MATHEMATICAL ESTIMATION OF ROUGHNESS Rz OF THREADED SURFACE OBTAINED BY MACHINING METHOD

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The paper presents a mathematical model of the helical surface roughness Rz, obtained by the form-generating method with a to-size tool with a standard profile of cutting tool inserts. This machining method has maximum productivity with large pitches of the helix. The surface roughness of the auger flight is an important parameter since it works in a friction pair with an elastic element. The resulting dependence makes it possible to predict surface roughness in any of its sections, considering the helix curvature, depending on the feed and the cutting tool tip radius. The obtained dependence allows comparing the numerical solution with the linearized one obtained by finding the minimum distance from the intersection points of the tool edge circles at helical surface adjacent cutting points to the straight line connecting these adjacent points.

KEYWORDS

helical surface, to-size tool, roughness, machining, form-generating method

Nomenclature

$\bar{R}$ - the radius vector to an eccentric circle with a moving centre O_{shape};
O_{shape} – the moving centre of an eccentric circle;
$\bar{R}_{shape}$ - the hodograph of the spiral trajectory radius vector;
$\bar{R}_{edge}$ - the radius vector of the thread shaping point measured from the center of the thread to the points of the contour of the thread cross-section in the XOY plane;
d_{tool} - the diameter of the to-size tool in mm;
d - the nominal thread diameter in mm;
H - is the height of the thread profile in mm;
p - thread pitch in mm;
φ - the angular pitch of the thread shaping point in degrees;
ψ - the angular pitch of the forming thread spiral in degrees;
ψ_0 - the shift by onset phase of ψ;
n - the number of the thread starts;
$(z_1;\ R_1)$ and $(z_2;\ R_2)$ - two shaping points adjacent in the order of cutting;
Δz – the space from each other adjacent shaping points along the z-axis;
i_t - the number of cutting teeth of the tool;
n_t - the rotation frequency of the tool in rpm;
r_t - the cutting tool tip radius in mm;
f - the feed in mm;
$(z_c;\ R_c(z))$ - coordinates of the centers' points of the circles' arcs of the tool at these adjacent points;
$(z_{1c};\ R_{1c})$ and $(z_{2c};\ R_{2c})$ - coordinates of the adjacent centers of the circles;
R_{1peak} and R_{2peak} – radii coordinates of intersection points of the adjacent circles;
δ - distance from an intersection point of the adjacent circles to the ideal rope thread curve;
Rz – roughness in µm.

1 INTRODUCTION

Improvement of machined surface quality is one of the primary tasks of mechanical engineering. The threaded surfaces' low roughness determines the products' high-performance properties. The presence of a refined mathematical model of roughness formation makes it possible to select the optimal parameters of the cutting processes. Many papers are devoted to assessing the various technical factors that influence the cutting processing quality [Thien 2021], [Brown 2020]. Different mathematical dependences on the influence of the cutting speed, feed, cutting depth [Astakhov 2020], angular parameters of the cutting tool [Shvets 2020], [Bodnariuk 2019], cutting fluid [Liu 2021], materials grade [Melentiev 2020], vibration, cutting temperature [Kolesnyk 2022], and other factors on the roughness have been developed.

Many studies made by leading scientists have been conducted on the internal threads [Neshta 2016] processing due to the difficulty of machining large size stock volumes extraction under low tool rigidity [Kushnirov 2013], [Povstyanoy 2021]. According to the generator cutting pattern, the chip formation is studied and described in [Astakhov 2020], [Standard 2014]. Surface roughness is much affected by friction conditions in the interface zone [Ivchenko 2020]. Modelling thread machining based on the copying method of surface formation with cutters is described in [Sandstrom 2000]. At the same time, the study of asymmetric profile thread machining is described in [Vargus 2021].

The possibility of machining various thread types by the form-generating method is considered in [Nekrasov 2021], which shows that this method [Nekrasov 2013] enables the machining of rope threads with large pitches and other types of threads. However, it was reported that some limitations of machining metric and trapezoidal threads depended on their pitch. It was also indicated that the form-generating method allows machining of all ranges of an inch and rope threads. Obtaining a mathematical dependence of the formed profile is partially considered in [Nekrasov 2018]. The conducted studies make it possible to establish the tool and path tool diameters but lack a mathematical relationship between cutting parameters and their influence on surface roughness [Budnik 2016]. It was reported about the possibility ensuring of significant cutting-edge dimensional wear compensation via altering the shaping point trajectory with maintaining the specified geometry of the thread [Dehtiarov 2020].

Based on the state of art analysis, the method of processing internal threads with a to-size tool of a cutting insert needs more detailed theoretical studies.

