SOME TOPICS IN PROCESS PLANNING OF ROTATIONAL TURNING

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Abstract:

There could be different procedure variants of chip removal by the applied kinematic relations in turning operations. Recently, some research and analysis of these variants have come to the front since turning can replace grinding in precision machining operations due to the development of tools with geometrically defined cutting edge(s) and tool materials, even in machining of hardened surfaces. This frequently occurs in finish machining, therefore the application of the topography meeting the functional requirements best and also the procedure leading to that has become crucially important. Some of the technological issues of one of the variants – rotational turning – is the subject of this work.

Rotational turning does the cutting with a long, oblique and spatial positioned cutting edge instead of the single-point cutting tools applied in traditional turning. The slow rotation of the cutting edge on a large diameter causes a skiving-like material removal mechanism. In order to calculate the cutting parameters as well as to determine the machining times and the productivity, the rotation angles of the tool needed for the run-in, run-out and the constant phases must be known.

In this paper the rotation angles based on geometrical conditions are determined and a method for their calculation is given. The structure of the applied tool and the applicable technological parameters are described and in addition, the high productivity of this procedure is shown. Finally, the method for determining the cutting parameters is described.

1 Introduction

Turning with rotational feed (rotational turning) of outer cylindrical surfaces can be characterized by a tool which works with a slow, rotational movement – in contrary to the axial feed in traditional longitudinal turning – thus generating the machined surface by the linear contact of the cutting edge and the workpiece instead of point contact [1]. The cutting edge can be made from a material capable of machining hardened steels, and therefore, rotational

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turning is also applicable to the finishing operations of hardened surfaces.

Longitudinal hard turning is used with increasing frequency in finish machining, however, in some cases the prescribed accuracy for the machined workpiece and/or the topography meeting the functional requirements are not obtainable [2-4]. The surface topography generated by this procedure is mentioned but not properly discussed in detail in the technical literature. The topography generated by single-point turning tools is disadvantageous in the following cases: the surfaces carrying dynamic seals; the working surfaces of the inner and outer rings of needle roller bearings; the surfaces of the synchronizing cones on parts of gear-boxes; and contact surfaces of freewheels in transmission [5].

Among these, the surfaces carrying dynamic seals are the most significant. In the automotive industry no oil leak can be permitted between sealings and drive shafts in gear-boxes and differential housings. This is important not only to lower the oil loss caused by the numerous vehicles but also to reduce global environmental pollution. Thus it is necessary to study the surface topography generated in finishing machining methods, and decide if the functional requirements allow us to apply methods that produce topography with some kind of twist (lead, or *drall* in German) structure. These surfaces are defined by the standard (for example DIN EN ISO 25178-3:2008-03 [5]) and five parameters are given for the measurement of twist structure. The mathematical determination [6] and the 3D visualization [7] of the topography can help in the analysis.

The five characteristic parameters of the twist structure are shown in Fig. 1 (twistparameters):

1. *DP* – period length of the twist [mm]
2. D_γ – twist angle [°]
3. *Dt* – twist depth [µm]
4. *DG* – number of threads
5. *DF* – theoretical cross section of twist [μm^2]

The problem of twist structure generation on the surface is solved mainly by the use of grinding procedures, since the generated, so-called “random” topography is suitable in the cases described above. Therefore, up to the present, production engineers have recommended the use of grinding for finishing operations.

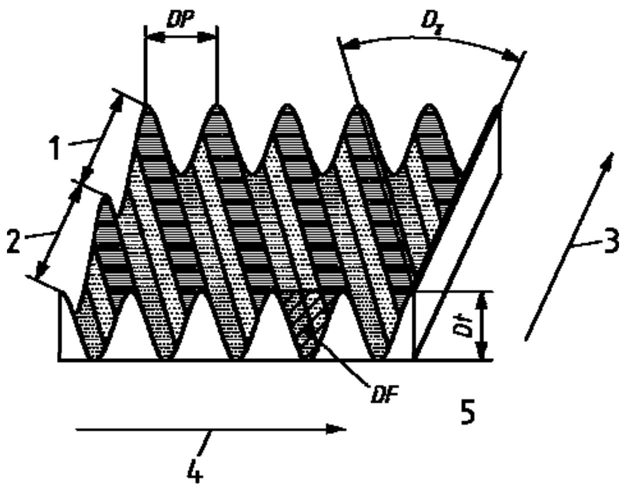


Figure 1. The shape of twist structure and its geometrical characteristics (1: Spiral I, 2: Spiral I., 3: Unwind perimeter, 4: Axis direction, 5: 2 right-handed) [5].

