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Analysis of the thread profile of the ZA cylindrical worm manufactured using universal tools and cutting inserts

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ABSTRACT

This study presents a method for turning cylindrical worms using universal turning tools. The surface preparation for testing was conducted using a point method, employing V–shaped cutting inserts to turn the worm thread, which has a profile angle of 20 degrees. To facilitate the turning of the thread, we analytically derived a formula to determine the distance from the corner of the insert to the side of the thread at the contact point. Additionally, we presented a theoretical calculation for the height of the roughness profile. The mean absolute error between our predicted Rt roughness parameter and the measured value is 2.8 µm, which results in a mean absolute percentage error of 13.6%. We developed special software to assist in preparing NC code for a numerically controlled machine tool. Ultimately, we obtained a theoretical profile that will be used to assess the size of deviations. The results of the thread profile measurements conducted on a coordinate measuring machine, along with the surface quality evaluation from roughness measurements, classified the worm within the 9th accuracy class. This confirms that our method is appropriate for roughing or semi–finishing operations. The analysis of the results validates the use of this method in machining worm gears, and the findings from our experimental studies align closely with theoretical expectations.

Keywords: tooth profile, worm gear, turning lathe, machining, cutting inserts.

INTRODUCTION

Recent developments in gear technology have emphasized the need for more accurate modeling and optimization of gear tooth geometry to improve performance, durability, and noise characteristics. Analytical and numerical techniques have been widely applied to study gear meshing behavior, especially in non-standard gear profiles such as convexo-concave Novikov gearing, where contact patterns can be evaluated using differential geometry-based methods [1]. Expanding on this, recent studies have introduced tensor-based approaches for tooth contact analysis in both planar and spatial gear systems, offering enhanced precision and computational efficiency in determining sliding behavior and transmission error [2]. These advanced methods have also been extended to gear profile optimization using evolutionary algorithms, where integration of the Reuleaux method with tensor kinematics has enabled the generation of novel tooth shapes with improved tribological and mechanical characteristics [3]. Comparative analyses between eccentric-cycloidal, Novikov, and conventional involute profiles further highlight the advantages of unconventional geometries in reducing sliding velocities and improving contact conformity [4]. The progression of these approaches reflects a broader trend toward higher accuracy and functional robustness in gear manufacturing—an imperative that becomes especially critical in the case of worm gears, where complex surface profiles and sensitive contact conditions demand meticulous control of tool geometry and machining strategies [5].

Worm gears are widely used in various mechanical systems requiring high reduction ratios, compact designs, and smooth, quiet operation.

These gears play a critical role in applications ranging from automotive transmissions to aerospace actuators and industrial machinery. Their performance, however, heavily depends on the precision and quality of the machining processes involved in their manufacture. Numerous studies have explored advanced manufacturing methods to improve the efficiency, accuracy, and surface integrity of worm gear components. Early investigations focused on developing basic techniques such as cylindrical frontal milling for roughing helical flanks [6] and milling with removable plate heads on NC lathes [7]. These methods laid the foundation for integrating NC (numerical control) technology into worm gear production [8]. To achieve better conformity with complex geometries, researchers have proposed forming processes using roller tools for conical-like helical surfaces [9] and innovative methods for concave-profiled worm gears [10]. Geometry and machining of concave profiles, particularly ZK-type threads, have received focused attention due to their enhanced contact characteristics and load distribution capabilities [11]. With the advancement in computational modeling, power-skiving methods for ZI-type worm machining have been modeled and implemented to offer efficient production with precise tooth formation [12]. In parallel, parametric design of milling cutters has been optimized to improve cutting performance and extend tool life in double-arc configurations [13]. The evolution of five-axis and CNC-based machining has introduced new capabilities, enabling the development of internal skiving cutters for ZC-type cylindrical worms [14] and flexible manufacturing processes that support both regular and modified gear profiles [15, 16]. Additionally, experimental techniques for machining involute-profile gears using CNC lathes with driven tools have shown promise in improving adaptability across gear types [17]. Scaling the production of larger worm gears, especially those with Niemann profiles, has been addressed through machining strategies on CNC machining centers [18]. Meanwhile, methods like whirling simulation and tool profiling have contributed to understanding the geometric precision and tool design aspects of worm machining [19]. Modern approaches have also emphasized integrated manufacturing methods, such as combining roughing, finishing, and chamfering operations on general CNC lathes to support toroidal worm production [20]. Studies on high-precision machining for large-modulus ZC1 worm gears further highlight the importance of robust machining strategies [21], while cycloid screw production using five-axis milling has illustrated how surface roughness can be optimized through tool trajectory control [22]. Finally, specialized grinding techniques have been developed for finishing concave worm threads, utilizing unique grinding wheel geometries to improve profile accuracy and reduce stress concentrations [23]. Collectively, these developments underscore a trend toward greater integration of computational modeling, multi-axis machining, and tool design optimization in the field of worm gear manufacturing. The current research seeks to build upon these advancements by proposing a novel machining strategy aimed at enhancing accuracy, reducing tool wear, and improving overall process efficiency.

