UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

ANALYSIS OF ROTATIONAL TURNING IN PRECISION FINISH MACHINING

BOOKLET OF PHD THESES

Prepared by:

István Sztankovics
Mechanical Engineer, MSc

ISTVÁN SÁLYI DOCTORAL SCHOOL OF MECHANICAL ENGINEERING SCIENCES
TOPIC FIELD OF ENGINEERING MATERIAL SCIENCE,
PRODUCTION SYSTEMS AND PROCESSES
TOPIC GROUP OF MANUFACTURING SYSTEMS AND PROCESSES

Head of Doctoral School:

Prof. Dr. Gabriella Vadászné Bognár
DSc, Full Professor

Head of Topic Group:

Dr. Zsolt Maros
Associate Professor

Scientific Supervisor:

Prof. Dr. János Kundrák
DSc, Professor Emeritus

Miskolc
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NOTATIONS USED IN THE THESIS BOOKLET

Parameters describing geometric relations

r_s – tool radius [mm]
d_s – tool diameter [mm]
λ_s – inclination angle [°]
d_m – diameter of the machined (finished) surface [mm]
L_m – length of the workpiece [mm]
a_p – depth of cut [mm]

Parameters describing kinematic relations

v_c – cutting speed [mm/min]
f_a – axial feed rate [mm/wp. rot.]
n_s – revolutions of the tool [1/min]
n_m – revolutions of the workpiece [1/min]
$v_{f,t}$ – tangential feed rate of the tool [mm/min]
$v_{s,a}$ – additional axial feed rate of the tool [mm/min]
t – time parameter [s]
$v_{f,i}$ – feed rate of the machine tool resulted from interpolation [mm/min]

Notations used in experiments

X – x axis of the machine tool in the plane of the machine table
Y – y axis of the machine tool in the plane of the machine table
Z – z axis of the machine tool perpendicular to the plane of the machine table
M – workpiece
S – cutting tool
$\mathrm{K_m}$ – workpiece fixture
$\mathrm{K_s}$ – cutting tool fixture
R13 – cutting tool with 13.45° inclination angle
R15 – cutting tool with 15° inclination angle
R30 – cutting tool with 30° inclination angle
R45 – cutting tool with 45° inclination angle
R50 – cutting tool with 50° inclination angle
CNMG – cutting tool used for longitudinal cutting
F – cutting force [N]
F_x – X directional force [N]
F_y – Y directional force [N]
F_z – Z directional force [N]
Ra – Arithmetic Mean Roughness [μm]
Rz – Average Peak-to-Valley Roughness [μm]

1 INTRODUCTION

In the first chapter, the place of rotational turning is presented among the circular feed procedures. I describe the requirements of research and development. The objectives of the dissertation are identified based on the literature review.

1.1 Scientific background

Rotational turning [1] is a patent of the German machine tool manufacturer J.G. Weisser Söhne GmbH & Co. KG [2], for which the special tools were produced by MAS GmbH [3]. It can be considered as a combination of coaxial turn milling and skiving turning [4]. A surface topography can be achieved by this procedure that meets the strict requirements for precision machining, making it an alternative to grinding [5], thus reducing production chain lengths [6]. The process of chip formation can be compared to diagonal cutting [7]. The type of chip and its angle of movement on the rake plane depend on technological and material structural properties [8], yet chip formation is continuous due to constant material removal.