However, we must highlight that according to recent studies twist structure can be observed also on grinded surfaces. According to the standard mentioned above it can occur in two cases:

1. if the dressing of the grinding wheel was done with a single point diamond – this is dressing twist.
2. if the axis of the workpiece and the axis of the grinding wheel are not parallel (Quickpoint Grinding) – this is setting twist.

Therefore, the general statement that the twist structure does not show up in grinding or that the topography is twist-free (drallfrei in German) is not accurate. In the above described two cases, the switch to another grinding procedure where the twist structure does not show up (like infeed grinding without traverse feed) is also recommended by engineers.

Due to the efficiency and economic benefits of the procedures done by geometrically defined cutting edge tools, it is necessary to study how the twist structure could be reduced. It can be seen in Figure 1 that the lower the value of the *Dt* or *DF* parameter, or the higher the value of the *DP* or D_γ parameter, the smoother the surface will be.

This can help the further spread of turning with rotational feed, because – unlike in traditional longitudinal turning – smoother surfaces can be machined, and instead of the 0.1 … 0.01 mm topography frequency, one order larger periodicity and / or lower total height of surface profile can be achieved [8, 9]. (However, supposedly the grinded-like random topography is only possible in a range equal with the wavelength of the profile roughness and it does not occur in higher wavelength ranges [9-12]. The further investigation of this question should be a target of future studies.)

Skiving-like material removal is done by the slow rotary movement of the tool having a helical cutting edge with large diameter. Therefore the rotational method creates a topography closer to random grinding-like topography [5, 6, 7]. The advantages of the method show up mainly in machining external cylindrical surfaces (shafts) because the above mentioned special type of surfaces presented primarily on these and the distribution of the cutting force (the value of the passive force component) is more important for the accuracy in this case.

In the process planning of rotational turning the exact kinematic relations and the needed rotation angle of the tool must be known in order to determine the machining time. The basic manufacturing geometry correlations must be known for the calculation of the procedure performance and for the adjustment of the cutting parameters. The needed rotation angle of the tool, the geometrical conditions of the run-in and run-out phases and further data are necessary for the determination of the material removal rate and machining times.

2 Cutting with the rotational feed turning procedure

The material removal in rotational turning is caused by the chip formational movement of the long cutting edge, the section of which is linear in a laid-out plane but in reality it is on a helical curve on a cylinder surface with ds diameter. In Fig. 2 the cutting edge can be seen in plane, so it creates a line, whose line and the axis of the workpiece are skewed. Here the PV distance can be found which is in cut at the moment and which generates the chip. In geometrical view, the skewed position means that the radius of the generated workpiece (with d_w diameter) is equal to the normal transversal of the lines (in Fig. 2 the OP distance).

The explanation of the symbols in Fig. 2 is the following: $d_{w,z}$ – raw diameter of the workpiece (contains radial direction allowance, z); n_w – angular frequency of the workpiece; v_c – cutting speed; v_s – the speed vector of the rotation of the workpiece; a_p – the depth of cut; λ_s – the skew angle of the cutting edge.

Fig. 2 also demonstrates that the complete surface of the workpiece is machined by a long section of the cutting edge, meaning that the tool life of the cutting edge will be longer. Furthermore, it can be seen that there is no need for feed from the machine because the axial component of the speed vector (v_c) works as "axial feed" during machining.

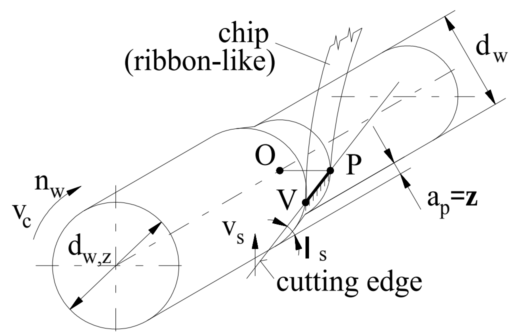


Figure 2. The principle of material removal in rotational feed turning.

Figure 3 explains the required angle of the rotation of the tool. The first specific position of the tool: the initiation of cutting when the cutting edge reaches the workpiece in point P. The second specific position: with the further rotation of the tool (by the angle of which is ϑ_{in}) the P point gets to the P' point where the constant phase begins. The third specific position: the point V gets to the point U while the tool rotates with the angle ϑ_{const}. The fourth specific position: the initiation of the run-out phase as the point V reaches the U' point. The needed angle of the rotation is ϑ_{out}.

