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THE INFLUENCE OF CUTTING CONDITIONS AND TOOL WEAR ON MACHINING EFFICIENCY IN CNC MACHINE TOOLS

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Abstract: In this paper, the primary technological factors influencing the productivity and quality of the machining process in Computer Numerical Control (CNC) multi-operational machine tools – cutting conditions and cutting tool wear – are systematically analyzed. The study indicates that enhancing productivity and improving machining quality are directly dependent on the optimization of the toolpath, the minimization of operational and auxiliary times, as well as the proper selection of cutting conditions. The characteristics of cutting tool wear, particularly radial and flank wear, were analyzed using experimental methods during the machining of workpieces made from various materials, and radial wear was determined to be a more stable indicator. Based on this finding, it is proposed that radial wear be adopted as the primary criterion for the selection of machining parameters. Furthermore, the potential to significantly reduce machine time and increase the efficiency of the production process has been demonstrated through the planning of tool entry and exit paths, the overlapping of passes, and the application of multi-tool machining methods. Different toolpath strategies (such as looping, zigzag, plunging, and contour machining) are presented as factors that directly influence the machining accuracy and surface quality of the part during the creation of control programs. Consequently, in the optimization of technological processes on CNC machine tools, the toolpath strategy, the proper selection of cutting conditions, and the precise analysis of cutting tool wear play a crucial role. The proposed approaches hold practical significance for enhancing productivity and quality in an industrial environment.

Keywords: *CNC machines, machining on multi-operation machines, technological optimization, machining schemes, tool trajectory and transition planning.*

Introduction.

In the modern manufacturing industry, enhancing the quality of machined parts and the efficiency of production is directly linked to the improvement of technological processes. The role of CNC multitasking (multi-operational, multi-axis) machine tools is particularly significant in the implementation of these processes. CNC machine tools create a competitive advantage in production through their high precision, flexible configuration, and ability to consolidate operations in a single center. For this reason, the optimization of machining technologies on such machines—particularly the proper planning of the toolpath, the reduction of machine and auxiliary times, and the selection of machining parameters on a scientific basis—is of significant relevance [1-5].

Simultaneously, tool wear indicators (particularly radial and specific wear) are key factors in CNC technologies for predicting both machining quality and cutting tool life. The dynamics of tool wear are closely linked to the properties of the workpiece material and the selected cutting conditions. In this regard, determining the optimal parameters allows not only for an improvement in the surface quality of the machined part but also for a reduction in overall production costs and an increase in labor productivity.

The objective of this research is to analyze the influence of cutting conditions and tool wear on the productivity and accuracy of machining processes in CNC multitasking machine tools, and to enhance the efficiency of the technological process through the structural optimization of the toolpath. The paper presents the justification for technological decisions based on both theoretical analyses and practical examples.

Technological characteristics of machining processes on CNC multitasking machine tools. The primary distinguishing feature of CNC multitasking machine tools is the presence of a tool magazine, automatic tool changing systems, and tool condition monitoring systems. These features enhance the machines' technological capabilities, enabling the complex machining of parts for various tasks while ensuring the process is performed with high productivity and precision.

CNC multitasking machine tools also possess a number of significant characteristics, such as a further increase in labor productivity, an improved equipment utilization rate, simplicity of setup when transitioning from one part to another, the potential for multi-machine operation, the elimination of the impact of operator errors on machining quality, a reduction in the volume of inspection operations, and lower skill requirements for personnel.

Although multitasking machine tools are suitable for producing any part, their high cost reduces their profitability for manufacturing simple parts. The more complex the part is and the more passes and operations the technological process requires, the more effective the application of multitasking machine tools becomes.

As is known, within the inventory of metal-cutting CNC machine tools, lathes account for 29.2%, grinding and finishing machines for 15.8%, milling machines for 13.2%, and gear-processing machines for 7.2%. Additionally, typical parts machined on multi-functional machines can be categorized as follows: complex body-type parts (36%), stepped shafts (42%), and sleeve-type parts (22%) [2-6].

Economically, the application of CNC machines is justified not only for machining complex body-type parts that cannot be produced on universal machines, but also for machining shafts with a dimensional accuracy of IT8–IT10 [7] and a surface roughness of Rz 5 to 20 μm [8-10]. The economic efficiency of machining on CNC multitasking machine tools is enhanced primarily through the maximum concentration of operations.

Research indicates that the methods proposed by process engineers to achieve the required quality indicators for parts incur significant costs [3]. Among the specialists who participated in the survey, the proposed solutions to the problem were distributed as follows:

- ❖Reducing machining parameters – 34%
- ❖Applying automatic control systems and special equipment – 27%
- ❖Increasing the rigidity of the technological system – 26%
- ❖A combination of the above options – 13%

The high cost of the equipment places specific demands on multitasking CNC machines, requiring the implementation of a well-founded and highly efficient technological preparation of production. This preparation must ensure the minimum possible machining time for forming the part's elementary surfaces by optimizing both material removal and non-cutting time.