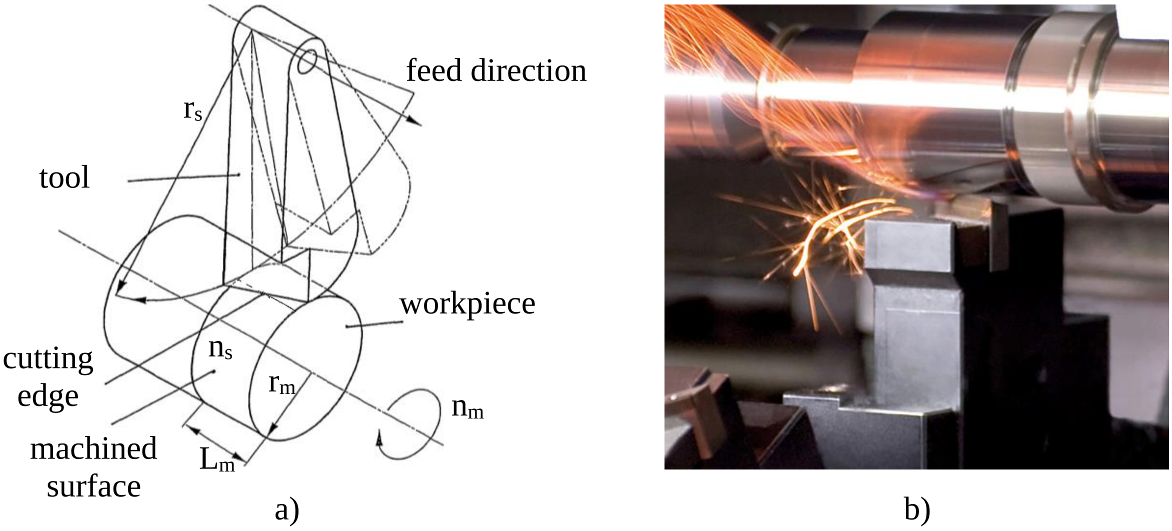

Figure 1.1. Kinematics of rotational turning (a) [1] and its tooling (b) [2]

Geometric and kinematic relations of rotational turning are presented based on Figure 1.1. The most important feature of the procedure is the design of the applied tool and the resulting non-conventional kinematic conditions. The cutting edge has a helical geometry whose centre line is parallel to the axis of the workpiece rotation. The tool performs circular feed for surfaces shorter than the tool edge length and a combination of circular and longitudinal feed for longer surfaces. The cutting speed is the peripheral speed of the rotating workpiece. The depth of cut can be adjusted by the alteration of the axle distance between the tool and workpiece. The active edge section moves along the helical edge during cutting.

Among Hungarian researchers, Kundrák et al. determined the approximate value of the required angular rotation based on the characteristic edge positions in the reference plane and in the normal section of the tool and the workpiece, then analysed the productivity of the procedure [9]. They showed that rotational turning can be a realistic alternative to hard turning in the machining of hardened surfaces. Derived from the geometric analysis, the influencing role of the minimal removable chip thickness was pointed out based on the high value of the chip width and thickness ratio [10].

A relatively low number of publications are available in the international literature about rotational turning, and their aim is mainly the research of surface quality. To determine the theoretical roughness, Klocke et al. proposed a calculation method in which the reference plane projection of the cutting edge is approximated by a circle, thus tracing back the procedure to longitudinal turning with radial insert [4]. They found in their experimental work that the increasing feed leads to a more significant effect of the edge geometry. The calculated values follow the measured values correctly with the increase of the feed; however, the calculations resulted in 60% less value on 0.4 mm feed and 20% less value on 1.0 mm feed. Degen et al. found in their research, that significantly (10 – 15 times) lower roughness can be achieved with rotational turning compared to hard turning [11]. However, they experienced high tool vibrations due to the low chip thickness. For the calculation of the total height of roughness profile, Šajgalík et al. analysed the reference plane projection of the helical cutting edge and they approximated it by trigonometric functions [12]. Based on the result they calculated the peak height of the machined surface profile. Martikan et al. showed their custom-designed conventional lathe-mounted driven tool holder, which can provide the circular feed needed for rotational turning [13]. From the experiment, Mrazik et al. [14] found that the workpiece hardness has a significant role on the accuracy of the determined roughness calculation method by Šajgalík et al. [12]. They experienced 97% accuracy on 50HRC hardness, 61% accuracy on 40 HRC hardness and 27% accuracy on 60 HRC hardness. They proposed further research to make this equation more accurate.

Rotational turning can provide an answer to some of the questions of machining with a defined cutting edge, making it possible to perform tasks that currently are difficult to achieve in part finishing. Meeting the requirements of productivity and surface quality at the same time is a challenge, as reducing production time usually leads to a deterioration in surface parameters, and vice versa. In addition, other requirements prescribed on part drawings must be met, such as different accuracy or operational requirements. The application of longitudinal turning is limited by shape accuracy in machining hard surfaces of long, slender shafts, for example. During machining of these parts, high passive forces act on the workpiece due to the applied negative rake angles, thus a significant elastic deformation occurs in the machining system. Due to this buckling effect, it is not possible to machine shafts with high length/diameter ratio by longitudinal turning with single point cutting tools and grinding is required. In addition, operational requirements include maintaining the degree of twist-structure on the machined surface below a specified level. This requirement occurs on surfaces where the helical periodic topography on the surface is a problem (sealings, active surfaces of needle roller bearings, synchronising cones of gearboxes).

