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Simulation-aided Design of Thread Milling Cutter

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Abstract

Thread milling has become quite popular in recent years as an alternative to tapping or other forms of threading because of diversity and complexity of parts and flexibility of the process in industries such as biomedical applications, aerospace and die-mold manufacturing. Today the design of the tooth profile is, however, predominantly feasible by the expertise and "trial and error" principle.

Presented in this paper are a novel methodology to design the tooth profile of the thread mill by comparing the "to-be" thread profile and the "as-is" thread profile which is analyzed by means of NC cutting simulation. The simulation kernel enables to continually subtract the swept volume of thread milling cutter undergoing helical movement from the workpiece and to calculate the virtual workpiece (VWP). Combined with the standardized "to-be" thread profile, the tooth profile of to-be-designed thread mill is adaptively modified until the thread profile on VWP and the "to-be" thread profile become congruent with each other. The proposed methodology could be integrated into CAD/CAM systems.

Keywords: Design, Simulation, Thread milling, Tool Design

1. Introduction

Helical surface machining (either grinding or milling) is a widely adopted process used to generate helically-swept surfaces for drill flutes, end mill cutters, helical gear teeth, screw mechanisms, and so on [1-2]. It is extremely complex due to the helical motion of the disk-type (grinding wheel, slab mill) or axial-type (mounted wheels, end mill) cutters along the helical tool path on cylindrical stocks. During machining of a helical surface, the rotating cutter moves along the axis of the workpiece, while the workpiece rotates about its own axis. The combined relative motion of the cutter and workpiece results in a helical motion [3].

The problem of helical surface machining, however, is that it is still usually approached by many manufacturers with an empirical trial-and-error method. The geometry of the helical surface not only depends on the geometry of the tool, but also on the operating (machine setup) parameters. Identical surfaces can be manufactured under radically different conditions with respect to the machine setup and tool geometry used. For that reason, the choice of operating parameters and cutter profiles depends on the machine operator and his know-how about the process [4].

Classical application areas of form-milling cutters are, among other things, the gear cutting and the production of helical slots, for example, those of threads. For thread milling by using form-milling cutters (generally referred to as thread milling cutter) as well as for the fast development of special threads, there arises a need for computer-based construction and simulation-supported functional verification of thread cutters.

When it comes to the fabrication of threads, thread-milling is advantageous in comparison to tapping for several reasons. Firstly, thread-milling produces far superior threads as compared to tapping due to a much higher cutting speed. Secondly, thread milling is a practical solution for threading large holes. However, it demands a careful, deliberate approach, as well as several other prerequisites. At first, up-to-date CNC machine tools are a necessity. To perform thread milling,

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the machine must be capable of helical interpolation. Second to none, a thread milling cutter, the profile of which is to be designed slightly different from the thread profile due to the helical movement of the cutter, is required. Other aspects to consider in relation to thread milling are the issues of right-handed/left-handed threads, internal/external threads, and multi-start threads [5-6].

This paper presents a novel approach to the pre-profiling of rotating thread milling cutters. The pre-profiling of cutter profile is based on the envelope profiles [8-9] of the moving cutter and the helical motion that results from the relative motion between the cutter and workpiece. To demonstrate the validity of the proposed method, an ISO metric screw thread is chosen as an example in this work [7].

Fig. 1 shows the sectional view of ISO metric screw thread defined by two design parameters, pitch p and major diameter D, in the plane which goes through the axis of screw thread. Additionally, H is the height of the fundamental triangle, D2 is the pitch diameter and D1 is the minor diameter of the external thread. The basic profile is the theoretical profile of the thread. An essential principle is that the actual profiles of both the internal/external threads must never cross or transgress the theoretical profile. So, external threads will always be equal to, or smaller than, the dimensions of the basic profile. Internal threads will always be equal to, or greater than, the basic profile [7].

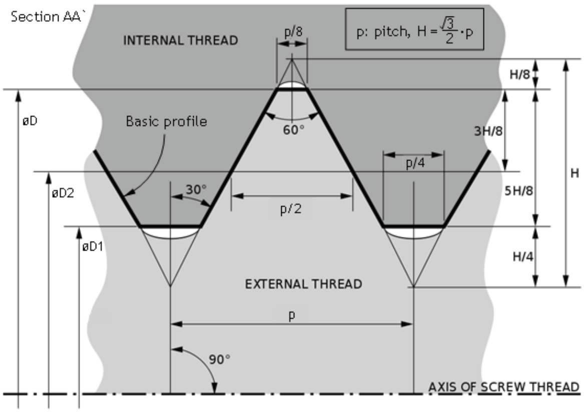


Fig. 1 Cross sectional view of ISO metric screw thread after [7].