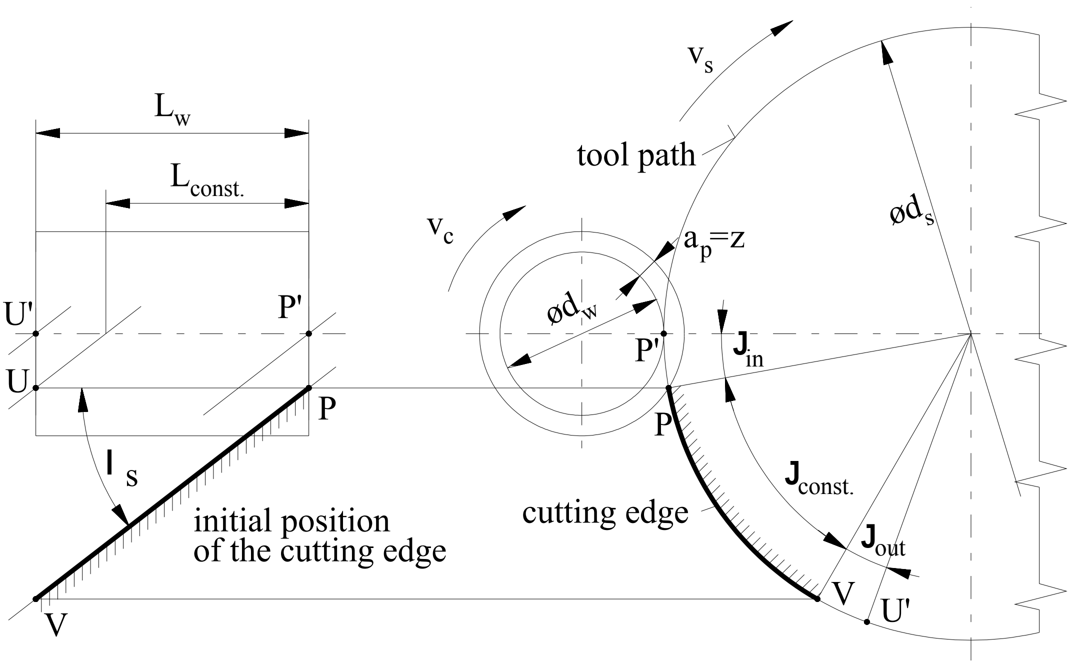


Figure 3. The four specific positions of the cutting edge and the needed rotation angles.

3 Determining the angles of rotation of the tool

One of the main steps in the process planning of a procedure is the determination of machining times. In rotational turning this can be calculated on the basis of the tool rotation. For this the angular frequency of the tool and the needed rotation for the machining of the whole length of the workpiece must be known. For the determination of the latter, Figure 3 is used where the needed parameters for the calculations are shown.

It is practical to divide the rotation angle by the three main phases of the procedure (run-in, constant, run-out). The first and the third component are equal to each other due to the symmetry of the kinematic relation. The rotation angle for the run-in phase can be calculated by the $\widehat{PP'}$ arch and the radius of the cutting edge helix. However, the applied depth of cut (a_p) is around 0.1...0.2 mm and the tool diameter is high compared to the previous, therefore, the arch can be approximated well with the chord between the P and P’ points:

$$\widehat{PP'} \cong h \tag{1}$$

Using this, the arch related to the ϑ_{in} angle ($\widehat{PP'}$) can be calculated from the tool diameter (d_t), the workpiece diameter (d_w) and the depth of cut (a_p):

$$\widehat{PP'} = \sqrt{a_p \cdot \frac{d_t \cdot d_w}{d_t + d_w}} \tag{2}$$

Furthermore, the rotation angle of the run-in phase and the angle of one complete revolution (360°) are proportional to each other as the arch is related to the angle ($\widehat{PP'}$) and the perimeter of the circle with d_t diameter:

$$\frac{\widehat{PP'}}{d_s \cdot \pi} = \frac{\vartheta_{in}}{360°} \tag{3}$$

With the application of Equation (2) and (3) the rotation angle related to the run-in phase can be determined. The final equation is expressed in degree [°] and radian, and therefore, the needed form can be used for further calculations:

$$\begin{aligned} \vartheta_{in} &= \frac{360°}{d_t \cdot \pi} \cdot \sqrt{a_p \cdot \frac{d_t \cdot d_w}{d_t + d_w}} \quad [°] \\ \vartheta_{in} &= \frac{1}{r_t} \sqrt{2 \cdot a_p \cdot \frac{r_t \cdot r_w}{r_t + r_w}} \quad [rad] \end{aligned} \tag{4}$$

