

Influence of the Length of a Linear Interpolation Line Segment on the Accuracy of a Grinding Wheel Characterized by Variable Curvature

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ABSTRACT

The paper concerns an analysis regarding geometry of a grinding wheel used in grinding of cylindrical worm threads characterized by various geometry. It presents geometrical and physical factors having impact on the dressing process and quality of the grinding wheel. In particular, an attention is paid on the accuracy of a grinding wheel's outline if it is approximated by linear interpolation line segments which are obtained in the case of dressing on a CNC machine tool. On the basis of two grinding wheel outlines (Archimedes and circular-arched one), the relevance of the length of the segment line on the geometrical accuracy of wheel's outline has been presented. In the case of development of a wheel dresser path on the CNC machine tool, the necessity of a customized approach has also been indicated.

Keywords: linear interpolation, grinding wheel, tool's outline

INTRODUCTION

An accurate product manufacturing process depends on various factors. Such factors as: accuracy of machine tools, devices or fixtures, physical phenomena, machining parameters and a tool geometry play the crucial role in manufacturing. In the selected cases a tool geometry (i.e. a grinding wheel's outline) plays a significant role. The abovementioned statement is *inter alia* applicable in the case of an active surface of grinding wheel. In the case of machining process of a worm thread performed by the use of a disk-shaped grinding wheel, the outline of wheel should be developed properly in order to obtain a required worm's shape and worm's surface quality. Size and positioning of the grinding wheel plays also an important role in the grinding process [18]. The issues indicated above are discussed in the literature in terms of worms characterized by various outlines, including a concave outline [1, 2]. In the case of papers [11, 20], investigations concerning the process of grinding of worms are presented. Authors

stated that in the finishing process, grinding reveals crucial benefits in the case of machining process performed by the use of grinding wheel fitted to a required outline. Due to the linear contact of wheel's surface with the shaped surface of a product, better grinding conditions assigned to the tool were observed. It causes increased process performance and machining accuracy compared to the tool having a standard outline. The need of a precise manufacturing of such the wheel was also highlighted together with the process monitoring because it decides on the final geometry of product's surface. The papers [12–14, 32] present aspects and methods of tool conditioning. Authors of papers [23, 34] analysed an influence of selected conditioning methods on the accuracy of grinding of gears. The benefits indicated in the abovementioned papers concern the opportunity of obtaining various outline shapes, including gears having internal teeth. Various projects regarding a grinding wheel's profile shaping process by the use of many CNC controls are presented in papers [5–8, 28]. Tailor made dressing

units are equipped with the diamond dressers, drives and ball linear guides that allow to perform moves along X and Y axes.

Investigations regarding conditioning of disk-shaped grinding wheels by the use of diamond dressers are presented in different publications, e.g. [3, 4, 9–11, 24–27, 33]. Authors analysed mainly an influence of the changes of conditions and parameters on the topography of grinding wheel that has an impact on process performance and quality of a product. A cutting ability of a grinding wheel can be shaped by changing speed, feed and depth of dressing. Size and radius of a diamond insert of dresser and its lubrication is also crucial. Depending on the abovementioned parameters performance-related aspects or surface-related aspects can be discussed. In the first case, grinding wheels are conditioned in order to remove the maximum amount of material taking into account energy requirements. The second aspect is crucial in the case of finishing grinding process, that requires proper subsurface and small values of surface roughness parameters of a product. In that case, besides outline's shape, preparation of topography of an active surface of grinding wheel is also important. Authors of papers [19, 20] present methods and algorithms that allow an active surface topography modelling. The abovementioned issues have an important meaning in the case of shaping of grinding wheels characterized by complex outline.

Disk-shaped grinding wheels having ceramic or resin binder and simple geometry are relatively cheap. Their dressing is easy even by using conventional machine tools, and relatively large active surface leads to the high efficiency of grinding. Usually, the linear outline is used in the case of such grinding wheels.

Circumferential machining of worm threads leads to cone-shaped outline (ZK1). It should be also mentioned that cone-shaped (convex) outline determines the large concentration of contact stress in the area of contact with worm wheel teeth. Moreover, high sliding speed and friction between the pair of wheels leads to the decrease of efficiency and durability of worm gears. Concave outlines may be used then. Research proves better efficiency and load capacity of gears that consists of worm threads characterized by concave outlines due to better lubrication and lower stress in the area of contact [29–31]. The main problem concerns a need of preparation of the required grinding wheel's outline if

worm threads characterized by a concave outline are machined.