This paper is organized as follows: Section 2 presents the helical projection which is the foundation for the proposed approach. The approach to the calculation of envelope profile of the thread milling cutter and the method of the simulation-aided design of the thread milling cutter are presented in Section 3 and Section 4, respectively. Section 5 presents the implementation and two demonstration-examples by using the proposed method exemplarily. Section 6 concludes and summarizes the work.

2. Helical Projection

A (linear) projection is the mapping of three-dimensional (3D) points onto a two-dimensional (2D) plane by connecting corresponding points with parallel lines.

On the other hand, a curvilinear projection of 3D points onto a 2D plane along a helix with an axis and a pitch is called helical projection. In contrast to linear projection, helical projection connects the corresponding points along helical curves that could have a common pitch but different radii of helix.

Helical projection is very useful in the formulation of the helical surfaces or grooves embedded in rotor, milling or boring cutters, worm gear or threaded screws, etc. Hereafter, any mention of projection refers to helical projection if it is not specified.

The family of Euclidean congruence transformations, which is parameterized by the angle parameter θ [rad], and maps points in a suitable Cartesian coordinate system according to

$$P \to x(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot P + \begin{bmatrix} 0 \\ 0 \\ p\cdot\theta/2\pi \end{bmatrix} \qquad (1)$$

is called a one-parameter group of helical motions if $p \neq 0$. If $p = 0$, it is called a one-parameter group of rotations, or a uniform rotation. A uniform helical motion is the superposition of a uniform rotation and a translation by the vector $(0, 0, p\cdot\theta/2\pi)$. The line $x = y = 0$ is called its axis, and p is called its pitch (see Fig. 2).

If an arbitrary point P as in Eq. (2)

$$P = (l \quad m \quad n) = (R\cos\varphi \quad R\sin\varphi \quad n) \text{ where } \cos\varphi = \frac{l}{\sqrt{l^2+m^2}},\ \sin\varphi = \frac{m}{\sqrt{l^2+m^2}},\ \varphi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right], \qquad (2)$$

is given, the helix $x(\theta)$ with pitch p through P could be rewritten from Eq. (1) and Eq. (2) as Eq. (3)

$$x(\theta) = (R\cos(\theta+\varphi) \quad R\sin(\theta+\varphi) \quad n + p\cdot\theta/2\pi),\ \theta \in [0, \pi/2] \text{ or } x(\theta) = (l\cos\theta - m\sin\theta \quad m\cos\theta + l\sin\theta \quad n + p\cdot\theta/2\pi),\ \theta \in [0, \pi/2] \text{ where } x(0) = P. \qquad (3)$$

Then, the helically projected point Q of the helix $x(\theta)$ onto plane Σ is found by substituting Eq. (3) into the plane equation $\Sigma: (a \quad b \quad c) \cdot \overrightarrow{OX} = d$ as in Eq. (4) (see Fig. 2).

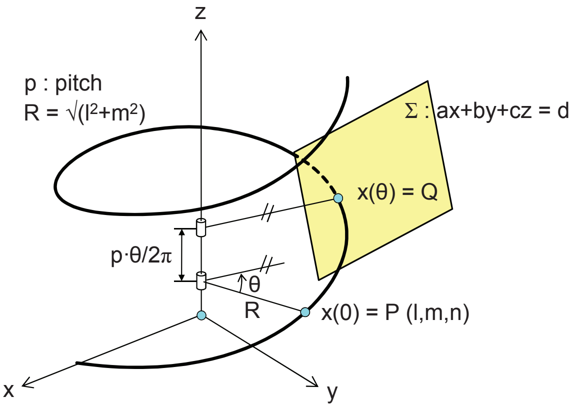


Fig. 2 Helical motion and helical projection of the helix onto plane Σ

$$(a \quad b \quad c) \cdot \overrightarrow{OX} = (a \quad b \quad c) \cdot x(\theta) =$$

$$(a \quad b \quad c) \cdot (R\,cos(\theta+\varphi) \quad R\,sin(\theta+\varphi) \quad n + p \cdot \theta/2\pi) = d.$$

