RIGA TECHNICAL UNIVERSITY

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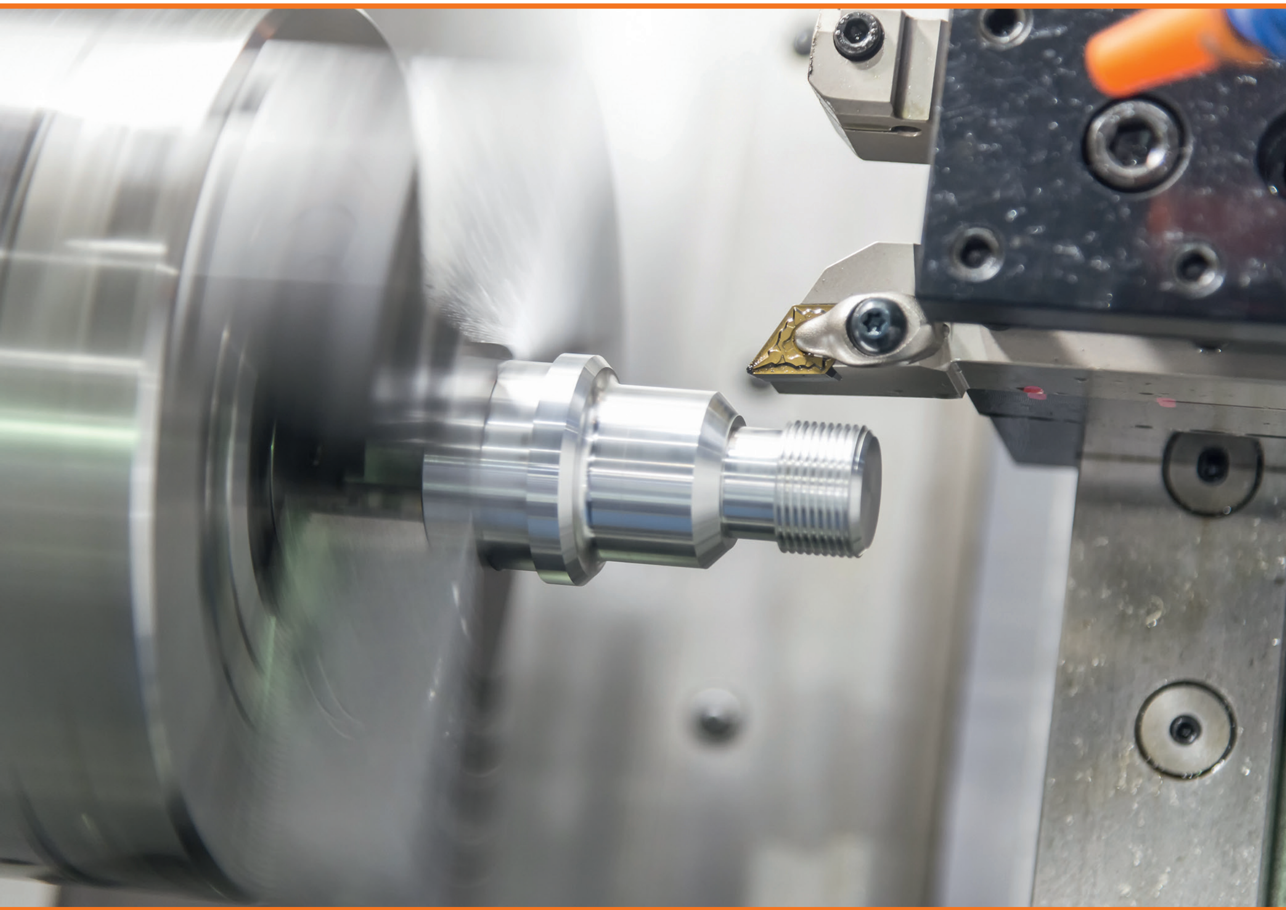
PRECISION OF STAINLESS STEEL TURNING PROCESS DEPENDING ON AL_2O_3 NANO-COATED CUTTING TOOL WEAR

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Mechanics and Mechanical Engineering

Viktors Gutakovskis

Doctoral Student of the Study Programme "Production Technology"

PRECISION OF STAINLESS STEEL TURNING PROCESS DEPENDING ON AL_2O_3 NANO-COATED CUTTING TOOL WEAR

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 22 February, 2023 at 16.00 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Kipsalas Street, Room 417.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Viktors Gutakovskis............................ (signature)
Date:...........................

The Doctoral Thesis has been written in Latvian. It consists of Introduction, 4 chapters, Conclusions, 66 figures, 17 tables; the total number of pages is 130. The Bibliography contains 100 titles.

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GENERAL CHARACTERISTICS OF THE THESIS

Actuality of the topic

Along with the increase in the use of stainless steels in the world, the application of new processing technologies and instruments, as well as the development of materials and coatings of cutting tools, the research and prediction of the distribution of wear and temperature fields has become relevant. It is important to study the modes of the processing process and their effect on the result. Since stainless steel itself is a strong and difficult-to-process material and contains several alloying elements, which in turn complicate processing and cause significant inconvenience in the chipping process (chips must be broken, sharpened) because these alloying elements increase the plasticity and hardness of the steel, which in turn creates difficulties for processing by cutting. As a result, we get flowing chips, which is not acceptable in modern automated production of large series of parts, so it can be concluded that the study of the chip formation process is very relevant. One of the problems is that tools from different manufacturers for the same material group will give different quality of the turned surface. In the turning process, the influence of factors such as the structure of different workpiece materials can lead to an invalid machining result. In this case, AISI 304 and AISI 420 stainless steels with martensite and austenite structure were compared. For the first time, the wear-resistant nano-coating with Duratomic technology has been studied at increased cutting speeds and other variable machining regimes that normally affect the machining result. This coating is characterized by higher wear resistance.

In the Theis, the main elements of the machining process are investigated – the chip formation process, the temperature field distribution in the cutting tool blade, vibrations and tool wear. These elements, together with the difference in material structures, have a serious impact on the result of the turning process. The mathematical model (equation) of the turning process for several processing modes and materials has been developed with the help of n-factor experiments. In the conducted experiments, the results that represent the effect of cutting modes on the final result are clearly visible. It has also been established that the tools of different manufacturers, which are intended for identical processing operations, do not provide the required result of a processed surface. An actual problem is the study and improvement of the influence of analog tools on the machining process and the machined surface. Therefore, the topic of the chosen Doctoral Thesis is relevant.

Aim and objectives of the Thesis

The aim of the Doctoral Thesis is to investigate the accuracy of the stainless steel turning process depending on the wear of Al_2O_3 nano-coated cutting tools. This will make it possible to find out the effect of increased technological processing parameters (cutting speed, feed and cutting tool setting angle) on the turning result of the machinability of two stainless steels (AISI 420 and AISI 304) – ferrite and martensite structure – the surface roughness parameter R_a,when using new cutting tools covered using Duratomic-technology, compare it to these applied tools and develop a mathematical model for determining the roughness (R_a) of a processed surface.

To achieve the goal of the Doctoral Thesis, the following tasks have been determined:

- to perform a comprehensive analysis of selected processing technologies and applied tools;
- to perform turning process experiments and analysis of the results, clarifying the dependence of the roughness (R_a) of the turned surface on increased processing modes: cutting speed, feed and cutting blade setting angle;
- to compare the results of the turned surface of two stainless steel grades – AISI 420 and AISI 304;
- to develop mathematical models of the turning process technology for determining the surface roughness (R_a) and to compare it with the experimental results;
- to compare the influence of tools produced by different manufacturers when processing blanks of two stainless steel grades (AISI 420 and AISI 304) at increased cutting speeds;
- to perform an analysis of the tool wear mechanism using increased processing modes;
- to perform an analysis of the chip formation process using increased cutting speeds.

Hypothesis

By accepting the set R_a value of the surface roughness of the turned part, it is possible to create models of cutting tools coated with the wear resistant Duratomic technology for the turning process, which allows to choose the technologically achievable processing modes according to the set surface roughness: cutting speed, feed or cutting tool setting angle.

Research methodology

To achieve the set goal and fulfill the given tasks, the following research methods were applied in the process of developing the Doctoral Thesis: before the practical experiment, a simulation of the turning process was carried out using the analysis of the finite element method (FEM). A lathe, an AISI 304 stainless steel workpiece with an austenitic structure, and an AISI 420 stainless steel workpiece with a martensitic structure were used to realize the experimental part. The new cutting tools of *Seco*, *Walter*, *Sumitomo*, and *Kennametal* were used, which are characterized by a wide application area for various stainless steel brands and structures. Data processing of the R_a value results of the processed surface roughness profile obtained in the practical experiment was carried out with the help of a computer, implementing a 3-factor experimental plan.

The software used

The selected software provides the opportunity to numerically model the metal cutting process, taking into account the combination of coatings of the cutting tool and their thickness. Computer modeling of the turning process was carried out in collaboration with Aalto University, Finland, using the *Third Wave AdvantEdge* program, in which the turning process with different combinations of machining modes was simulated using FEM for the two steel grades.