Irregular outline of an active surface of grinding wheel requires application of complex shaping systems. It causes the limited application of disk-shape grinding wheels. This is due to the fact of complex mathematical modelling and difficult processing. The outline of such wheel depends not only on the outline of a worm thread but also on diameter and width of a grinding wheel. These dimensions change due to wear and subsequent conditioning tasks [21]. In this scenario, the worn active surface of a grinding wheel determines the need of a new outline design and manufacturing.

Significant meaning in terms of worm accuracy is assigned to the accuracy of product outline. This is a common issue in the case of CNC machining because the variable geometry is approximated by segments of a line. CNC programming process should also be performed taking the length of line segments into account. In the case of the CAD/CAM environments in terms of accuracy of machined CAD model an outline error can be analysed [16, 17]. However, not all projects are developed by using this environment. Some cases of machining are based on tailor-made programming approaches (i.e. direct programming) and the knowledge of CNC programmers concerning outline accuracy is crucial. It leads to the maximum length of the interpolation segment for the defined accuracy. An example may be the development of an NC code for the aims of dressing of a ceramic grinding wheel, or preparation of a base for an electroplated grinding wheel, the outline of which is calculated based on a mathematical model. It gives information about the size of geometrical components of the outline deviations.

Authors defined the aim of the work on the basis of the analysis of existing methods and tools applicable for shaping of grinding wheels which are used in manufacturing of worm threads. In this area CNC machining is an effective method, however, it requires a proper determination of interpolation parameters (i.e. a length of the linear interpolation line segment) that meets all the requirements of technological process. In this context, the aim of study concerns a methodology and examples of a proper determination of a maximum length of the linear interpolation line segment which allows to obtain a non-linear grinding wheel's outline taking into account an acceptable outline's deviation value.

GEOMETRICAL PARAMETERS CONCERNING OUTLINES: DRESSING PROCESS PERSPECTIVE

Preparation of the defined grinding wheel’s outline is associated with its machining. The final dressing effect depends on the number of factors including geometry of dresser and parameters of dressing. It is obvious that surface quality is associated to feed and depth of cut. The ideal process conditions (if the physical phenomena are not included) and taking into account that a used tool is a dresser having a circular outline of cutting edge a theoretical Rz parameter is calculated on the basis of assumptions presented in Figure 1.

The maximum height R_{ts} is calculated as [35]:

$$R_{ts} = \frac{f_d^2}{8r_d} \tag{1}$$

where: R_{ts} – theoretical height of a profile [mm],
 r_d – tool nose radius [mm]

The deviations in the profile presented above can be minimized by a small value of the tool feed or a small value of the radial depth of cut.

However, the variable contour of the workpiece causes another contour deviation, which does not occur in the case of machining of rectilinear surfaces with the programmed tool path. It results from the approximations of the contour curvature with segments of straight lines being components of the NC program. It is a widespread issue in terms of CNC machine tools control. The essence of this deviation is shown in Figure 2.

Value of deviation can be calculated:

$$\delta = R - \sqrt{R^2 - (L/2)^2} \tag{2}$$

According to the equation, the deviation of the outline depends on the radius of curvature and the length of the interpolating segment. Therefore, it remains to determine the radius of curvature of the outline at a given point. Assuming that the outline is a circular arc, the radius of curvature can be derived from the coordinates of the three points. In determining the radius of curvature, the angle of the outline at a point can also be used, and then the coordinates of two outline points are sufficient to determine it. A convenient way to determine the radius of curvature at a point is to