1.2 Aims of the dissertation

The aims of my dissertation are to carry out a theoretical and experimental study of finishing with rotational turning and to analyse surfaces of produced parts, as well as to increase efficiency and accuracy by the evaluation and accurate determination of unexplored or less explored areas of chip removal. The research is done in the following steps:

- Finding the accurate analytic equation of the machined surface based on method of the constructive tool geometry.
- Determining the equation needed to calculate the characteristic parameters of the chip cross-section and the effect analysis of the affecting parameters on the theoretical values.
- Providing the equations needed for the calculation of material removal rate, and investigating the effect of the cutting date and edge geometry.
- Carrying out experiments on the major cutting force, feed force and passive force in machining with different cutting data and edge geometry.
- Analysing theoretically the roughness and twist characteristics of the machined surfaces and studying the effect of kinematic and geometric parameters.
- Studying the surface roughness in function of the cutting data in experiments.
- Determining the correlation between the theoretical and experimental values of surface roughness.

Figure 1.2. shows the research steps of rotational turning and the evaluated parameters. The expected results are the more precise definition of the chip removal in rotational turning and the determination and analysis of the parameters that affect the technological process, but not yet identified scientifically.

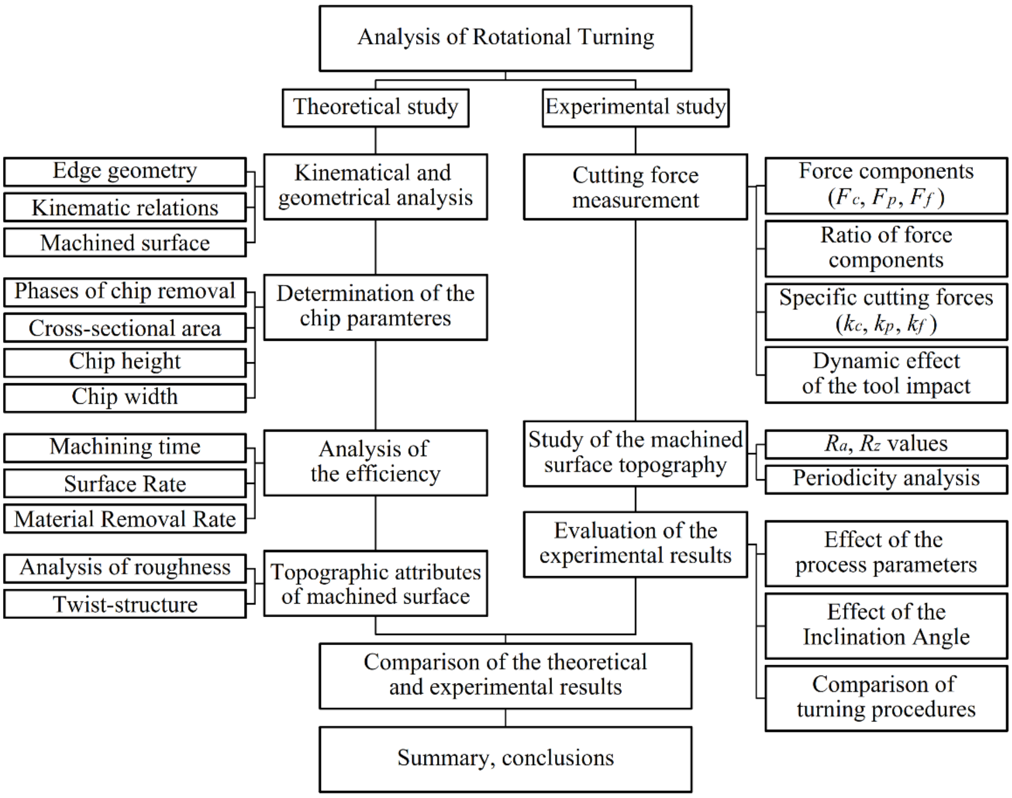

Figure 1.2. Research steps

2 RESEARCH METHODS AND CONDITIONS

I intend to achieve the stated aims though theoretical and experimental studies. The applied mathematical method and the analysis process are presented in this chapter, as well as the purpose and conditions of the experiments.