Scientific novelty

The following studies wer done for the first time:

1. The precision of the turning process of stainless steel has been investigated depending on the wear of cutting tools with Al_2O_3 nano-coating.
2. A numerically modeled turning process of AISI 304 and AISI 420 stainless steels has been created by processing them with increased cutting speed without cooling, creating an accurate chip breaker geometry of cutting tools, applying a new finite analysis method software *Third Wave AdvantEdge* taking into account the thicknesses of coatings of cutting tools and their combinations. TM4000 Duratomic coating data was obtained directly from the manufacturer during a site visit. As a result, the values of minimum

cutting temperature of 700 ºC and the maximum temperature of 1150 ºC without cooling emulsion and their distribution in the cutting area and in the cutting tool were determined.

3. The R_a value of the roughness of the processed surface in the turning process has been determined depending on the processing parameters – cutting speed, feed, cutting tool setting angle, and tool wear.
4. Several mathematical models for predicting machining parameters characterizing the turning process have been developed, which allow choosing machining modes according to the set surface roughness (R_a): cutting speed, feed or cutting tool setting angle for two grades of stainless steels AISI 304 and AISI 420 with different structures.
5. Using models, it was demonstrated how the mathematical model of the machining process changes depending on the increase in cutting speed.

The theses of the research presented for defense

1. The results of stainless steel turning accuracy test depend on the wear of Al_2O_3 nano-coated cutting tools.
2. A numerically modeled turning process of AISI 304 and AISI 420 stainless steels was created by processing with increased cutting speed without cooling, creating an accurate chip breaker geometry of cutting tools, applying a new analysis software of the finite element method (*Third Wave AdvantEdge*), considering the thicknesses of the coatings of cutting tools and their combinations. It is determined that the cutting temperature values range from a minimum of 700 ºC to a maximum value of 1150 ºC without cooling emulsion. Also the distribution of the cutting temperature field in the cutting zone and the tool was modeled.
3. The R_a value of the surface roughness of the turning process depends on the processing modes – cutting speed, feed, wrapping angle, and tool wear.
4. Several mathematical models for predicting machining parameters characterizing the turning process, which allow choosing technological machining parameters according to the surface roughness (R_a): cutting speed, feed or cutting tool setting angle for two grades of stainless steels AISI 304 and AISI 420 with different structures.
5. By applying the models, it was demonstrated how the mathematical model of the machining process changes depending on the increase in the cutting speed.

Practical application

- The results of the given research are necessary for the needs of *Seco Tools AB* instrument manufacturers and the local representatives of this company.
- The experimental data have been used in the publications of several scientists and in the development of doctoral theses (as evidenced by the citation data).
- Cutting tools coated with Duratomic technology have been proven to last longer than described in catalogues, creating great potential for increased productivity.
- The results of the present Thesis can be applied in the development of the next generation tools and technological processes, in the development of the production process within the framework of Industry 4.0, by applying the adaptive numerical control processing process monitoring, reading the processed surface values, and making corrections to improve it by applying mathematical models.
- Scientific articles written during the development of the Doctoral Thesis have been cited in the publications of several scientists and in doctoral theses.

Approbation of the results

The main results of the Doctoral Thesis were presented at the following conferences:

1. 6th ICCSM International Congress of Croatian Society of Mechanics, Sept. 30 – Oct. 2, 2009, Dubrovnik, Croatia.
2. 7th International DAAAM Baltic Conference "Industrial Engineering", 22–24 April 2010, Tallinn, Estonia.
3. 16th International Conference "Mechanika-2011", 6–9 April 2011, Kaunas, Lithuania.
4. 10th International conference Vibroengineering – 2011, October 13-14, Kaunas, Lithuania.
5. 8th International DAAAM Baltic Conference "Industrial Engineering", 19–21 April 2012, Tallinn, Estonia.
6. 17th International Conference "Mechanika-2012", 7–8 April 2012, Kaunas, Lithuania .
7. 9th International DAAAM Baltic Conference "Industrial Engineering", 24– 26 April 2014, Tallinn, Estonia.

8. 12th International Conference "Mechatronic Systems and Materials 2016", Bialystok, Poland.
9. 17th International Conference "Mechanika-2019", 7–8 April 2012, Kaunas, Lithuania.
10. Industrial Engineering-2019, 7–8 April 2012, Kaunas, Lithuania.
11. 28th International Baltic Conference Materials Engineerig and Modern Manufacturing 2020, 22–23 October 2020, Kaunas, Lithuania.
12. 32nd DAAAM International Symposium, 28–29 October 2021, Vienna, Austria.
13. APMAS 2021, 11th International Sdvances in Applied Physics & Materials, 17–23October 2021, Turkey.
14. 21st International Scientific Conference Engineering for Rural Development, 25–27 May 2022, Jelgava, Latvia.

List of scientific publications

1. Gutakovskis, V., Bunga, G. "Turning with high feeding", Proceedings of the 2009 6th ICCSM International Congress of Croatian Society of Mechanics ISBN 978-953-7539-11-5, Book of abstracts, 156 p, 2009.
2. Gutakovskis, V., Bunga, G., Niemi, E., Laakso, S. "Finite element method modelling of the stainless steel cutting process using different machining" RTU Scientific Journal, TMF, 6. sērija, 31. sējums, RTU Izdevniecība, 51.–55. lpp., 2009. g.
3. Gutakovskis, V., Torims, T., Bunga, G. Stainless steel machining with nanocoated Duratomic cutting tools, Proceedings of the 7th International DAAAM Baltic Conference "Industrial Engineering", 22–24 April 2010, Tallinn University of Technology, Tallinn, Estonia, pp. 171–176.
4. Gutakovskis, V., Bunga, G., Pikurs, G. Cutting tool vibration in the metal cutting process, Journal of Vibroengineering. December 2011. Vol. 13, Iss. 4, Kaunas University of Technology, Lithuania, pp. 676–681. ISSN 1392-8716
5. Gutakovskis, V., Bunga, G., Pikurs, G., Brutāns, V., Ratkus, A. An Experimental Study of the Cutting Forces in the Metal Cutting Process. Proceedings of the 8th International DAAAM Baltic Conference "Industrial Engineering", Tallinn, Estonia, 19–21 April 2012, Pp. 140–145.

6. Gutakovskis, v., Gerins, E., Rudzitis, J., Kromanis, A. “The Effect of the Cutting Parameters on the Machined Surface Roughness”, Solid State Phenomena, Vol. 260, pp. 219–226, 2017. (SCOPUS)
7. Gutakovskis, V., Geriņš, Ē. Adaptive Control for the Metal Cutting Process. *International Journal of Engineering Research in Africa*, 2020, Vol. 51, pp. 1–7. ISSN 1663-3571. e-ISSN 1663-4144. Available: doi:10.4028/www.scientific.net/JERA.51.1 (SCOPUS)
8. Gutakovskis, V., Šteklējns, A., Avišāne, A., Muižnieks, G., Varma-Buddaraju, A. Study and Analysis of Machine and Tool Parameters of Stainless Steel Turning Using Multi Coated Tools. *32nd DAAAM International Symposium: Proceedings*, 2021, Vol. 32, No. 1, pp. 555–565. ISSN 1726-9679. (SCOPUS)
9. Gutakovskis, V., Avišāne, A., Mozga, N. Finite Element Analysis of the Stainless Steel AISI 420 Cutting Process Using Different Machining Parameters to Predict Cutting Forces and Temperature Distribution in the Duratomic-Coated Cutting Tool. In: *21st International Scientific Conference "Engineering for Rural Development": Proceedings. Vol. 21*, Jelgava, Latvia, 25–27 May 2022. Jelgava: LLU Press, 2022, ISSN 1691-5976. (SCOPUS)

1. LITERATURE REVIEW

1.1. Characterization and evaluation of the cutting process.

Nowadays, there are many types of external and internal surface turning operations, for example, turning a normal cylindrical surface (Fig. 1 a), forming a complex profile (performable only on CNC machine tools) (Fig. 1 b), turning the workpiece from the edge (Fig. 1 c), deep internal buckling (Fig. 1 d), normal internal buckling (Fig. 1 e), internal complex profile buckling (Fig. 1 f). All these operations are similar in that they have a cutting tool – a mobile (quick-changeable) plate with a special geometry and wear-resistant coating for an appropriate group of materials and a holder that ensures a specific angle of the cutting blade. Each of the cutting tool geometries provides a stable, high-yield machining process due to a stable chip formation process (Fig. 2) in the specific area of machining parameters (Fig. 3). In the event when this process is not stable, serious problems may arise, from the deterioration of the quality of the processed surface to the failure of the machine tool.

