Int J Adv Manuf Technol (2012) 61:15–24
DOI 10.1007/s00170-011-3687-6

ORIGINAL ARTICLE

A study on helical surface generated by the primary peripheral surfaces of ring tool

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Received: 1 June 2011 / Accepted: 3 October 2011 / Published online: 22 October 2011

Abstract Often in the engineering practice, cutting tools bounded by primary peripheral surfaces of revolution are used because of their effectiveness. Among these, ring and tangential tools can be used for the generation of constant pitch cylindrical helical surfaces. In this paper, we present an algorithm for the profiling of these types of tools. The algorithm is based on the topological representation of the tool's primary peripheral surface. The main goal is to devise a methodology for the profiling of tools whose surfaces are reciprocally enveloping with cylindrical helical surfaces. We present a numerical example for the numerical determination of the axial section form for this type of tools. The application method for this algorithm was developed in the CATIA graphical design environment within which the procedure is developed as a vertical application. In addition, we present a solution for the shape correction of the tool's axial cross-section by considering the existence of singular points on the profile of the helical surface to be generated where multiple normals to the surface exist.

Keywords Ring tool · Helical surfaces generation · Topological representation

1 Introduction

The ring and tangential tools are tools bounded by a revolution primary peripheral surface. The ring tools are tools designated for the generation of the cylindrical helical surfaces with constant pitch (threads) on specialized machine tools or using specialized technological equipments for longitudinal turning machines.

The ring tool is frequently made as an enwrapping milling tool. The advantage of this technological solution is the increased productivity of this process. Although the tools of this type generate in the cutting motion a revolving surface, the issue of profiling the primary peripheral surface of this surfaces reciprocally enveloping with cylindrical helical surfaces with constant pitch, is a problem different from the profiling of the side mill [1–4].

The profiling method of this type of tool uses the fundamental theorems of the surfaces generation [1, 5] or the complementary methods as "the minimum distance method" [1], "the in-plane generating trajectories method" [6]. Also, the development of the graphical design environment allows solving these problems using 3D design environment [7–10] or using solid modeling [11, 12].

2 Ring tool's profiling algorithm

The basic idea behind the proposed algorithm is that a helical movement, with $\vec{V}$ axis and p helical parameter, can be decomposed in two rotations conjugated with this relative motion as shown in Fig. 1.

The three movements, as shown in Fig. 1, are:

I is the translation movement correlated with the rotation movement II, in order to produce a helical motion with the same helical parameter p as of the surface to be generated. In most cases, this motion is executed by the workpiece;

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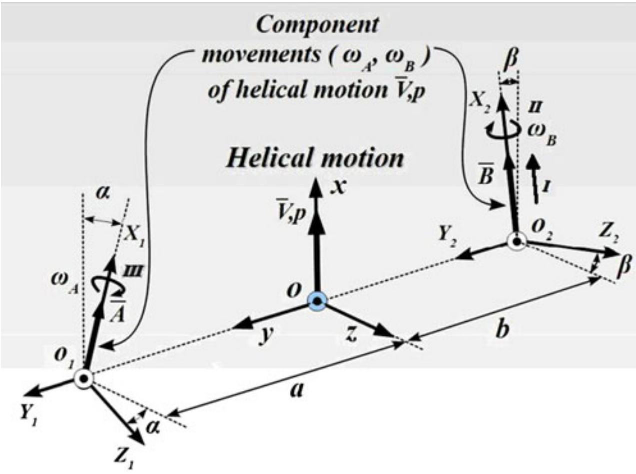

Fig. 1 The decomposition of the helical motion into two rotation motions

II the rotation movement of blank around its own axis, $\overline{B}$. In the most practical cases, this motion is uniform; and

III the rotation motion of tool around its own axis, the axis $\vec{A}$. This axis is positioned regarding the axis $\overline{B}$ at a distance and inclined with angle α regarding the Z axis.

One can represent these relative motions as

$$(\vec{V},p) \approx \left(\vec{A},\omega_A\right) + \left(\vec{B},\omega_B\right) \tag{1}$$

where

$$p = a \cdot tan(\beta) = b \cdot tan(\alpha) \tag{2}$$

with p is the helical parameter.

In this way, it is possible to choose as revolution surface's axis, the B axis, which may be established as the axis of the ring surface. Also, it is possible to arbitrarily choose the values b and β according to the dimension of the helical surface and the diameter of the ring tool (see Eqs. 1 and 2).

The Nikolaev's theorem [5] for the determination of the characteristic curve between the Σ helical surface, Fig. 2, and the primary peripheral surface of ring tool allows to determine the geometrical locus of points which belongs to the Σ surface where the condition is accomplished:

$$\left(\vec{B},\vec{N}_{\Sigma},\vec{r}_2\right) = 0 \tag{3}$$

where, $\vec{B}$ is the vector that overlapped the ring tool's axis; $\vec{N}_{\Sigma}$ is the normal to the helical surface; and $\vec{r}_2$ is the position vector of the current point that belongs to the helical surface, regarding the O_2 origin of the reference system joined with the axis X_2.