$$\therefore R\sqrt{a^2+b^2}\sin(\theta+\varphi+\alpha) = d - c \cdot n - \frac{c \cdot p}{2\pi} \cdot \theta \tag{4}$$

where $\cos\alpha = \frac{b}{\sqrt{a^2+b^2}}$, $\sin\alpha = \frac{a}{\sqrt{a^2+b^2}}$ and $\cos\varphi = \frac{l}{\sqrt{l^2+m^2}}$, $\sin\varphi = \frac{m}{\sqrt{l^2+m^2}}$, $\alpha \in \left[\frac{\pi}{2}, \pi\right]$, $\varphi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$.

Then, the solution θ could be found appropriately by restricting the valid projection angle interval $[0, \pi/2]$.

3. Envelope Profile of a Thread Milling Cutter

The envelope profile is a line of contact along which the thread milling cutter touches the generated thread surface [9]. This profile produces the contour on the workpiece and is therefore also referred to as a generator, depending exclusively on the geometry and the motion of the tool.

Accordingly, in order to calculate pre-profiling of a tool profile, the kinematics of a thread milling cutter needs be examined first. Then, envelope profiles are to be determined from the analysis of the velocity distribution of the tool.

During thread milling, the cutter moves along a helical trajectory around the cylindrical geometry. Fig. 3 shows the relative positioning of a thread milling cutter that cuts raw stock and forms a thread. Given a pitch p of the “to-be” thread, that of the corresponding thread cutter, and that of the helical trajectory should be identical with p (see Fig. 3).

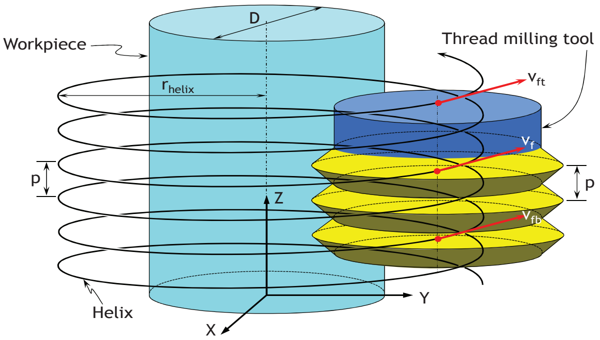


Fig. 3 Relative positioning of thread milling tool to workpiece at thread milling.

Because the tool moves with a fixed tool axis along the helix, the velocity vectors $\boldsymbol{v}_b$ and $\boldsymbol{v}_t$ of the cutter at the bottom and on the top are identical with the feed vector $\boldsymbol{v}_f$. As denoted in Fig. 4, $\boldsymbol{v}_f$ is calculated from the relationship between pitch p of the screw thread and the distance r_{helix}, which is measured from the axis of the workpiece to the axis of the cutter. Due to the fact that the tool undergoes the three-axis motion, the velocity vector $\boldsymbol{v}_P$ of any point P on the tool surface is congruent with $\boldsymbol{v}_f$ $(\boldsymbol{v}_P = \boldsymbol{v}_f)$.

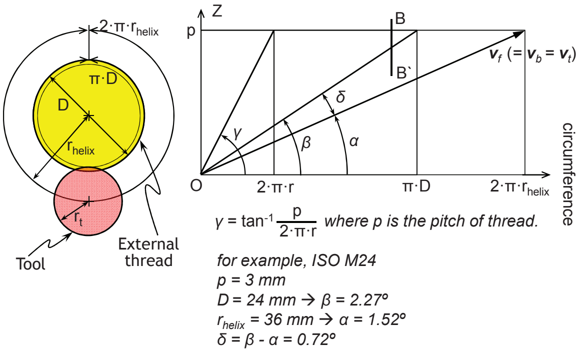


Fig. 4 Definition of a feed vector v_f.

Fig. 5 schematically illustrates the fundamental procedure used to determine the geometrically exact profile of the thread milling cutter. Because the teeth of the thread milling tool are connected with each other, just one tooth is considered here and the principle is applied to other teeth repeatedly. It is assumed that a point P of interest is placed on the tooth. At first, the unit surface normal vector $\boldsymbol{n}_P$ is obtained for any given point P on the tooth surface ($\boldsymbol{n}_P$ can fall into one of both $\boldsymbol{n}_u$ and $\boldsymbol{n}_d$) and mapped onto a unit sphere. Then, small circles C_u, C_d can be built by using $\boldsymbol{n}_u$ and $\boldsymbol{n}_d$ (see Fig. 5 (a)-(b)). Secondly, since $\boldsymbol{v}_P$ is already given, the unit circle that is perpendicular to $\boldsymbol{v}_P$ is mapped onto the unit sphere as the great circle C_g, so that the intersection points $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ between the circles C_u, C_d and C_g are calculated (see Fig. 5 (c)-(b)).