Methods of their production can be currently used from CNC multi-axis turning to 5-axis milling [Peterka 2008, Beno 2013, Peterka 2014]. In the field of copy milling, roughness dependencies have been experimented with and calculated. The most common profile of the cutting edge shape in the calculation of surface roughness is the tip radius in turning and the cutter radius in copy milling [Peterka 2004, Pokorny 2012, Vopat 2015].

This article will determine the mathematical relationships that include the pitch, thread profile shape, roughness, accuracy of tool dimensions, and setup of the turning or milling CNC machine.

In such a way, the key motivation for implementing the current study was to determine the parameters of a spiral path for machining an internal thread of a specific size. It was utilized by obtaining the mathematical dependence of the helical surface roughness *Rz* for the form-generating method with a to-size tool of a standard profile of the cutting inserts.

2 METHODS

The current paper presented a theoretical mathematical model which allows simulating possible minimal roughness, concerning geometrical parameters of the helical surface, the reverse feed, and the tooltip radius, disregarding cutting speed, depth of cut, angular parameters of the tool, the lubrication, grade of the workpiece material, and vibrations which accompanied machining process. For feature mathematical modelling of surface roughness was utilized a machining method which considers machining of external thread with a to-size mill. The kinematic of the proposed machining method combines the rotational movement of the mill (axis *Z*) with feed movement along a spiral path. The interface point moves a circular arc. The diameter circular arc is equal to the cutter diameter [Nekrasov 2021], [Nekrasov 2017]. The rotational movement and feed along the spiral path form the helical surface. However, the shape of this surface remains unknown. To establish the formed surface's geometry, the shaping point's movement in the interface zone under given conditions was considered (Fig. 1).

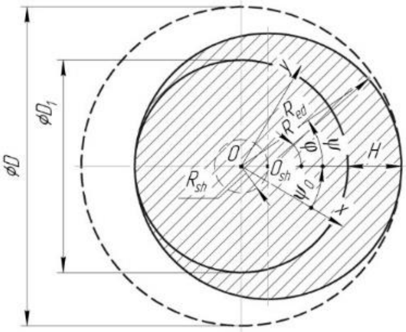


Figure 1. Schematic profile of the cross-section of the thread in the polar coordinate system *r ψ*

The projection of the thread shaping point onto the *XOY* plane in the global Cartesian coordinate system *XYZ* moves along the radius vector $\bar{R}$ to an eccentric circle with a moving centre O_{shape} - the hodograph of the spiral trajectory radius vector $\bar{R}_{shape}$. $\bar{R}_{edge}$ - the radius vector of the thread shaping point measured from the center of the thread to the points of the contour of the thread cross-section in the XOY plane, considering the parameters of the relative movement of the cutter in the internal tolerance system, is defined as:

$$R = \frac{d_{tool}}{2} \tag{1}$$

where d_{tool} is the diameter of the to-size tool.

It should also be noted that in ISO technical terms here $R_{shape} = \frac{H}{2}$ and $R = \frac{d}{2} - R_{shape}$, where d is the nominal thread diameter and H is the height of the thread profile.

In such a way, the trajectory vectors (Fig. 2) are calculated according to the equation (2):

$$\left(\bar{R}_{\text{edge}} - \bar{R}_{shape}\right)^2 = \bar{R}^2;$$

$$R_{\text{edge}}{}^2 - 2 \cdot R_{\text{edge}} \cdot R_{shape} \cdot \cos\psi + R_{\text{edge}}{}^2 - R^2 = 0; \tag{2}$$

$$R_{\text{edge}} = R_{shape} \cdot \cos\psi \pm \sqrt{R^2 - R_{shape}{}^2 \cdot \sin^2\psi},$$

The vector $\bar{R}_{shape}$ rotates relative to the vector $\bar{R}_{edge}$ in the process of profile formation by an angle $\varphi°$, called the angular pitch of the thread shaping point, and $\bar{R}_{edge}$ rotates in the *XOY* coordinate system by an angle $\psi + \psi_0$, where ψ is called the angular pitch of the forming thread spiral. The angle ψ_0 is the shift by its onset phase. A polar coordinate system r_ψ is also assigned, in which the ray *r* is directed from point O to point O_{shape}. The *r* axis is the axis of symmetry for the coordinate system of forming circles.