The scientific research presented in the articles on worm gears only slightly addresses the issues of their production using turning. Research using the point method mainly concerns milling.

MATERIALS AND METHODS

The preparation of the surface for testing was carried out using the point method. The point method consists of programming successive passes of the turning tool. The advantage of this method is the possibility of using universal cutting inserts and foldable turning tools. The idea of point turning is presented in Figure 1a. It involves turning successive passes of the winding with gradual tool insertion. As a result of this method of processing, unevenness is created on the helical surface of the worm winding, as shown in Figure 1b. The hight of roughness profile (Rt) depends on the cutting depth (ap) and the radius of the insert corner (r_ε).

The angle of the threads profile for the cylindrical worm is 20°, while the angle of the cutting insert is 35°. The insert is finished with a corner radius r_ε. In order to be able to turn the worm using the presented method, it is necessary to conduct a geometry analysis for this method. Figure 2 shows a diagram of the threads turning, for which it is necessary to take up material in two directions X and Z which correspond to the axis on the turning lathe.

In order to be able to turn the threads, it is necessary to analytically derive the formula for the parameter (z) which is the distance from the side

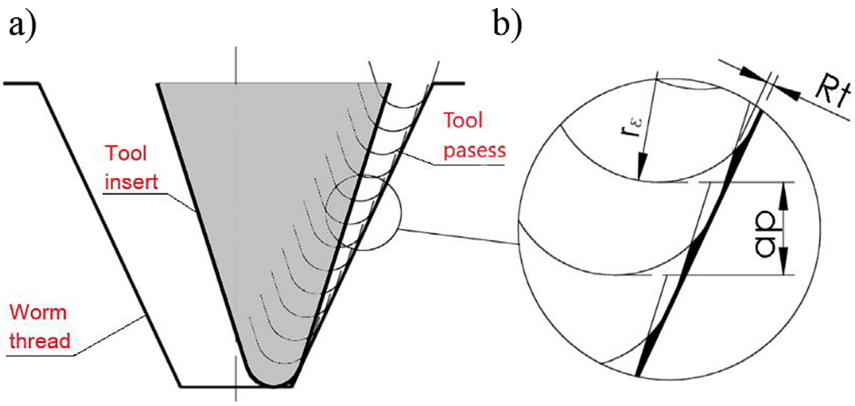


Figure 1. Turning by point method: a) tool pasess, b) hight of roughness profile Rt

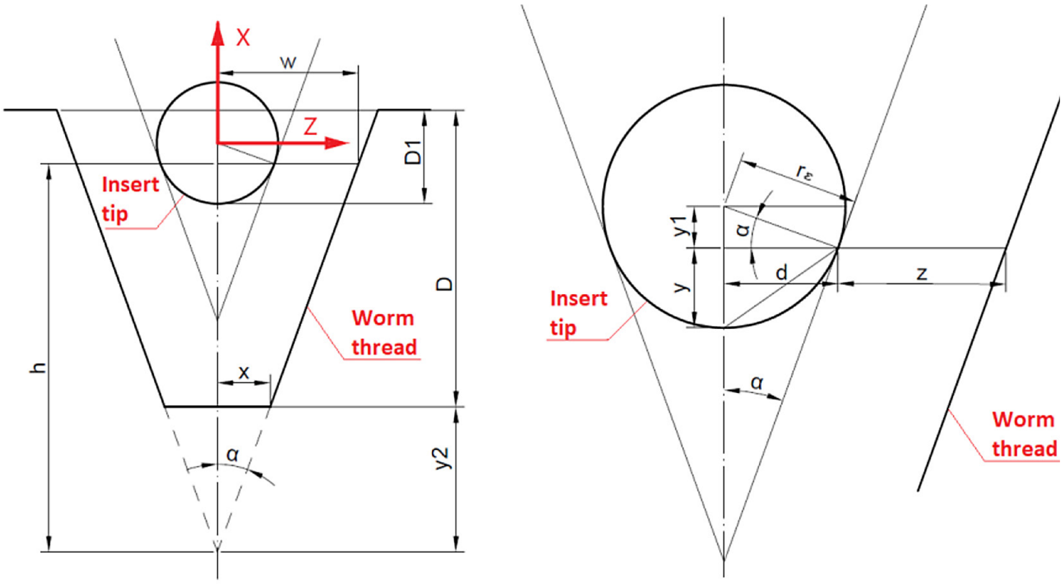


Figure 2. Tool and worm threads geometry analysis

of the insert corner to the side of the threads at the contact point. At the same time, this parameter depends on the insert radius r_ε, half thread width on a bottom (x), depth of the threads (D) and pressure angle (α), as well as the depth at which the threads will be turned in subsequent passes (D1). The r_ε emaining variables were added as auxiliary to the calculations. The final form of the formula is presented in Equation 1.