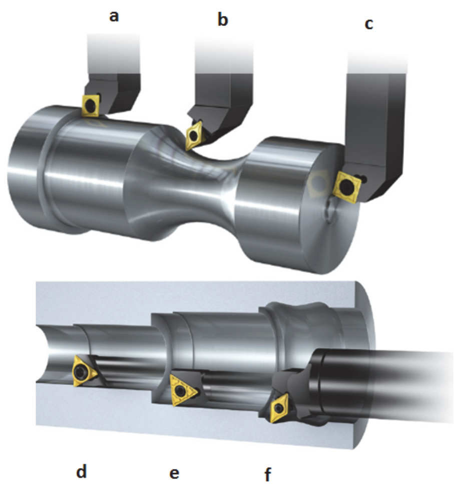


Fig. 1. Types of cutting operations in lathe [20].

Fig. 2. Shapes and types of *Seco* mobile cutting inserts and chip breakers [22].

Nowadays, along with the technological process, computer-based or simulation research is also developing. Every year it becomes more and more accurate. Until now, in order to clarify the modeling results, it was necessary to conduct a practical experiment at least at some control points in order to compare the obtained data and find out what the inaccuracy in computer modeling is. Now, even the complex study of the metalworking process can be done thanks to various programs: *Ansys, Abaqus, ADINA, Ls-Dyna, CosmosWorks, Third Wave AdvantEdge*. Everything is based on conventional finite element models developed by many researchers who are good at mathematics. Today, thanks to various programs, simulative modeling of process occupies an increasingly important place in design and comparative research – when modeling is carried out before a practical experiment and results that can be obtained experimentally are predicted, or data that are difficult to measure directly in a practical experiment are obtained. In order to increase the production and the quality of the processed surface, several scientists around the world are doing a lot of research, such as V. P. Astachov [18], A. V. Sharma [19] and others. However, all these researchers carry out both simulations and practical experiments either with common cutting tools and materials that have been used for a long time – either easy-to-machine materials that are already widely used in production, or studying the difficult-to-machine heat-resistant materials of titanium and other impurities and their chip breaking process. [1]–[17]. Nothing has been published about stainless steel machining with new cutting tools and new modeling programs (in this case *Third Wave AdvantEdge*).

1.2. Development trends of tungsten carbide cutting tools

When looking at the development trends of other instrument manufacturers, it can be seen that most of them stick to the classical types of coatings. It is determined by both the technological parameters and the capabilities of the machine tools. Currently, classical methods are used in the entire field of metalworking – TiC and Al_2O_3 coated tools and quenching emulsion are used, not exceeding classical processing parameters. By analyzing the given situation, it can be concluded that the development of the latest wear-resistant cutting tool coatings and the application of increased processing parameters to increase production capacity will become relevant in the coming years.

1.3. Instrumental tungsten carbide cutting tools and coatings

Hard alloys are used in more than 40 % of all tool materials. According to ISO 513 regulations, metal-ceramic hard alloys are divided into six groups (P, M, K, N, S, and H) depending on how the workpiece material resists machining and what kind of chip is produced during machining. The M group material processing hard alloys are used for the processing of stainless steels and their castings, when a flowing chip is formed during the processing. In the designations of hard alloys, the higher the number after the letter of the corresponding group, the lower the resistance of the hard alloy but the higher the strength. In order to improve the cutting ability of hard alloys and reduce friction, a thin plasma vaporization of the material is deposited on their surface in a vacuum using the PVD (physical vapor deposition) method, i.e., physically with ion impacts at 500 °C. The CVD (chemical vapor deposition) method is used less often, i.e., by performing chemical-thermal evaporation deposition of the material at 900 °C. Consequently, hard and wear-resistant 3 to 5-layer nano-coatings with crystalline sizes around 5–10 nm are formed on the surface of the hard alloy. The total thickness of the nano-coating layer reaches 3–l0 μm and in 87 % of cases it consists of TiN. A TiN (2200 HV) nano-coating is formed on the hard alloy surface for the processing of tough materials, e.g., alloy steels. $A1_2O_3$(2500 HV) nano-coating is formed on the hard alloy top layer by the CVD method for processing stainless steels. For the processing of hardened steel, a TiAlN (3300 HV), Ti (C, N) (3000 HV) interlayer nano-coating or a diamond (8000 HV) nano-crystalline layer is formed on the hard alloy surface. The base layer of coatings is more often made of TiC, Ti (C, N) and TiN [18]–[28]. Over the past ten years, there has been research focused on the development of the technology, which has only resulted in the development of Duratomic technology for wear-resistant coatings. Refined grit and Duratomic technology create versatile tools optimized for high and reliable performance in specific cutting materials and applications. Together with increased stiffness it provides performance beyond the capabilities of traditional wear resistant Al_2O_3 coatings. In addition, the new coatings improve heat resistance and chemical inertial properties and reduce the tendency of workpiece materials to stick to the tool (sticking is minimized). The introduction of the first TM4000 and TP2500 cutting tools with Duratomic technology proved to be very successful and set a new standard for coatings. In the examined sources of the indicated literature, no information can be found that the effect of the combination of several coatings and their thickness variants on the quality of the treated surface has been studied in the metalworking process.

Significantly inferior to hard alloys in terms of heat resistance and wear resistance, high-speed steels are the most resistant to bending loads (σ_i up to 400 MPa) and impact resistance, in this respect the other materials are unable to compete with them. In addition, tools made of high-speed steel can be sharpened to the maximum possible sharpness of the cutting edge, which is very important in cleaning processes; they have high stability of cutting properties and safety at work, which, in turn, is of great importance when used in automatic equipment with multi-tool setups [22].

CVD-deposited aluminum oxide Al_2O_3 (Figs. 3 and 4) shows that the largest grains of the material are positioned vertically, which makes it harder and stiffer and dissipates heat more efficiently. It is this modified structure that allowed the company *Seco Tools* to claim that the Duratomic coating is “the world’s first atomically modified coating”.

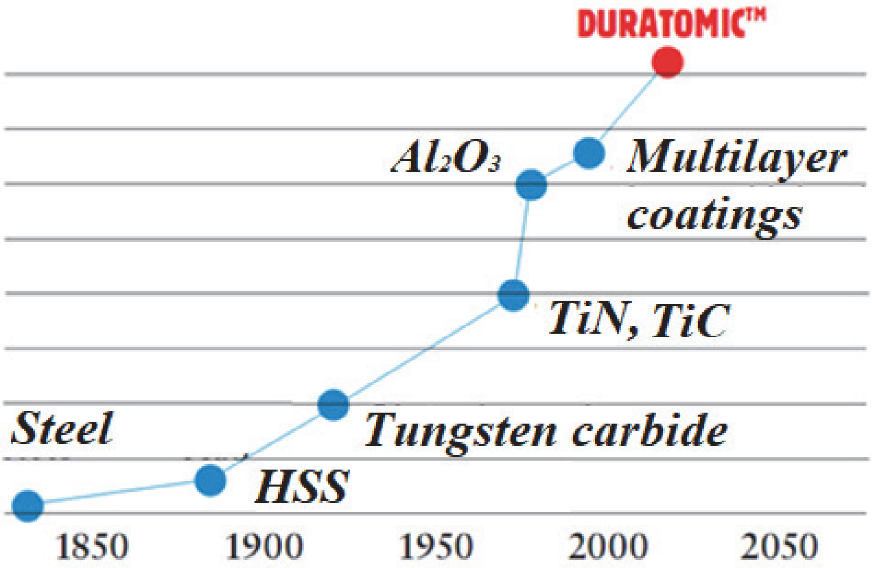


Fig. 3. General development of cutting tools [22].

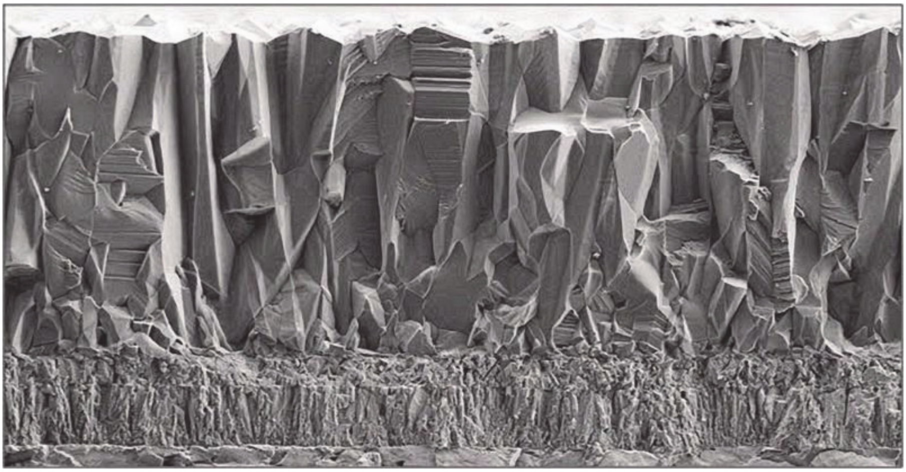


Fig. 4. Cutting tool coated with Duratomic technology, the vertical crystal positioning structure of the Al_2O_3 coating is visible [22].