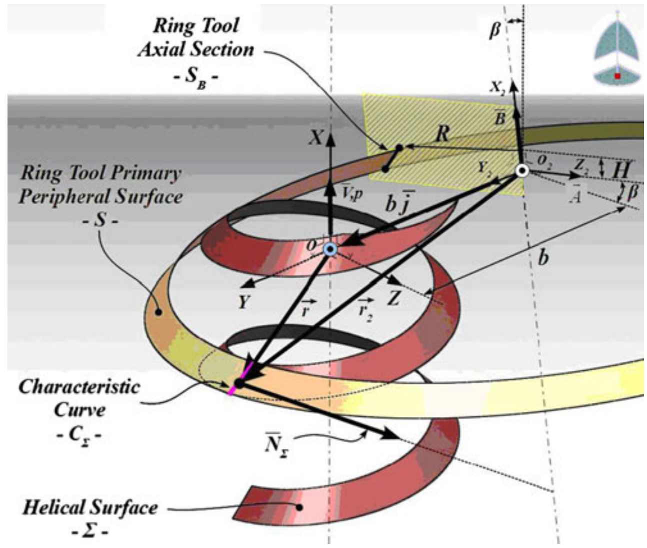

Fig. 2 Ring surface reciprocally enveloping with helical surface

The condition 3 has the geometrical significance, the fact that the three vectors are in the same plane. Moreover, the contact points (the tangency points) between the Σ helical surface and the primary peripheral surface of the ring tool defines the characteristic of Σ surface, in the rotation movement of this around the $\vec{B}$ axis. The characteristic curve represents the geometric locus of intersection points between the normal draws from the points belongs to the $\vec{B}$ axis to the surface to be generated (so, the projection of the $\vec{B}$ axis to the Σ surface).

In this way, for the Σ surface known in the $X_2Y_2Z_2$ reference system by equations form:

$$\Sigma\left|\vec{r}_2 = X_2(u,v)\vec{i} + Y_2(u,v)\vec{j} + Z_2(u,v)\vec{k},\right. \tag{4}$$

with u and v as independent variable parameters. In the $X_2Y_2Z_2$ reference system, it is defined the normal to the surface,

$$\vec{N}_{\Sigma} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \dot{X}_{2u} & \dot{Y}_{2u} & \dot{Z}_{2u} \\ \dot{X}_{2v} & \dot{Y}_{2v} & \dot{Z}_{2v} \end{vmatrix}. \tag{5}$$

The axis of the future ring tool has directrix parameters

$$\vec{B} = \vec{i}. \tag{6}$$

After developing, the condition 3 will be,

$$\begin{vmatrix} X_2(u,v) & Y_2(u,v) & Z_2(u,v) \\ N_{X2} & N_{Y2} & N_{Z2} \\ 1 & 0 & 0 \end{vmatrix} = 0 \tag{7}$$

equivalent with a link between the variable parameters,

$$v = v(u) \tag{8}$$

In this way, the characteristic curve on the Σ surface is given by the 4 and 9 equations assembly:

$$C_{\Sigma}|X_2 = X_2(u); Y_2 = Y_2(u); Z_2 = Z_2(u). \tag{9}$$

By revolving the characteristic curve 10 around the X_2 axis, the axis overlapped to $\vec{B}$ is generated the primary peripheral surface of the ring tool—S_B. The axial section of the primary peripheral surface of the ring tool, $(C_{\Sigma})_{X_2 Y_2 Z_2}$ is determined as:

$$(S_B)_{X_2 Y_2 Z_2}\left| \begin{array}{l} H = X_2(u); \\ R = \sqrt{Y_2^2(u) + Z_2^2(u)}. \end{array} \right. \tag{10}$$

2.1 Profiling of tool in CATIA design environment

An application of the presented algorithm for the profiling of the ring tool for the generation of a trapezoidal thread was presented (see Fig. 2). The 3D method to profile the ring tool—*HSGT* (helical surface generating tool)—is grounded on the generative shape design environment facilities. The worked piece (in fact, the generated surface) is 3D modeled, as it can be observed in Fig. 3. The worked piece reference system, XYZ, and the ring tool reference system, $X_2Y_2Z_2$, the last one as Euler system, are created (see Fig. 2).

By giving the "projection" command, the ring tool axis projection onto the Σ surface is realized; thus, the characteristic curve is determined. By subsequently using the "revolve" command, the tool primary peripheral surface (S) results after rotating the characteristic curve around Z_2 axis.

