End mill tool profiling by CAD method

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In orthopedics a lot of specialized tools and reconstructive elements are being used. Most of these tools are bounded by helical surfaces, significantly different from those used in similarly constructions with general character. The characteristics of these elements are defined by the structure and the composition of the material where the reconstructive elements are mounted, namely the bone. Hence result the necessity to imagine new fastening elements on screw type, characterized by a specific form. This paper presents a method developed in a CAD environment for profiling tools bounded by the revolution surfaces of the specifically helical drill used in the orthopedic reconstruction surgery. On the other hand, the surgery tools, like drills, must have cutting tools distinct from those used in the inorganic materials. Their shape has to assure a minimum heating of the machined material and to allow a good ejection of the material resulted from processing. An analysis of the cutting zone of the helical drills is also made by graphical methods, based on the CATIA design environment. A profiling algorithm of the end mill tool for generating helical surfaces with imposed axial section is also defined.

Keywords: Helical surfaces, End mill, CAD profiling method, Orthopedic bone drill, Prosthetic dental implants

The helical drills used in the orthopedic reconstruction surgery are characterized by the materials (usually stainless steel alloys), as so as, by the geometry. Their geometry differ from the geometry of the drills for general purposes by the value of the working angle ($2\kappa = 90^\circ$, for drills used in orthopedics) and by the helical flute inclination angle, $\omega = 30^\circ$ (Fig. 1)\textsuperscript{1-4}. The side mill or end mill’s profiling for the generation of this type of helical flute, demands specific approach, which, for analytical methods, may be very laborious. In this paper, a new design method is proposed for the peripheral primary surface of the side mill (or end mill) for the generation by milling of this type of helical surfaces.

The profiling method is developed in the CATIA design environment and it is based onto the geometrical interpretation of the specifically enveloping condition, at generation of the helical surface with a tool bounded by a revolution surface. The prosthetic screws for dental implants are parts which meet shape and material special conditions, adapted to the purposes of their utilization\textsuperscript{6}. A special issue of these parts is the form of the thread used for the implant. Now, each company proposes various types of threads\textsuperscript{7} (Fig. 2).

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The constructive form of these threads may be very different from the threads used in mechanical constructions. The generation of the threaded surfaces of the screws used in dental implants may be done by turning, as so as by another processes, for which it is needed the profiling of the special tools (thread rolling dies, side mill etc). A method for profiling side mill for generation of the dental screw is also presented.

**Side Mill – Generating Kinematics**

The generation of the helical surface with a tool bounded with a peripheral primary surface, revolution surface, need a movement assembly (Fig. 3), which have the significance: the movement assembly which generate a helical movement with the $V$ axis and $p$ helical parameter, identical with the axis and the parameter of the surface to be generated; and the rotation movement of the end mill tool around its own axis $\tilde{A}$; this is the cutting movement.

The position of $\tilde{A}$ axis of the $S$ surface regarding the $V$ axis, will be defined from technological considerations (the external diameter of the side mill) and from positioning considerations (the axis of the end mill being perpendicularly to the axis of the helical flute, being in the same time the symmetry axis of the flute).

If they are known the equations of the surface to be generated, in vectorial form:

$$(\Sigma) \mathbf{r} = \mathbf{\tilde{r}}_{i_x}(u,v) \cdot \mathbf{i} + \mathbf{\tilde{r}}_{i_y}(u,v) \cdot \mathbf{j} + \mathbf{\tilde{r}}_{i_z}(u,v) \cdot \mathbf{k} \quad \ldots (1)$$

with $u$ and $v$ independent variables, the contact condition between the $\Sigma$ and $S$ surfaces (the peripheral primary surface of side mill and the surface to be determined) is of the form:

$$\left(\tilde{A}, \mathbf{N}_\Sigma, \mathbf{r}\right) = 0 \quad \text{(Gohman condition)} \quad \ldots (2)$$

Where $\tilde{A}$ is versor of $\tilde{A}$ axis, overlapped to the gap axis, the $X$ axis;

$$\tilde{A} = \mathbf{i} \cdot \sin \alpha + \mathbf{j} \cdot \cos \alpha \cdot \mathbf{k} \quad \ldots (3)$$

$\mathbf{N}_\Sigma$ is the normal to the helical surface (2); In principle,

$$\mathbf{N}_\Sigma = N_{x_i} \cdot \mathbf{i} + N_{y_i} \cdot \mathbf{j} + N_{z_i} \cdot \mathbf{k} \quad \ldots (4)$$

so, the (2) condition if a function of type

$$q(u,v) = 0 \quad \ldots (5)$$

The assembly of Eqs (1) and (5) represent in the reference system attached with the peripheral primary surface of the side mill, the characteristic curve - the tangency curve between the helical surface $\Sigma$ and the peripheral primary surface of the side mill tool, in principle,

$$\left(C_\Sigma\right) \mathbf{r} = \mathbf{\tilde{r}}_{i_x}(u) \cdot \mathbf{i} + \mathbf{\tilde{r}}_{i_y}(u) \cdot \mathbf{j} + \mathbf{\tilde{r}}_{i_z}(u) \cdot \mathbf{k} \quad \ldots (6)$$