2. MATHEMATICAL MODELING OF THE CUTTING PROCESS

2.1. Finite element method

The selected software *AdvantEdge* with GEM methodology was developed specifically for machining process studies, including several options: automatically programmed tool movement for different machining processes, customized tool and workpiece geometry import, automatically determined and applied finite element studies and post-processing results processing functions that allow easily analyze and compare multiple simulations.

AdvantEdge is the primary computer simulation tool, a finite element analysis (FEA) simulation program used to understand the metal cutting process without actually performing experiments. With *AdvantEdge* it is possible to perform a complete set of studies for analysis, including the formation of microstructure distribution, temperature in the contact zone, contact stresses and forces generated by the tool and the workpiece. The program has developed and implemented material models built into the program's library, which will give an opportunity to obtain the maximum reliability value and verify the final result without physical examination [23]–[37].

2.2. Simulation of machining process, cutting temperature and forces

The selected program *AdvantEdge* allows users to analyze machining processes in 2D and 3D environments. Manufacturers around the world find *AdvantEdge* a valuable tool for simulation and research in turning, milling, drilling, sawing and drawing. *AdvantEdge* users also have the ability to analyze contact zone temperatures and stresses to predict tool wear resistance and performance. By comparing the effect of each individual parameter, the user can easily determine and implement the optimal parameters. It is also important that there is an opportunity to create any geometry of the tool and to choose wear-resistant coatings, their properties and thickness.

2.3. Application of the finite element method in the modeling of the turning process

To model the stainless steel cutting process, the program *Third Wave AdvantEdge*, which is based on finite element mathematical analysis (FEM analysis), was applied. AISI 420 grade stainless steel and a TNMG 160412 TM-4000-MF4 Duratomic cutting tool were selected. In this case, a cross-sectional profile of the 2D cutting tool geometry has been precisely created and the thicknesses of the TiN and Al2O3 coatings (obtained from the manufacturer of these tools) have been entered. To achieve the set goal, the following tasks were formulated:

1) to create the precise geometry of the cutting insert and the combination and thickness of the coatings;
2) to perform simulation modeling of the turning process at basic processing modes (cutting speed 90 m/min, without cooling emulsion) and at increased processing modes (cutting speed 150 m/min, without cooling emulsion);
3) to analyse the chip formation process;
4) to determine and distribute cutting temperature;
5) to determine the values of cutting forces;
6) to investigate the deformed state of the treated surface.

The *Third Wave AdvantEdge* software, based on finite element mathematical analysis, was used to model the stainless steel cutting process. AISI 420 stainless steel and TNMG 160412 TM-4000-MF4 Duratomic cutting tool were selected. Modeling of cutting modes (minimum and maximum values) is shown in Table 1.

Table 1

Cutting Parameters for the Simulation

Simulation variant	**1**	**2**
Feeding, *f*, mm/rev	0.1	0.35
Cutting depth, a_p, mm	0.5	0.5
Cutting speed, V_c, m/min	90	150
Temp. in the lab., °C	20	20
Part material	AISI 420	AISI 420

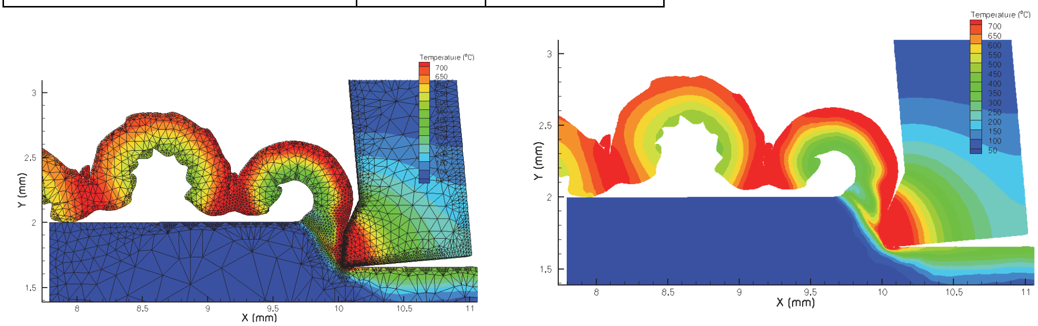


Fig. 5. General view of chip formation process and heat distribution field

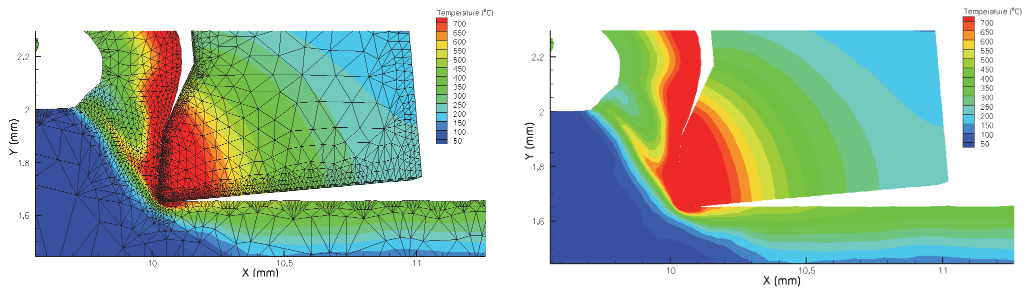


Fig. 6. The heat distribution field modeled during the cutting process in the enlarged scale with and without meshing.

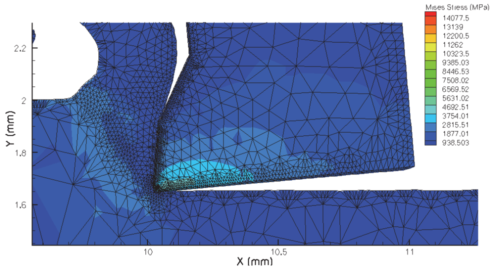


Fig. 7. Modeled distribution of contact stresses during the cutting process.

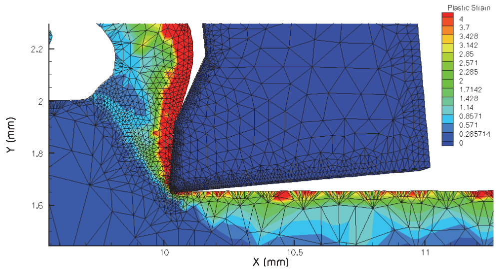


Fig. 8. Modeled distribution of plastic deformations during the cutting process.

As a result of modeling, the chip formation process corresponding to the experimental results was obtained, which was provided by the geometry profile of the cutting tool (MF 4), values of minimum cutting temperature of 700 °C and maximum temperature of 1150 °C without cooling emulsion and their distribution in the cutting tool were determined. The values of the cutting forces along the X and Y-axes are minimal in the medium/finishing processing modes and do not exceed the specified relationships and are in the Px range of 100–150 N/mm^2 and in the Py range of 250–400 N/mm^2. The modeling results are shown in Figs. 5–8. As a result of modeling, the chip formation process is visible as accurately as possible and in accordance with the practical experiment. The values of cutting force and temperature are shown in Figs. 9 and 10.

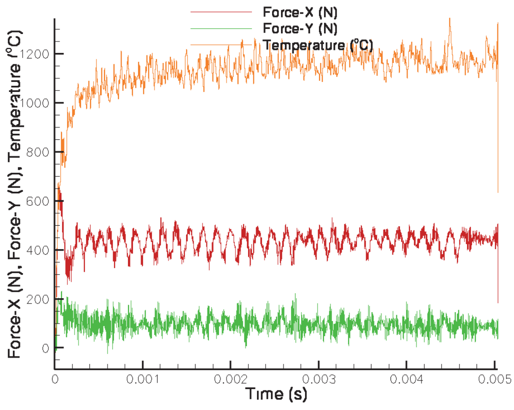


Fig. 9. The cutting force and temperature values are a representation of the first simulation case [developed by author].

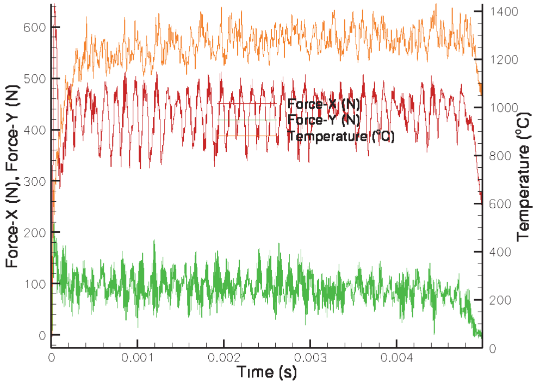


Figure 10. Cutting force and temperature values are a representation of the second simulation case [image by author].

3. EXPERIMENTAL STUDIES OF STAINLESS STEEL TURNING PROCESS

3.1. Selection of cutting tool geometry in experimental studies

Among the different types of turning operations cutting tool geometries were selected that are designed for medium or medium/finishing turning operations – MF4 and MF5 with coatings CP500, TP3500, and TM4000 Duratomic, designed for machining stainless steels. Analogues intended for similar operations from other manufacturers were also selected: *Sumitomo, Kennametal, Walter* (Table 2). General characteristics of the experiments are shown in Table 3.