$$z = \left(D - D1 + r_\varepsilon - r_\varepsilon \sin\alpha + \frac{x}{\tan\alpha}\right)\tan\alpha - r_\varepsilon \cos\alpha \quad (1)$$

Figure 3 presents the geometric analysis of the parameter Rt responsible for the height of the unevenness of the roughness profile. In order to determine the Rt parameter, the process kinematics were reduced to the Cartesian system x, y. As a result of the analysis of the contact between the insert and the side surface, it was found that, in each of the considered cases, the contact occurs on the tool tip radius.

$$Rt = \frac{|a_m x_T - y_T - b_m|}{\sqrt{a_m^2+1}} = \frac{|aE - a_m E + (a^2+1)\cdot(b-b_m)|}{(a^2+1)\sqrt{a_m^2+1}} \quad (2)$$

where:

$$E = D1a - ab + x_1 + \quad (3)$$
$$\sqrt{-D1^2 + 2D1ax_1 + 2D1b + a^2{r_\varepsilon}^2 - a^2x_1^2 - 2abx_1 - b^2 + {r_\varepsilon}^2}$$

$$b = \frac{r_\varepsilon \sin^2\varphi - r_\varepsilon \cos^2\varphi}{\sin\varphi} \quad (4)$$

$$a = \cot\varphi \quad (5)$$

$$b_m = \frac{r_\varepsilon \sin^2\alpha - r_\varepsilon \cos^2\alpha}{\sin\alpha} \quad (6)$$

$$a_m = \cot\alpha \quad (7)$$

The height of the roughness Rt depending on the depth of cut and the corner radius is shown in Table 1. The depth of cut has the greatest influence on the value of the roughness Rt. For roughing the threads, an insert with a corner radius of 0.4 mm was used, while the cutting depth was 0.5 mm.

In machining the worm threads using the point method, it was necessary to select tools that would