For the formation of an elementary surface, the unit time (T_{unit}) is defined as the sum of three components: operation time (T_{op}), workplace servicing time (T_{serv}), and allowance time (T_{allow}):

$$T_{unit} = T_{op} + T_{serv} + T_{allow} \tag{1}$$

Here, the operation time (T_{op}) is the sum of the main machining time (T_m) and the auxiliary time (T_{aux}). The auxiliary time, in turn, consists of two components: working travel time (T_{travel}) and idle travel time (T_{idle}):

$$T_{op} = T_m + T_{aux} = T_m + T_{travel} + T_{idle} \tag{2}$$

where: T_{travel} - working Travel Time: The time spent on the tool's non-cutting movements at a working feed rate (e.g., lead-in, lead-out, and retraction before the next pass); T_{idle} - Idle Travel Time: The time spent on the tool's idle movements in rapid traverse mode (e.g., approaching the work zone from the tool change position and returning to that position).

An analysis of the components in the presented equations shows that the unit time (T_{unit}) can be reduced primarily by decreasing the operation time (T_{op}), since the contribution of the other components of the unit time is significantly smaller.

The operation time (T_{op}) can be reduced in two ways:

1. By decreasing the main machining time (T_m);
2. By ensuring the complete or partial overlapping of passes within the operations.

The reduction of the main machining time (T_m) is possible based on the components of the equation used for its calculation [10]:

$$T_m = \frac{\left(l_a + l_c + l_e\right) \cdot i}{n \cdot S} \tag{3}$$

where: l_a – length of tool approach; l_c – length of cut on the workpiece surface; L_e – length of tool overtravel (exit); n – spindle speed (RPM); S – feed rate; i – number of passes.

The first method for reducing the main machining time (T_m) is to decrease the tool's travel path by shortening its approach (l_a) and exit (l_e) lengths, which are performed at the working feed rate (S). This can be achieved by implementing a proper automated control program that allows for the precise positioning of the cutting tool.

A second approach, aimed at reducing the number of passes (i), involves utilizing the capabilities of the highly rigid technological systems found in modern CNC machine tools. This rigidity allows for the application of intensive cutting conditions, known as “heavy cutting.” These conditions make it possible to minimize deformation (displacement) and vibrations within the system, despite the increased load (force) during the cutting process. This approach also serves to increase the overall efficiency of the technological process by enabling the use of workpieces with minimal machining allowance:

$$T_{c.p.} = \frac{\left(L_{app} + L_{dep} + L_{ret}\right) \cdot i}{n \cdot S} \tag{4}$$

where: L_{app} – tool approach length; L_{dep} – tool exit length; L_{ret} – tool retraction distance for the next pass.

The time for the tool to reposition in the machine's rapid traverse mode is determined by the following equation:

$$T_{idle} = \frac{L_{rapid}}{S_{rapid}} \tag{5}$$

where: L_{rapid} – total length of the tool's rapid traverse movements; S_{rapid} – the rapid traverse rate (speed).

The rapid traverse rate is determined by the machine's design specifications and is typically listed in its technical data sheet. During the technological process, this rate (or idle travel speed) is set to the machine's maximum dynamic capability and is treated as a constant parameter in calculations.

An analysis of the structure of the equation for operation time (T_{op}) shows that the main machining time (T_m) can be reduced through the proper selection of cutting parameters (n, S). This falls within the scope of parametric optimization problems for the formation of elementary surfaces [11-15].

The working travel time (T_{travel}) and idle travel time (T_{idle}) can be reduced by shortening the lengths of cut, approach, tool exit, and rapid traverse, as well as by modifying the tool's travel trajectories during these movements, without compromising the surface formation process. This falls within the scope of the structural optimization of machining cycles for elementary surfaces. A promising approach is to enhance machining efficiency by establishing an optimal structure for the multi-pass cycle used to form the part's elementary surfaces.

As is known, on conventional machine tools, the reduction of main machining time (which constitutes the bulk of the machine time) can be achieved through the following methods [13]:

- Shortening the travel lengths for tool approach (l_a), cutting (l_c), and exit (l_e);
- Reducing the number of working passes (i);
- Intensifying the cutting conditions;
- Overlapping the main passes in time.

As is known, on conventional machine tools, the greatest efficiency in shortening the tool's working travel path is achieved by distributing the length of the cut along the workpiece surface among several cutting tools. For example, machining the surface of a shaft with two tools (Figure 1), compared to machining the same surface with a single tool, results in an approximate twofold reduction in machine time (T_m) [13].

Figure 1 shows the surface of a shaft being machined by two cutting tools. Each tool machines a specific portion of the surface, resulting in the total length of the working pass (L) being divided into two sections.