The ring tool axial section is then obtained as an intersection between the surface S and a plain which includes the Z_2 ($\vec{A}$) axis—by applying the "intersection" command. The coordinates of points that defined the generating profile of the thread and the distance between axes are given in Table 1. In Fig. 3, the 3D model of the thread axial profile was shown. In Fig. 4, the HSGT–visual basic application (VBA) was presented, where the profile's elements and the tool's type are given. Figure 5 presented the relative position of the primary peripheral surface for the ring tool, its axis, the characteristic curve, and the axial section of the surface. Because the axial section of the helical surface has singular points, the points C and D will result in discontinuity points on the surfaces in enveloping (see Fig. 5).

Table 1 Input parameters of the trapezoidal thread

Symbol	Description	Z (mm)	X (mm)
A	Initial point on thread crest	50	20
B	Initial point on thread flank	50	0
C	Initial point on thread bottom	40	−10
D	Final point on thread bottom	40	−20
E	Final point on thread flank	50	−30
S_e	Flute sense	Right	
P_e	Helix pitch	50	
b	Distance between tool's axis and thread axis	100	

2.2 Numerical results—ring tool for trapezoidal thread

In Table 2 and Fig. 6, we present the coordinates of the characteristic curves and of the axial cross-section of ring tool. The existence of the singular points (see Fig. 5, the points C' and D') leads to intersection points for the characteristic curves on adjacent flanks, which impose to take a decision regarding the form of the axial section. The simplest solution is to eliminate the portions from the characteristic curve, in points C' and D', if there are acceptable modifications of the generated surfaces at the thread bottom. In Fig. 6, the intersection zone of the profiles that forms the axial section and eliminates further in the profile board construction for the ring tool was shown.

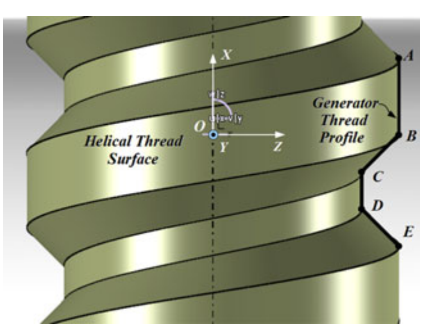

Fig. 3 Generating profile of the trapezoidal thread

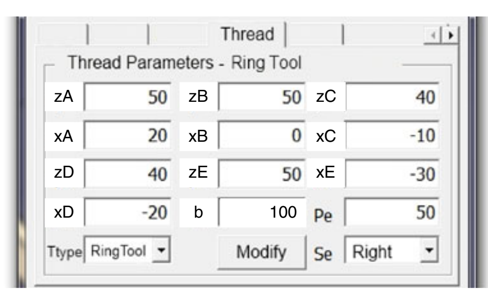

Fig. 4 The HGST-VBA application

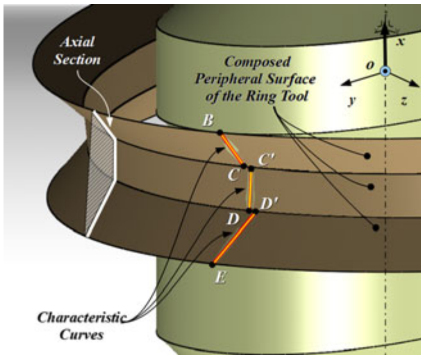

Fig. 5 The primary peripheral surface for the ring tool, the axis, the characteristic curve, and the axial section of the surface

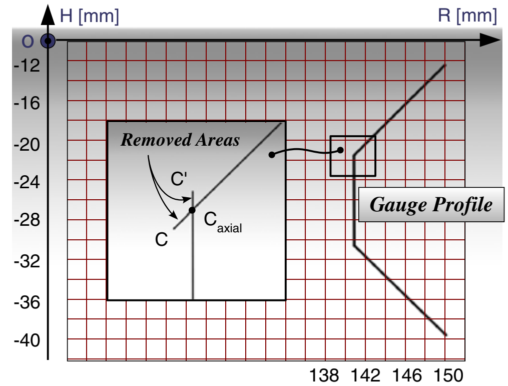

Fig. 6 The axial section of the primary peripheral surface for ring tool

2.3 Ring tool for ball thread

Figure 7 showed the model of the ball thread and its axial section (an assembly of circle's arc, filleted), as so as the following reference systems:

Xyz	is the reference system associated with the ball thread;
$X_1Y_1Z_1$	reference system associated with the ring tangential tool's primary peripheral surface; and
$x_0y_0z_0$ and $x_0'y_0'z_0'$	additional reference systems.

The generation movement assembly, the movements I, II, and III, has the significances given in Fig. 1. In Table 3, the input parameters correlated with the HGST-VBA application. Figures 7 and 8 present the forms and the coordinates of the characteristic curve and the axial section for the helical surfaces assembly that composes the ball thread flute. Obviously, in this case, singular points on the profile do not exist.

3 Tangential tool

The tangential tool is a tool bounded by a revolution primary peripheral surface. The tangential tools are tools designated for the generation of the cylindrical helical surfaces with constant pitch (threads) on specialized machine tools or using specialized technological equipments for longitudinal lather machines. The tangential tool may used on a grinder machine.