Consequently, both points P on the tool surface, which correspond to the intersection points $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ on the unit sphere, satisfy the tangency condition ($\boldsymbol{v}_P \cdot \boldsymbol{n}_P = 0$) which enables finding the envelope profile on tooth surface (see Fig. 5 (d)).

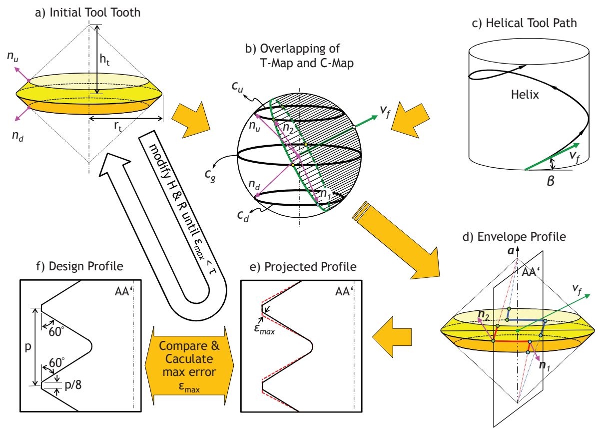


Fig. 5 Schematic flow diagram for the calculation of optimal thread milling cutter tooth design from thread data and helical tool path.

Fig. 6 shows in detail the envelope profile that is calculated by the proposed method. The thread milling tool is a double frustum of a cone which has the height h_t and the radius r_t. Please note that $P_4 = P_1 + p \cdot \boldsymbol{d}_1$ and $P_5 = P_2 + p \cdot \boldsymbol{d}_2$ according to the definition of the screw thread in Fig. 1. Thus, the envelope profile of the thread milling tool is comprised of the arc segment $\widehat{P_1 P_2}$ and both line segments $\overline{P_4 P_1}$ and $\overline{P_2 P_5}$.

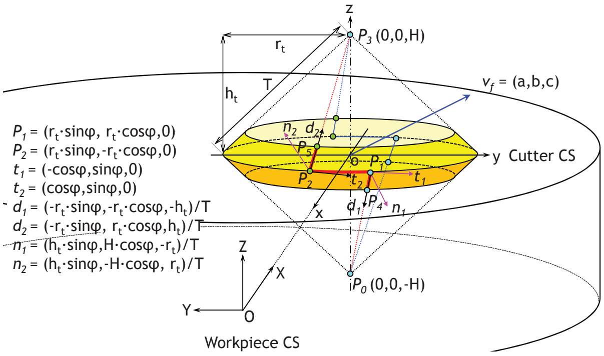
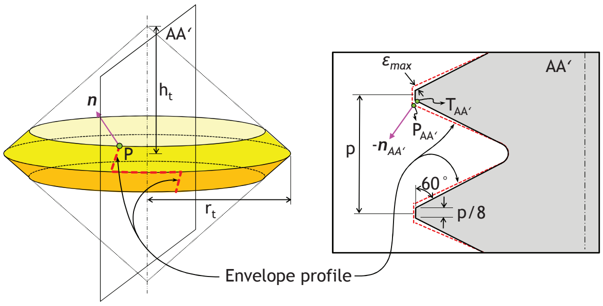


Fig. 6 Envelope profile on the thread milling tool.

4. Simulation-aided Design of the Thread Milling Cutter

The modification of the tool shape leads to the deformation of the thread profile because the envelope profile is modified correspondingly. Fig. 5 (e) shows the projected view of the envelope profile in the section AA' which goes through the tool axis $\boldsymbol{a}$ (see Fig. 7 in detail).