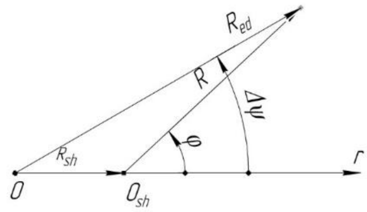


Figure 2. Vector sum $\bar{R}_{edge} = \bar{R}_{shape} + \bar{R}$

Only one of two solutions is chosen according to the positive definition from the geometric meaning of the length of the segment.

$$R_{shape} \cdot \cos\psi < \sqrt{R^2 - R_{shape}{}^2 \cdot \sin^2\psi};$$

$$R_{shape} < R; \frac{H}{2} < \frac{d-H}{2}; \tag{3}$$

$$2 \cdot H < d.$$

The last trivial inequality reduces to the requirement that the height of the ridge does not exceed its radius.

In addition, expression (2) imposes the following restriction on the positive definition of the radical expression:

$$R^2 - R_{shape}{}^2 \cdot \sin^2\psi > 0;$$

$$R_{shape} \cdot |\sin\psi| < \text{R}, \tag{4}$$

Since the projection of the vector $\bar{R}_{edge}$ hodograph onto the XOY plane accurately forms the perimeter of the circumference of the to-size tool. Therefore, the thread profile can be uniquely assigned to the z coordinate so that the full rotation of the vector $\bar{R}_{edge}$ corresponds to the angle $\psi=2\cdot\pi$ rad, where $\psi = \angle(\bar{R}_{shape}; \ \bar{R}_{edge})$ equal to $\psi = 2 \cdot \pi \cdot \frac{z}{p \cdot n}$, and n - is the number of thread starts. The fulfillment of n ≠ 1 is technologically impossible. Therefore, here, and below, only the case of a single-start thread is considered.

A mathematical model is obtained by transforming the resulting equation (2) concerning the z coordinate along the thread axis:

$$R_{edge} = R_{shape} \cdot \cos\left(\frac{2\cdot\pi\cdot z}{p\cdot n}\right) + \sqrt{R^2 - R_{shape}{}^2 \cdot \sin^2\left(\frac{2\cdot\pi\cdot z}{p\cdot n}\right)}. \tag{5}$$

Through the definition of two adjacent positions of the tooth, cutting the helical surface in the plane with the cylinder's axis. It is postulated that the surface is cut by an arc of a circle of a tool with radius rt, which touches the formed contour at the shaping point in the interface surface. Considering two shaping points adjacent in the order of cutting $(z_1; \ R_1)$ and $(z_2; \ R_2)$, spaced from each other along the z-axis by $\Delta z = \frac{s}{i_t \cdot n_t}$ (Fig. 3), where sf is the minute feed in mm/min, i_t is the number of cutting teeth of the tool and n_t is the rotation frequency of the tool in rpm, i.e., $z_2 = z_1 + \Delta z$, $R_1 = R_{edge}(z_1)$, and $R_2 = R_{edge}(z_2)$. The centers of the circles are displaced from the pivot points to the contour by the distance of the cutting tool tip radius r_t at an angle $\left[\frac{\pi}{2} - arctg\left(\frac{dR_{edge}(z)}{dz}\right)\right]$, rad to the OZ axis. The coordinates of the centres' points of the circles' arcs of the tool at these adjacent points (z_c; $R_c(z)$) are defined by the equation (6):

$$\begin{cases}\dfrac{dR_K(z)}{dz}=\dfrac{\Delta z_c}{\Delta R_c};\\ {\Delta z_c}^2+{\Delta R_c}^2=r_t^2;\end{cases}$$

$$\begin{cases}R_c(z)=R_K(z)+\Delta R_c=R_K(z)+\frac{1}{\sqrt{1+\left(\frac{dR_K(z)}{dz}\right)^2}}\cdot r_t;\\ z_c=z+\Delta z_c=z+\frac{\frac{dR_K(z)}{dz}}{\sqrt{1+\left(\frac{dR_K(z)}{dz}\right)^2}}\cdot r_t,\end{cases} \qquad (6)$$

where,

$$\frac{dR_{edge}(z)}{dz}=-R_{shape}\cdot\frac{2\pi}{p}\cdot sin\left(\frac{2\pi z}{p}\right)-\frac{{R_{shape}}^2\cdot\frac{\pi}{p}\cdot sin\left(\frac{4\pi z}{p}\right)}{\sqrt{R^2-{R_{shape}}^2\cdot sin^2\left(\frac{2\pi z}{p}\right)}}$$