3.1 Ring tangential tool: algorithm

The problem of profiling the ring tangential tool, Fig. 9, is, in principle, similar with the known problem of the side mill tool's profiling. In principle, the Nikolaev [5] condition for the determination of the characteristic curve—the tangency curve between a cylindrical helical surface with constant pitch, Σ, and a revolution surface with $\vec{A}$ axis, with position known in the reference system of the Σ surface—is:

$$\left(\vec{A}, \vec{N}_{\Sigma}, \vec{r}_1\right) = 0, \tag{11}$$

Table 2 Coordinates of points on the characteristic curves and the axial section of ring tool

Profile	Crt. no.	X (mm)	Y (mm)	Z (mm)	Crt. no.	X (mm)	Y (mm)	Z (mm)
Characteristic curve	1	−3.7081	39.8280	−23.2389	26	−1.3370	44.4147	−37.1742
	2	−3.4432	40.9627	−22.0605	27	−0.9506	43.3140	−35.9989
	3	−3.1696	42.0962	−20.8829	28	−0.5724	42.2112	−34.8229
	4	−2.5961	44.3593	−18.5303	29	−0.2025	41.1065	−33.6461
	⋮	⋮	⋮	⋮	30	0.1589	39.9999	−32.4685
Profile		R (mm)		H (mm)		R (mm)		H (mm)
Axial section	1	150.0197		12.3447	26	145.7095		37.5908
	2	148.9044		13.4541	27	146.8372		38.6877
	3	147.7900		14.5646	28	147.9658		39.7835
	4	146.6766		15.6760	29	149.0955		40.8784
	⋮	⋮		⋮	30	150.2260		41.9723

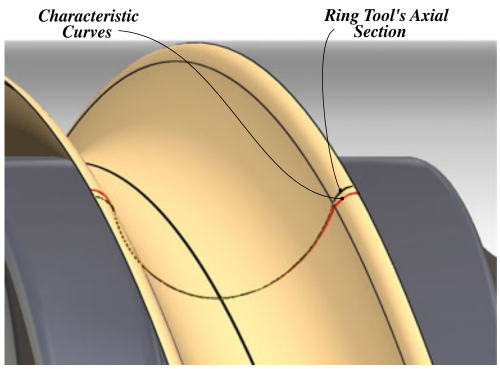

Fig. 7 Characteristic curve and axial section of the ring tool

where $\vec{A}$ is the versor of the rotation axis of the tool bounded by a revolution surface;

$\vec{N}_{\Sigma}$ is the normal at the helical surface; and

$\vec{r}_1$ is the vector which link the current point onto the Σ surface with a point of the $\vec{A}$ axis (frequently, the origin of the reference system joined with this axis, here $X_1Y_1Z_1$).

Condition 11 is equivalent with the statement: the characteristic curve of a cylindrical helical surface with constant pitch, Σ, in the rotation motion around a fixed axis, $\vec{A}$, is composed by all the points belongs to the Σ surface, which represent the projection of the $\vec{A}$ axis to the Σ surface. The specific problem is that the tool's axis position is deferent regarding the position of the side mill, regarding the blank.

The generation process kinematics presumes the following motions:

I is the rotation motion of the blank,

II translation motion of the blank correlated with the motion I, and

Table 3 Input parameters of the ball thread

Symbol	Description	Value
p	Helical parameter	2.5464 mm
r	Flank radius	5.4 mm
e	Half distance between the centers of circles with radius r	0.155 mm
D_j	Diameter of centers cylinder of the axial profile	49 mm
h	Distance between the D_j diameter and the center of circle with radius r	0.17 mm
D	External diameter of thread	48 mm
r_0	Fillet radius	1 mm
S_e	Helix sense	Right
D_{axis}	Distance between axis	150 mm
β	Tool's angle in plane XZ	10°
α	Tool's angle in plane ZX	6.0566°

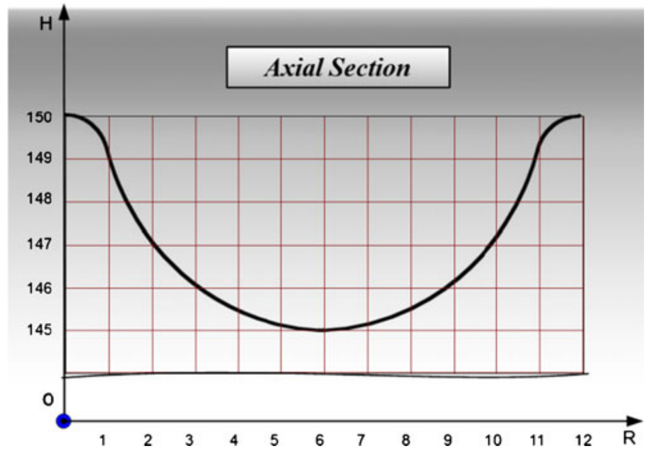

Fig. 8 Axial section of ring tool

III the rotation movements of the ring tangential tool (the cutting motion).