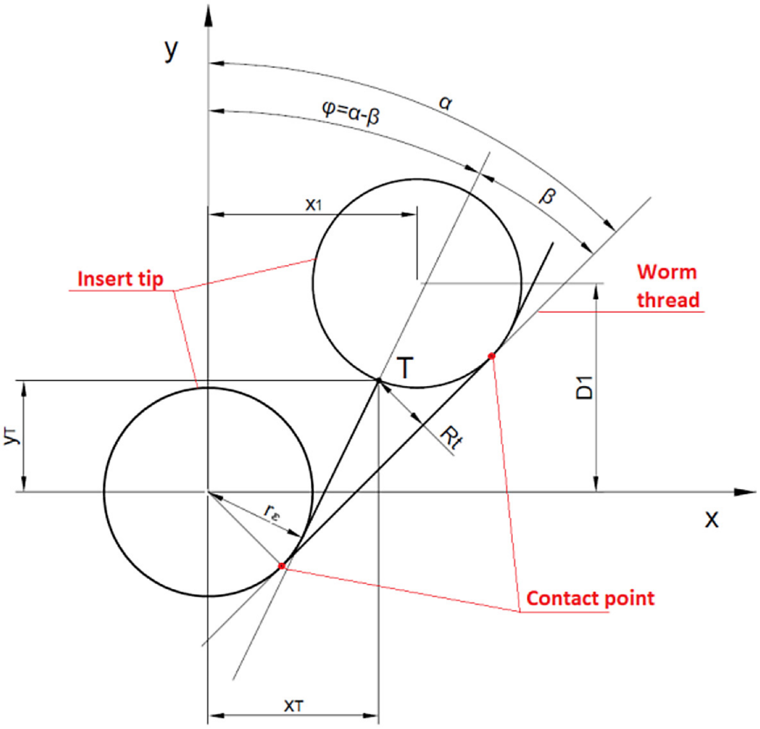


Figure 3. Total hight of surface roughness geometrical analysis

Table 1. Total hight of roughness profile Rt for point turning

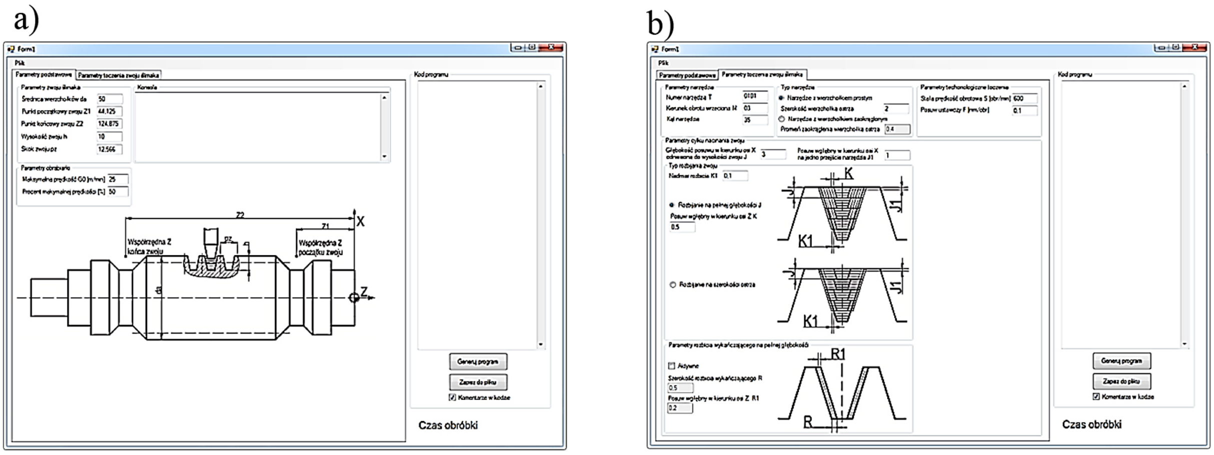
Total high of roughness profile Rt [μm]				
Tip radius r_ε [mm]	Depth of cut a_p [mm]			
	0.2	0.3	0.4	0.5
0.2	6.8	10.9	15.1	19.3
0.4	5.9	9.7	13.7	17.7

allow cutting on both sides of the notch. Neutral cutters with V–shaped cutting inserts (angle 35°) were selected. The shape of the insert was determined by the need to use a cutting insert with a profile angle smaller than the profile angle of the worm notch. Tools with two different methods of insert clamping were used for machining the worm threads. The first selected clamping system is CoroTurn TR from Sandvik [19]. The tool holder is equipped with rails, which correspond to the grooves in the insert, which guarantees high clamping force. The use of such a clamping system ensures high stability, repeatability of setting when changing the insert blade and to a large extent protection against micro–movements during cutting.

Another clamping system is available for all insert shapes and for different entry angles. The system enables very good chip evacuation and easy cutting. The screw clamping system offers secure insert clamping. The support insert used is designed to protect the seat from wear, ensure good adhesion of the cutting insert to the substrate and protection of the holder from damage in the event of a blade breakage.

Based on the above analysis the Sandvik Coromant TR–VB1304 and VBMT 130404–PF insert was selected for further testing.

For the machining of the worm threads, a special application has been prepared, which allows for the design of the technology of lathe machining of the worm threads. The program automates the process of preparing the machining of the worm threadss (Figure 4). Both data entry and code generation are carried out in the basic program window. The program has a modular structure. Individual modules are used to determine the basic parameters of the worm threads and the parameters of the threads turning. A necessary condition for preparing the code is to provide the diameter of the tops, height and pitch of the threads, as well as the coordinates of the start and end points of the threads.



Parametry zwoju ślimaka
Średnica wierzchołków da: 50
Punkt początkowy zwoju Z1: 44,125
Punkt końcowy zwoju Z2: 124,875
Wysokość zwoju h: 10
Skok zwoju pz: 12,566

Parametry obrabiarki
Maksymalna prędkość G0 [m/min]: 25
Procent maksymalnej prędkości [%]: 50

Parametry narzędzia
Numer narzędzia T: 0101
Kierunek obrotu wrzeciona M: 03
Kąt narzędzia: 35

Typ narzędzia
● Narzędzie z wierzchołkiem prostym
Szerokość wierzchołka ostrza: 2
○ Narzędzie z wierzchołkiem zaokrąglonym
Promień zaokrąglenia wierzchołka ostrza: 0.4

Parametry technologiczne toczenia
Stała prędkość obrotowa S [obr/min]: 600
Posuw ustawczy F [mm/obr]: 0.1

Parametry cyklu nacinania zwoju
Głębokość posuwu w kierunku osi X odniesiona do wysokości zwoju J: 3
Posuw wgłębny w kierunku osi X na jedno przejście narzędzia J1: 1

Typ rozbijania zwoju
Nadmiar rozbicia K1: 0,1
● Rozbijanie na pełnej głębokości J
Posuw wgłębny w kierunku osi Z K: 0.5
○ Rozbijanie na szerokości ostrza

