Title
Automated Drill Modeling for Drilling Process Simulation

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Publication Date
2006-07-01

AUTOMATED DRILL MODELING SOFTWARE

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Sponsored by
NSF Grant DMI-0300549 – “GOALI: Development of Comprehensive Drilling Simulation Tool”

ABSTRACT

This 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 drilling. The tool outputs the drill in a variety of solid geometry formats which can then be meshed and used in different FE modeling packages.

Keywords: Drilling, finite element modeling, geometry.

INTRODUCTION

This 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 then 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.

DESIGN AND MANUFACTURING OF DRILLS

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 (1957) and the ASM Handbooks (1999).

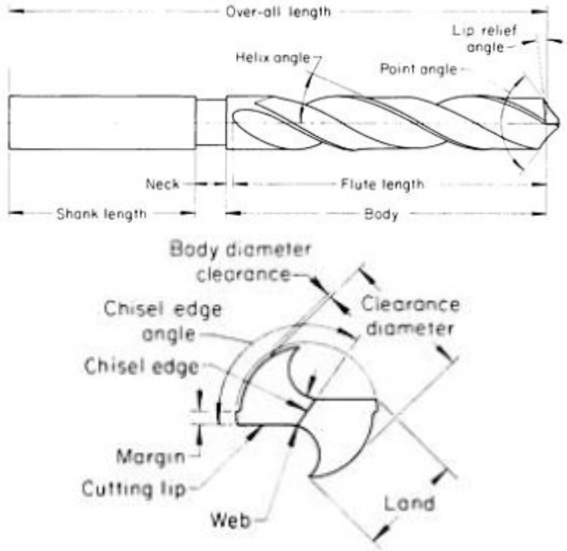


FIGURE 1: STANDARD GEOMETRY OF TWO-FLUTE TWIST DRILL (ASM HANDBOOKS, 1999).

Manufacturing of 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 determine 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 of the 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 (USCTI, 1989).

During flank grinding, the grinding wheel rotates about a fixed axis to form a "grinding cone" of cone-angle θ (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 also shows some of the control parameters during flank grinding. The coordinate system of the grinding cone is rotated counter-clockwise by angle φ in the xz plane with respect to the drill's coordinate system. The grinding cone's vertex is located at 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 the drill. A similar grinding cone is symmetrically positioned to grind the right cone surface.

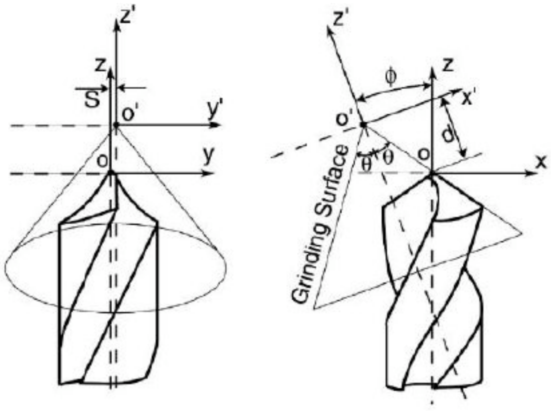


FIGURE 3: FLANK GRINDING (REN AND NI, 1999).

Following sections 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.

LITERATURE REVIEW

Galloway (1957) 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. (1970a, 1970b) developed algorithms to develop drill models by 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 (1957) 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 the development of meshed drills for FE-applications, Hsu (2002) 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 can output a surface mesh as well as a hexahedral volume mesh in different formats for use in various packages. Choi et al. (2003) used analytically defined flank sections and twisted them down following a helical path to fully define the drill geometry. An applet was developed to generate a 3D FE-mesh based on this technique for processing in Abaqus. This applet was capable of generating *n*-flute geometries.

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 makes sense to use the powerful geometric modeling capabilities of these packages instead on relying on manually written equations and algorithms. Also, as we desire to use these drill models in various FEM packages, it would be cumbersome to generate meshes specific to each package. As modern software packages can import open-source standard solid models (e.g. 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 an 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.

ANALYTICAL FORMULATION

Basics

It is useful to first define a coordinate system that will serve through the analysis. The same coordinate system from previous studies (Tsai et al. 1970a, b; Tsai and Wu, 1979) 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
- y-axis: Orthogonal to the x and z axes
- z-axis: Parallel to the axis of the drill.

Flute Shape

The cross-section of 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, and 4 are un-ground 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 (*r* is a variable in the polar equation, and is varied from W/2 to *R*):

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

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.

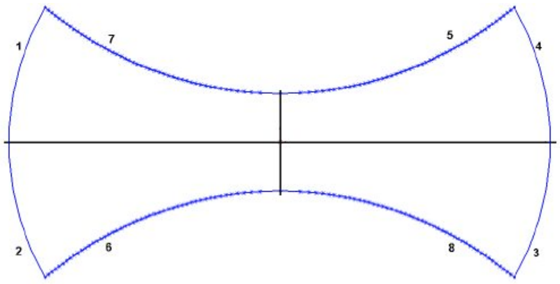


FIGURE 4: FLUTE CROSS-SECTION.