The assembly of motions I and II defines a helical motion with axis and helical parameter identical with the axis and the helical parameter of the surface to be generated.

They are defined the reference systems:

xyz is the reference system where is defined the helical surface (the Z axis is the axis of the helical surface).

$X_1Y_1Z_1$ reference system joined with the ring tangential tool (the X_1 axis is the axis of the ring tangential tool).

If, in the XYZ reference system, it is defined the Σ helical surface:

$$\Sigma : \vec{r} = x(u,v) \cdot \vec{i} + y(u,v) \cdot \vec{j} + z(u,v) \cdot \vec{k} \qquad (12)$$

with u and v variable parameters, then, by the coordinates transformation, see Fig. 9,

$$\left\| \begin{matrix} X_1 \\ Y_1 \\ Z_1 \end{matrix} \right\| = \left\| \begin{matrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{matrix} \right\| \cdot \left\| \begin{matrix} x+a \\ y+b \\ z-c \end{matrix} \right\| \qquad (13)$$

the helical surface Σ refers to the reference system $X_1Y_1Z_1$, by equations:

$$\Sigma \left| \begin{array}{l} X_1 = [x(u,v) - a]\cos\beta - [z(u,v) - c]\sin\beta; \\ Y_1 = y(u,v) - b; \\ Z_1 = [x(u,v) - a]\sin\beta + [z(u,v) - c]\cos\beta, \end{array} \right. \qquad (14)$$

with a, b, and c technological constants.

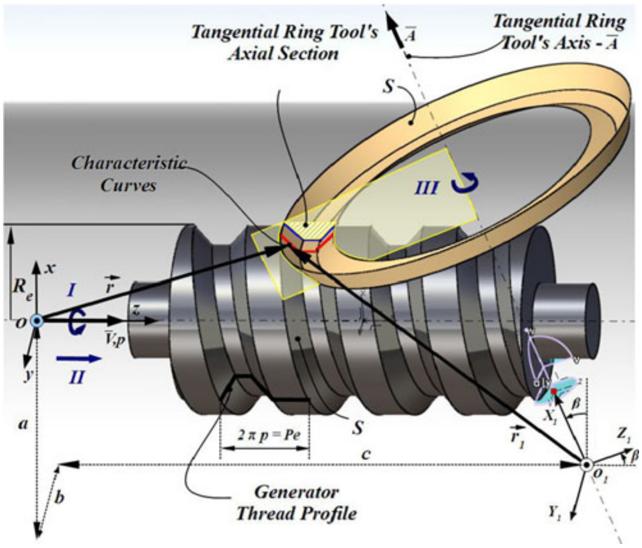

Fig. 9 The generation process kinematics with the ring tangential tool

In the condition for the determination of the characteristic curve 11 defining:

$\vec{A}=\vec{i}$ the versor of the ring tool;
$\vec{N}_{\Sigma}$ the normal to the Σ surface, in the reference system $X_1Y_1Z_1$

$$\vec{r}_1 = X_1(u,v)\cdot\vec{i} + Y_1(u,v)\cdot\vec{j} + Z_1(u,v)\cdot\vec{k}, \tag{15}$$

the current vector on the Σ surface, in the reference system $X_1Y_1Z_1$, Eq. 14.

The Eqs. 11 and 14 assembly represents the characteristic curve, in principle, in form:

$$(C_{\Sigma})_{X_1Y_1Z_1}\left| \begin{array}{l} X_1 = X_1(u); \\ Y_1 = Y_1(u); \\ Z_1 = Z_1(u). \end{array} \right. \tag{16}$$

By revolving, the characteristic curve around the X_1 axis is determined the primary peripheral surface of the ring tangential tool. The constants a, b, c, and β are determined from the condition that the trajectory of the S point, corresponding to the external diameter of the Σ surface, to be tangent at the helix (see Figs. 9 and 10).

Also, the projection of the helix corresponding to the R_e blank radius, in the same plane yz, is a curve with form:

$$L_E\left| \begin{array}{l} y = R_e \sin\varphi; \\ z = p\cdot\varphi, \end{array} \right. \tag{17}$$

with φ variable and p helical parameter, $p = \frac{p_e}{2\pi}$.