Table 2

Geometry and Areas of Application of the Selected Cutting Tools

Cutting insert geometry	Marking	Operation	a_p/f (mm)
	TNMG 160408-NM4 WPP20 (*Walter*)	Stainless steel, medium machining	0.25–4.5/ 0.10–0.40
	TNGP 160408 KC730 (*Kennametal*)	Stainless steel, medium/ finishing machining	0.2–4.0/ 0.10–0.30

Table 2 continued

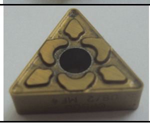
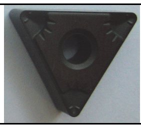
	TNMG 160408 ESX AC2000 (*Sumitomo*)	Stainless steel, medium machining	0.25–2.5/ 0.05–0.5
	TNMG 160412 MF4 TM4000 Duratomic (*Seco*)	Stainless Steel, medium machining	0.5–4.0/ 0.15–0.5
	TNMG 160408 MF4 CP500 (*Seco*)	Stainless steel, medium/ finishing machining	0.5–4.0/ 0.15–0.5
	TNMG 160408 MF4 TP3500 Duratomic (*Seco*)	Stainless steel, medium/ finishing machining	0.15–0.5/ 0.5–4.0
	TNMG 160408 MF5TP2500 Duratomic (*Seco*)	Stainless steel, medium/ finishing machining	0.2–0.8/ 0.2–2.7

Table 3

General Description of the Experiments

Exp. No.	Part material	Cutting insert	Cutting parameters
1	420	TNMG 160412 TM4000 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 90; 112 m/min.
2	420	TNMG 160412 TM4000 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 117; 141 m/min.
3	304	TNMG 160412 TM4000 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 117; 141 m/min.
4	420	TNMG 160412 TM4000 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 144; 176 m/min.
5	304	TNMG 160412 TM4000 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 144; 176 m/min.
6	304	TNMG 160408 CP500 MF4 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
7	420	TNMG 160408 CP500 MF4	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
8	304	TNMG 160408 TP2500 MF5 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.

Table 3 continued

9	420	TNMG 160408 TP2500 MF5 (Seco)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
10	420	TNMG 160408 TP2500 MF5 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 273; 343 m/min.
11	304	TNMG 160408 TP2500 MF5 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 273; 343 m/min.
12	304	TNMG 160408 MF4 TP3500 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
13	420	TNMG 160408 MF4 TP3500 (*Seco*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.

3.2. A possibility analysis of a multifactorial experiment

Properties of a 2^k-type full factorial experiment

There are three simple options for drawing up 2^k-type plans, one of which is based on the law of changing the order of signs. In the first column, the signs are changed sequentially, in the second column they are changed after each two, in the third after each four, and in the fourth – after each eight rows, etc.

The full factorial experiment matrix has some properties that make it an optimal means of constructing a mathematical model based on the results of experiments [38]–[45]. Two of these properties derive from the matrix construction:

- Symmetry with respect to the center of the experiment. It is defined as the algebraic sum of each vector column, excluding the free term column, which is equal to zero (Eq. (1):

$$\sum_{v=1}^{n} x_{jv} = 0; i=1,\ 2,\ \ldots,\ 2^k-1\ , \qquad (1)$$

where n is the number of different points in the plan and v is number of the point.

- The sum of the squares of the elements of each column is equal to the number of points (Eq. (3.2)):

$$\sum_{v=1}^{n} x_{iv}^2 = n; i=1,\ 2,\ \ldots,\ 2^k-1 \qquad (2)$$

3.3. Development of an experimental model in turning

As an example, let us look at the first treatment of experimental data with the help of a three-factor experiment. According to the previous experiments, we assume the supply values: 0.1; 0.35 mm/rev. According to the information sources, we accept cutting speed values (base values): 90...115 m/min, as well as values of the main setting angle of 60°–90°. The experimental planning matrix and factor levels and variation intervals are shown in Tables 4 and 5. The resulting R_a values of the turned surface are shown in Table 6. Material: 420 stainless steel, workpiece diameter 89 mm. Selected tool: cutting plate TNMG 160412-MF4, TM4000, intended for medium to finishing processing of this brand of materials at speeds from 90 to 115 m/min.

Table 4

2^n Planning Matrix

Plan No.	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	**Optimization parameter**
1	+	–	–	–	+	+	+	–	Y1
2	+	+	–	–	–	–	+	+	Y2
3	+	–	+	–	–	+	–	+	Y3
4	+	+	+	–	+	–	–	–	Y4
5	+	–	–	+	+	+	–	+	Y5
6	+	+	–	+	–	–	–	–	Y6
7	+	–	+	+	–	+	+	–	Y7
8	+	+	+	+	+	–	+	+	Y8

Table 5

Factor Levels and Variation Intervals

Factor levels	**Marking**	***V* (m/min)**	***S* (mm/rev)**	**φ (°)**
		$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$
Nominal	0	100	0.225	75°
Variation interval	ΔXi	10	0.125	15°
The upper one	+1	110	0.35	90°
The bottom one	–1	90	0.1	60°

Table 6

Average Values of R_a (Y_i)

No.	*V*	*f*	*ϕ*	Y1	Y2	Y3	Y4	Y5	Yv	S2v
1	90	0.1	90	7.08	6.85	6.12	6.35	3.2	5.92	2.45
2	90	0.35	90	5.44	4.25	5.16	4.48	3.52	4.57	0.58
3	90	0.1	60	5.48	5.8	4.38	5.67	4.29	5	0.51
4	90	0.35	60	3.47	7.08	6.63	6.95	4.48	5.71	2.69
5	112	0.1	90	3.84	7.72	4.2	6.81	5.16	5.54	2.79
6	112	0.35	90	3.29	3.33	3.1	3.52	4.06	3.46	0.045
7	112	0.1	60	5.16	4.2	5.16	5.67	6.85	5.4	0.92
8	112	0.35	60	5.12	4.71	3.33	4.93	4.34	4.49	0.83

3.4. Determination of the mathematical model of the object

The orthogonality of the planning matrix allows to simplify the calculation of the coefficients of the regression equation. This is one of the advantages of designing an experiment like this. The coefficients are calculated according to the formula [45] (Eq. (3)):

$$b_i = \frac{\sum_{v=1}^{n} x_{jv}\overline{y_v}}{n}, \quad (3)$$

where i = 0, 1, 2...k is the number of the factor and Yv is the average score after r trials at the point numbered v (Eq. (4)):

$$y_j = \frac{\sum_{j=1}^{r} y_{jv}}{r}, \quad (4)$$

As a result, dividing by the number of points of the plan gives the required coefficient (Eq. (5)):

$$b_0 = \frac{\sum_{v=1}^{n} x_{0v}\overline{y_v}}{n}, = 1/8 * (5.92 + 4.57 + 5 + 5.71 + 5.54 + 3.46 + 5.7 + 4.49) = 5.04 \quad (5)$$

Similarly, we calculate the other coefficients: b_1 = –0.49; b_2 = 0.176; b_3 = –0.25; b_{12} = 0.36; b_{13} = –0.33; b_{23} = 0.12; b_{123} = 0.03.

The equation with transformed variables x is formulated as follows [45] (Eq. (6)):

$$Y = 5.04 - 0.49x_1 + 0.176x_2 - 0.25x_3 + 0.36x_1x_2 - 0.33x_1x_3 + 0.12x_2x_3 + 0.03x_1x_2x_3, \quad (6)$$

where Y is roughness of the surface profile (R_a – average arithmetic deviation of smoothness) and x_1, x_2, x_3 is cutting speed, feed, main setting angle respectively.

In planning the experiment, the statistical nature of the relationships is taken into account, so the obtained equations were carefully statistically analyzed. Such an analysis has two purposes:

1) to obtain the maximum amount of information from the results of the experiment;
2) to ensure the reliability and accuracy of the obtained connections.

The variance that characterizes the experimental error

Every experiment contains some error. To reduce errors, it is necessary to repeat the experiments under the same conditions, i.e., in each scheduling line. Row variances can be calculated using the formula [45] (Eq. (7))

$$s_v^2 = \frac{\sum_{v=1}^{n}(y_{vji}\overline{y_v})2}{r-1}, \tag{7}$$

where r is the number of repeated experiments in plan points (8).

$$s_{v1}^2 = \frac{\sum_{v=1}^{n}(y_{vj}-\overline{y_v})2}{r-1} = 2.45\ . \tag{8}$$

Similarly, it is calculated: $S^2_{v2} = 0.58$; $S^2_{v3} = 0.51$; $S^2_{v4} = 2.69$; $S^2_{v5} = 2.79$; $S^2_{v6} = 0.045$; $S^2_{v7} = 0.92$; $S^2_{v8} = 0.83$.