Parametry rozbicia wykańczającego na pełnej głębokości
☐ Aktywne
Szerokość rozbicia wykańczającego R: 0.5
Posuw wgłębny w kierunku osi Z R1: 0.2

☑ Komentarze w kodzie

Figure 4. NC code generator aplication: a) parameters of worm, b) parameters of technology

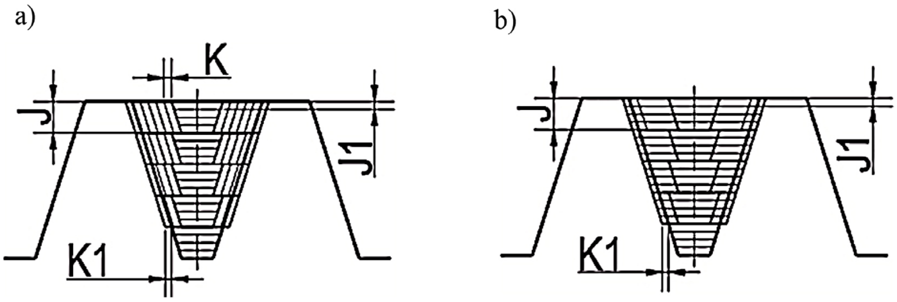


Figure 5. Worm gear cutting method: (a) on a full depth, (b) on a cutting insert width

The same functions are used to create worm threads as for thread turning, except that the worm is modified accordingly for machining. Each such function requires the depth of feed in the Z direction and the infeed in the X direction for one pass of the tool, while all other options are added in order to shorten the machining time as much as possible and to use the tool for as long as possible.

The program contains two methods of creating a thread:

- at full depth (Figure 5a),
- at the insert width (Figure 5b).

In both cases, parameter J is responsible for the cutting depth in the X–axis direction in relation to the threads height, while parameter J1 is the depth for one tool pass. In turn, parameter K is the width of one tool pass in the Z–axis direction and K1 is the allowance for the last pass. The choice of the method of removing the allowance affects the shape of the cross–section of the cutting layer, which in turn affects the smoothness of the turned surface. In the case of roughing the worm winding, a cutter that allows cutting both sides of the notch should be used, while for fine machining, a cutter that can cut both or only one side of the notch can be used.

The research model is a cylindrical worm. It is made of 42CRMo4 alloy steel. Due to its properties, this steel is used to build high–strength machine elements that are exposed to variable loads. The design parameters of the worm are presented in Table 2.

Haas ST–20 CNC machine was used to machine the worm shaft and its winding. For the machining of the threads of the tested worm, the method of breaking the threads at full depth was chosen, consisting of gradual penetration into the material and then breaking it on both sides. In the application, the infeed in the X direction was set at 0.1 mm per one tool pass, and after reaching a depth of 0.5 mm, the threads

Table 2. Worm gear parameters

Parameter	Symbol	Value
Teeth of the worm	z	1
Module	m	4
Pressure angle	α	20°
Axial pitch	p_z	12.566
Lead angle	γ	5.71°
Worm direction	–	right
Type of worm	–	ZA

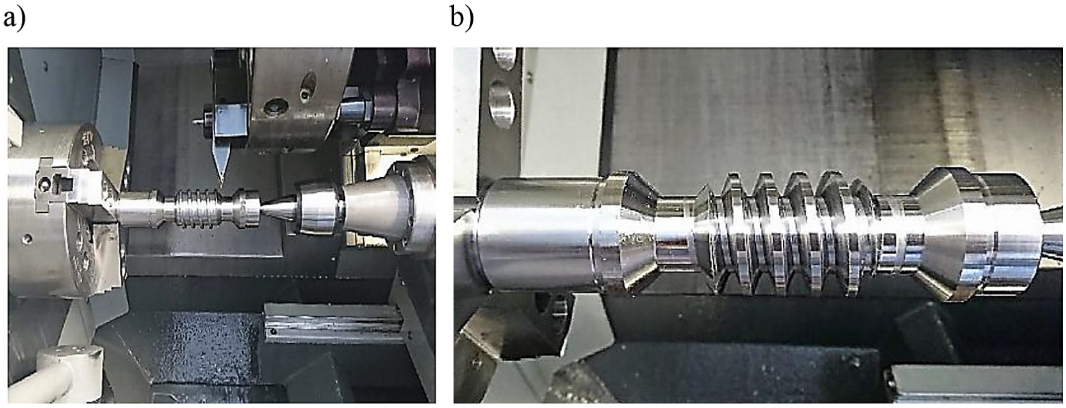


Figure 6. Worm gear turning: a) during process, b) after turning

was broken every 0.1 mm in the Z direction. Using the application, the NC code was generated and the machining was carried out on the machine tool (Figure 6).