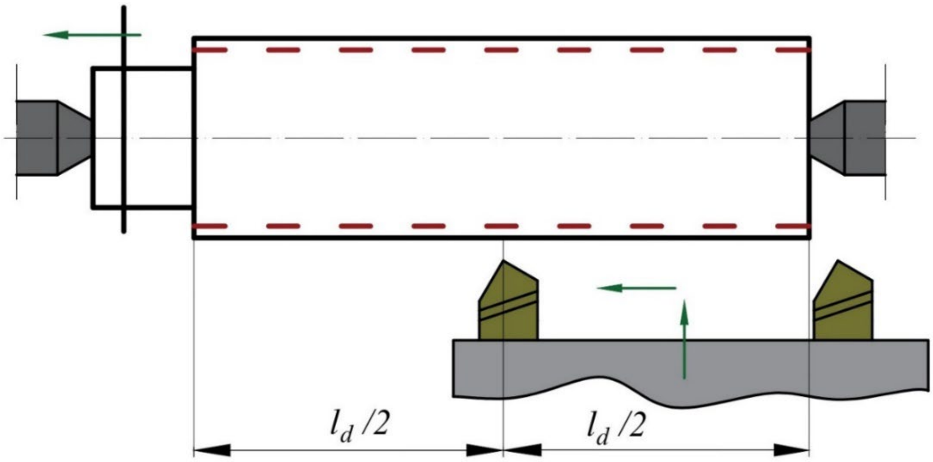


Fig. 1. *Diagram showing the distribution of the length of the machined surface between two cutting tools [13]*

This approach reduces the machine time (T_m) by approximately half, as the tools operate simultaneously, thereby ensuring much faster completion compared to machining the entire surface with a single tool. This technique is highly beneficial for increasing productivity and enhancing the overall efficiency of the machining process.

Shortening the relative travel path of the tool and workpiece can also be accomplished by reducing the tool's approach and exit lengths during the working feed motion. From this, it can be concluded that the traditional practice from conventional machines — that of minimizing the travel path by shortening the tool's approach (l_a), cutting (l_c), and exit (l_e) lengths — should be adapted and applied to CNC machines wherever possible, and the technical challenges required to do so must be resolved. Naturally, any such solution must also be economically viable under the specific production conditions.

The number of working passes (i) depends on the machining allowance on the workpiece, the power of the machine, and the required dimensional accuracy. To reduce the number of passes, it is essential to use near-net-shape workpieces, whose dimensions and form are as close as possible to the finished part. Adaptive control systems that manage elastic deformations within the technological system can also contribute to this objective [14, 15].

Intensifying the cutting conditions is one of the most effective ways to reduce machine time. The selection of these conditions is closely linked to the required accuracy of the parts, the quality of the workpiece's surface layer, and cutting tool life.

The choice of feed rate is limited by the allowable cutting force during machining. This force influences elastic deformations within the technological system and affects the quality of the machined surface.

Cutting speed is limited by the dimensional stability of the cutting tool (tool life) and the amount of heat generated during the cut. Heat causes thermal deformations in the technological system and impacts surface quality.

For this reason, the selection of machining parameters must be based on achieving the required quality in an economically optimal manner.

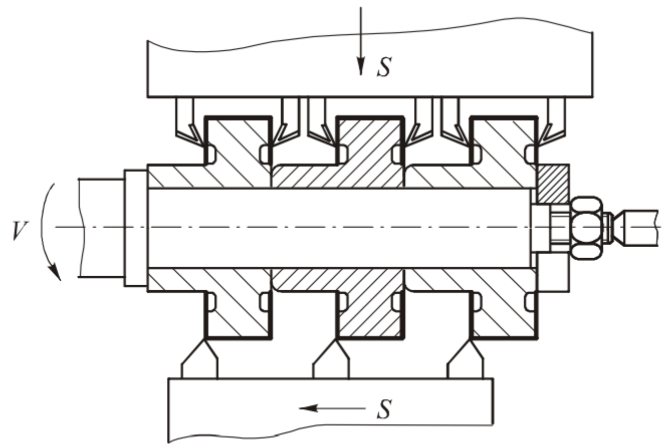


Fig. 2. Overlapping the main passes in time during the multi-tool machining of a gear cluster [16]

Intensifying the cutting conditions offers significant potential for reducing machine time. The use of new high-performance tool materials and advanced tool designs, wider speed ranges for the machine's moving components, and equipping machines with automatic control systems for accuracy make it possible to leverage this potential and increase the productivity of machining processes.

Overlapping the main passes in time is another effective method for reducing machine time. An example of this approach is the machining of a gear cluster with 12 tools on a multi-tool machine, where surfaces of various diameters are processed concurrently (Figure 2).

In this case, the machine time for the entire operation will be equal to the time required for the longest-duration main pass.

The time-overlapping technology allows for main passes to be performed concurrently, which increases the productivity of the production process and significantly reduces the overall machine time. This leads to the efficient utilization of CNC machine resources and enables faster, more complex machining of intricate parts.

Auxiliary time can be shortened in two ways: by directly reducing the time spent on auxiliary movements and by performing auxiliary movements concurrently with main cutting passes.

- The direct reduction of auxiliary time can be achieved through the following methods:
- Reducing the time required to replace a machined workpiece with one from the next batch (part changeover time);
- Increasing the speed of the tool's idle movements (rapid traverse rate);
- Reducing the time spent on the actuation of equipment and fixtures;
- Reducing the time spent on monitoring the progress of the technological process (in-process inspection).