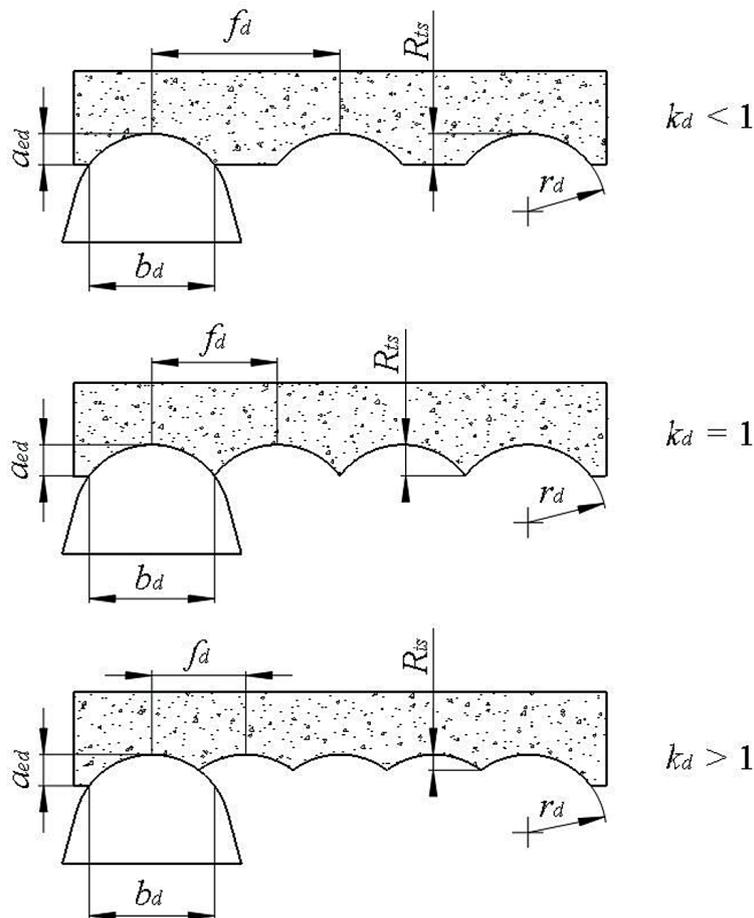


Fig. 1. Theoretical height of a profile [15]

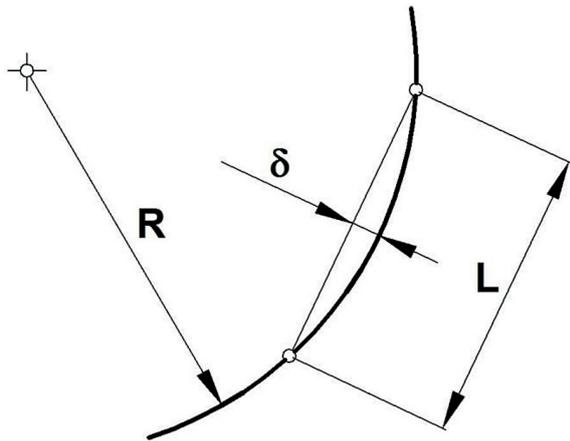


Fig. 2. Theoretical outline deviation

describe the outline using a mathematical function of the form:

$$y = f(x) \tag{3}$$

In this case, the radius of curvature is described by the equation:

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{d^2y/dx^2} \tag{4}$$

where: $\left(\frac{dy}{dx}\right)$ – first derivative,

$\frac{d^2y}{dx^2}$ – second derivative.

The abovementioned equations can be used in the analysis of straight line approximations of any contour of a workpiece with variable geometry. In this paper, the presented equations are used for the aims of determination of an influence of linear interpolation line length (G1) in NC code on the accuracy of the shaped outline of a disk-shape grinding wheel.

MATHEMATICAL MODEL OF A GRINDING WHEEL OUTLINE

Geometry of a worm thread should be analysed prior to the preparation of a mathematical model of a grinding wheel’s outline. Model of a helical surface having any outline is created based on the helical movement of any line around one axis of a coordinate system. The idea of such a surface creation is presented in work [30]. Kinematics regarding shaping of a worm thread by the use of a disk-shape tool is presented in Figure 3. Preparation of a mathematical model of a grinding wheel outline requires the definition of a worm geometry.

According to Figure 3 the tool axis is shifted (a_N angle) and rotated (χ_N angle that equals an angle of a helical line γ). The coordinate system $x_2y_2z_2$ is a stationary one, and rotation is realised by the tool’s coordinate system $x_Ny_Nz_N$ using ϕ_N angle. In this context, an equation of an active surface of a grinding wheel as a function of worm thread outline is as follows:

$$\left. \begin{aligned} x_N &= x_2 \cos \phi_N + y_2 \sin \phi_N \cos \gamma + z_2 \sin \phi_N \sin \gamma - a_N \cos \phi_N \\ y_N &= -x_2 \sin \phi_N + y_2 \cos \phi_N \cos \gamma + z_2 \cos \phi_N \sin \gamma + a_N \sin \phi_N \\ z_N &= -y_2 \sin \gamma + z_2 \cos \gamma \end{aligned} \right\} \tag{5}$$

An outline of an active surface of rotational tools is defined by using the course of contact line between a tool, shaped worm thread. This requires the determination of tangential and normal to the surface vector components, which are presented in work [30]. The set of equations (5) includes 3 coordinates. In order to ensure compliance with the plane notation of the profile expressed by the equation (3), the x_N or y_N coordinate should be equated to 0, then an equation on the plane is obtained that corresponds to an outline of grinding wheel in the axial section.

