Thread milling errors

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Abstract. The study shows that thread milling (including internal threads) is one of the most forward-looking technologies that offers max thread cutting performance. The reasons are the shortest cut-in path equal to the thread depth, and the full thread profile machining time equal to the period of one revolution of the workpiece. The paper highlights that thread milling is an efficient, general-purpose machining process. In this study, we solved the thread profile error estimation problem. Thread milling with parallel workpiece and cutter axis was investigated with a milling simulation model. The optimal thread milling tool parameters for internal thread machining were found. The method efficiency was proven by measuring undercuts and overcuts in pipe thread milling. For instance, the thread error (overcuts/undercuts measured flatwise to the thread profile) diametral compensation does not exceed 0.0268 mm while the pipe thread tolerance G1.25 is 0.36 mm.

1. Introduction
Thread milling (including internal threads) is one of the most forward-looking technologies that offer max thread cutting performance [1...7].

Standard CNC thread milling cycles can be used. It is preferable to develop an NC program with CCS (an application that estimates the cutting mode and selects the machining strategy.)

The study objective is reducing efforts, milling time and cost through investigating the thread milling process and measuring the undercuts and overcuts in special buttress threading on thin-walled pipes for selecting the most suitable cutter.

We used simulation to estimate the undercuts and overcuts.

2. Research method
The simulation and under- (over-)cuts calculation were made to achieve the aim. Other researchers tried to solve this problem analytically [8]. The solution was two-dimensional, while shaping is a three-dimensional process.

It was noted in [10]: “The difference between the 3D part model and the 3D reference model is the undercut (overcut) volume.” In this paper, we identified errors of radiator nipple pipe thread milling.

The final stage of the simulation is creating a 3D model of the thread milling errors. The overcuts were generated by subtracting the resulting part model from the reference model (figure 1); for the undercuts, the reference model was subtracted from the resulting part 3D model (figure 2.)
To find the max value of the overcuts or undercuts (the max distance between the resulting thread surface and reference one) we used the "Surface deviation" tool in the CCS software.

With the surface deviation results we traced the max deviation point, then cut a section at this point, and estimated the errors. Then the simulation model was used in a series of experiments to find the most suitable cutter in terms of minimizing the shape errors. Afterwards, we generated a fitting criterion function.

The simulation objective was minimizing the thread geometry errors.

The geometric errors have two components: thread profile overcuts and undercuts. In real applications, one error component is sometimes emphasized. We considered all the components. The objective function is the sum of two components:

$$ f(R_u, z) = f_n(R_u, z) + f_u(R_u, z). $$

The function arguments are the cutter radius $R_u$ and the number of teeth $z$. Hereinafter, we will denote the variables as follows:

$$ \overline{\omega} = (R_u, z). $$

The function $f_n(R_u, z)$ describes the max thread profile overcut value, while $f_u(R_u, z)$ describes the maximum undercut value. The fitting criterion is:

$$ \max_{\Omega} f(\overline{\omega}) < \delta, $$

where $\Omega$ is the $f(\overline{\omega})$ domain, $\delta$ is the max acceptable thread geometry error.

We used a numerical method for finding the multi-valuable function extremum to find the max value of the two-argument function $f(\overline{\omega})$.

A solution to the problem is generating a sequence $\omega^{(k)}, k = 0, 1, ..., $ where the $f(\overline{\omega})$ function values are a decreasing convergent sequence.

These sequence generating methods are called ‘descent methods’ [10]:

$$ \overline{\omega}^{(k+1)} = \overline{\omega}^{(k)} + \alpha_k \cdot \overline{P}_k, $$

where $\overline{P}_k$ is the descending vector from $\overline{\omega}^{(k)}$ to $\overline{\omega}^{(k+1)}$, and $\alpha_k$ is the distance increment.
Since the function gradient at the specific point is oriented towards the largest function increase its value is $\nabla f_k$ [2]:

$$\nabla f_k = \hat{f}'(\nabla f(k)) = \left[ \frac{\partial f(\nabla f)}{\partial R}, \frac{\partial f(\nabla f)}{\partial z} \right]_{\nabla f = \nabla f(k)}.$$ 