The positioning of some parts can be very time-consuming. In such cases, the use of specialized and universal fixtures reduces setup time. For instance, fixtures composed of standardized components such as supports, plates, and shims ensure part location according to the six-point location principle, thereby reducing time consumption. Additionally, fast-acting pneumatic, hydraulic, and electromechanical clamping systems can be incorporated into these fixtures.

To reduce the time spent on auxiliary movements, modern machine tools are equipped with mechanisms for high-speed travel of their moving components, and automated devices are used to accelerate the transition to the working feed rate.

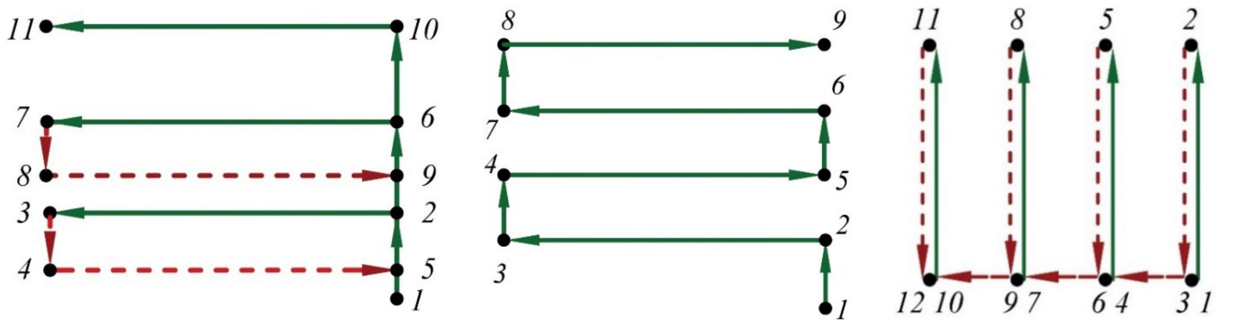
By centralizing all controls in one location, it is possible to reduce the time spent managing the machine and its fixtures. On large machines, control panels are often duplicated, allowing the operator to manage the machine from various working positions.

The reduction of operation time is possible through the complete or partial overlapping of auxiliary passes with main cutting passes. An example of this is the setup on a milling machine with a rotary table (pallet changer), where the next workpiece is loaded onto one position while the previous workpiece is being machined in another. After machining is complete, the table rotates 180°, the next part begins machining, and the previous part is replaced with a new one on the now-idle position [15-19].

The time for a tool change in the magazine, in-process measurement of the workpiece, adjustments to cutting parameters, and other auxiliary actions can be overlapped with the main cutting passes. In the case where auxiliary actions are fully overlapped with the main passes, the operation time becomes equal to the main machining time.

This approach helps to optimize operation time and accelerate the overall production process.

Factors affecting multi-pass machining cycles. When preparing control programs for a CNC machine, the workpiece is divided into machining zones, which are defined based on the requirements for dimensional accuracy, specified surface roughness, as well as the capabilities of the cutting tools and workholding methods. Typically, machining within these zones is categorized into roughing and finishing passes. In this context, the greatest overall processing effort (encompassing control program design and direct on-machine machining) occurs in pocketing areas, which can be open, semi-open, or closed. To improve the efficiency of process planning, standard cycles have been developed, which allow for the removal of the machining allowance within a zone to be performed using various strategies. When creating the toolpath for pocketing areas, standard machining strategies are recommended (Figure 3).