For the purpose of determining the needed rotation angle in the second phase (where the cross-section of the chip is constant), the pitch (p) of the helical cutting edge must be calculated. For this the radius of the tool envelope cylinder (r_t) and the spatial position of the cutting edge are correlated to the reference plane of the tool (inclination angle, λ_s):

$$p = 2 \cdot r_t \cdot \pi \cdot \tan(90° - \lambda_s) \quad (5)$$

The rotation angle related to the constant phase can be expressed by the length of the workpiece (L_w) and the determined pitch of the cutting edge (p). However, the rotation angle of the run-in phase must be subtracted from the rotation angle related to the workpiece length ($\overline{P'U'}$ section) because the constant phase lasts until the cutting edge gets to the point U:

$$\vartheta_{const} = \frac{L_w}{p} \cdot 360° - \vartheta_{out} \quad (6)$$

From Equation (6) the rotation angle of the constant phase can be determined, which is expressed in degree and radian as in the previous case:

$$\vartheta_{const} = \frac{360°}{d_t \cdot \pi} \cdot \left[\frac{L_w}{\tan(90° - \lambda_s)} - \sqrt{a_p \cdot \frac{d_t \cdot d_w}{d_t + d_w}} \right] [°]$$
$$\vartheta_{const} = \frac{1}{r_t} \left[\frac{L_w}{\tan(90° - \lambda_s)} - \sqrt{2 \cdot a_p \cdot \frac{r_t \cdot r_w}{r_t + r_w}} \right] [rad] \quad (7)$$

To calculate the machining time in rotational turning, the sum of the rotation angles of the three phases must be divided by the tool's angular frequency (ω_t):

$$t_m = \frac{\sum \vartheta_i}{\omega_t} = \frac{\vartheta_{in} + \vartheta_{const} + \vartheta_{out}}{\omega_t} \quad (8)$$

After the substitution of Equations (4) and (7) into Equation (8) the proper form for the calculation of the machining time can be expressed (with the degree form applied):

$$t_m = \frac{360° \cdot \sqrt{a_p \cdot \frac{d_t \cdot d_w}{d_t + d_w}} + \frac{L_w}{\tan(90° - \lambda_s)}}{d_t \cdot \pi \cdot \omega_t} \quad (9)$$

4 The practical use of rotational turning

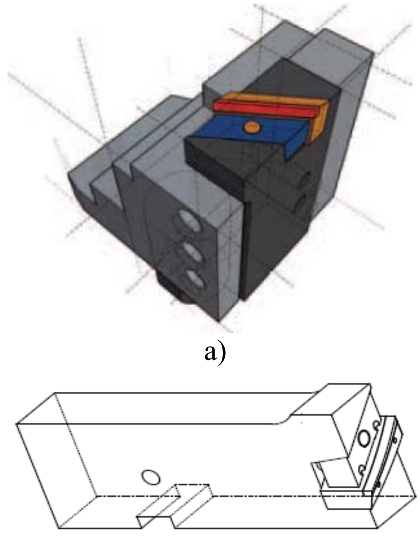
Rotational turning is capable of machining not only external cylindrical surfaces but also bore-holes and flat surfaces. There is also no limitation for machining interrupted surfaces. The advantages of use of rotational turning as opposed to grinding are:

- shorter machining times,
- no need for coolant,
- lower investment costs,
- higher process stability [9].

The method and the needed machine tool is based on the patent announcement by J. G. Weisser Werkzeugmaschinenfabrik. The tools are manufactured by MAS GmbH. The following results are obtainable [13]:

- roundness tolerance <0.003 mm,
- straightness tolerance <0.003 mm,
- concentricity <0.004 mm,
- diameter IT5…IT6,
- roughness Ra<0.02 µm; Rz<1.00 µm.

The cutting is performed with a special tool with a PCBN cutting edge which can be held in the turret of the lathe (Fig. 4). The tool life is long because not only one point of the edge works but the whole length of the edge, the size of which can be around 30 mm.



a)

b)

Figure 4. The rotational turning tool mountable into a turret of a lathe: a) 3D view of the tool, b) design of the tool [15].

The edge is made of boron-nitride with middle CBN content, TiN binder, and around 2µm grain size. Its relatively high shock resistance enables the cutting of interrupted surfaces.