Taking into account the time consumption regarding calculations, a tailor-made application has been developed at the Department of Manufacturing Processes and Production Engineering of the Rzeszów University of Technology. It allows the determination of any contour of the worm thread and the precise preparation of the geometry of the active surface of the grinding wheel dedicated for the worm thread machining. The attention was

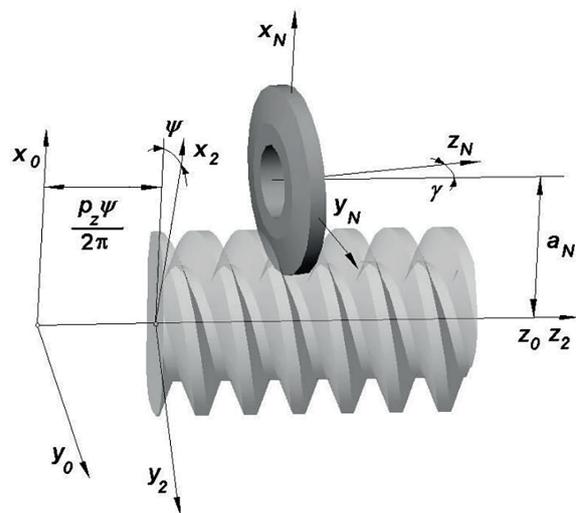


Fig. 3. Kinematics of shaping of a worm thread outline by the use of a disk-shape tool

paid to the accuracy of the approximations of the grinding wheel contour with straight sections (linear interpolation), which takes place during CNC-based dressing process.

THE INFLUENCE OF LINEAR INTERPOLATION POINTS LAYOUT ON OUTLINE ACCURACY

The presented mathematical model allows to determine a grinding wheel outline as a continuous line. The dressing process performed on a CNC machine tool requires the definition of straight line segments (linear interpolation, G1 function) in the plane created along the worm thread's axis (Fig. 4).

It causes the outline deviation presented in Figure 2. The presented equations (2–4) enable to determine the value of the outline deviation resulting from the length of the interpolation segment. It is shown on the example of the outline of a circular grinding wheel intended for the circumferential machining of a cylindrical worm. It was assumed that the theoretical heights described by relations (1, 2) equal zero. This situation takes place at a low feed value, which occurs in the case of dressing the grinding wheel. Calculations of the grinding wheel outline coordinates were carried out for a single-convolution worm with an axial module of 4 mm and a diameter index of 10, machined by using a disc grinding wheel with a nominal diameter of 200 mm. Two worm contours were used for the analysis. They are rectilinear (Archimedes worm thread) and circular-arched with a radius

of 30 mm. An axial cross-section of the worm thread is presented in Figure 5.

In each case, the worm outline angle was 20° . Calculations of the grinding wheel contour coordinates were carried out according to the equations provided in [17]. Coordinates of the grinding wheel outline in the radial direction, for which the calculations were performed, were evenly distributed. This is shown in Figure 6.

The regular distribution of the coordinates of the profile along the X axis causes that the length of the interpolation segment is not identical and it changes depending on the angle of the grinding wheel. The results of calculating the parameters of the outline of the grinding wheel intended for machining of Archimedes worm, with a distance between points of 2 mm and 1 mm, are presented in Tables 1 and 2.

While the values in Tables 1 and 2 are analysed, it can be stated that the contour of the grinding wheel intended for Archimedes worm grinding (with a rectilinear profile) is convex and results from the specificity of the circumferential machining. This is expressed by changing the value of the profile angle along its height as well as changing the value of the radius of curvature. The deviation of the outline resulting from approximating it with straight sections decreases its value, which is mainly caused by the lower value of the curvature. The angle of the grinding wheel outline slightly deviates from the angle of the worm thread.

The results of calculations of the parameters of the profile of a grinding wheel for machining a circular-arc worm with a profile radius of 30 mm with a distance between points of 2 mm and 1 mm are presented in Tables 3 and 4.