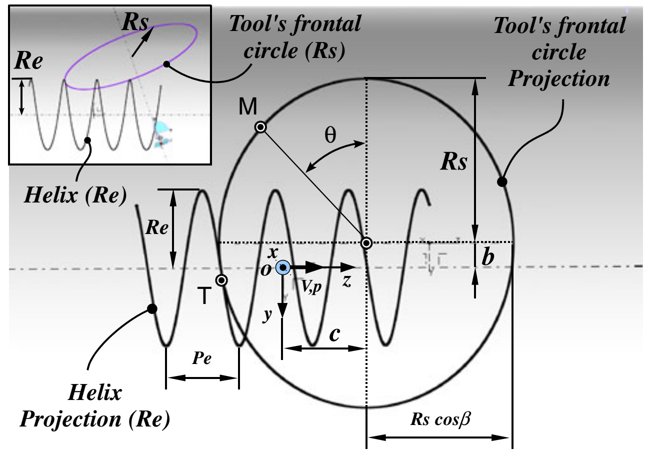

Fig. 10 The ring tangential tool's axis position

From the condition that the two curves 16 and 17 to be tangents in the M point, is determined the equations assembly:

– the condition of common point:

$$R_S \cos\theta + b = R_e \sin\varphi; \tag{18}$$

$$R_S \cos\beta \sin\theta + c = p\cdot\varphi; \tag{19}$$

– the condition of common tangent:

$$-R_S \sin\theta = R_e \cos\varphi; \tag{20}$$

$$R_S \cos\beta \cos\theta = p; \tag{21}$$

The 18, 19, 20, and 21 equations assembly determine the values b, c, φ, and θ (the linear value a and the angle β have to be accepted from a constructive point of view, $a = R_e$).

3.2 Applications

3.2.1 Ring tangential tool for trapezoidal thread

In the following, an application of the proposed algorithm for the determination of the primary peripheral surface of the ring tangential tool, for generation of a trapezoidal thread, with generatrix of helical surface presented in Fig. 3

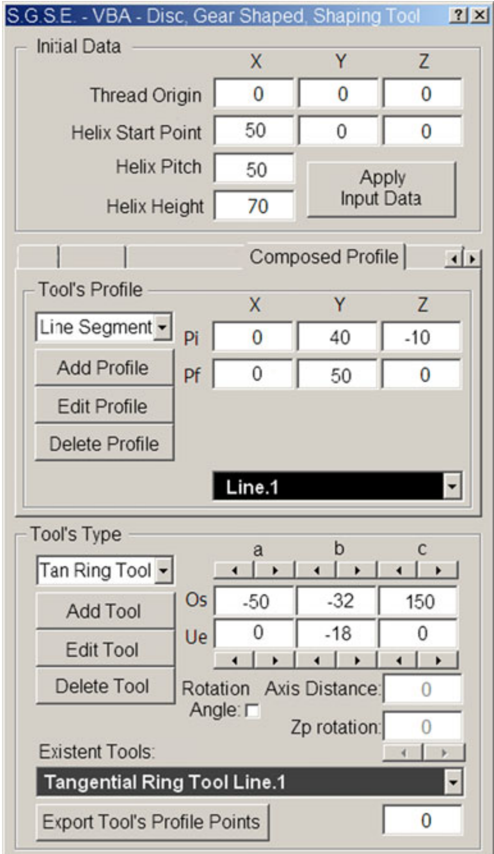

Fig. 11 HSGT application—ring tangential tool, trapezoidal thread

is presented. The method is the same with those described in paragraph 2.1.

The input data for the profile of the thread, the helix pitch, and the distance between the tool's axis and the thread's axis are inserted in the HSGT application, presented in Fig. 11, according to Table 4. Figure 12 represented the surfaces of the trapezoidal thread's flank, characteristic curves on the thread's flanks, primary peripheral surfaces of the ring tangential tool, and the axial section.

The form of the axial section of the ring tangential tool (the plane X_1Y_1) is represented in Fig. 13. We have to notice that the axial tool's profile is asymmetric. Obviously, in the points B and C (see Fig. 12) on the composed profile of the tool, emerged discontinuities that may be solved by link this zones and accepting a deformation of the thread bottom, according to a required target.

Table 4 Input parameters of the trapezoidal thread (straight lined segments)

Symbol	Description	Y (mm)	Z (mm)
A	Initial point of thread head	50	20
B	Initial point of thread flank	50	0
C	Initial point of thread bottom	40	−10
D	Final point of thread bottom	40	−20
E	Final point of thread flank	50	−30
S_e	Helix sense	Right	
p_e	Helix pitch	50 mm	
a	x coordinate of tool's origin	−50 mm	
b	y coordinate of tool's origin	−32 mm	
c	z coordinate of tool's origin	150 mm	
U_e	Tool's rotation around Y_1 axis	−18°	

3.2.2 Ring tangential tool for ball thread

Figure 14 presented the model of the ball thread and its axial section, an assembly of circle's arc, filleted, as so as the reference systems:

Xyz	is the reference system associated with the ball thread;
$X_1Y_1Z_1$	reference system associated with the ring tangential tool's primary peripheral surface; and
$x_0y_0z_0$ and $x_0'y_0'z_0'$	additional reference systems (see Fig. 15).

The generation movement assembly, the movements I, II, and III, has the significances given in Fig. 9.