The variances of the optimization parameter (y) are the arithmetic mean of the variances of all individual experimental variants. The variance of the optimization parameter is calculated according to the formula (Eq. (9))

$$s^2\,\{y\} = \frac{\sum_{v=1}^{n} s_v^2}{n} = \frac{\sum_{v=1}^{n}\sum_{j=1}^{r}(y_{vj}-\overline{y_v})^2}{n(r-1)} = 1{,}35 \tag{9}$$

where s_v^2 is dispersion of results at plan point v, where repeated experiments r_v are carried out; $f_v = r_v - 1$, is the number of free degrees of such variance; f_E is total number of free degrees of combined variance $s^2\,\{y\}$. The coefficients of the formula shown above should not be used here. Reproducibility should be checked before variances are combined.

Testing the equality of variances

Equality of variances has been tested using various statistical methods, e.g., Fisher, Cochran, Bartlett method. The use of Fisher's F-criterion is ineffective when the number of variances is greater than two, since in that case only the smallest and largest variances participate in the estimation. Cochran's G criterion is used in cases where the number of experimental repetitions is the same at all points of the plan. From all s_v^2 variances the largest $s_v^2{}_{max}$ should be chosen, which is divided by the sum of all variances. Cochran's criterion G is the ratio of the maximum variance to the sum of all variances [45] (Eq. (10)):

$$G = \frac{s_v^2{}_{max}}{\sum s_v^2} = \frac{2.79}{10.81} = 0.26\,. \tag{10}$$

As the critical value of Cochran's criterion is G_{kr} = 0.52 (at the significance level a = 0.05), the hypothesis of equality of variances is correct if the experimental value of Cochran's criterion is less than the critical value in Fig. 11:

0.26 < 0.52

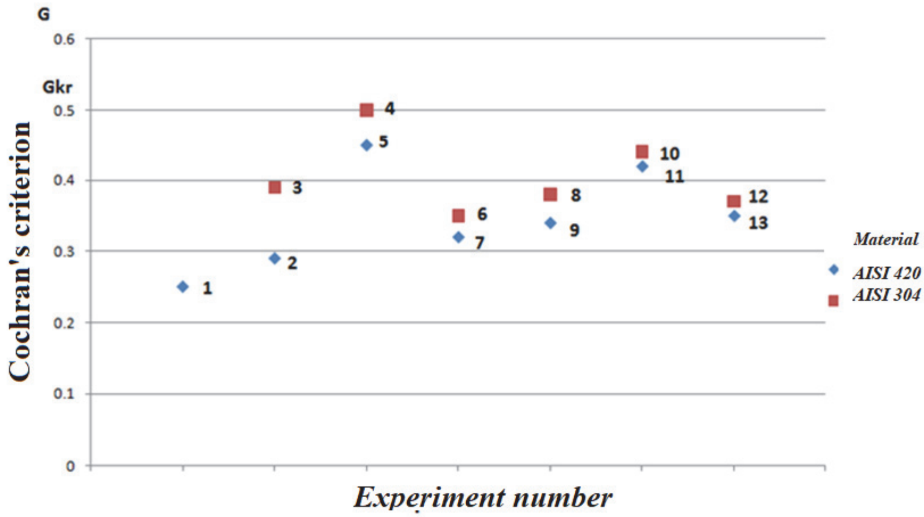


Fig. 11. Graphic representation of Cochran's criterion according to the experiment number.

Significance test of model coefficient

The significance test for each coefficient has been performed independently. The T or Student's criterion can be used for testing. In the case of using a full factorial experiment, the confidence intervals for all coefficients are the same. First, the variance of the $s^2\ \{b_1\}$ regression coefficient is found. It can be calculated according to the Eqs. (11) and (12):

$$s^2\{b_i\} = \frac{s^2\{y\}}{n*r} = \frac{1.34}{8*5} = 0.0337 \quad (11)$$

$$s\{b_i\} = \sqrt{0.0337} = 0.184 \quad (12)$$

The formula shows that the variances of all coefficients are the same because they depend only on the experimental error and the number of trials. Then the calculation of the values of the t-criterion is done according to the formula (Eq. (13)):

$$t_i = \frac{|b_i|}{s\{b_i\}}. \quad (13)$$

For this experiment, they are as follows:

$t_0 = 27.39$; $t_1 = 2.66$; $t_2 = 0.96$; $t_3 = 1.36$; $t_{12} = 1.95$; $t_{13} = 1.79$; $t_{23} = 0,65$; $t_{123} = 1.63$.

A coefficient is significant if its absolute value is also greater than half the length of the confidence interval. Orthogonal planning allows you to set confidence limits separately for each of the regression coefficients. If one of the coefficients turns out to be insignificant, it can be discarded without recalculating the other coefficients. After that, the mathematical model of the object is compiled in the form of an equation in which only significant coefficients are recorded.

The critical value t_{kr} is found according to the tables at $n(r-1) = 32$ degrees of freedom and at significance level $a = 0.05$: $t_{kr} = 2.04$.

The following equation was obtained for the given experiment:

$$Y = 5.04 - 0.49x_1. \quad (14)$$

To obtain a model with natural variables, the x_i expressions from the transformation formulas must be inserted into Eqs. (14), (15) and (16):

$$x_1 = \frac{\tilde{x}_1 - 100}{10}; \quad (15)$$

$$x_2 = \frac{\tilde{x}_2 - 0.225}{0.125}; \quad (16)$$

$$x_3 = \frac{\tilde{x}_3 - 75}{15}. \quad (17)$$

This results in Eq. (18):

$$R_a = 5.04 - 0.49\left(\frac{\tilde{x}_1 - 100}{10}\right), \quad (18)$$

where $\tilde{x}_1$ is cutting speed, m/min.

Plans for other experiments have been drawn up in a similar manner. Summarized data from all experiments are presented in Table 3.

In Experiment No. 2 (Table 3), a tool with Duratomic coating TM-4000 was used and a cutting speed range was 117/141 m/min, for steel AISI420; the experimental plan is shown in Table 7 and the result is obtained by Eq. (19).

In Experiment No. 3 (Table 3), a tool with Duratomic coating TM-4000 was used and a cutting speed range of 117/141 m/min, for steel AISI304; the experimental plan is shown in Table 7 and the result is obtained by Eq. (20).

Table 7

Factor Levels and Variation Intervals for Experiment Nr. 2 and Nr. 3

Factor levels	**Marking**	***V* (m/min)**	***f* (mm/rev)**	**φ (°)**
		$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$
Nominal	0	129	0.225	75°
Variation interval	ΔX_i	12	0.125	15°
The upper one	+1	141	0.35	90°
The bottom one	–1	117	0.1	60°

$$R_a = 2.0 + 0.96\left(\frac{\tilde{x}_1 - 129}{12}\right) + 0.04\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) + 0.14\left(\frac{\tilde{x}_3 - 75}{15}\right) + 0.11\left(\frac{\tilde{x}_1 - 129}{12}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) + 0.45\left(\frac{\tilde{x}_1 - 129}{12}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right) \quad (19)$$

$$R_a = 1.12 + 0.25\left(\frac{\tilde{x}_1 - 129}{12}\right) + 0.06\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) + 0.17\left(\frac{\tilde{x}_3 - 75}{15}\right) + 0.7\left(\frac{\tilde{x}_1 - 129}{12}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) + 0.35\left(\frac{\tilde{x}_1 - 129}{12}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right) \quad (20)$$

In Experiment No. 4 (Table 3), a tool with Duratomic coating TM-4000 was used and a cutting speed range of 144/176 m/min, for steel AISI420; the experimental plan is shown in Table 8 and the result is obtained by Eq. (21).

In Experiment No. 5 (Table 3), a tool with Duratomic coating TM-4000 was used and a cutting speed range of 144/176 m/min, for steel AISI304; the experimental plan is shown in Table 8 and the result is obtained by Eq. (22).

Table 8

Factor Levels and Variation Intervals for Experiment Nr. 4 and Nr. 5

Factor levels	**Marking**	***V* (m/min)**	***f* (mm/rev)**	**φ (°)**
		$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$
Nominal	0	160	0.225	75°
Variation interval	ΔX_i	16	0.125	15°
The upper one	+1	176	0.35	90°
The bottom one	–1	144	0.1	60°

$$R_a = 4{,}14 - 1{,}76\left(\frac{\tilde{x}_1 - 160}{16}\right) - 0.41\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) - 0.07\left(\frac{\tilde{x}_1 - 160}{16}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right) \quad (21)$$

$$R_a = 2.17 - 1{,}18\left(\frac{\tilde{x}_1 - 160}{16}\right) - 0.29\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) - 0.12\left(\frac{\tilde{x}_1 - 160}{16}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right) \quad (22)$$

In Experiment No. 10 (Table 3), a tool with Duratomic coating TP-2500 was used and a cutting speed range of 273/343 m/min, for steel AISI420; the experimental plan is shown in Table 9 and the results ar obtained by Eq. (23).

In Experiment No. 11 (Table 3), a tool with Duratomic coating TP-2500 was used and a cutting speed range of 273/343 m/min, for steel AISI304; the experimental plan is shown in Table 9 and the results are obtained by Eq. (24).