In this case, it is impossible to estimate the partial derivatives (there is no analytical relation), so we replaced them with finite differences [3]:

$$\frac{\partial f(\nabla f)}{\partial R} = \frac{f(\nabla f(k)) - f(\nabla f(k-1))}{R(k) - R(k-1)}, \quad \frac{\partial f(\nabla f)}{\partial z} = \frac{f(\nabla f(k)) - f(\nabla f(k-1))}{z'(k) - z'(k-1)}.$$ 

The function value is decreased every time the distance increment increases, that is:

$$f(\nabla f(k)) > f(\nabla f(k)) - \alpha_k \cdot \hat{f}'(\nabla f(k)).$$ (3)

As a result, the iterative process meeting the condition (3) is as follows. Two initial approximations are specified: $\nabla f(0)$ and $\nabla f(1)$. Refer to Table 1.

| Table 1. Initial approximations for finding the $f(\nabla f)$ error function maximum |
|-------------------------------|-----------------|-----------------|
| Iteration No. | $\nabla f(k)$ | $f(\nabla f(k))$ |
|----------------|----------------|-----------------|
| $k$ | $R_u(k)$ | $\zeta(k)$ | $f(\nabla f(k))$ |
| 0 | $R_u(0)$ | $\zeta(0)$ | $f(\nabla f(0))$ |
| 1 | $R_u(1)$ | $\zeta(1)$ | $f(\nabla f(1))$ |

The distance increment $\alpha$ is found. It is constant for subsequent iterations. Eq. (2) is estimated, and the condition (3) is checked at every iteration.

If the condition is met, the same distance increment is used for the following iterations. Otherwise, the increment is decreased until the condition is met. The process stops when the following condition is met:

$$\left| f(\nabla f(k)) - f(\nabla f(k-1)) \right| < \delta.$$ (4)

The key milling variable is the engagement angle between the cutter and the blank $\psi$. Refer to Table 2 for the results. The diagrams based on the table are shown in figure 3.

| Table 2. Cutter-to-workpiece engagement angles $\psi$ for external thread milling |
|-----------------|-----------------|-----------------|
| $R_u(k)$ | Engagement angle $\psi$ | Engagement angle $\psi$ |
| Front of tooth | Back of tooth |
|----------------|-----------------|-----------------|
| 15 | 78 | 222 |
| 20 (22.5) | 62 (56) | 152 |
| 25 | 52 | 152 |
| ... | ... | ... |
| 50 | 30 | 44 |
| 100 | 16 | 18 |
Figure 3. Effect of the milling radius on the engagement angle for thread milling

Figure 4. Part model for the first iteration

Refer to Table 3 for the initial data used to find the \( f(\overline{m}) \) error function maximum value.

**Table 3.** Initial data and errors found with the external thread milling simulation (cutter and workpiece rotate in the same direction)

| File | Iteration No. | \( k \) | \( R_{n}^{(k)} \) | \( z^{(k)} \) | Undercut | Overcut | Facet pattern defects |
|------|---------------|--------|-----------------|------------|----------|--------|----------------------|
| 0    | 1             | 15     | 6               | 0.56       | 0.0989   | 1.17   | 0.3986               |
| 1    | 2             | 20     | 6               | 0.3993     | 0.0532   | 0.7735 | 0.6793               |
| 2    | 3             | 20     | 8               | 0.45       | 0.0424   | 0.8599 | 0.7939               |
| 2    | 4             | 25     | 8               | 0.1132     | 0.0403   | 0.3788 | 0.3788               |
| ...  | ...           | ...    | ...             | ...        | ...      | ...    | ...                  |
| 7    | 13            | 50     | 32              | 0.01       | 0.0303   | 0.07   | 0.1753               |
| 8    | 14            | 100    | 32              | 0.0385     | 0.0375   | 0.0768 |                      |

We began the simulation process with the min radius cutter \( R_{n}^{(k)} = 15 \) mm having \( z^{(k)} = 6 \) teeth. Assuming the height of engagement being \( H=1.478515 \) mm, the max undercut at the thread crest is 1.17 mm.