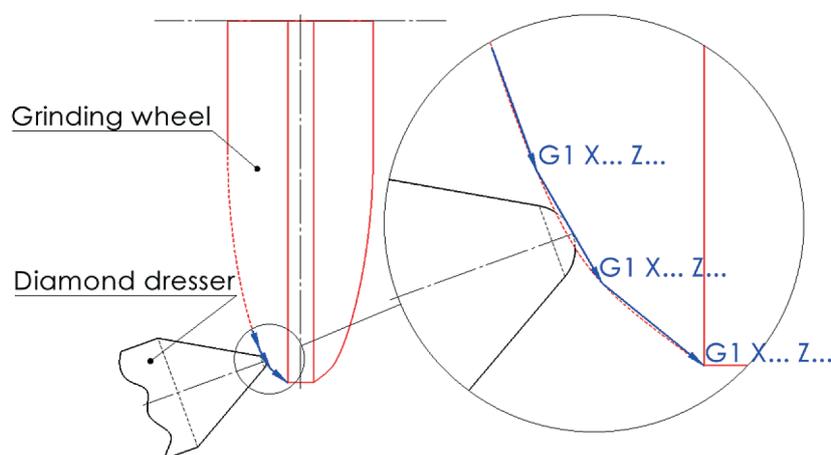


Fig. 4. Mechanism of a grinding wheel outline shaping process by the use of a CNC machine tool

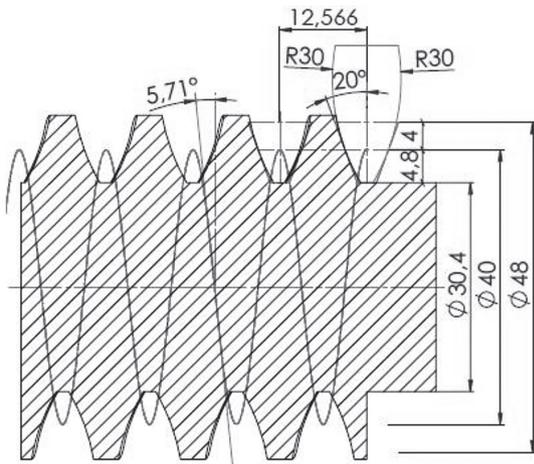


Fig. 5. ZRO1 cylindrical worm thread characterized by a concave outline $R = 30$

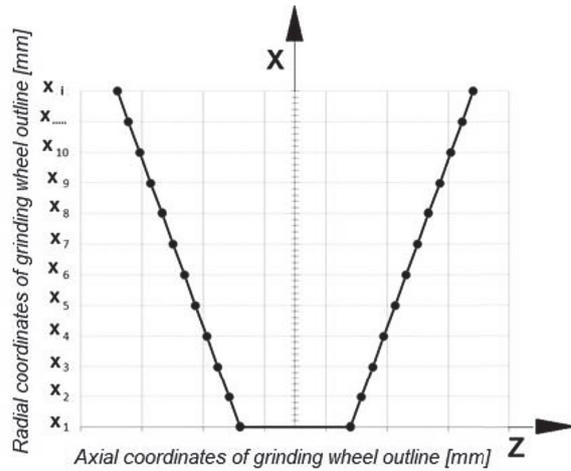


Fig. 6. Layout of wheel outline coordinates

Table 1. Grinding wheel for Archimedes worm (points distance 2 mm)

No.	X [mm]	Z [mm]	Outline angle [°]	Radius R [mm]	Deviation δ [mm]
1	-104.849	1.351	20.35	455.594	0.00124
2	-102.849	2.088	20.127	663.034	0.00085
3	-100.849	2.818	19.973	961.783	0.00058
4	-98.849	3.543	19.867	1380.86	0.0004
5	-96.849	4.264	19.793	2024.9	0.00027
6	-96.021	4.562	19.771	2455.23	0.00023

Table 2. Grinding wheel for Archimedes worm (points distance 1 mm)

No.	X [mm]	Z [mm]	Outline angle [°]	Radius R [mm]	Deviation δ [mm]
1	-104.849	1.351	20.35	455.594	0.00031
2	-103.849	1.721	20.228	549.342	0.00025
3	-102.849	2.088	20.127	663.034	0.00021
4	-101.849	2.454	20.043	799.55	0.00017
5	-100.849	2.818	19.973	961.783	0.00014
6	-99.849	3.181	19.915	1153.35	0.00012
7	-98.849	3.543	19.867	1380.86	0.0001
8	-97.849	3.904	19.827	1659.33	0.00008
9	-96.849	4.264	19.793	2024.9	0.00007
10	-96.021	4.562	19.771	2455.23	0.00005