2.1 Method and process of theoretical research

I reviewed the solutions applied for different machining procedures that consider the geometrical and kinematic characteristics for the mathematical description and exact determination of rotational turning, taking into account the helical cutting edge and complex kinematic relations. The geometrical and analytical tools of mathematics have long been used in design and process planning to describe special cases of connection. Litvin's work [15] is considered a fundamental work for the determination of part surfaces in the international literature. In his description, complex surfaces can be easily determined in practice by the combined application of differential geometry and kinematic method. Perepelica described a method [16] that is suitable for not only the mathematical analytical description of shaped tools [17], but also for determining the geometrical conditions in cutting using affine geometry [18]. The vector of the cutting speed can be determined among other parameters, with the description of the cutting edge motion [19].

Numerous Hungarian-related studeis have also been published on the application of the kinematic method in recent decades. Szeniczei is one of the initial researchers on worm gear drives and was one of the first to propose the use of conjugated surface pairs [20]. Tajnafői, using his own derivation theory, introduced new design methods for the generation of machine tool structure variants [21]. Lévai analysed the gear machining issues of skew-axes gear drives [22]. Drobni studied the theory of curved profile and globoid worm gear drives, achieving significant results for grindable globoid worm gear drives [23]. Drahos analysed the manufacturing geometry of different tool geometries and helical surfaces [24]. Bercsey determined the connection conditions of globoid gear drives based on the kinematic method [25] and analysed the toroidal drives [26]. Dudás studied the curved profile worm gear drives on kinematic basis [27] and developed the production theory of helical surfaces [28]. He also developed a general mathematical model for the description of worm gear drives and the geometrical relations between the worm and the wheel [29]. Balajti developed a new kinematics-based mathematical description that allows the tracking of conical worm shapes [30]. Research has been initiated to apply the Monge projection to describe the mathematical model [31].

It is possible to solve various design and technological problems by the application of kinematic based mathematical description. Researchers have developed and applied methods of connection theory, motion geometry, tool geometry and production geometry. In my dissertation, I applied the method of constructive tool geometry (which uses the multiparameter mapping of the affine space) for the mathematical description of rotational turning and the analytical determination of the machined surface.

The following steps were carried out in my research work for the mathematical-analytical description of rotational turning:

- definition of the required number and positional coordinate-systems;
- interpretation of the transformations between the coordinate-systems;
- specification of the cutting edge vector-function;
- mathematical determination of the machined surface generated on the workpiece from the geometrical and kinematic relations.

I determined and analysed the attributes of rotational turning during the theoretical study. Based on the equations resulted by the analytical determination, the effect of the geometrical and kinematic parameters is evaluated for the discussed parameters of rotational turning (study range: n_m = 800 – 2400 revolutions/min., n_s = 1 – 3 revolutions/min., $v_{s,a}$ = 0 – 8 mm/s, d_m = 20 – 60 mm, r_s = 20 – 60 mm, λ_s = 15 – 45°).

I defined the phases of chip removal for the analysis of the geometrical attributes of the chip to be removed. From the equation of the machined surface, I determined the equation of the chip width using arc length calculation, then expressed the equation of the equivalent chip thickness using the cross-sectional area of the chip.

The efficiency of the chip removal is analysed by the determination of the machining time, the material removal rate and the surface rate. The angular movement of the tool, the axial work path and the cutting time are determined for the three phases of chip removal by the evaluation of the boundary conditions written for the mathematic model.

The description of the machined surface topography in rotational turning is carried out by the determination of the theoretical values of roughness and twist-structure. Using the equation of the projection of the machined surface in the base plane, I determined the Arithmetic Mean Roughness, the Average Peak-to-Valley Roughness, the Period Length, the Twist Angle and the Twist Depth.

2.2 Cutting experiments

Experiments are carried out with rotational turning for the determination and analysis of the cutting forces and surface roughness. The study was carried out using the machine and device park of the Institute of Manufacturing Science at the University of Miskolc. I describe the cutting conditions, the devices for force and roughness measurement and the applied methods.

2.2.1 Experimental conditions

The characteristic kinematic relations of the procedure are realised by a Perfect-Jet MCV-M8 machining centre. This machine has the necessary power and stiffness for the experiments, and the force measurement device of the Institute can be also mounted on it. 5% emulsion of Rhenus TS 25 coolant and lubricant is used during the machining.