In this way, the helix belongs to the ball thread flute and situated onto the cylinder with radius R_e:

$$\begin{aligned} x &= R_e \cos\varphi; \\ y &= R_e \sin\varphi; \\ z &= -p\varphi, \end{aligned} \tag{22}$$

is transferred, by coordinates transformation:

$$\left\| \begin{matrix} X_1 \\ Y_1 \\ Z_1 \end{matrix} \right\| = \left\| \begin{matrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{matrix} \right\| \cdot \left[\left\| \begin{matrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{matrix} \right\| \cdot \left\| \begin{matrix} R_e\cos\varphi \\ R_e\sin\varphi \\ p\varphi \end{matrix} \right\| - \left\| \begin{matrix} 0 \\ R_e \\ 0 \end{matrix} \right\| \right] - \left\| \begin{matrix} 0 \\ 0 \\ -R_S \end{matrix} \right\| \tag{23}$$

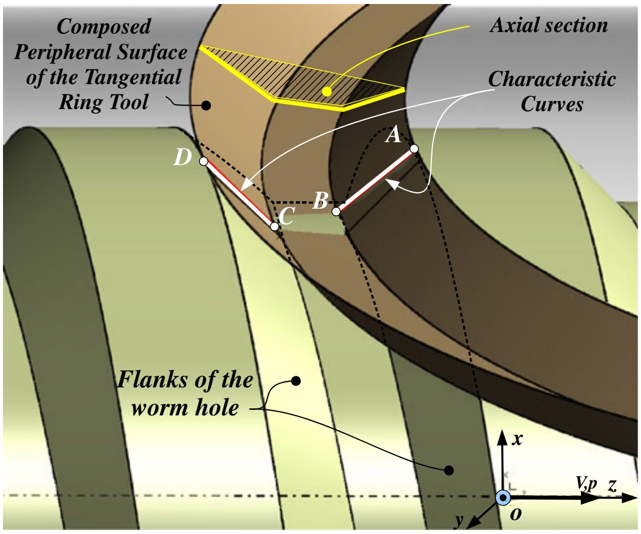

Fig. 12 3D model of the helical surface; 3D model of the ring tangential tool's primary peripheral surface

The helix, in the reference system $X_1Y_1Z_1$, associated with the ring tangential tool with the circle:

$$X_1 = R_S \cos\theta;\quad Y_1 = 0;\quad Z_1 = R_S \sin\theta, \tag{24}$$

of the ring tangential tool's primary peripheral surface, allow to determine the parameters: α, β, θ, and φ.

Other solution may be obtained by knowing the angle of helix for the cylinder with radius R_e,

$$\alpha = \mathrm{arctg}\frac{p}{R_e} \tag{25}$$

and the normal plane to the helix in the point O_0 (see Fig. 15).

The plane of the circle R_S is revolved around the axis x_0 (x_0'), with the angle β determined from constructive point of view from the condition to avoid the interference between the tool and the opposite flank, see Fig. 14. The x axis is symmetrical with the arcs with radius r. In Table 5, the input parameters correlated with the application HSGT.

In Figs. 16 and 17, we present the forms and the coordinates of the characteristic curve and the axial section for the helical surfaces assembly that composes the ball thread flute. Obviously, in this case, it is not possible to define singular points on the profile.

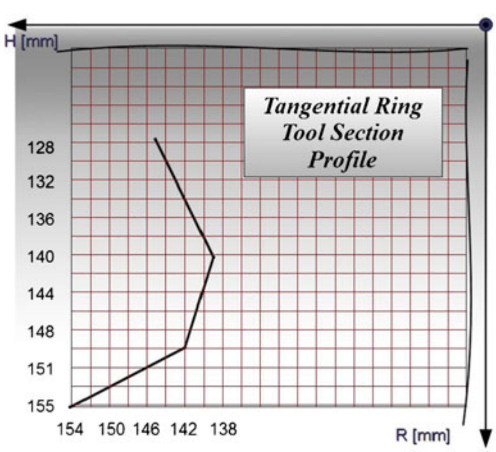

Fig. 13 Axial section of the ring tangential tool's primary peripheral surface

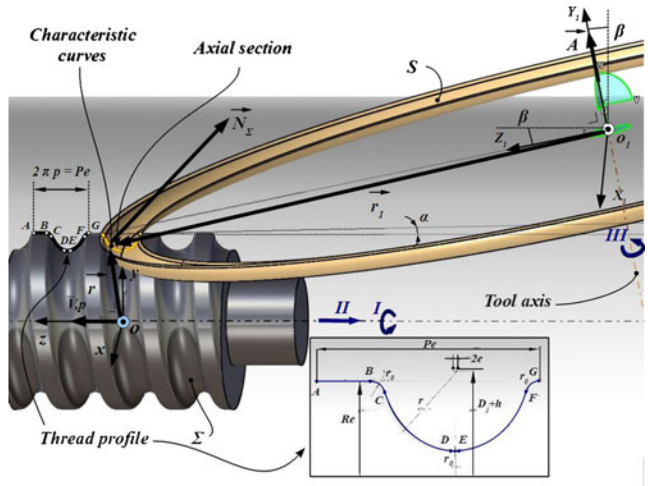

Fig. 14 Ball thread; axial profile, and reference systems

4 Conclusions

This paper presents algorithms and numerical applications for the profiling of ring tools for the generation of cylindrical helical surfaces with constant pitch, based on the topological representation of the tool's primary peripheral surface. The proposed method uses the capabilities of the CATIA graphical design environment. This method