In Fig. 4 it can be seen that only a thin, lath-like insert of CBN is made in the tool and hence the costs remain on a moderate level. Unusually careful preparation of the edge is needed: both the rake and the flank surfaces are lapped multiple times. The thin (h = 0.01…0.02 mm) and wide chip is cut down in a ribbon-like way in the cutting zone. The cutting speed is very high: 160…240 m/min (which is typical of CBN tools); for tangential feed (f_t) – or rotational feed – 0.14…0.18 mm/workpiece revolution is recommended by the manufacturers [8, 9, 13]. The allowance in diameter is: $z \leq 0.02$ mm.

5 Process planning of rotational turning

The first phase of technology planning contains the comparison of the length of the surface to be machined (L_w) and the length of the cutting edge (PV). According to the data provided by the manufacturer, the maximum length of the cutting edge is 30mm. This length is long enough to cover the L_w length for the majority of the cases because the lengths of sealing carrier surfaces of shafts are short. However, the case should not be excluded when the L_w length is much longer than the length of the cutting edge; or when the length of the workpiece to be machined surface is much shorter than the projection of the edge. The three possible initial relations can be seen in Fig. 5.

In Row 1a of Fig. 5 we encountered a case when the so-called constant phase is not observable.

At first the chip thickness grows, but it begins to decrease after reaching the maximum value, without occurrence of the constant phase. In Row 1b of Fig. 5, the projection of the cutting edge is equal or slightly higher than the L_w length of the workpiece. In this case, the constant phase comes into existence: thus, there will be a section of the rotation during the slow rotation of the tool where the active length of the cutting edge is constant. In this section, the chip width (b) is also constant.

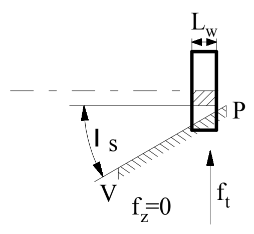
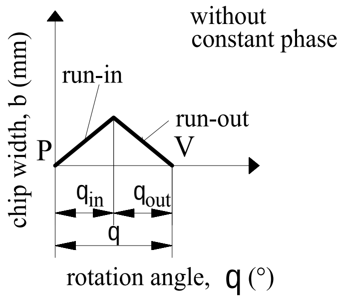
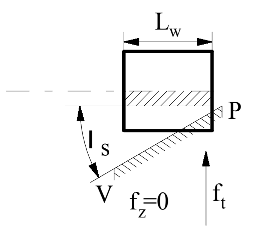
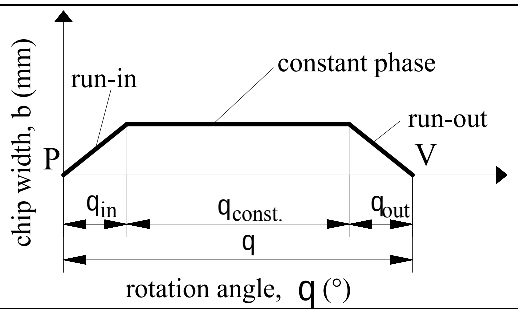
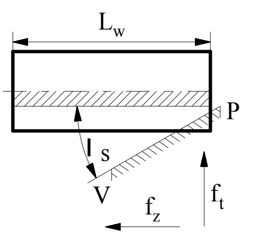
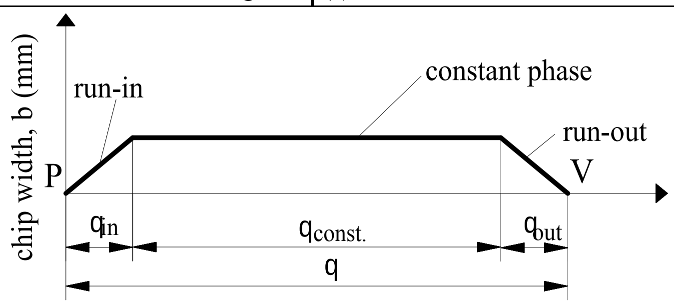
	Sketch	Condition	Alteration of the chip width
1a		$L_w <<< PV \cdot \cos\lambda$	
1b		$L_w \leq PV \cdot \cos\lambda$	
2		$L_w > PV \cdot \cos\lambda$	

Figure 5. Three typical cases of rotational turning. 1: rotational feed: 1.a. without constant phase; 1.b. with constant phase 2. rotational and axial feed (with the constant phase).

In Row 2 of Fig. 5 the projection of the cutting edge is lower than the L_w length of the workpiece. In this case, there must be an additional feed component in direction of the Z axis besides the feed component from the rotation of the tool. Attention must be paid to the fact that the sum of the two feed components should not be higher than the values in the recommendations.