The projected envelope profile is shown as a dotted curve and the sectioned profile of the thread surface is depicted bold in Fig. 7 (b). On the section AA', the projected envelope profile can be compared with, and be modified to the sectioned thread surface. For example, a point P lies on an envelope profile and the projected point $P_{AA'}$ onto the section AA' can be transformed slightly by changing the position of P along the surface normal $\boldsymbol{n}$. P is adjusted such that $P_{AA'}$ could coincide with the "to-be" point $T_{AA'}$ on a sectioned thread surface. It implies that the fundamental analytical condition of engagement between the generating cutter and generated helical surface is established, which in turn says that the surface normal of the thread milling tool at $P_{AA'}$ is parallel to the surface normal of the thread at $T_{AA'}$ when the thread milling tool is in contact with the point $T_{AA'}$. Please note that the direction of $\boldsymbol{n}$ of the cutter is inverted in AA' because the thread surface is the conjugated surface of the cutter surface.



a) Initial dimension of cutter tooth

b) Projected envelope profile

Fig. 7 Transformation of a point P on the cutter surface in surface normal direction n.

By comparing the modified thread profile with the design profile of the thread, a preformed profile of the thread milling cutter is calculated (Fig. 5 (e),(f)).

The initial dimension of the thread milling cutter is r_t and h_t, which can be derived from the definition of the screw thread in Fig. 1. h_t is modified iteratively until the slope of the projected envelope profile becomes parallel with the basic profile in the interval $d \in [D1, D]$ under prescribed tolerance τ (see Fig. 5(a),(e)). After h_t^* has been determined, r_t is modified, keeping the ratio r_t/h_t^* until the projected envelope profile coincides with the basic profile in Fig. 1 (see Fig. 5 (e),(f)).

The same solving procedure can be applied to internal screw threads.

5. Implementation and Results

The NC simulation kernel (NCSK) for thread milling machining has been developed with C++, OpenGL version 2.0 [10] and the standard template library. The simulation module runs on AMD® Athlon II X4 630 CPU 2,81 GHz and 8 GB RAM which is equipped with an nVidia® Quadro FX 580 PCI-E graphics accelerator with 512 MB RAM.

Based on the envelope profile calculation and the helical projection of the envelope profile, some results are presented hereafter.

Fig. 8 shows the 3D model of a virtual thread milling cutter which is designed for cutting the external ISO M24 x 3 metric screw thread. Because the profile design of a thread milling cutter is focused on in this work, the slots along the tool axis are ignored in the visualization.

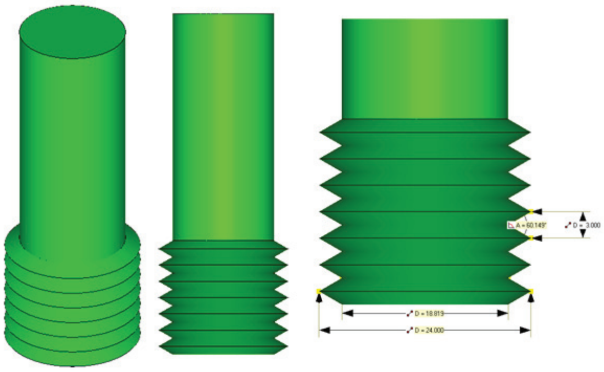


Fig. 8 Virtual thread milling cutter: simulated-aided design of a thread milling cutter for the screw thread ISO M24 x 3.

The surface of thread is the conjugate surface of the thread milling cutter. Therefore, by applying the tool profile designed in Fig. 8, the thread of ISO M24 x 3 can be "virtually" machined [11].

Fig. 9 shows some examples of the internal and external ISO M24 x 3 metric screw threads of the major diameter D = 24mm and the pitch p = 3 mm which are simulated by NCSK. Fig. 9 (a) denotes the external M24 screw thread and the cross sectional view with heightened sectional curve. Fig. 9 (b) shows the internal M24 screw thread, which is the counterpart of the external M24 screw thread, and the cross sectional view with heightened sectional curve.

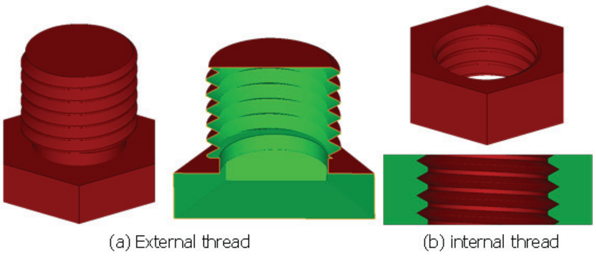


Fig. 9 Simulated-aided design of ISO M24 screw thread.