The lateral undercut is 0.29 mm. That is, such cutter dimensions produce unacceptable machining results. Refer to figure 4 for the part model machined as described above.

**3. Discussion**

As can be seen from the simulation results presented in Table 3, increasing the cutter diameter while maintaining the number of teeth leads to a small thread profile error increase (by 3...9 % depending on the number of teeth.)

Still, with larger cutter radius, more teeth can be fitted, and it minimizes the errors (to 0.0268 mm if the number of teeth is 32.) This value fits into \( T_{d2} = 0.36 \) mm tolerance.

The thread errors shall fit into the mean size tolerance that is \( T_{d2} = 0.36 \) mm for the pipe thread. It is assumed that the front and rear surfaces of the thread are flat but the defects are caused by, for example, incorrect cutter setup or the cutter manufacturing errors.
In this case, the thread profile has linearity errors. For the simulation, we measured these errors flatwise to the nominal thread profile. Then we found a factor to recalculate the overcut values measured flatwise into the actual thread profile error values. These errors are recalculated by the mean diameter as follows:

\[
f_{\text{prof}} = \frac{\Delta_{\text{overcut}}}{\sin \frac{\alpha}{2}},
\]

where \( f_{\text{prof}} \) is the thread error (overcuts/undercuts measured flatwise to the thread profile) diametrical compensation, \( \Delta_{\text{overcut}} \) is the overcut, \( \alpha \) is the flank angle; for the pipe thread it is \( \alpha = 55^\circ \).

At the 12\textsuperscript{th} iteration, \( f_{\text{prof}} = (0.0132 + 0.0305)/\sin 27.5^\circ = 0.0946 \) mm. It is quite acceptable for the 0.0864 mm root faceting.

At the 13\textsuperscript{th} iteration, \( f_{\text{prof}} = 0.0873 \) mm for the 0.07 mm root faceting; at the 14\textsuperscript{th} iteration \( f_{\text{prof}} = 0.149 \) for the 0.0268 mm root faceting. So, the proposed simulation method helps to choose the most suitable cutter meeting the design solutions and the manufacturing constraints. In this case, we recommended stopping at the 13\textsuperscript{th} iteration. The cutter diameter is 100 mm. It is just slightly larger than at the 12\textsuperscript{th} iteration but the errors are smaller because more teeth can be fit (\( k = 32 \)). These cutter parameters ensure smoother cutting and longer tool life. It is really important for mass production.

Refer to figure 5 for the relation between the root faceting, the cutter radius, and the number of teeth. With this relation, one can assess the impact of the cutter radius and the number of teeth on the root facet formation, so the process planner can choose the optimal tool parameters on an ad hoc basis.

\[\text{Figure 5. Root faceting vs. the cutter radius and the max number of teeth (maintaining the specified pitch)}\]

\[\text{Figure 6. Root faceting vs. the cutter radius and number of teeth}\]

The diagrams of the root faceting (figure 5) and the side profile undercuts (figure 7) are similar. It was expected: the facet on roots and crests are formed similarly. The simulation results shown in Figs. 6...7 visualize the formation of the thread profile errors. The results can be used for further analysis of the thread profile formation in such a complicated machining operation as thread milling. This is a benefit of simulation since it provides an objective and dynamic model of the process.
4. Conclusion

The 13\textsuperscript{th} iteration simulation results (the cutter diameter is 100 mm and the number of teeth is 32) are the best for the pipe thread G1.25” milling.

What we found is: milling simplifies the manufacturing process. Moreover, it requires a fewer number of tools, the machining time is reduced, while the manufacturing becomes more flexible and efficient.

With the presented thread milling simulation, the optimal cutter parameters for the specific thread milling can be found.

With a larger cutter radius, more teeth can be fitted, and it minimizes the errors (to 0.0268 mm if the number of teeth is 32.) The error is within the average diameter tolerance equal to 0.36 mm.

Thread milling is even more efficient for cutting oppositely directed threads like radiator nipples.

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