Table 9

Factor Levels and Variation Intervals for Experiment Nr. 10 and Nr. 11

Factor levels	**Marking**	***V* (m/min)**	***f* (mm/rev)**	**φ (°)**
		$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$
Nominal	0	308	0.225	75°
Variation interval	ΔX_i	35	0.125	15°
The upper one	+1	343	0.35	90°
The bottom one	–1	273	0.1	60°

$$R_a = 7.11 - 3{,}03\left(\frac{\tilde{x}_1 - 312}{35}\right) - 2.1\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) - 0.74\left(\frac{\tilde{x}_1 - 312}{35}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right) \quad (23)$$

$$R_a = 5.17 - 2{,}161\left(\frac{\tilde{x}_1 - 312}{35}\right) - 1.28\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right) - -0.62\left(\frac{\tilde{x}_1 - 312}{35}\right)\left(\frac{\tilde{x}_2 - 0.225}{0.125}\right)\left(\frac{\tilde{x}_3 - 75}{15}\right), \quad (24)$$

where $\tilde{x}_1$ is cutting speed, V, m/min.; $\tilde{x}_2$is feed, f, mm/ rev; and $\tilde{x}_3$is cutting angle, $\boldsymbol{\phi}$ °.

3.5. Formation and analysis of turned surface roughness using other manufacturers' cutting tools

Graphical results (Figs. 12 and 13) show how significantly different the result of the turned surface (R_a) is when using tools from different manufacturers, which are supposedly intended for similar operations with the same processing modes. The general characteristics of the experiments are shown in Table 10.

Table 10

General Description of the Experiments using other manufacturer cutting tools

Exp. No.	Part material	Cutting insert	Cutting parameters
14	304	TNMG 160408-NM4 WPP20 (*Walter*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
15	420	TNMG 160408-NM4 WPP20 (*Walter*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
16	304	TNMG 160408 ESX AC2000 (*Sumitomo*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
17	420	TNMG 160408 ESX AC2000 (*Sumitomo*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
18	304	TNMG 160408 KC730 (*Kennametal*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.
19	420	TNMG 160408 KC730 (*Kennametal*)	a_p = 0.5 mm, f = 0.1; 0.35 mm/rev., V = 210; 268 m/min.

Table 11

Average Values of Surface Roughness ($R_{a\ vid}$) for Different Workpiece Materials and Tools

		AISI 304			**AISI 420**		
n	**φ^o**	**WPP20**	**AC2000**	**KC730**	**WPP20**	**AC2000**	**KC730**
1	90	5.36	6.17	2.95	3.85	8.72	4.23
2	90	6.83	6.51	6.09	10.67	17.35	8.20
3	60	4.26	7.37	10.65	10.61	8.89	13.37
4	60	8.36	9.89	9.81	10.69	13.50	13.01
5	90	7.05	6.65	2.53	5.80	8.06	3.29
6	90	7.83	6.64	6.38	8.81	7.95	7.81
7	60	9.34	7.51	7.79	8.80	11.91	11.52
8	60	8.32	8.75	8.76	10.63	14.75	13.14

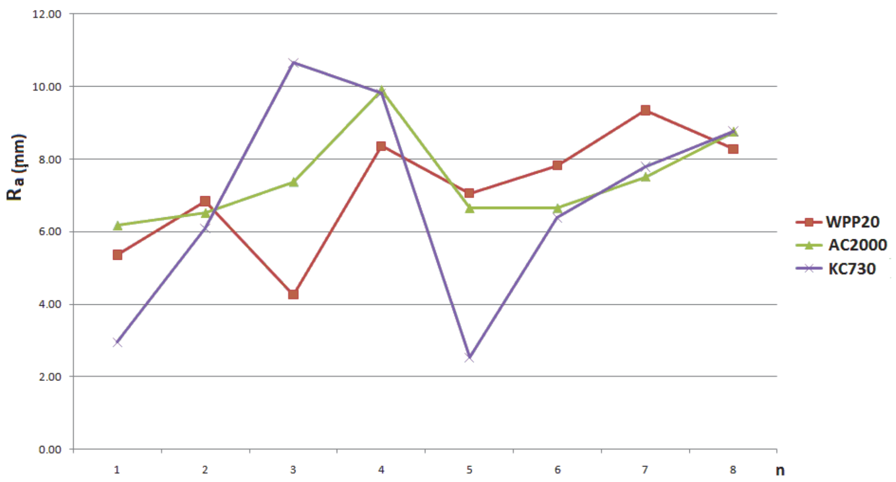


Fig. 12. AISI 304 graphic representation of the average roughness values of the surface of stainless steel turned with tools of different materials.

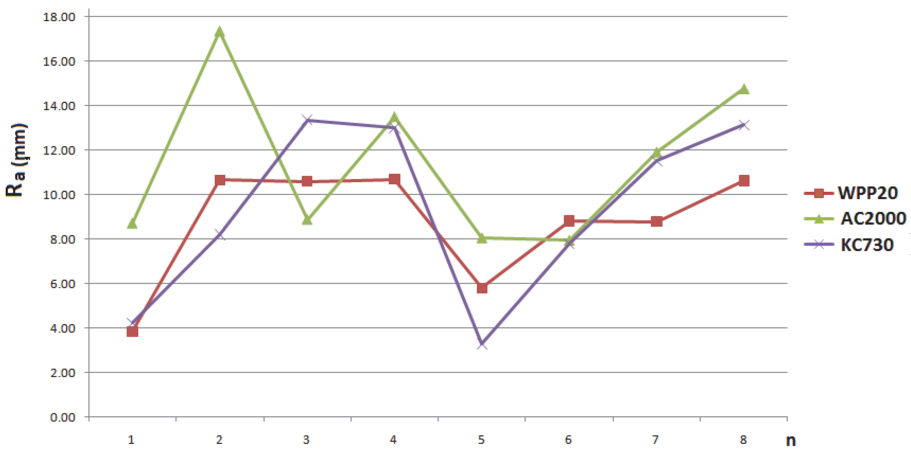


Fig. 13. AISI 420 graphic representation of average roughness values of the surface of stainless steel turned with tools of different materials.

By choosing several tools of other manufacturers in accordance with the ISO standard cutting geometry, which was intended for identical operation for a specific group of materials (AISI 304, AISI 420), by performing the turning process with increased processing modes and measurements of the machined surface, it was found that the tools of other manufacturers do not provide identical machined surface quality. In various cases, when applying combinations of processing modes, the dispersion of the values of the R_a range of roughness values of the processed surface reached 100 % at identical processing modes (e.g., from 3.0 to 6.0 μm).

3.6. Experimental studies of tool wear

During the cutting process the values of the tool angles change compared to the standardized position at variable modes. Under normal cutting conditions, these changes are insignificant and are usually ignored, but at high feeds it is necessary to increase the main angle φ by 3 ... 5° and, if necessary, consider changes in other modes.

The optimal value of the geometric elements of the tool and the shape of the front surface depends on several factors and, first of all, on the material to be processed, the physical and mechanical properties of the material, the cutting part of the tool, the shape and dimensions of the workpiece to be processed, and cutting modes.

The dimensions of the corners (edge geometry of the cutting insert) are selected according to the corresponding reference books to ensure that the tool design and production achieve the desired result. When processing with a blade tool, much attention is paid to controlling the shape of the chips and the direction of their movement. There are several ways to control the chip flow, such as changing the angles and orientation of the cutting tool, changing the cutting speed, feed and depth of cut, and using variable or intermittent feed. Changing the angles of the cutting tool affects the trajectory of the chips.

The initial trajectory is determined by the angle of the cutting tool and the bevel angle of the main cutting edge. Changing the shape of the front surface of the tool, thresholds, and slots (the geometry of the cutting tool) affects the shape of the chips, the direction of their movement and cutting into segments.

Changing the cutting conditions also changes the geometry of the cutting tool in the cutting zone and the chip formation parameters, which affect the chip formation process and cause additional vibrations that are reflected on the quality of the processed surface.

When examining all the results of the conducted experiments, it can be seen that the tools of different manufacturers are not intended for use at increased cutting modes.

When applying cutting tool nanocoatings, it is important to compare the wear resistance of cutting tools. The following cutting tools with coatings were chosen for the wear comparison experiment: KC730, TM4000, AC200, CP500, WPP200, TP3500.

The tool wear was measured on the cutting surface and flank of the insert tip and after the cutting process for each combination of turning parameters (Table 1).

The wear parameters and designations of the cutting edge are shown in Fig. 14:

In Fig. 15 the geometry angles of the cutting insert are shown:

The bevel angle λ of the main cutting edge is the angle between the cutting edge and the plane parallel to the base plane and is visible when looking from the side of the main cutting edge.

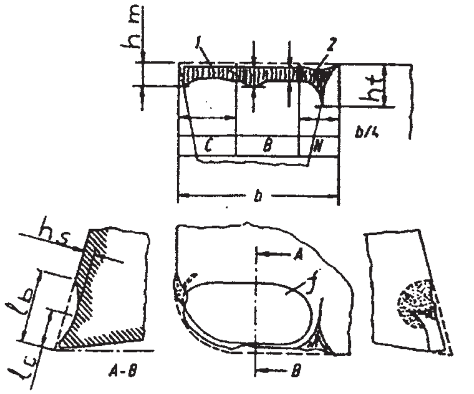


Fig. 14. Cutting edge wear parameters and designations, where: C, B, N – wear areas; l_b – length of wear hole; l_c – distance to the center of the wear hole; h_s – depth of the wear hole; h_m – flank wear; h_t – shock load wear; f – dimple wear form. [19].

