Thread turn milling simulation

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Abstract. The study shows that the high-performance thread turn-milling process with a synchronous rotation of the helical milling cutter and the workpiece is not widely adopted since there are no reliable methods to estimate the organic thread formation errors. The thread is machined as an envelope curve along the elementary surfaces of each cut shifted along the workpiece axis by a fraction of the thread pitch inversely proportional to the number of the cutter teeth. Domestic and international researchers tried to analytically estimate the thread formation errors at the part face. Such an approach failed to produce acceptable results since thread turn-milling is a three-dimensional process. We analyzed the thread formation errors in 3D using COMPAS 3D CAD system and developed a simulation model. We modelled a reference 3D thread machined on the workpiece; a 3D resulting thread; a single cutter tooth path in the plane perpendicular to the workpiece axis; 3D cut by a single cutter tooth. We also simulated the entire process and made a 3D model of the machining errors by subtracting the reference part geometry from the 3D thread model, and estimated the errors. The results were checked for consistency (max deviations) and acceptability for each dimension. The undercut dimensions were obtained by subtracting the 3D part model from the 3D reference model. Conversely, the overcut dimensions were obtained by subtracting the 3D reference model from the 3D part model.

1. Introduction
The thread turn-milling process was first presented in 1941 by S.I. Skukhtarov and S.I. Khlunov in their paper published in Manufacturer [1]. However, it is not widely adopted so far despite its theoretically high performance [2-5]. The cutting forces and tool life for thread turn-milling were investigated [6-11]. One of the reasons that inhibit the process adoption is the lack of an adequate simulation model of the thread formation by turn-milling. Paper [12] is an attempt to develop an analytical model of the thread turn-milling process. We propose to apply simulation for selecting the milling cutter as in [13-19].

2. Simulation
The input variables are the part and workpiece geometry, the output variables are the milling cutter properties (Figure 1). The independent variables, in this case, are the dimensional tolerances. They define the target function or the process criterion: minimizing the machined surface errors.

Figure 1. Structural and functional model of the machining strategy and milling cutter selection for thread turn-milling.
For real-life applications, it is sufficient that the selected cutter properties meet the specified thread properties. The simulation tool was a 3D CAD such as COMPAS 3D.

The simulation steps were as follows:
1. 3D modeling of the reference thread on the workpiece.
2. 3D modeling of the part machined with turn-milling.
   2.1. Drawing the cutting path for a cutter tooth in the plane perpendicular to the workpiece axis.
   2.2. Creating a 3D model of the cut made with a cutter tooth.
   2.3 Simulation of the entire machining process.
3. Creating a 3D model of the deviations by subtracting the reference model part from the 3D model of the resulting thread.
4. Generating projected views of the deviations.
5. Estimating the deviations quantitatively.
6. Verifying the results for consistency (max deviations) and meeting the max acceptable dimensional tolerances.

To make a reference thread model, the thread and workpiece geometry is required. To model the real tool marks on the workpiece, the machining strategy and the milling cutter properties are pre-selected. The selection should provide the least error possible. It is an iterative process since the optimal cutter parameters are re-adjusted until the deviations (undercuts and overcuts) stop decreasing.

One of the most significant stages of preparing input data for simulation is generating a cutter tooth path. For this, we should estimate the 3D point coordinates, and draw an enveloping contact curve. That is why special software tools are needed [14, 15].

We used a parametric CAD to rapidly rebuild the models as new cutter parameters are specified. One of such systems is COMPAS 3D.

For external threads, we simulated the outer contract as the milling cutter and the workpiece rotate in the same direction. It is the simplest machining strategy to implement (Figure 2).

We progressively changed the milling cutter diameter and the number of cutting edges.

Then we developed an equation for the cutter tooth tip path in a single cut.

