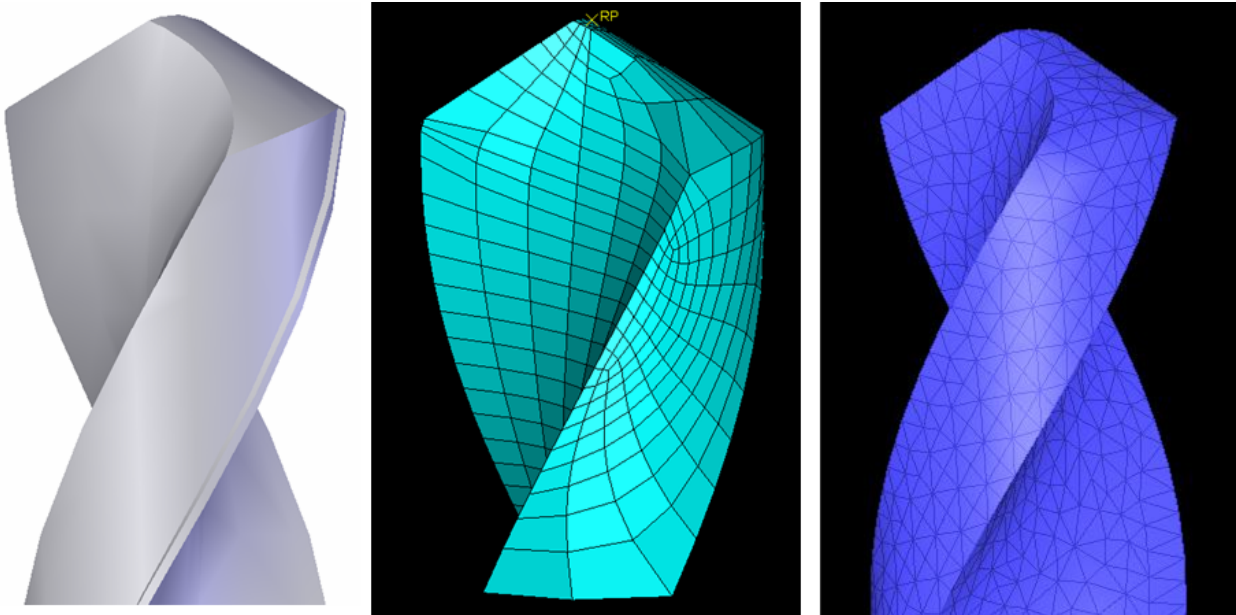


Figure 14: Solid Model (left), Meshed in Abaqus (middle), and Meshed in DEFORM (right).

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