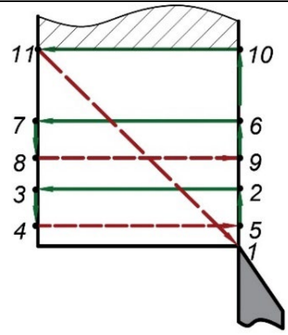
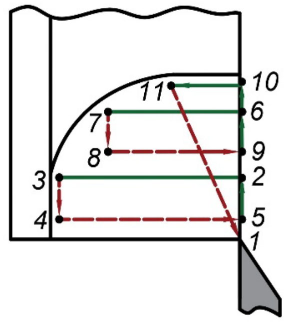
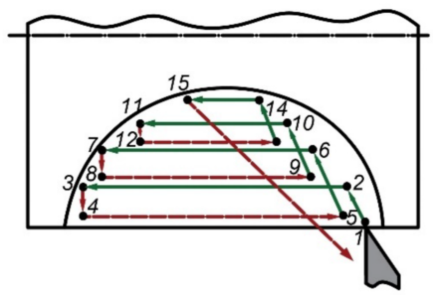
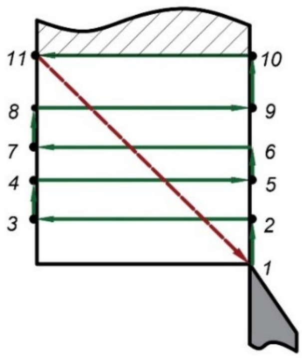
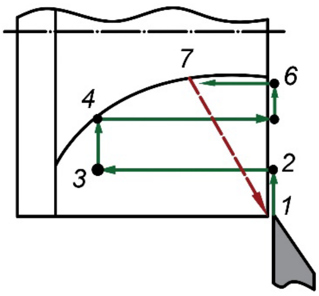
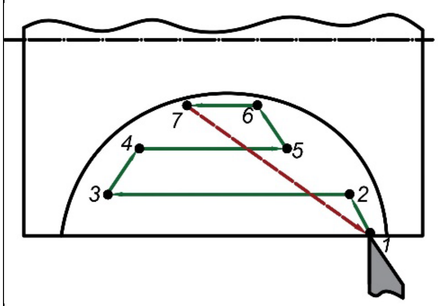
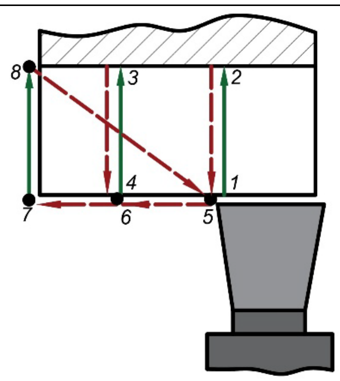
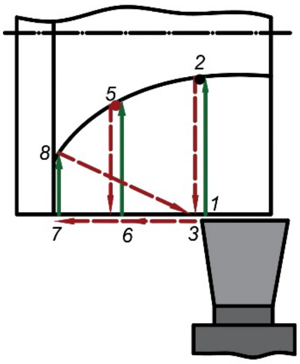
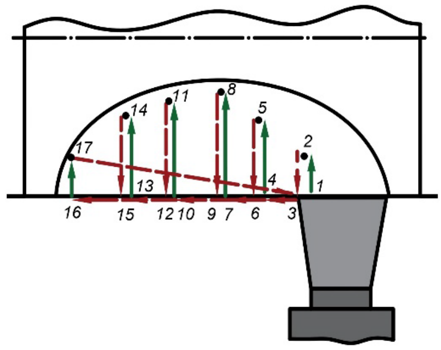
a) b) c)

Fig. 3. Toolpath strategies: a) One-way; b) Zigzag; c) Plunging [19]

The “One-way” strategy is used to maintain a consistent cutting direction for each pass. The "Zigzag" strategy is primarily used for machining deep pockets with end mills, cutting in both directions. The "Plunging" strategy is designated for use with grooving or slotting cutters.

Implementation options for these strategies for various types of pockets are shown in Table 1.

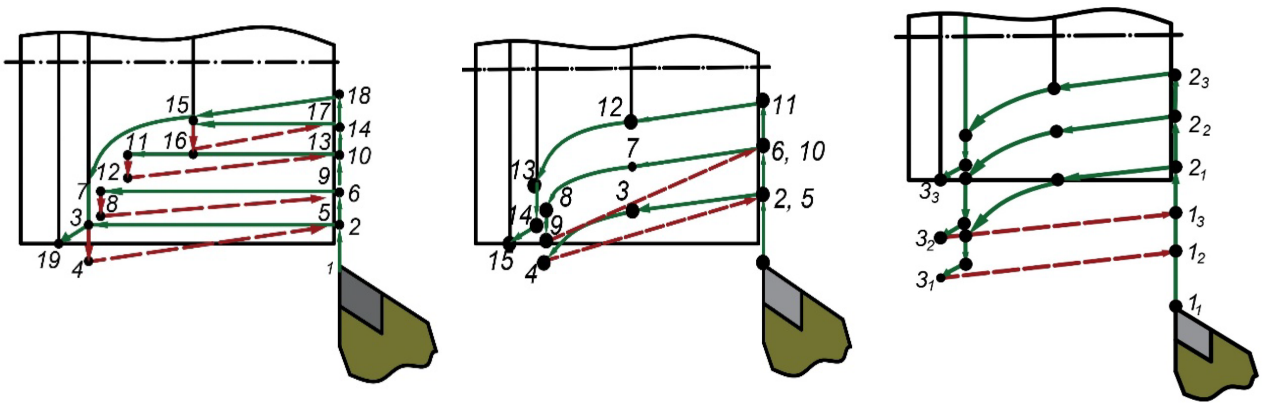
Table 1. Implementation of Machining Allowance Removal Strategies [19]

Strategy for passes	Typical passes in various machining zones		
	Open pocket	Semi-open pocket	Closed-pocket
One-way			
Zigzag			
Plunging			

An analysis of the range of parts produced on CNC machines shows that a significant proportion consists of parts with semi-open pockets. When machining such parts, more complex toolpath strategies than those discussed above are utilized (Figure 4).

Figure 4, a illustrates the machining of semi-open pockets, where an initial roughing pass is followed by a "clean-up" (semi-finishing) pass to enhance surface accuracy. This approach ensures the effective removal of excess material and provides an optimal transition to the subsequent finishing stage. The equidistant (offset) strategy (Figure 4, b) organizes the toolpath trajectories to conform to the workpiece's contour. The contour strategy is formed by repeating tool passes that are equidistant from the machined profile (Figure 4, c). Each working pass, combined with an auxiliary movement, creates a specific trajectory. This trajectory corresponds to a closed loop, within which the tool approaches the part's contour by moving along a straight line from its starting point.