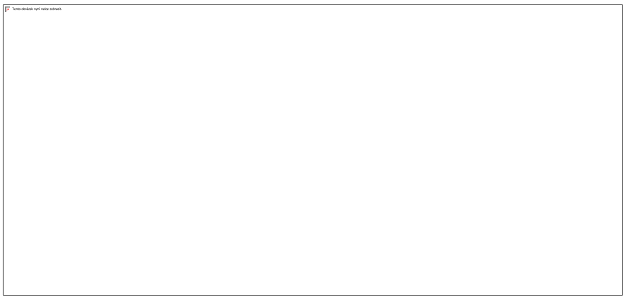


Figure 3. Roughness due to the cutting-edge geometry

Further, the intersection points of the tool circles at adjacent points are analytically found. The coordinates of the adjacent centres of the circles are denoted by (z_{1c}; R_{1c}) and (z_{2c}; R_{2c}), then

$$\begin{cases}(z-z_{1c})^2+(R-R_{1c})^2=r_t^2;\\ (z-z_{2c})^2+(R-R_{2c})^2=r_t^2;\end{cases}$$

$$\begin{cases}R=\frac{z_{2c}^2-z_{1c}^2+R_{2c}^2-R_{1c}^2}{2\cdot(R_{2c}-R_{1c})}-z\cdot\frac{z_{2c}-z_{1c}}{R_{2c}-R_{1c}};\\ z^2\cdot\left(1+\left(\frac{z_{2c}-z_{1c}}{R_{2c}-R_{1c}}\right)^2\right)-z\cdot\frac{[(z_{2c}-z_{1c})^2+(R_{2c}-R_{1c})^2]\cdot(z_{2c}+z_{1c})}{(R_{2c}-R_{1c})^2}\\ +\left(\frac{\left(z_{2c}^2-z_{1c}^2\right)^2+2\cdot\left(z_{2c}^2+z_{1c}^2\right)\cdot(R_{2c}-R_{1c})^2+(R_{2c}-R_{1c})^4}{4\cdot(R_{2c}-R_{1c})^2}-r_t^2\right)=0.\end{cases} \qquad (7)$$

Next, the shortest distance from the intersection points of the tool circles at the adjacent interface surface point when machining thread points to the contour line is determined, which is considered the minimum geometrically acceptable value of roughness. It is proposed to divide $\Delta z=\frac{s}{i_t\cdot n_t}$ into a finite number of segments (N = 10) and determine Rz numerically using the algorithm (Fig. 4).

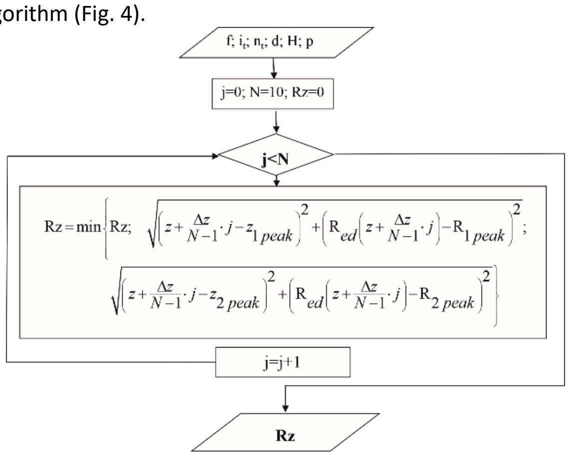


Figure 4. Scheme of the roughness Rz numerical calculation

It is possible to compare the numerical solution with the linearized one for further verification: it was proposed to find the minimum distance from the intersection points of the tool circles at adjacent threading points to the straight line that connects these adjacent points. Having designated the adjacent points of the threaded contour as before (z_1; R_1) and (z_2; R_2) (Equation 8, 9, 10):

For straight lines:

$$\frac{z-z_1}{z_2-z_1}=\frac{R\ \ -R_1}{R_2-R_1};$$
$$A\cdot z+B\cdot R\ \ +C=0, \qquad (8)$$

where $A=\frac{1}{z_2-z_1}$; $B=-\frac{1}{R_2-R_1}$; $C=\frac{R_1}{R_2-R_1}-\frac{z_1}{z_2-z_1}$, then for the distance from a point to a line.

$$\delta=\frac{A\cdot z+B\cdot R_K+C}{\sqrt{A^2+B^2}}, \qquad (9)$$

and for linearized roughness:

$$Rz_{linearized}=min\{\delta(z_{1peak};\ \ R_{1peak});\ \ \delta(z_{2peak};\ \ R_{2peak})\}. \qquad (10)$$