Fig. 10 shows the virtual measurement of the simulated ISO M24 x 3 thread, which is "virtually" cut by the virtual thread milling tool that is designed in the framework of the NCSK (compare the dimensions in Fig. 1) [11]. As a result of the simulation, the pitch is proven to be exactly 3 mm after the ISO standard, and the "as-is" angle in the fundamental triangle is 59,986° with 0.012% deviation from the "to-be" angle (60°). The "as-is" thread band-width at the major diameter is 0.3744mm with 0.16% deviation from the "to-be" value (0.38mm). As a result, the simulation-aided design of the thread cutter enables generation of the profile of the thread milling cutter, which corresponds to the design profile of the thread with high precision.

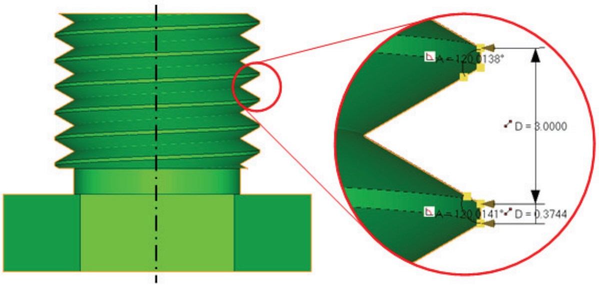


Fig. 10 Virtual measurement of "to-be" external M24 thread profile in cross section.

Practically, to make a thread, tolerances must be applied to ensure that the actual profiles of both the external/internal threads must never cross or transgress the theoretical profile. As a result, clearances must be applied to the basic profile of the threads so that an external thread can be screwed into an internal thread appropriately, which inevitably influences the geometry of the tool [12].

Fig. 11 shows the external/internal ISO M24 x 3 thread pair taking a clearance of 260 µm into consideration. Firstly, both thread profiles are calculated by making the external/internal thread profiles congruent with the basic thread profiles. After that, the external (internal) profile is translated radially outward (inward) so that the total clearance between both profiles amounts to 260 µm.

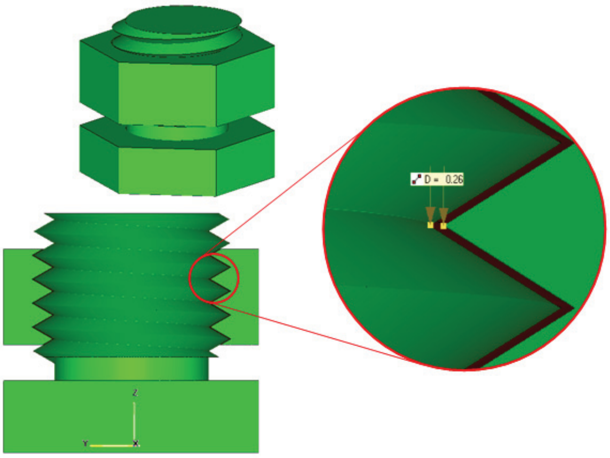


Fig. 11 Tolerance design via simulated-aided design.

6. Conclusion and Outlook

Presented in this paper is a novel methodology to design the tooth profile of the thread milling cutter by comparing the “to-be” thread profile and the “as-is” thread profile which is simulated by a virtual thread milling cutter in the framework of the NC simulation kernel (NCSK). The NCSK enables continual subtraction of the swept volume of the thread milling cutter from the workpiece and calculation of the virtual workpiece (VWP). Intermediate output of NCSK is the simulated thread which is “virtually” cut with the virtual thread milling cutter in NCSK. Combined with the standardized “to-be” thread profile, the tooth profile of the virtual thread milling cutter is iteratively modified until the “as-is” profile of the simulated thread becomes congruent with the “to-be” thread profile.

The proposed approach is proven to be practically applicable to design tooth profile of thread milling cutters in a virtual machining environment. The proposed methodology could be integrated into CAD/CAM systems to design the thread tool geometry by using the threading simulation, which is deficient in modern CAD/CAM systems.

The following subjects are left open for further research goals:

- Current cutter profile is the double frustum of a cone which forms a sharp edge at the minor diameter of the thread. The corner part could be further truncated for functionally stable threads, for which the envelope profile is to be calculated.
- Design of the thread milling tool for special thread types; e.g., dental implants in the healthcare industry is an emerging interest.
- A series of cutting tests could be conducted to verify the proposed methods in a real cutting environment.

Acknowledgements

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