By revolving the $\left(C_\Sigma\right)$ curve around the $\tilde{A}$ axis, it is generated the $S$ surface - the peripheral primary surface of the side mill of which axial section $S_A$ is expressed by:

$$S_A \left| \begin{array}{c} R = \sqrt{Y_i^2(u) + Z_i^2(u)} \\ H = X_i^2(u) \end{array} \right. \quad (i = 1 \ldots n) \quad \ldots (7)$$

The analytical method, although rigorous, have limits when the helical surface it is known in discreet form or the surface to be generated have a form which made difficult to define the characteristic curve.

**CAD Oriented Method for End Mill Profiling**

A method was developed in CATIA graphical design environment, based on the 3D virtual construction of the helical surface, in the Part product of all the graphical elements which refers to the helical surface: the datum and the reference system axis and the position of the end mill (Fig. 4).
In the *Generative Shape Design* product, by the *Project* command, it is projected the end mill tool’s axis onto the helical surface of the flute - the Σ surface - determining, in this way, the characteristic curve (the tangency curve between the Σ helical surface with the revolution surface of the end mill tool, the S surface).

This surface, as peripheral primary surface of the end mill, is obtained by revolving the characteristic curve around the Α axis, using the *Revolve* command. A simple form of the tool’s cutting edge may be obtained as intersection between the S revolution surface and an axial plane of this surface.

Next, using an in-house application - *SGSE-VBA*, it is possible to export the tool’s axial section profile coordinates, in order to use these coordinates for the machining of a physical template (the profile of cutting tool for turning this revolution surface), or for the programming a CNC machine-tool.

**Drill’s Flute Helical Surface**

For the helical drills used in orthopaedic, a specific geometry of the helical flute is presented in Fig. 5\(^9\)\(^{10,11}\). These construction types are usually for this helical drill. Based on this form a cross-section is made the 3D model of the helical drill (Fig. 6), for the values: \(D=4\) mm, \(R_0=2\) mm, \(R_c=2.24\) mm. The generation of the drill’s helical flute may be generated with and end mill of which axis is perpendicularly to the helical drill axis (Fig. 7).

According to the presented methodology, the common characteristic of the helical surface of the flute and of the peripheral primary surface of the end mill is obtained as projection of the tool’s axis onto the Σ surface. In this way it is determined the helical surface of the drill’s flute - the characteristic curve \(C_Σ\) (see Fig. 7).

The peripheral primary surface of the end mill tool is obtained revolving the characteristic curve \(C_Σ\)
around the axis of the tool. The axial section $S_A$ of the $S$ surface represents the secondary order tool’s profile for the generation, by enveloping, of the peripheral primary surface of the end mill tool. If the end mill tool is materialized as a grinding body, the $S_A$ profile represents the verification template (see Fig. 8 and Table 1).

**Helical Surfaces Reference Systems**

The specific type of these threads form is presented in Fig. 9. The $XYZ$ reference system has the $Z$ axis overlapped with the thread axis and the $X$ axis as symmetry axis of the axial section’s gap. They are also defined the $r_i$ internal radius and the $r_e$ external radius. They are also known the axial pitch $p_{ax}$, the gap’s width, $g$, and the fillet radius between the straight lined profiles, $r_f$ and $r_b$.

Table 2 shows the analytical expressions of the elementary profiles which compose the thread (see Fig. 10). Being known the profiles from the axial section of the thread, the helical surfaces corresponding to the elementary profiles are determined as:

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \omega Z(\phi)
\begin{bmatrix}
X_{\text{profile}} \\
Y_{\text{profile}} \\
Z_{\text{profile}}
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
p\phi
\end{bmatrix}.
$$

with $\phi$ angular parameter in the rotation movement around the $Z$ axis; $p$ is helical parameter of the thread; $X_{\text{profile}}$, $Y_{\text{profile}}$, $Z_{\text{profile}}$ are parametrical equations of the elementary profiles (see Table 2).
After development, the principal form of the helical surfaces equations is reached:

\[
\begin{align*}
X &= X_{\text{profile}} \cos \varphi - Y_{\text{profile}} \sin \varphi; \\
\Sigma Y &= X_{\text{profile}} \sin \varphi + Y_{\text{profile}} \cos \varphi; \\
Z &= Z_{\text{profile}} + p\varphi.
\end{align*}
\]

in the worm’s reference system (see Table 3).

In principle, the disc tool for generation of the helical flute of the thread is bounded by a surface of revolution, reciprocally enveloping with the helical surfaces of the flute. Two methods are proposed for the profiling of the disc tool for the generation of the helical flute of the dental implant.