The experiments were done on normalised C45 steel workpieces with 220 HV hardness, 12 mm length and 40 mm diameter. The length of the workpiece was chosen according to the geometrical data of the applied cutting tools.

Five tools with five kinds of inclination angles were used in rotational turning. The turning tools are shaped from the multi edged tools by the removal of non-active edged with grinding. The abbreviations of the applied tools: *R13* [32], *R15* [33], *R30* [34], *R45* [35] and *R50* [36]. I also carried out longitudinal turning with an insert tool [37] for the comparison of the results.

The kinematic relations of the experiment are shown in Figure 2.1. The revolutions of the workpiece (n_m) are realised by the clamping of the experimental piece (M) into the spindle of the milling machine (K_m). The cutting tool (S) is fixed into the fixture (K_s) placed on the machine table with an ER32 taping collets. The circular interpolation movement ($v_{f,i}$) of the tool along with the table around the spindle resulted in the necessary circular feed (“n_s”). Figure 2.2. shows examples for the tool positions in case of R15, R30 and R45.

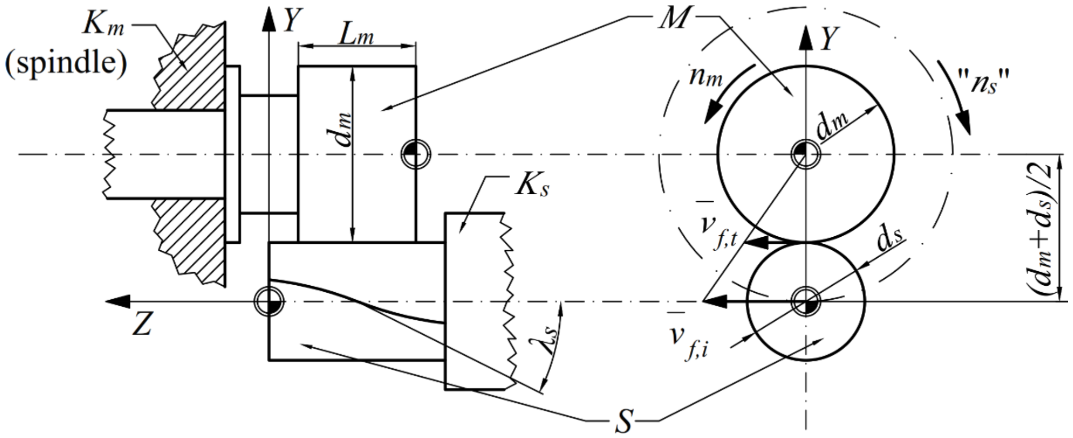

Figure 2.1. Relative position and movements of the tool and the workpiece


R15 *R30* *R45*

Figure 2.2. Cutting tools on the Force Measurement platform

The process parameters were chosen so that the effect of high feeds could be analysed in rotational turning, taking into consideration the tool geometry constraints. The studied feed ranges of the selected tools were the followings: 0.2 – 2.8 mm/wp.rev. for *R13*, 0.1 – 2.8 mm/wp.rev. for *R15*, 0.1 – 1.6 mm/wp.rev. for *R30*, 0.1 – 1.0 mm/wp.rev. for *R45*, 0.1 – 0.8 mm/wp.rev. for *R50* and 0.1 – 1.0 mm/wp.rev. for *CNMG*. Purely circular feed was adjusted for rotational turning. Three depths of cut (0.1 mm, 0.2 mm, 0.3 mm) were used for each feed. The experiments were carried out at three cutting speeds: 200 m/min, 250 m/min and 300 m/min for *R13, R15* and *CNMG*; 150 m/min, 200 m/min and 250 m/min for *R30, R45* and *R50*.

In summary, the studied ranges of the cutting data were: f_a = 0.1 – 2.8 mm/wp.rev., a_p = 0.1 – 0.3 mm, v_c = 150 – 300 m/min and λ_s = 13.45 – 50°.

2.2.2 Cutting force and surface roughness measurement

The applied measurement equipment can be seen in Figure 2.3. During the cutting experiments, I measured the cutting forces by a Kistler 9257A Three-Component Dynamometer, which was built in between the cutting tool and the machine table. The device recorded at every point in time three force components (F_x, F_y, F_z) acting in axes perpendicular to each other. Three Kistler 5011 Single-channel Charge Amplifiers transformed the output signals (generated by the force measurement device operating by piezoelectric principle) into voltage values, which were transmitted to the data processing computer by a NI-9215 Analog Input Module with a cDAQ-9171 casing made by National Instruments. The data was read with 1000 Hz sampling frequency displayed and saved by the NI Labview software for further analysis.