An analysis of the structure of multi-pass roughing and finishing cycles on CNC machines shows that the machining strategies for a zone differ in terms of programming effort, productivity, and machining error. For this reason, "clean-up" passes are implemented to increase the efficiency of the part manufacturing process on CNC machines. Thus, a multi-pass machining cycle is defined by its elements: the strategy for distributing the machining allowance, the presence or absence of a "clean-up" pass, the type of tool used, and the overall machining strategy.



a) b) c)

Fig. 4. Complex toolpath strategies used in machining parts on CNC machines [19]: a) Roughing strategy with a semi-finishing (clean-up) pass, b) Equidistant (offset) strategy, c) Contour machining strategy

As a result of our research, we conclude that the optimization of accuracy, efficiency, and costs during mechanical machining on CNC machines is a fundamental requirement of modern manufacturing. A crucial factor in this optimization is the **toolpath strategy**—the pre-programmed route that the cutting tool follows to shape the machined part. A toolpath strategy is a methodology developed to enhance machining processes for various materials and machine configurations.

Cutting tool wear and its effect on the machining process. Cutting tool wear is one of the key technological indicators of the machining process, directly affecting machining quality, accuracy, cutting tool life, and overall economic efficiency. Particularly in machining on CNC machines, the proper assessment of tool wear is essential for the optimal selection of cutting conditions and for ensuring the uninterrupted continuity of the machining process.

As the cutting tool wears, the geometry of its cutting edge is altered, which leads to an increase in the roughness of the machined surface, a loss of dimensional accuracy, and a degradation of the workpiece's quality characteristics. Different types of wear (such as radial wear, flank wear, and other specialized forms) exert varying influences throughout the tool's service life, and each type holds distinct technological significance.

Cutting tool wear, in particular, serves as one of the primary indicators in the selection of cutting conditions. A review of existing research indicates that several studies have been conducted in this area.

In a study by Asaad Dubaish and colleagues, the influence of cutting parameters—namely cutting speed, feed rate, and depth of cut—on both cutting force and tool wear was systematically investigated during the turning process of AISI 304 stainless steel. The objective of the research was to increase cutting tool life and optimize machining efficiency by determining the optimal relationship among these parameters [20].

In the study, Response Surface Methodology (RSM) was applied, and experiments were performed on a CNC machine tool across 20 different technological configurations. This approach enabled the evaluation of inter-factor interactions and allowed for the prediction of optimal results through the model. Based on the experimental data collected during the trials, multivariate statistical models were developed, and the results were analyzed.

The results of the investigation demonstrated that depth of cut is the parameter with the most significant impact on both cutting force and cutting tool wear. This is because it directly increases the amount of material entering the cutting zone, causing a rise in the mechanical and thermal load on the cutting tool. Conversely, the influence of feed rate and cutting speed was evaluated as being less pronounced, but still significant.

Optimal cutting conditions were observed at a cutting speed of 80 m/min, a feed rate of 0.2 mm/rev, and a depth of cut of 0.4 mm. A maximum deviation of 8% was recorded between the results of experiments conducted with these parameters and the outcomes predicted by the model, which demonstrates that the developed model represents the actual process with high accuracy. This approach is not only an effective tool for determining machining conditions on a scientific basis but also holds practical significance for industrial applications [20].

A study by Alper Uysal, Mirigül Altan, and Erhan Altan analyzed the dynamics of cutting tool wear during the drilling of workpieces made from an SMC (Sheet Molding Compound) composite. The SMC composite material used in the research—composed of 30% glass fiber, 25% polyester, and 45% calcium carbonate—creates a demanding environment for cutting tools due to its high strength and abrasive characteristics [21].

The drilling process was performed under various parameters for cutting speed, feed rate, and point angle. The Taguchi method was applied for the design of experiments and the optimization of results, and the statistical significance of the outcomes was evaluated using analysis of variance (ANOVA). This approach made it possible to assess the influence of different technological parameters on tool wear, both individually and through their interactions.

The analysis determined that feed rate and point angle are the factors that most significantly influence cutting tool wear. An increase in feed rate raises the load on the tool as well as the volume of chips and the amount of heat generated. Simultaneously, the point angle directly affects the tool's wear mechanism by altering the contact area between the tool and the material. Conversely, the influence of cutting speed was found to be minimal. This is attributed to the structural properties of the composite material, as its low thermal conductivity means that an increase in speed does not generate a significant additional thermal load on the tool.

During the experiments, chip volume was selected as a comparative criterion to indirectly assess the load level on the cutting tool. Based on the collected data, a multivariate linear regression model was developed, and a good agreement was observed between the results predicted by this model and the actual experimental data. This indicates that the developed model provides a reliable basis for selecting optimal machining conditions in a practical manufacturing environment [21].