Once the above is taken into consideration the machining time can be determined. The method of calculation can be seen in the algorithm in Fig 6., which has the following steps:

1. Determination of the workpiece rev per minute (n_w [1/min])
2. Calculation of the tangential feed ($v_{f,tan}$ [m/min])
3. Expression of the angular frequency of the tool (ω_t [degrees/sec])
4. Determination of the arch related to the run-in and run-out angles ($\widehat{PP'}$ [mm])
5. Calculation of the run-in and run-out angles (ϑ_{in}, ϑ_{out} [degree])
6. Calculation of the constant phase angle (ϑ_{const} [degree])
7. Expression of the whole angle of rotation (ϑ_{sum} [degree])
8. Calculation of the machining time (t_m [sec])

6 The alteration of the machining time as a function of different parameters

Following the completion of the algorithm presented in Fig. 6., we analyzed the effect of the main parameters to the machining time. From Equation (9) we can see that the machining time depends on the following parameters:

- workpiece diameter (d_w)
- tool diameter (d_t)
- depth of cut (a_p)
- length to be machined (L_w)
- inclination angle (λ_t)
- angular frequency of the tool (ω_t)

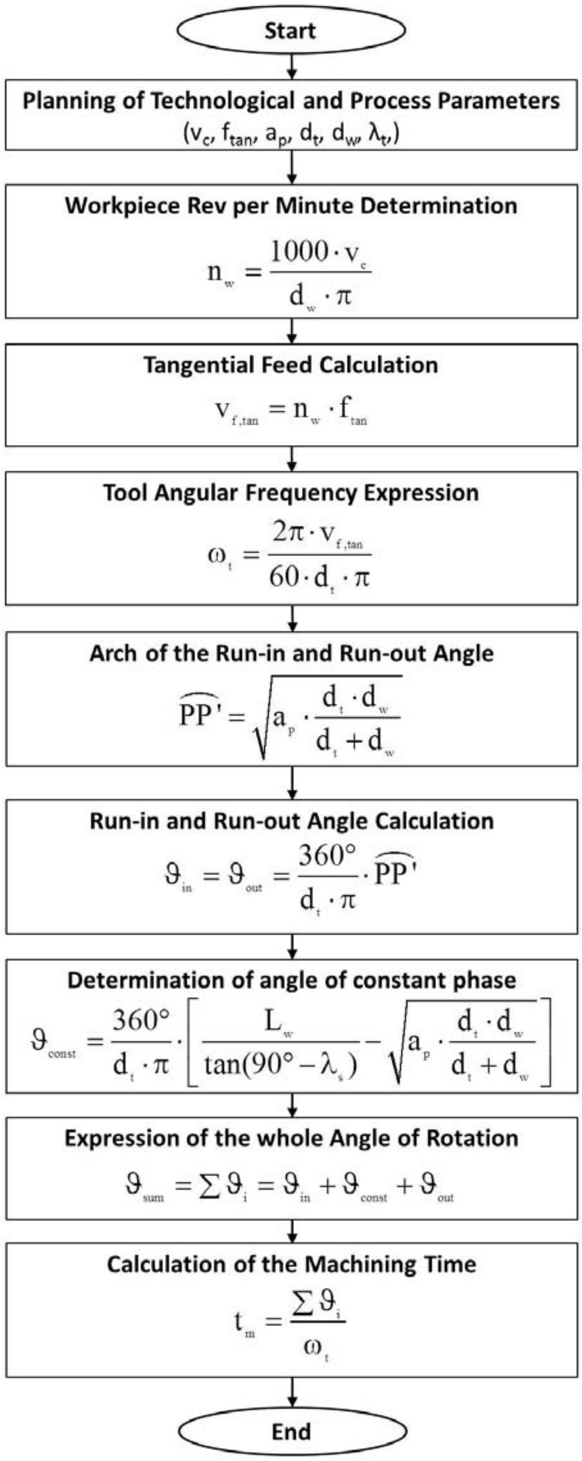
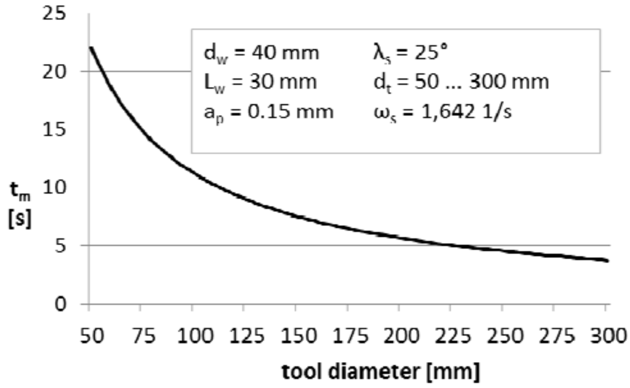


Figure 6. Algorithm of the machining time calculation.