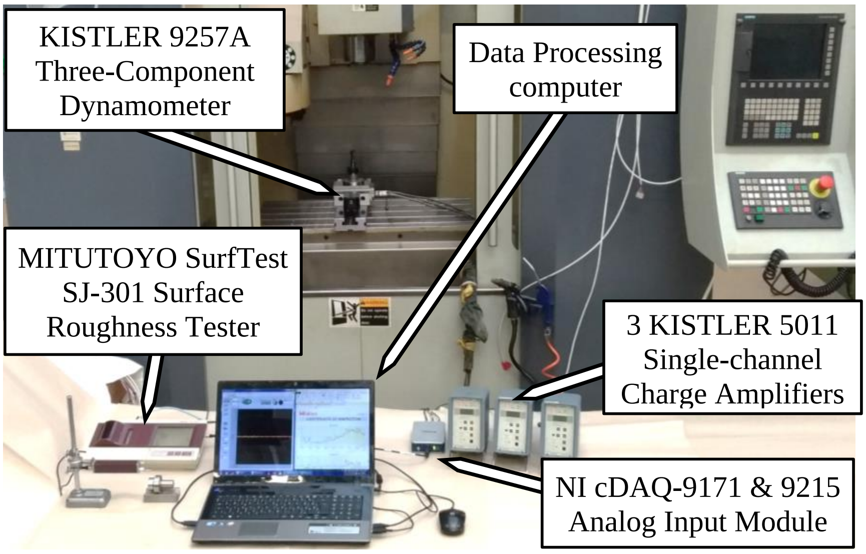

Figure 2.3. Cutting force and roughness measurement system

The cutting force measurement system recorded the *X*, *Y* and *Z* directional forces at every point in time during the experiments. The corresponding F_c, F_p and F_f forces in the tool coordinate system were calculated from the F_x, F_y and F_z forces in the machine coordinate system by the constantly changing relative position of the tool and workpiece. I determined and analysed the maximal values of the resultant $F_c(t)$, $F_p(t)$ and $F_f(t)$ curves, by which the constant cross-sectional cutting phase was characterised. Specific cutting forces of the F_c, F_p and F_f forces were calculated and compared. I studied the dynamic load on the cutting tool during the run-in phase.

I analysed the surface topography with measurements on the machined surfaces by a Mitutoyo SurfTest SJ-301 Portable 2D Surface Roughness Tester and an AltiSurf® 520 roughness measurement device. The 2D measurements were done on three generatrix of each surface. Surface roughness measurements were done to 1 setup for each tool in a 4 mm x 4 mm area. Cut-off length was adjusted according to the standard [38] for the different feeds as the following: 0.25 mm cut-off length at 0.1 mm/wp.rev., 0.8 mm cut-off length at 0.2 – 0.4 mm/wp.rev., 2.5 mm cut-off length at 0.6 – 1.2 mm/wp.rev. and 4 mm cut-off length at 1.6 – 2.8 mm/wp.rev. The Arithmetic Mean Roughness (R_a) and Average Peak-to-Valley Roughness (R_z) were analysed from the measured roughness values. Mean values of the three measurements were calculated for each setup. I studied the measured values as a function of the feed and tool geometry. The theoretical values of R_a and R_z were also calculated and compared to the experimental values.

3 NEW SCIENTIFIC RESULTS, POSSIBILITIES OF APPLICATION

Rotational turning implements a relatively novel application of circular feed. My research work has provided the answers to the questions expressed in the aims, in topics which had not been explored so far or were not worked out with sufficient depth. The most important conclusions that can be drawn from my study are summarised in the following theses. I present the possibilities of further development of my research work as part of the chapter.

3.1 Theses

T1. Based on constructive tool geometry modelling, I revealed the general correlations of rotational turning and I developed a mathematical-analytical model of the procedure as a function of the different kinematic and geometric parameters (*in the case of parallel workpiece and tool axes, circular and axial feeds, and a helical tool edge with constant pitch and radius*). I determined the two-parametric system of equations for the machined surface using the model.