In order to determine the accuracy of the threads profile, measurements were taken on a Wenzel LH87 coordinate measuring machine in axial cross–section, as shown in Figure 7a. The results obtained from the roughness measurement using a Surtronic 25 profilometer were used to assess the surface quality. In order to authenticate the obtained results, 3 measurements were taken in 3 different positions. The first measurement was taken at a length of 4 mm, while the other two, due to the limited access of the measuring thread, were taken at a distance of 2.5 mm. A Gaussian filter was used to remove waviness from a surface profile with 0,8mm cut-off length. The roughness parameters were determined based on the ISO 3274-1996, ISO 4287-1997 and ISO4288-1996 standard. The measuring station is shown in Figure 7b.

RESULTS AND DISCUSSION

In order to determine the value of the threads deviation, the theoretical profile had to be determined. Based on the NC code, the limit positions of the cutting insert in the threads notch were read Figure 8. Then, unnecessary lines were removed and a tangent was drawn to the subsequent corner roundings in all passes to determine the theoretical profile of the threads.

Finally, a theoretical profile was obtained, which will be used to determine the size of the deviations (Figure 9). The characteristic dimensions correspond to the diameters of the top and bottom of the notch. In the discussed case, the angle of the thread profile does not correspond to the angle of the tool profile and is 20°.

The results of the threads profile measurement on the coordinate machine were obtained in the form of point coordinates. These points were imported into CAD software, scaled 10 times for better graphical interpretation and compared to the theoretical profile in the form

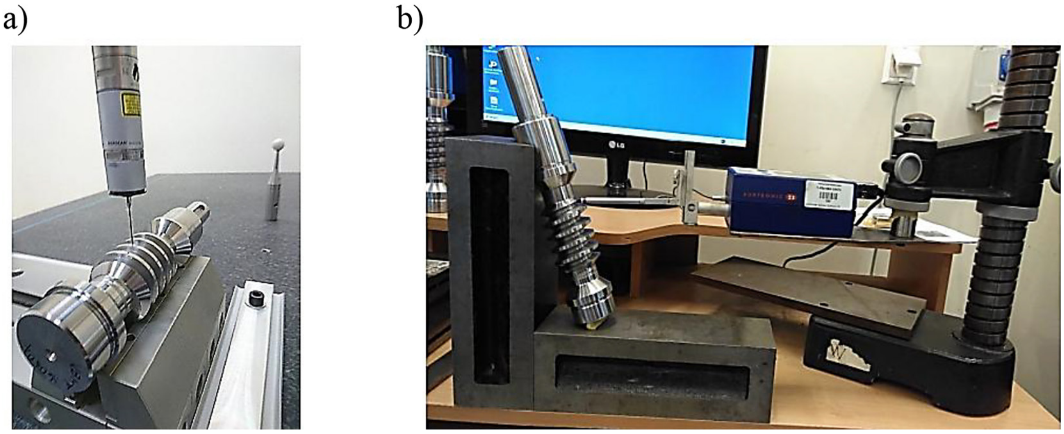


Figure 7. Worm gear threads mesurement: a) geometry, b) roughness

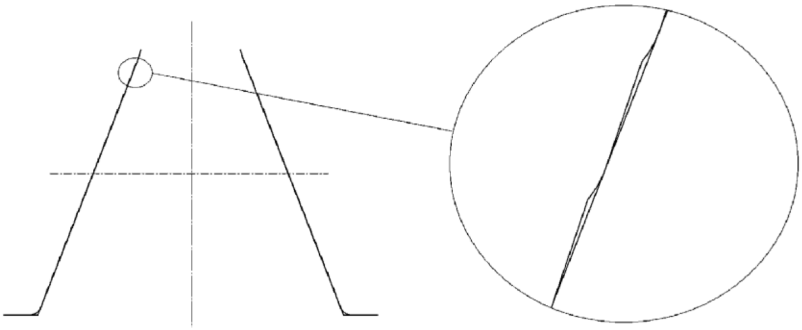


Figure 8. Determining the theoretical profile

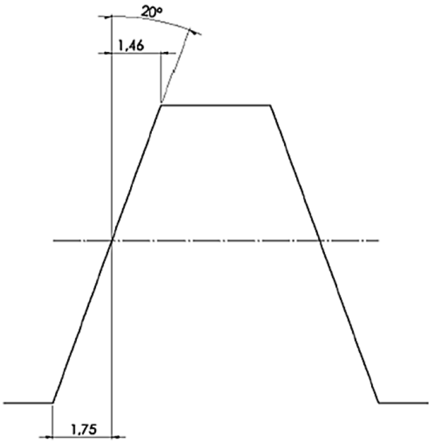


Figure 9. Theoretical profile of worm gear thread (linear dimensions are in milimeters)

of vectors. Figure 10 shows the threads profile deviation vectors. The results of surface roughness measurement are presented in Figures 11–13 and Table 3.