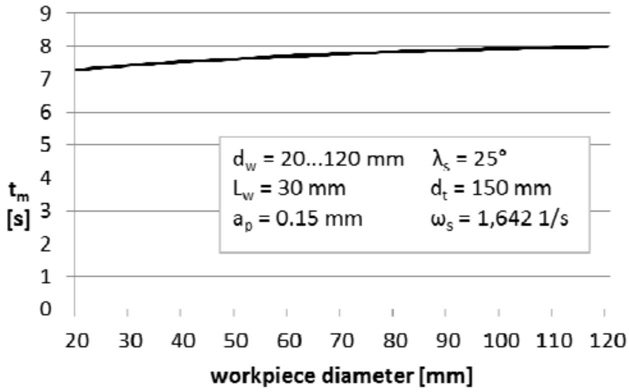
The base parameters values have been chosen from recommendations [16] for the investigation, and we examined the alteration effect of one parameter while the other values remained unchanged. Four diagrams, showing the alteration effect on the machining time, are presented in Fig. 7. The change of the angular frequency of the tool is in inverse ratio to the change of the machining time, as can be seen in Equation (9), and therefore, no diagram is presented for it.

In Fig. 7a, the alteration effect of the tool diameter can be seen. It is observable that if the value of the diameter is lower, the alteration effect on machining time is higher unlike in higher diameter values. In the former case, the curve decreases exponentially, while in the latter case it can be approximated with a linear curve. The reason for the decrease is that the tangential feed increases with the increase of the tool diameter while the angular frequency of the tool remains the same, so the machining time will decrease. On the other hand, it can be stated that the alteration of the tool diameter is more effective for lower values of the diameter if we want to decrease the machining time.

Fig. 7b shows the alteration effect of the workpiece diameter on the machining time. It is observable that the change of this value has little influence on the machining time. A similar conclusion can be drawn from Fig. 7c, which presents the alteration effect of the depth of cut. From Fig. 7b and Fig. 7c comes the fact that an increase in the workpiece diameter or the depth of cut causes a small-scale increase in the machining time.



a)



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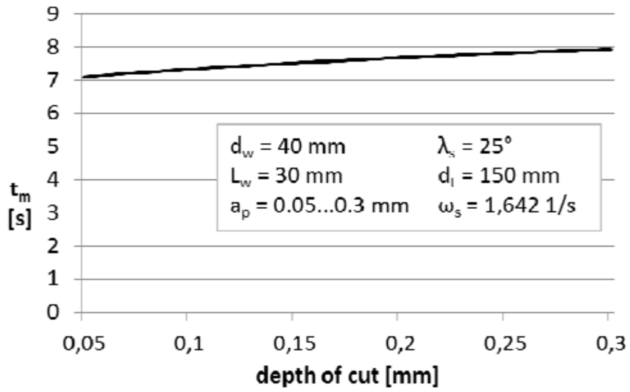
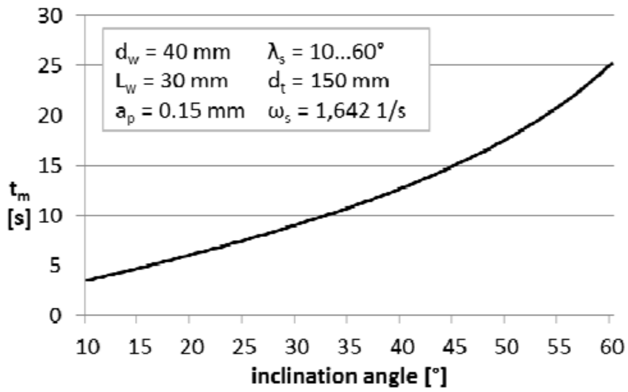


c)



d)

Figure 7. Alteration effects of parameters on the machining time in rotational turning, when a)the tool diameter, b) the workpiece diameter, c) the depth of cut, d) the inclination angle are altered.

However, the alteration effect of the depth of cut in rotational feed turning is interesting because in traditional turning this kind of result cannot be observed (if an increase of the cutting force is allowed at all). The reason for this behavior is the change of the run-in and run-out section length with the alteration of the depth of cut.