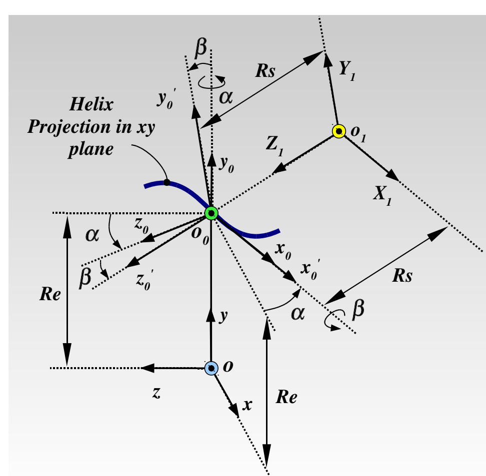

Fig. 15 Ball thread; axial profile, and reference systems

Table 5 Input parameters of the ball thread

Symbol	Description	Value
p	Helical parameter	2.5464 mm
r	Flank radius	5.4 mm
e	Half distance between the centers of circles with radius r	0.155 mm
D_j	Diameter of centers cylinder of the axial profile	49 mm
h	Distance between the D_j diameter and the center of circle with radius r	0.17 mm
D	External diameter of thread	48 mm
r_0	Fillet radius	1 mm
S_e	Helix sense	Right
D_{axis}	Distance between axis	150 mm
β	Tool's angle in plane *zy*	10°
α	Tool's angle in plane *xz*	6.0566°

allows to determine the composed characteristic curves of the helical surfaces (the case of the helical flutes of the motion threads) as so as, the highlighting of the singular points on the tool's profile, including modalities for the solving of the inherent discontinuities by the method of virtual extending of the profiles.

The results obtained in graphical and numerical form confirm the method quality. Based on this method, an original software, in VBA, was created.

The profiling of the ring tangential tool is similar to the profiling of the side mill tool. The particular position of tool's axis may limit the length of the machined thread.

The specific application HSGT allows the determination of the characteristic curve (in particular for composed characteristic curves for complex surfaces) and allows the solving of problems due of the singular points. The profile, in the tool's axial section, is rigorously determined in the specifically HSGT application.

The proposed method, developed in the CATIA graphical design environment, for the profiling of the ring tangential tool's primary peripheral surfaces allows determining the characteristic curves and the axial

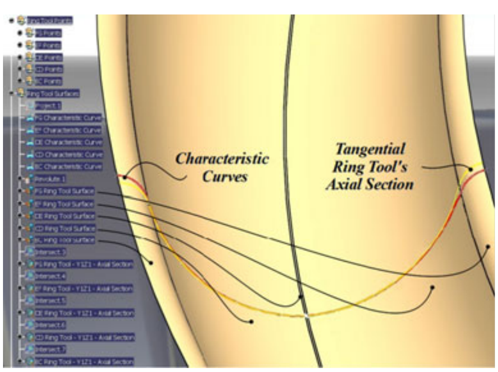

Fig. 16 Characteristic curve and axial section of ring tangential tool

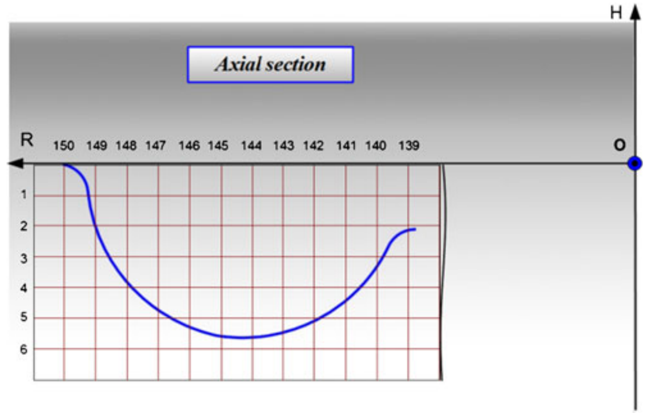

Fig. 17 Axial section of ring tangential tool

section. The HSGT application is based on the decomposition of the helical movement—the self-generating movement of the surface to be generated—a cylindrical helical surface with constant pitch. They are presented with analytical and graphical solutions for the determination of the constructive parameters of the generating tool. Also, four numerical applications for cylindrical helical surface with constant pitch used in machine part's construction were presented.

Acknowledgments The authors gratefully acknowledge the financial support of the Romanian Ministry of Education, Research and Innovation through grant PN_II_ID_791/2008.

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