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 a 2-dimensional to a 3-D 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*):

$$z_{flute} = \frac{tanh}{R} z \tag{2}$$

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

$$h = tan^{-1} \frac{2\pi R}{l} \tag{3}$$

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:

$$\begin{bmatrix} 1 \\ x^* \\ y^* \\ z^* \end{bmatrix} = T \begin{bmatrix} 1 \\ x \\ y \\ z \end{bmatrix} \tag{4}$$

Where *T* is the transformation matrix:

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\sqrt{d^2 \tan^2 \theta - S^2} & \cos\phi & 0 & \sin\phi \\ -S & 0 & 1 & 0 \\ d & -\sin\phi & 0 & \cos\phi \end{bmatrix} \tag{5}$$

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:

$$\begin{bmatrix} 1 \\ x_v \\ y_v \\ z_v \end{bmatrix} = T^{-1} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

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

Right Cone:

$$\begin{gathered} x_v = -(\sqrt{d^2 \tan^2 \theta - S^2} \cos\phi + d \sin\phi) \\ y_v = S \\ z_v = d \cos\phi - \sqrt{d^2 \tan^2 \theta - S^2} \sin\phi \end{gathered} \tag{7}$$

Left Cone:

$$\begin{gathered} x_v = \sqrt{d^2 \tan^2 \theta - S^2} \cos\phi + d \sin\phi \\ y_v = -S \\ z_v = d \cos\phi - \sqrt{d^2 \tan^2 \theta - S^2} \sin\phi \end{gathered} \tag{8}$$

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-coordinates)
S: y-shift of cone (in cone-coordinates)
Θ: 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 (ξ) is expressed as:

$$\xi = \pi - \tan^{-1}\left(\frac{\sqrt{\tan^2\theta d^2 - S^2}\cos\phi - \tan^2\theta d\sin\phi}{S}\right) \tag{9}$$

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

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

IMPLEMENTATION OF ALGORITHM IN SOLIDWORKS

Solidworks is a popular 3D modeling CAD package. It uses a feature-based parametric approach for 3-D 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.

The algorithm outlined in the previous section is implemented in Solidworks. A GUI was also created, as shown in Figure 5. The GUI also allows the user to save the drill in a variety of "open" formats including ACIS (SAT) and STL. Parameters supplied in the GUI are used to generate the model of the drill. For the following set of parameters, the drill shown in Figure 6 is generated:

Geometric:

r: 5 mm
w: 1.8 mm
h: 30 °
p: 118°

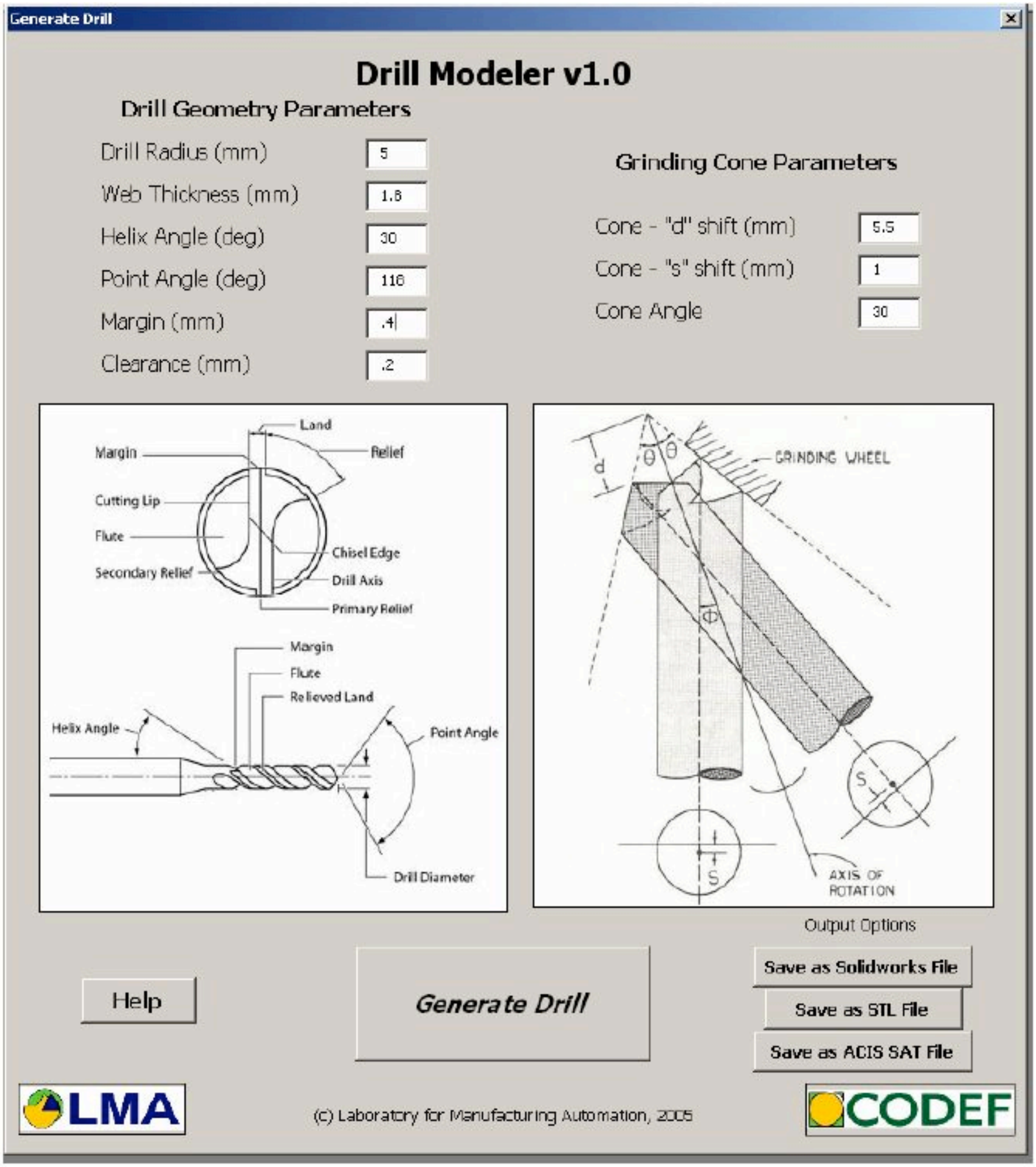
Manufacturing:

d: 5.5 mm
S: 1.2 mm
Θ: 30°

For a more specific discussion of the implementation in Solidworks, the reader is directed to Vijayaraghavan, 2005.

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 7.



Drill Radius (mm) 5
Web Thickness (mm) 1.8
Helix Angle (deg) 30
Point Angle (deg) 118
Margin (mm) .4
Clearance (mm) .2

Cone - "d" shift (mm) 5.5
Cone - "s" shift (mm) 1
Cone Angle 30

FIGURE 5: GUI FOR DRILL MODELER.

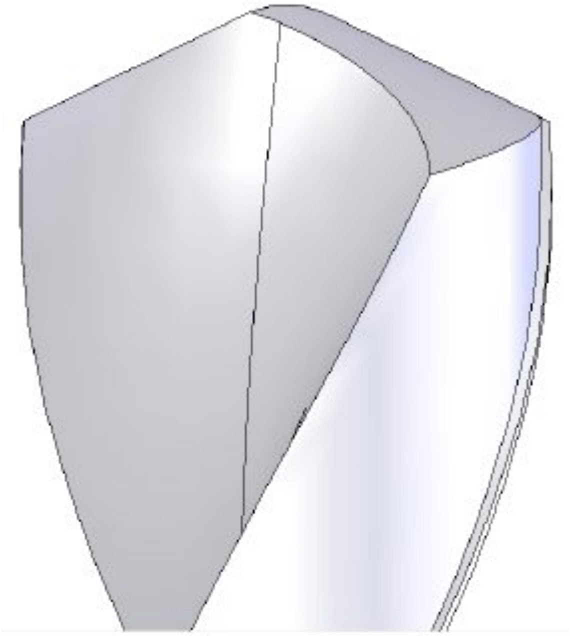


FIGURE 6: DRILL GENERATED FROM USER SUPPLIED PARAMETERS.

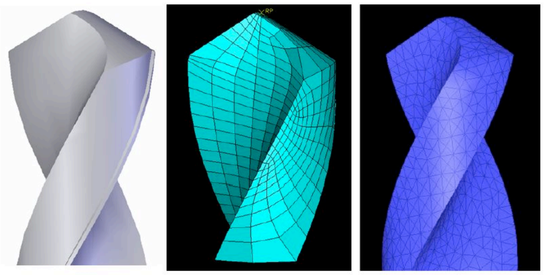


FIGURE 7: SOLID MODEL (LEFT), MESHED IN ABAQUS (MIDDLE), AND MESHED IN DEFORM (RIGHT).

ACKNOWLEDGEMENTS

This research was funded by National Science Foundation research grants DMI-0300549 – “GOALI: Development of Comprehensive Drilling Simulation Tool”. This work was also supported by the members of the Consortium on Deburring and Edge Finishing (CODEF). For more information, please visit, http://lma.berkeley.edu. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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