**Graphical Method for Profiling the Side Mill**

The 3D method developed in the CATIA design environment assume the modeling of the composed helical surface by generating a Part file which contain the graphical elements: the position of the reference system origin and the 3D model of the composed helical surface.

The axial profile of the thread, as composed profile, will be analyzed using an in-house application - SGSE - running in Visual Basic for Application (VBA) environment, using also Component Application Architecture (CAA). It will created the origin and reference system of the side mill using commands Point and Insert Axis System, as Euler system. It is accepted that the tool’s axis is the \( Z_1 \) axis (Fig. 11).

By Projection command it is determined the projection of side mill axis (\( Z_1 \)) on the composed helical surface \( \Sigma \), obtaining the characteristic curve model (see Fig. 12). By the Revolve command, it is obtained the primary peripheral surface of the side mill - \( S \), rotating the characteristic curve around the \( Z_1 \) axis (see Fig. 13). The tool’s profile in the axial section (the plane \( X_1Z_1 \)) is obtained using the command PointOnCurve, defining points on these, with command PointOnCurve (see Table 4).

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**Table 2–Elementary sections of the axial section**

<table>
<thead>
<tr>
<th>Section</th>
<th>Analytical equations</th>
<th>Parameters</th>
<th>Variation limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{AB} )</td>
<td>( X = X_{\text{ct}} + r_1 \cos v_1; ) ( Y = 0; ) ( Z = Z_{\text{ct}} + r_1 \sin v_1; )</td>
<td>( v_1 )</td>
<td>( v_{1\text{min}} = 0; ) ( v_{1\text{max}} = \frac{\pi}{2}; )</td>
</tr>
<tr>
<td>( \overline{BC} )</td>
<td>( X = X_{b} - t; ) ( Y = 0; ) ( Z = Z_{b}; )</td>
<td>( t )</td>
<td>( t_{\text{min}} = 0; ) ( t_{\text{max}} = (r_1 - r_1) - (r_1 - r_1); )</td>
</tr>
<tr>
<td>( \overline{CD} )</td>
<td>( X = X_{\text{ct}} + r_2 \cos v_1; ) ( Y = 0; ) ( Z = Z_{\text{ct}} + r_2 \sin v_1; )</td>
<td>( v_2 )</td>
<td>( v_{2\text{min}} = 0; ) ( v_{2\text{max}} = \frac{\pi}{2}; )</td>
</tr>
<tr>
<td>( \overline{DE} )</td>
<td>( X = X_{d}; ) ( Y = 0; ) ( Z = Z_{d} + u; )</td>
<td>( u )</td>
<td>( u_{\text{min}} = 0; ) ( u_{\text{max}} = \frac{\pi}{2} - r_1; )</td>
</tr>
</tbody>
</table>

**Table 3–Equations of the elementary helical surface**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Parametrical equations</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma_{AB} )</td>
<td>( X = [X_{\text{ct}} + r_1 \cos v_1] \cos \varphi; ) ( Y = [X_{\text{ct}} + r_1 \cos v_1] \sin \varphi; ) ( Z = Z_{\text{ct}} + r_1 \sin v_1 + p\varphi. )</td>
<td>( \varphi, v_1 )</td>
</tr>
<tr>
<td>( \Sigma_{BC} )</td>
<td>( X = (X_b - t) \cos \varphi; ) ( Y = (X_b - t) \sin \varphi; ) ( Z = Z_b + p\varphi. ) ( X_b = r_1 - r_1; ) ( Z_b = -g / 2. )</td>
<td>( \varphi, t )</td>
</tr>
<tr>
<td>( \Sigma_{CD} )</td>
<td>( X = [X_{\text{ct}} - r_1 \cos v_1] \cos \varphi; ) ( Y = [X_{\text{ct}} - r_1 \cos v_1] \sin \varphi; ) ( Z = Z_{\text{ct}} - r_1 \sin v_1 + p\varphi. ) ( X_{\text{ct}} = r_1 + r_1; ) ( Z_{\text{ct}} = -g / 2 + r_1. )</td>
<td>( \varphi, v_2 )</td>
</tr>
<tr>
<td>( \Sigma_{DE} )</td>
<td>( X = X_{d} \cos \varphi; ) ( Y = X_{d} \sin \varphi; ) ( Z = Z_{d} + u + p\varphi. ) ( X_{d} = r_1 - r_1; ) ( Z_{d} = 0. )</td>
<td>( \varphi, u )</td>
</tr>
</tbody>
</table>
Conclusions
The CAD method allows the rigorous analysis of the active surfaces of the drills. Also, the proposed methodology allows the design of the secondary order tool, in this case the end mill tool for the generation of the helical drill’s flutes. The constructive form of the screws used for orthopedic surgery are different from the usually thread constructive form. The profiling methods for the end mill, both analytical and graphical leads to the same constructive form of the end mill generating for this thread type. The graphical method developed in the CATIA design environment has the advantage to be rigorous, rapid and intuitive in the same time. The method has also the advantage to avoid major errors in the tool’s profiling.

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