T2. I have given the mathematical relationships for the calculation of chip width, equivalent chip thickness, angular rotation of the tool, axial path, machining time, surface rate and material removal rate as a function of the kinematic and geometric parameters for the three phases of rotational turning. I analysed the alteration of the theoretical values as a function of the technological and geometric characteristics with these equations *(study range:* $n_m = 800 – 2400$ *revs/min,* $n_s = 1 – 3$ *revs/min,* $v_{s,a} = 0 – 8$ *mm/s,* $d_m = 20 – 60$ *mm,* $r_s = 20 – 60$ *mm,* $\lambda_s = 15 – 45°$*).*

T3. I have assembled a measuring system suitable for measuring the forces acting in rotational turning. Based on the experimental work, I found that by using rotational turning the radial (passive) force between the tool and the workpiece can be reduced to 50% with $\lambda_s = 30°$, 40% with $\lambda_s = 45°$ and 35% with $\lambda_s = 50°$ compared to longitudinal turning, and the dynamic load on the tool during its initial contact can be reduced to 15% for these geometries *(experimental conditions: quenched C45 steel grade,* $f_a = 0.1 – 2.8$ *mm/wp.rev.,* $a_p = 0.1 – 0.3$ *mm,* $v_c = 150 – 300$ *m/min;* $\lambda_s = 13.45 – 50°$*).*

T4. I determined the theoretical roughness profile in the reference plane using the developed model for rotational turning, and I gave the equations for the calculation of the theoretical values of Arithmetic Mean Roughness, Average Peak-to-Valley Roughness, and twist parameters. I analysed the effect of the characteristic parameters on the theoretical values of the Arithmetic Mean Roughness and Average Peak-to-Valley Roughness and I found that to halve the values of Ra and Rz by varying the examined parameters individually, 29% lower tool rotations, 35% lower tool radius, 87% lower additional feed and 40% higher workpiece revolutions are needed *(study range:* n_m *= 800 – 2400 revs/min,* n_s *= 1 – 3 revs/min,* $v_{s,a}$ *= 0 – 8 mm/s,* d_m *= 20 – 60 mm,* r_s *= 20 – 60 mm,* λ_s *= 15 – 45°).*

T5. I proved with experiments that at fixed feed the Arithmetic Mean Roughness and Average Peak-to-Valley Roughness of the surface machined by rotational turning will be lower (as a function of the inclination angle) compared to longitudinal turning, by 2.5 – 5.5 times in the experimental range. The same surface roughness can be achieved in rotational turning by 2 – 6 times higher axial feed. *(experimental conditions: quenched C45 steel grade,* f_a *= 0.1 – 2.8 mm/wp.rev.,* a_p *= 0.1 – 0.3 mm,* v_c *= 150 – 300 m/min;* λ_s *= 13.45 – 50°).*

T6. I determined the correlation in parametric power exponent form between the theoretical and experimental values of the Arithmetic Mean Roughness and Average Peak-to-Valley Roughness in rotational turning and I determined the parameter values of the equation in the examined range *(experimental conditions: quenched C45 steel grade,* f_a *= 0.1 – 2.8 mm/wp.rev.,* a_p *= 0.1 – 0.3 mm,* v_c *= 150 – 300 m/min;* λ_s *= 13.45 – 50°).*

3.2 Possibilities of applications and further development

The research results presented in the dissertation are suitable for industrial purposes and for further investigation of rotational turning. From the utilization possibilities of the study, I would like to highlight that the obtained results allow the accurate determination of the theoretical roughness values of the machined surfaces, the geometrical characteristics of the chip cross-section, the machining time, the material removal rate and the surface rate. Due to the previously applied simplifications, the data in the international literature related to the procedure did not assist much in the development of the tool production and technological conditions that would allow the advantages provided by rotational turning to be utilised and the efficiency of the created solutions to be further increased. The development and optimal design of the tool geometry are enabled by the developed correlations and equations. The complex effect of altering each parameter can be determined based on the analysis presented in the dissertation.

I proved with the published solutions and experimental results that the machining efficiency of shaft-like parts can be increased by improving the (geometric) accuracy achieved through reducing the passive force, and the generation of favourable roughness values can be ensured with increased feed. The application of the procedure is also recommended in machining of difficult-to-machine materials.

The results can be further developed in several directions. The mathematical model can be further developed to study the machining of conical and flat surfaces by rotational turning, as well as to analyse the characteristics that determine the process of chip removal.

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