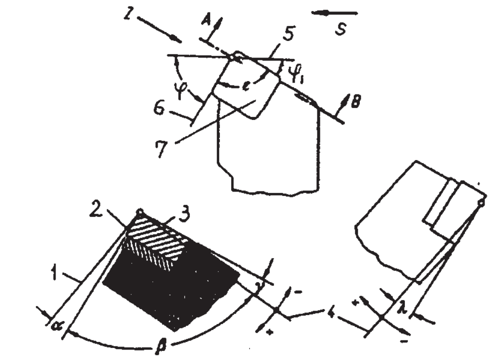


Fig. 15. Angles characterizing the cutting blade geometry , where: L – plane of the cutting edge of the tool; 2 – flank; 3 – chip surface; 4 – plane parallel to the basic plane of the tool; 5 – working plane; 6 – main cutting-edge setting plane; 7 – quick-changeable cutting insert; α – back angle; β – wedge angle; φ – main setting angle; ε – apex angle; λ – inclination angle of the main cutting blade; φ1 – auxiliary setting angle.[21].

As a result of the experiments, it was found that depending on the cutting conditions, different tool geometries and types of coatings, and the characteristics of the processed material (grade 304 and 420 stainless steel), the dominant wear is observed on the major flank h_m and on the chip surface shown in Figs. 16–19. In the case of tool wear, the radius of rounding of the cutting edge also changes Δr (Figs. 18,19.).

KC730 (*Kennametal*) showed a higher wear result (Figs. 17, 19). This tool, due to the rather uncomplicated chip breaker geometry, demonstrated better turned surface results than the other tools, but the wear values were very high. It is interesting that this tool, when turning two different grades of stainless-steel groups, showed different wear – minimum wear when turning AISI 420 and maximum wear when turning AISI 304 stainless steel. The data was obtained by reading the wear values after a complete machining cycle not exceeding the expected service life of the tool (15 min).

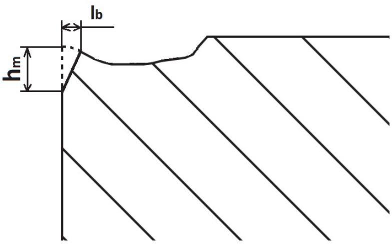


Fig. 16. Parameters of wear height h_m and wear length l_b on the insert in the cutting-edge slot.

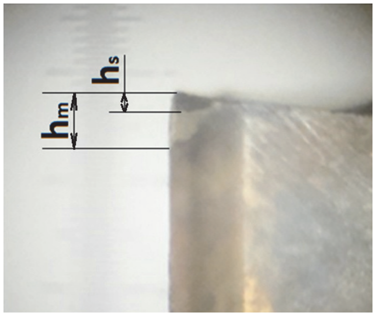


Fig. 17. Parameters of wear height h_m and wear dent length h_s.

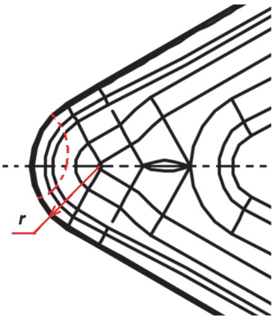


Fig. 18. Changes in the rounding radius r on the top of the plate (shown by the dashed line).

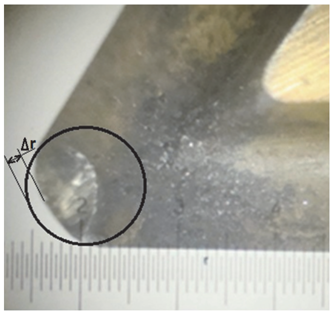


Fig. 19. Changes in the radius of rounding Δr on the wafer surface.

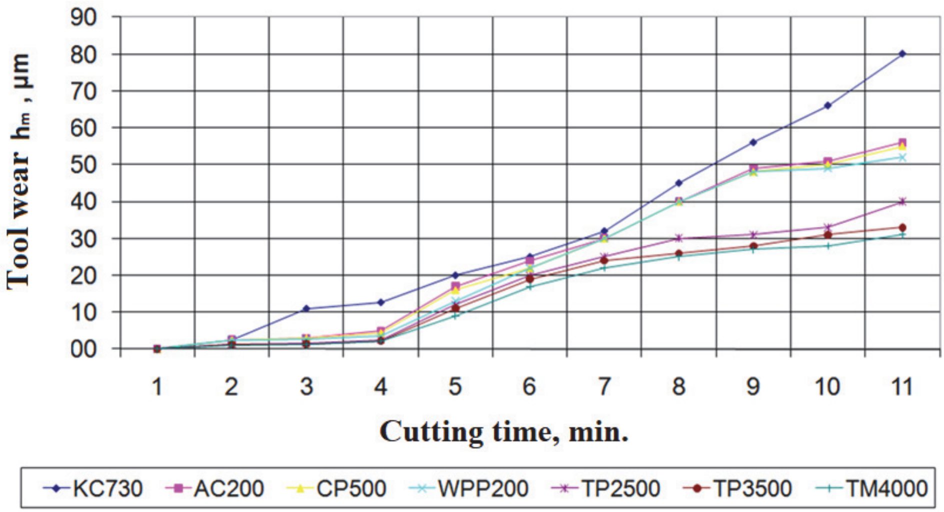


Fig. 20. Experimentally obtained results of tool wear.

From the obtained data it can be concluded that TM4000 cutting tools coated with Duratomic technology are more wear resistant. During the processing, vibrations occur, which deteriorate the quality of the turned surface.

Using higher cutting speeds, without cooling emulsions, the highest service life variant was achieved with Duratomic TM4000 coating (*Seco*), which showed minimal cutting-edge wear at 50 % increased cutting speeds (Fig. 20), providing good (judging from previous calculations) machined surface quality (in such a condition the tool could still be used).

Comparing the selected coatings, we can admit that from the point of view of wear, the coating made with Duratomic technology is considered the best because it causes less wear of the tool.

CONCLUSIONS AND APPLICATIONS

1. **The proposed hypothesis has been confirmed**: By accepting the set R_a value of the surface roughness of the turned part, it is possible to create models of cutting tools coated with the wear-resistant Duratomic technology of the turning process, which allows to choose the technologically achievable processing modes according to the set surface roughness: cutting speed, feed or cutting tool setting angle.

   By knowing the required surface roughness, it is possible to precisely set the cutting parameters, such as cutting speed, feed and cutting blade setting angle. It was demonstrated with specific examples of tools and processing modes.
2. Using the finite element method, as well as the *Third Wave AdvantEdge* program developed for the simulation of the metal cutting process, the technological turning process was modeled and analyzed with maximum reliability, using a new cutting tool chip breaker geometry, taking into account the thickness of its coating layer and the combination of material types.
3. Methodology for the selection of cutting tools was justified, experimentally tested with different cutting speeds and feeds, ensuring a stable cutting process: constant cutting force, temperature in the permissible range, chip formation and breakage process, as well as stable machined surface roughness (R_a).
4. From the plans of n-factor experiments, a three-factor analysis has been chosen for the work, which allows realizing the needs of the experiment and creating new models of the treated surface.
5. New machining process models have been developed using increased (from 25 % to 50 %) cutting speed values.
6. At higher cutting speeds, without cooling emulsions, the highest lifetime variation was achieved with the Duratomic TM4000 coating (*Seco*), which showed minimal cutting-edge wear at 50 % increased cutting speeds, ensuring good surface quality.
7. During the processing, the effect of the geometry of different cutting tools on the quality of the processed surface was studied (as a result, a range similar to the R_a base parameters from 3.0 to 10.0 µm is provided).
8. As a result of the experiments, it was established that by applying higher cutting speed values and lower feed values, lower surface roughness (R_a) values can be obtained when turning without cooling emulsion.

9. Studies have been carried out on the effect of the main setting angle of the cutting tool on the growth of cutting forces, surface roughness and the service life of the cutting tool. It was concluded that the optimal setting angle increases the life of the tool by 30–45 %.
10. The Thesis compares the processing results of two stainless steels AISI 420 and AISI 304 and the chip formation process. It was concluded that due to the influence of alloying elements, the materials undergo a different chip formation process.
11. Tools from different manufacturers do not provide a stable machining process and chip formation process at increased machining modes.
12. During the cutting process, studies using variations with combinations of cutting angles (60° and 90°) were analyzed and modeled, while predicting an increase in cutting forces, causing more vibrations, reducing the roughness of the machined surface and reducing the life of the cutting tools.
13. The modulated results can be applied in the modern automated production process or Industry 4.0, to obtain the required quality parts by applying the developed mathematical models.

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