A study by Asaad Ali Abbas investigated the wear intensity of the cutting tool during the turning of St 33 and St 52 grade low-carbon and structural steels using K20 grade carbide cutting tools. The primary objective of the research was to evaluate the influence of various cutting parameters on cutting tool life and machining quality and to determine the optimal machining conditions [22].

The Taguchi method was applied for the design of experiments. The advantage of this method lies in its ability to effectively determine the influence level of factors with a minimal number of trials, thereby facilitating a systematic analysis. Cutting speed, feed rate, and depth of cut were selected as the variable parameters for the experiments, and tool wear was monitored across various combinations of these parameters.

The analysis determined that cutting speed is the technological parameter with the greatest influence on cutting tool wear. This is attributed to the rapid increase in heat generated during cutting; this heat, combined with friction on the tool's working surface, accelerates the thermo-mechanical wear of the tool material. On the other hand, while feed rate and depth of cut also increase the mechanical loads on the tool, their impact was not as pronounced as that of cutting speed.

The research also demonstrated that when machining conditions are properly selected, not only is cutting tool life extended, but the surface roughness of the machined surface is also minimized. This outcome enhances the functional quality of the workpiece and allows for a reduction in the processing allowances required in subsequent technological stages, such as during polishing and assembly. The determination of optimal cutting parameters thus increases manufacturing efficiency from both an economic and a technological perspective [22].

A study by Ming Luo and colleagues investigated the influence of various cutting parameters on cutting tool wear during the milling of the Ti6Al4V titanium-based alloy using coated cutting tools. Although Ti6Al4V is widely used in the aerospace and medical industries, its machining is considered extremely difficult and highly conducive to tool wear due to its low thermal conductivity and high strength. These properties cause the cutting tool to heat up rapidly, resulting in accelerated wear [23].

During the research, the milling process was conducted with coated cutting tools at various parameters for cutting speed, feed rate, and radial depth of cut, and the results were systematically analyzed. The obtained experimental results demonstrated that feed per tooth and radial depth of cut are among the parameters with the most significant influence on cutting tool wear. As these parameters increase, the cutting load and contact area on the cutting tool expand, resulting in more intensive thermal and mechanical wear on the tool's cutting edge.

Furthermore, it was determined that the wear occurring on the cutting tool also affects the tangential cutting force coefficient. As wear increases, the efficiency of the cutting force decreases, which in turn increases the energy consumption of the process while also reducing cutting tool life. In such cases, a noticeable deterioration in surface quality is also observed.

These findings hold great practical significance for selecting optimal cutting conditions when machining titanium-based alloys. The application of appropriate tool coatings and the correct adjustment of tool parameters allows for the preservation of both productivity and surface quality, as well as the extension of tool life during the machining process [23].

In a study conducted by Yeoh Bing Quan, the dynamics of cutting tool wear and the mechanisms of its influence on the process were investigated during the milling of SUS316 grade stainless steel. As a type of austenitic stainless steel known for its high corrosion resistance and strength, SUS316 presents a severe wear challenge for cutting tools during milling from both a thermal and a mechanical standpoint [24].

The research utilized uncoated carbide tools from the company "High Precision Machining Tools" (HPMT) with radii of 20 mm, 40 mm, and 60 mm. These tools were tested at different radial depths of cut (0.1 mm, 0.6 mm, and 1.2 mm). All experiments were performed under constant cutting parameters: a spindle speed of 1700 rev/min, a feed rate of 110 mm/min, and a depth of cut of 4.2 mm. During the machining process, each tool was operated over a total cutting length of 7 meters, and tool wear was recorded at *1*-meter intervals.

During the cutting process, tool wear was measured using a microscope, and vibration was measured with a vibrometer. The collected experimental data were analyzed using Design-Expert software, and optimal technological conditions were determined based on the results.

The analyses revealed that as the level of vibration increases during milling, the wear rate of the cutting tools also increases. This finding is explained by the destructive effect on the tool from unstable kinetic regimes arising at the tool-material interface, particularly the heat generated by friction and micro-impacts. High vibration also causes a deterioration of surface quality and a reduction in dimensional accuracy.

The research results indicate that managing vibration during the milling of stainless steels is of critical importance for both extending cutting tool life and ensuring process stability. In this regard, the selection of appropriate tool geometry and the determination of the optimal width of cut play a vital role in enhancing overall process efficiency [24].

These investigations into the effect of cutting conditions on cutting tool wear demonstrate that cutting tool wear is one of the key indicators that determines the technological and economic efficiency of the machining process. The study of wear characteristics for various material types and machining conditions enables the optimization of both tool life and product quality. In this respect, the results of these practical investigations form the basis for methods that define machinability and are expressed in the form of tool life relationships.

Established methods for determining the machinability of various material types, expressed as tool life relationships in the form $v=f(T,t,s)$ and $v=f(T)$, are based on practical investigations of the wear patterns of various cutting tools, both domestically and foreign-produced. Such relationships define the connection between cutting speed and the rate of tool wear. The indicators used to characterize cutting tool wear include: the size of the crater on the tool's rake face, the width of the flank wear land, and the radial shortening of the tool, among others. The basis for the corresponding tool life relationships should be the type of wear that increases continuously and in the most predictable manner as operating time increases [25, 26, 27].