Table 3. Grinding wheel for circular-arc worm (points distance 2 mm)

No.	X [mm]	Z [mm]	Outline angle [°]	Radius R [mm]	Deviation δ [mm]
1	-104.819	0.869	30.238	29.893	0.0224
2	-102.819	1.935	25.87	29.622	0.02084
3	-100.819	2.815	21.631	29.455	0.01963
4	-98.811	3.526	17.476	29.016	0.01893
5	-96.819	4.077	13.314	28.012	0.01884
6	-96.061	4.245	11.71	27.455	0.01898

Table 4. Grinding wheel for circular-arc worm (points distance 1 mm)

No.	X [mm]	Z [mm]	Outline angle [°]	Radius R [mm]	Deviation δ [mm]
1	-104.819	0.869	30.238	29.893	0.0056
2	-103.819	1.427	28.036	29.721	0.00539
3	-102.819	1.935	25.87	29.622	0.00521
4	-101.819	2.397	23.736	29.549	0.00504
5	-100.819	2.815	21.631	29.455	0.00491
6	-99.819	3.191	19.548	29.291	0.0048
7	-98.819	3.526	17.476	29.016	0.00473
8	-97.819	3.821	15.403	28.597	0.0047
9	-98.819	4.077	13.314	28.012	0.00471
10	-96.061	4.245	11.71	27.455	0.00474

In the case of the circular-arc outline of the worm, different values characterizing the grinding wheel can be noticed. The angle of the grinding wheel outline varies within a wide range, while the radius of curvature changes slightly. Much greater values are obtained for the outline deviation reaching hundredths of a millimetre. Assuming the deviation of the profile equal to 0.001mm and comparing the analysed contours of the grinding wheels, the following information can be obtained. Assuming that the value of the deviation is defined and a curvature radius is calculated using equation (4), the equation (2) enables to calculate the length of a linear interpolation segment:

$$L = 2\sqrt{R^2 - (R - \delta)^2} \quad (6)$$

Taking into account the equation (6) for a grinding wheel used in machining of an Archimedes worm, the maximum distance between the profile points may not exceed 1.7 mm. With this assumption, the outline of the grinding wheel can be approximated with seven points. On the other hand, for a grinding wheel for machining a circular-arc worm, the gap must not exceed 0.4 mm. The number of points ensuring that this deviation value is obtained is 23.

CONCLUSIONS

The knowledge regarding errors of outlines characterized by variable curvature is a key element in technological process planning, including NC-code development. It allows to define the maximum values of linear interpolation motion taking into account the expected accuracy of part. The presented calculations state that not only

low values of technological parameters lead to the high accuracy of parts. The significant meaning of geometrical errors resulting from NC programming must be also taken into consideration. In the case of grinding wheels characterized by the complex geometry, the geometrical accuracy of an outline plays an important role, because it constitutes the final geometry of a machined product. Due to that fact, this is crucial to know the deviation resulting from the approximation of an outline having variable curvature. It is an important element of CNC programming. The obtained results allowed to determine the maximum length of the interpolation segment, which enables to obtain the permissible deviation at the defined accuracy (0.001 mm). The conducted research revealed that the increase of the curvature value determines the need of decreasing the length of interpolation segment. This causes the increased workload in terms of CNC code preparation due to the greater number of outline's points. Direct CNC programming may be used in the case of simple shapes. However, complex outlines require CNC programming process automation. The machining process preparation presented in the paper is based on the tailor-made outline definition.

The calculations are a base for further research in the area of worm threads machining because they present the exemplary values of length of linear interpolation line segment which meet the requirements of construction of various worm threads.

The methodology presented in the paper theoretically proves that it is possible to obtain a required grinding wheel's outline if a linear interpolation line segment is properly calculated. Focusing on the geometrical analysis of machining

process, it can be stated that the linear interpolation segment plays the crucial role in shaping of the final accuracy of part. However, due to the tool wear, machine tool accuracy, blank accuracy, etc., it is not enough to focus on the length of line segment only. Further research may concern an analysis of the influence of machine tool errors on the final accuracy of a worm thread.

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