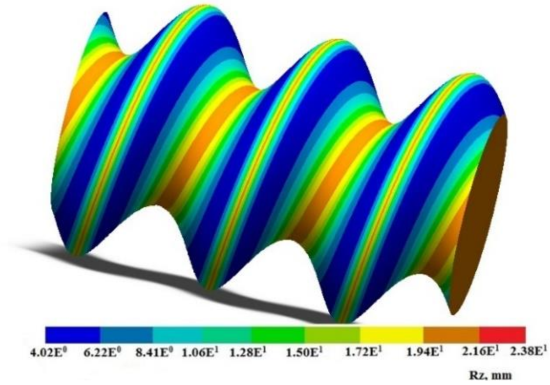


Figure 5. The lowest theoretically possible roughness distribution of over the surface of the thread helix for (d = 40 mm; H= 10 mm; rt= 0.8 mm; s=0.25 mm/rev; n= 1500 rpm) (for a single-start thread cut with a single-tooth cutter)

The formulas for determining the numerical roughness *Rz* and the linearized roughness *Rz* linearized, made it possible to obtain the numerical values of these roughness for the rope thread *R32* according to ISO 10208, while changing such parameters as the cutting tool tip radius r_t, and the minute feed *f*. The parameters of the rope thread *R32* according to ISO 10208 (Figure 6) are as follows: outer diameter *d* = 32 mm, thread depth *H* = 1.5 mm, thread pitch *p* = 12.7 mm. The obtained roughness values (Figure 7).

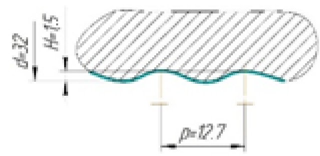
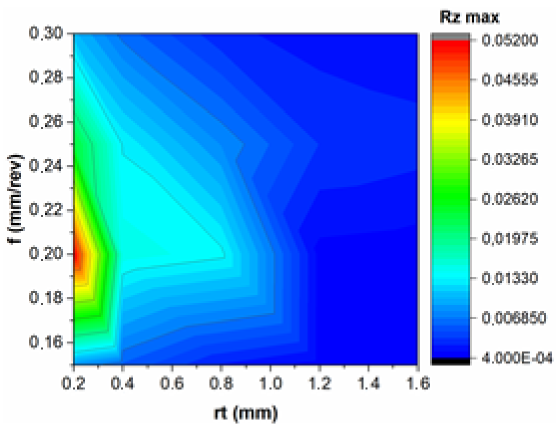
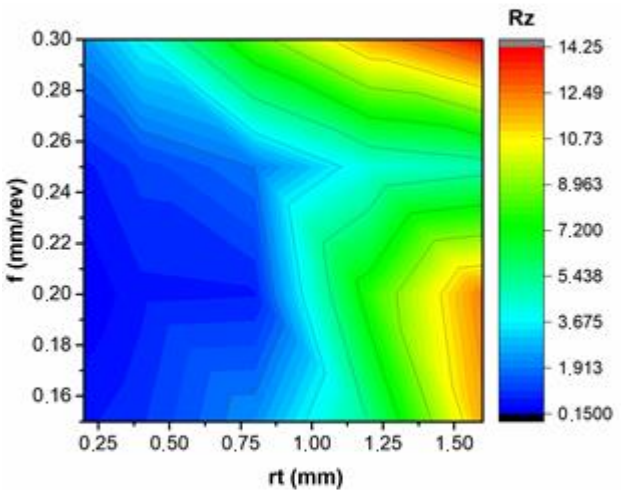


Figure 6. *R32* rope thread parameters according to ISO 10208



a)



b)

Figure 7. Numerical values of roughness for rope thread *R32* according to ISO 10208, when changing such parameters as the cutting tool tip radius r_t, and minute feed *f*: a) - linearized roughness *Rz* linearized max, mm; b) - relative difference between the maximum roughness numerically obtained and linearized, %

3 CONCLUSIONS

1. A mathematical model of the helical surface roughness *Rz* has been obtained by the form-generating method for the helical surface with a to-size tool equipped with a cutting insert.
2. Comparison of the numerical solution with the linearized solution has been carried out by finding the minimum distance from the intersection points of the tool circles at adjacent threading points to the straight line connecting these adjacent points. The results make it possible to establish that the difference between the numerical and linearized solution increases with increasing feed. The variation of the cutting tool tip radius effects roughness more intense than equivalent on a percentage basis variation of feed. Overall, proposed in a paper identification of minimal roughness is capable of mechanical processing assessment due to it's ultimate nature.
3. The definition of speed, depth of cut, the cutting tool angular parameters, coolant supply, the grade of the workpiece material, and the effect of vibrations is promising in calculating response surfaces for feature specification the of proposed mathematical model for prediction of surface roughness *Rz*.
4. It is necessary to add that the analytical model concerned in the paper has predicted theoretically minimal realizable value roughness for any kind of a raw part or to-size mill. Features of the technological system as machine-tool-workpiece relation or cutting tool design are the topic for further research.

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