Let us investigate the equation in detail. Figure 3 shows a diagram of the workpiece and milling cutter cross-sections. As the cutter tooth is at its max penetration the axis of the cutter and the workpiece are concentric at the line $O_1O_{u_1}$ while the tooth is at point $B$. As the workpiece rotates by the angle $\Delta\phi$, the cutter tooth rotates around the milling cutter axis also by $\Delta\phi$. As a result, the cutter axis would shift to $O_{u_2}$, and the tooth would move from $B$ to $B_1$. Since the angles are equal, the line $B_1O_{u_2}$ is always parallel to the line $O_1O_{u_1}$ and to $\angle O_1AB_1 = 90^\circ$. The coordinate $y_{B_1}$ can be estimated from the triangle $O_1AB_1$:

$$y_{B_1} = d_{\mathbf{n}_1} \cdot \sin\Delta\phi.$$

Here the center-to-center distance is a constant value that does not depend on the rotation angle:

$$d_{r_1} = O_1O_{u_2} = O_1O_{u_1} = R_u + R_s - h = \text{const},$$

where $R_u$ is the cutter radius, $R_s$ is the workpiece radius, $h$ is the thread root-to-crest height.

The $Ox$ coordinate is the difference between the second leg of the triangle and the cutter radius:

$$x_{B_1} = AO_{u_1} - B_1O_{u_1} = d_{\mathbf{n}_1} \cdot \cos\Delta\phi - R_u.$$

We used 3D modeling for building the reference geometry, the geometry of the thread machined by turn-milling, and the geometry of deviations.

A 3D model of the workpiece is used for this. It is modeled to the specified design. The model structure is shown in figure 3.
Figure 2. Cutter tooth coordinates estimation for external thread turn-milling with outer cutter-to-workpiece contact.

The sequence is represented as a design tree in a CAD system such as COMPAS 3D.

The workpiece dimensions are constant, so the model was suitable for all the subsequent experiment campaigns.

Then a reference 3D model was built. This model does depend on the thread properties as specified. The reference model included the workpiece model and an extra operation: the tooth profile extrusion along a helix path (Figure 4).

Figure 3. A 3D workpiece model building sequence.

Figure 4. A 3D reference model building sequence.

The resulting model is shown in figure 5.

The core of the simulation is simulating the thread turn-milling process for a range of cutters. The simulation parameters are the milling cutter diameter and the number of teeth.

The tooth path depends on the machining strategy used. The number of teeth affects the thread profile formation. It is built with the Pattern Along Path command where the generatrix is the cutting profile (defined by the tooth path), and the directrix is a helix around the thread inner diameter.

Figures 6 and 7 show the sequence of building the 3D model of the resulting part machined by turn-milling.
Figure 5. Example of a 3D reference model.

Figure 6. Building sequence for the 3D model of the machined thread.

Figure 7. The simulation model state diagram and transformations.

First, the coordinates of a 3D curve representing the cutter marks on the workpiece are estimated. Then a spline is drawn that represents the spatial tooth path.

Then the tooth profile is drawn on a plane passing across the workpiece axis and the penetration point, i.e., the tooth path to the workpiece intersection point.

Then a profile of a single tooth cut is modeled by extrusion along a path, where the directrix is a 2D projection of the tooth path, and the generatrix is the tooth profile.

The last modeling stage is building the thread profile. The operation used is a pattern along a curve. The number of generatrix profiles along a revolution depends on the number of milling cutter teeth.
3. Simulation Results
As a result, we obtained a 3D model of the part with two oppositely directed threads machined by turn-milling (Figure 8). Figure 9 shows a simulated thread profile. The undercut dimensions were obtained by subtracting the 3D part model from the 3D reference model. Conversely, the overcut dimensions were obtained by subtracting the 3D reference model from the 3D part model (Figure 10).

![Figure 8. 3D model of a part machined by turn-milling.](image)
![Figure 9. A typical simulated thread profile section.](image)
![Figure 10. 3D model of the thread profile overcuts.](image)

4. Results and Discussion
With the simulation, we estimated threading errors. By comparing the errors with the thread tolerances we can verify if the manufacturing process is correct.

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