In Fig. 7d the alteration effect of the inclination angle can be seen. It can be observed that the increase of the inclination angle leads to an increase in the machining time. The proportionate increase of the needed rotation angle with the increase of the inclinational angle is the reason for this behavior.

Fig. 7d shows that the change is linear till around 30°, and above that it is exponential.
The alteration effect of the workpiece length on the components of the machining time can be seen in Fig. 8, and also the duration of the three main phases (run-in, constant, run-out) within the machining time for different workpiece lengths.
The length of the run-in (and, due to the symmetry, the run-out) phase can be expressed in function of the radius of the tool, (r_t) the angular speed of the tool (ω_t), the inclination angle (λ_t), and the machining time of the run-in section:

$$s_{in} = \frac{r_t \cdot \omega_t}{\tan(\lambda_t)} \cdot t_{in} \qquad (10)$$

In the previously described phase the maximal length of the run-in phase is 4.66 mm. Figure 9 shows that the run-in and run-out phase divide the machining time equally if the length of the workpiece to be machined is lower than the above calculated value. If the length is higher, the time of the constant phase appears while the time of the run-in and run-out phase remains the same. The rate between the constant phase and the run-in/run-out phase constantly increases.

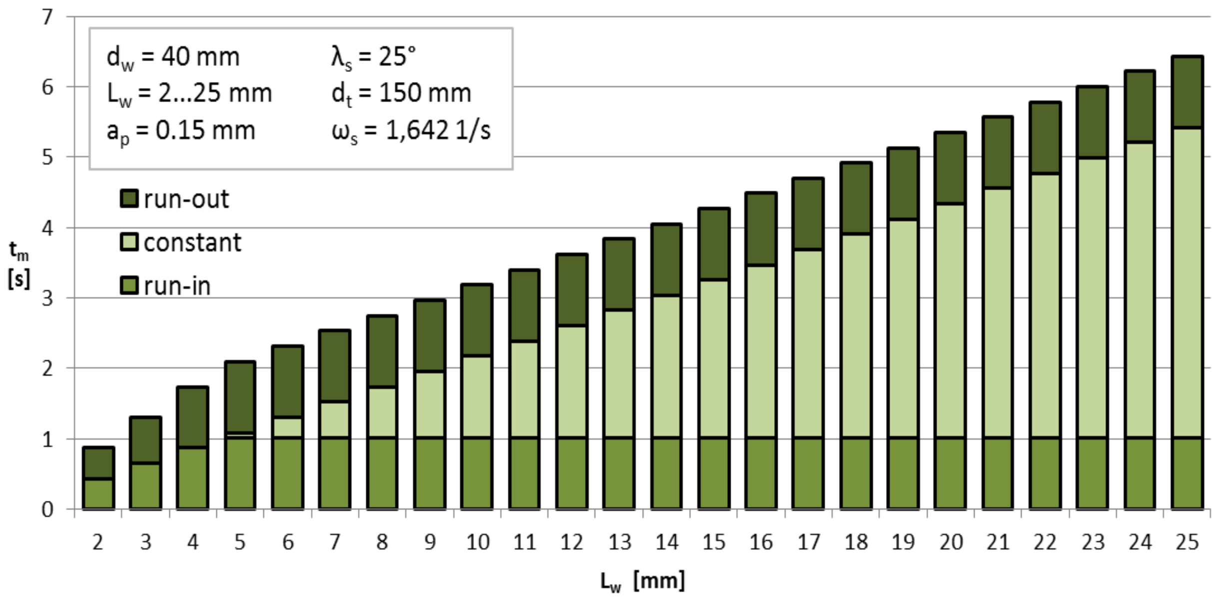


Figure 8. The components of the machining time as a function of the workpiece length to be machined.

It can be stated that the alteration of the machining time in function of the workpiece length is linear. However, the slope of the curve changes with the appearance of the constant phase.

7 Conclusion

The calculation of machining time is seemingly difficult due to the complex characteristics of chip geometry. The easiest calculation e is based on the determination of the needed rotation angle of the tool. All angles related to the run-in, run-out or the constant phase can be simply expressed. Once the angles and the angular speed of the tool are known, the machining time can be calculated.
With this it has become possible to compare rotational feed turning to other hard turning procedures. Rotational turning is a very productive method due to its high material removal rate. The surfaces of bearing seats and sealing can be completely machined in several seconds.
Based on our calculations, we can state that the machining time (which leads to the efficiency) of rotational feed procedure is affected mostly by the diameter of the tool and the inclination angle of the cutting edge along the length of the workpiece to be machined, while the workpiece diameter and the depth of cut have little effect.

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