Due to the quality of the measured profile, the measurement results for profiles 2 and 3 were accepted for further analysis. Analysing the resulting distributions of the profile shape deviations shows that the profile made with the knife with the TR–VB1304–F 4325 insert attached is characterised by lower values. The smallest deviation value is at the top of the thread and is 3 µm. The maximum deviation value is 45 µm and occurs at the base of the thread notch. The remaining part of the profile is characterised by repeatable deviation values in the range of 10–20 µm. The increased deviation value at the base of the thread is related to the increasing wear of the insert during the process and the smaller number of passes at the bottom of the notch. In the case of the thread profile made with the VBMT 160404–PF 5015 insert, the deviation values are higher. As in the first case, the smallest deviation value is at the top of the thread. The largest value is 54 µm and is below the pitch diameter. The remaining values are repeatable in the range of 20–45 µm. Higher deviation values compared to the first case result from the used insert mounting system. The deviation values for modules in the range of

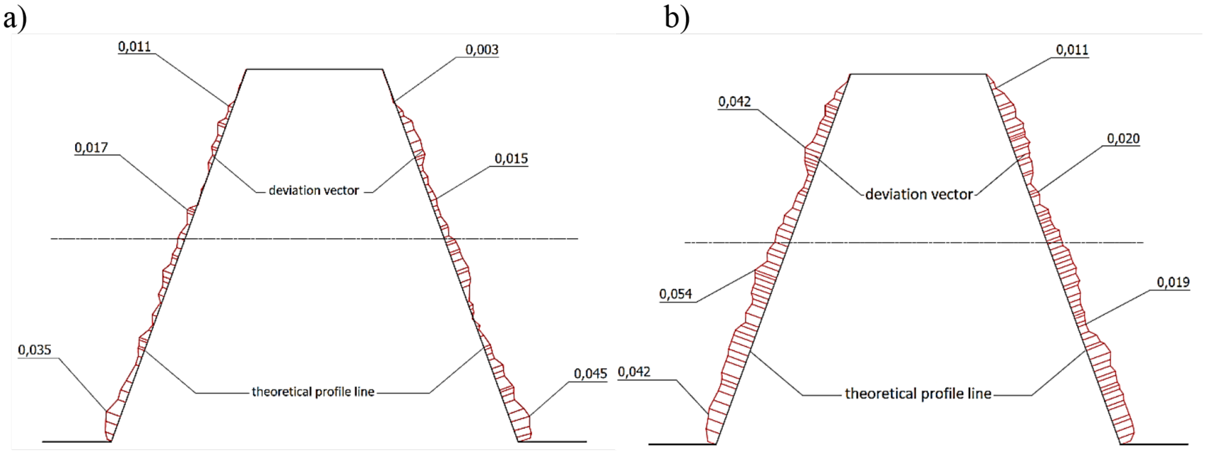


Figure 10. Deviation of the worm threads profile (dimensions are in milimeters): (a) TR–VB1304 insert, (b) VBMT 160404–PF 5015 insert

Table 3. Value of roughness profile parameters

Measurement number	Rp [µm]	Rv [µm]	Rz [µm]	Rc [µm]	Rt [µm]	Ra [µm]	Rq [µm]	Rsk	Rku	RSm [mm]
1	12.9	11.8	24.8	20.8	29.9	5.93	6.91	0.178	2.07	0.41
2	13.6	11.4	25.0	20.1	28.6	5.76	6.68	0.238	2.18	0.43
3	13.5	13.7	27.1	28.6	28.6	6.9	7.75	–0.08	1.75	5.5

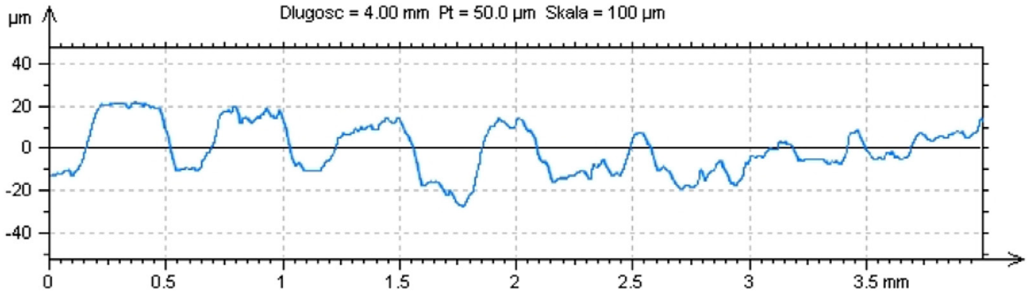


Figure 11. Measurement roughness profile 1

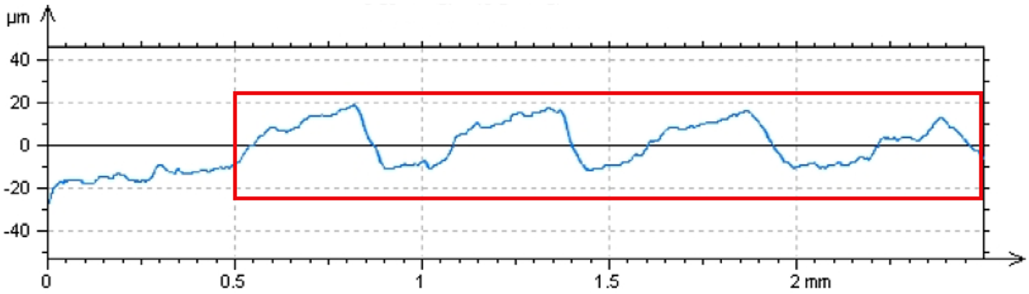


Figure 12. Measurement roughness profile 2

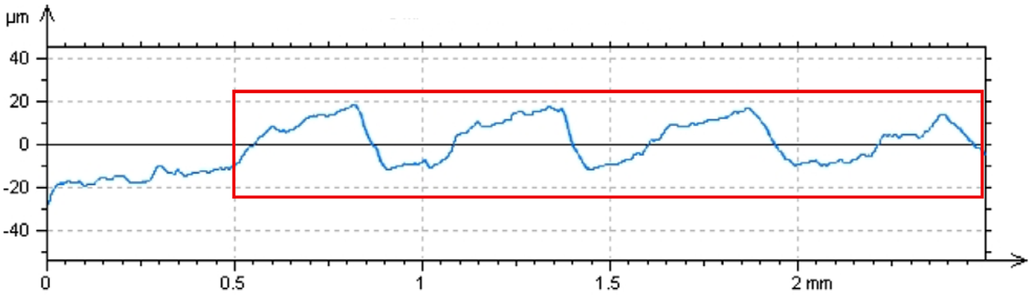


Figure 13. Measurement roughness profile 3

3.5–6.3, presented in the ISO standard, according to which there are 11 classes of profile accuracy, will be used to assess the profile accuracy class. In both cases, the thread profile deviation qualifies for the 9th profile accuracy class. Therefore, it should be emphasised that the presented method is sufficient for roughing or semi–finishing. The obtained roughness measurement results show that the value of the roughness parameter Ra is in the range of 5.76–6.90 µm, which also qualifies this method as sufficient for roughing. The value of the Rt parameter based on Table 1 should be 17.7 µm for turning a cylindrical worm using the V–shape point method (angle 35°) with a cutting depth of 0.5 mm. The Rt parameter values obtained from the measurement are in the range of 20–21 µm (profile marked in red frame). The mean absolute error between our predictions and measurements is 2.8 µm which corresponds to 13.6% mean absolute percentage error. Such error occurs because predictions are based on a purely geometrical model, which does not consider any deflections from cutting forces and thermal behaviour as well as cutting insert wear. Attention should also be paid to the RSm parameter, which precisely reflects the value of the cutting depth of 0.5 mm.

CONCLUSIONS

This study developed and analyzed a method for machining cylindrical worms using universal turning tools equipped with V–shaped inserts. The approach employed the point method for surface preparation and focused on accurately turning the worm thread with a 20° profile angle. An analytical formula was derived to determine the critical distance from the insert corner to the thread side at the contact point, which is crucial for precise thread formation. Additionally, a theoretical model for calculating the roughness profile height was introduced. Experimental tests were carried out using a cutting depth of 0.5 mm and an insert corner radius of 0.4 mm. To support this process, dedicated software was developed to generate NC code for CNC machining, allowing for the production of a theoretical thread profile that was used to evaluate manufacturing deviations.

The presented machining method allowed the use of universal folding tools for worm machining. This approach is justified due to their general availability, price, and the possibility of manufacturing on a universal CNC machines. The use of the TR–VB1304–F 4325 insert allowed to significantly reduce the insert repulsion caused by the large feed resulting from the helical pitch. Moreover, the derived geometrical model allowed for accurate predictions of roughness parameter Rt giving a low mean absolute error of 2.8 μm.

The research conducted is of significant industrial importance due to its immediate applicability in industrial settings. It addresses the gap in the use of universal turning tools and their application on conventional numerical machines. This study lays the foundation for future research, including:

- testing other cutting inserts applicable to different types of worms,
- evaluating the influence of machining parameters on the surface quality of worm threads,
- applying the same methodology to cutting gears on universal CNC milling machines.

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