When machining structural materials with carbide cutting tools, the depth of the crater on the tool's rake face is the first to increase in a highly predictable manner, followed by the width of the wear land on its flank face. Because measuring the width of the wear land on the flank face is more accurate and easier than measuring the depth of the crater on the rake face, researchers prefer to establish tool life relationships based on flank wear. A microscope with a digital scale, the magnifier of a Brinell hardness tester, or other similar instruments are used to measure this type of wear. In this process, the indexable insert (SMP) is removed from the tool holder, placed on the microscope's stage, and the size of the wear land is recorded during visual observation. The results are entered into a table, and when necessary, a photograph of the image is captured.

Radial wear, also known as dimensional wear, is the type of cutting tool wear that is directly related to the dimensional accuracy of the parts. The advantage of using radial wear as a wear criterion stems from its direct correlation with the specified requirements for the surface roughness and accuracy of the machined surface [28].

A characteristic curve of flank wear on the cutting tool is shown in Figure 5. The flank wear curve consists of three distinct regions. The OA section represents the break-in period of the cutting tool's operating life. During prolonged operation of the cutting tool, the rate of increase in flank wear decreases because, as the wear area expands, the tangential contact stresses in this zone are reduced [25, 28].

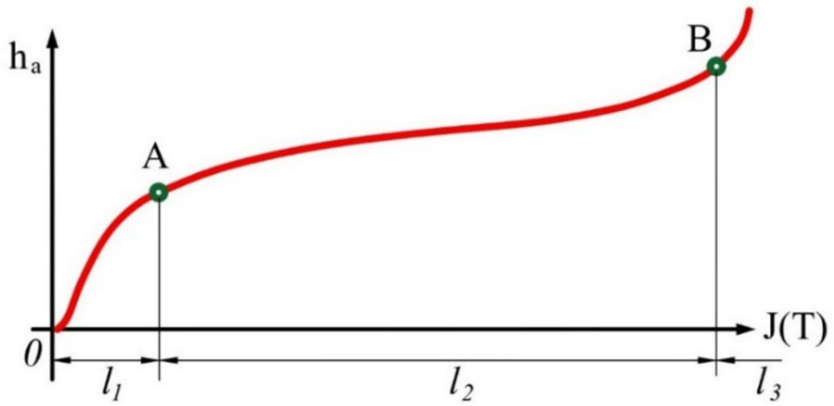


Fig. 5. Characteristic curve for flank wear of the cutting tool [25, 28]:
h_a – total width of the flank wear land on the cutting tool, μm; J(T) – Change in wear intensity over time; l_1 – break-in length (distance traveled by the tool during the initial wear period); l_2 – normal wear length; l_3 – critical wear length (the additional distance before catastrophic wear; the hazardous region)

The AB section characterizes the tool's normal wear period. After point B, the wear curve rises sharply, which indicates a rapid acceleration of wear. The region after point B represents the tool's catastrophic wear stage.

The normal wear period constitutes 85-90% of the specified tool life. An increase in cutting speed leads to a shortening of the wear period. The tool's cutting edges must have geometric parameters that maximize the normal wear period and shorten the break-in period.

Relative and specific wear of the cutting tool at various cutting lengths. The linear relative wear of the cutting tool, $h_{rel.lin.}$, characterizes the intensity of radial wear and is determined by formula (6) [22]:

$$h_{rel.lin.} = \frac{\left(h_r - h_{i.r}\right)\cdot 1000}{l - l_i} \quad \text{mkm/km}, \tag{6}$$

where: h_r – current value of radial (dimensional) wear, μm;

$h_{i.r}$ – initial radial wear, μm;

l – final or current cutting path length, m;

l_i – length of the initial portion of the cutting path, m.

The specific wear on the tool's flank face, Δ_x, is calculated using formula (7) [24]:

$$\Delta_x = \frac{\left(h_a - h_{a.i}\right)}{T - T_{initial}} \quad \text{mkm/min}, \tag{7}$$

where: h_a – current width of the flank wear land, μm;

$h_{a.i}$ – width of the wear land on the cutting tool's flank face at the end of the initial wear period, µm;

T – tool life period; the total or current operating time of the tool, min;

$T_{initial}$ – operating time of the tool during the initial wear period, min.

Relative and specific wear are calculated for the steady-state (normal) wear stage.

Studies indicate that relative wear, a characteristic measure of the intensity of dimensional wear, is a more stable quantity across various cutting path lengths than specific wear, which characterizes the rate of change in the width of the flank wear land. The constancy of the slope of the radial wear curve, $h_r = f(T)$, has also been noted by several other researchers.

Figure 6 presents graphs for a T30K4 grade turning tool, showing the radial wear of the edges (h_r) and the width of the flank wear land (h_a). These graphs were plotted as a function of the cutting path length during the turning of a Steel 45 workpiece with various cutting parameters v, s, and t [27].

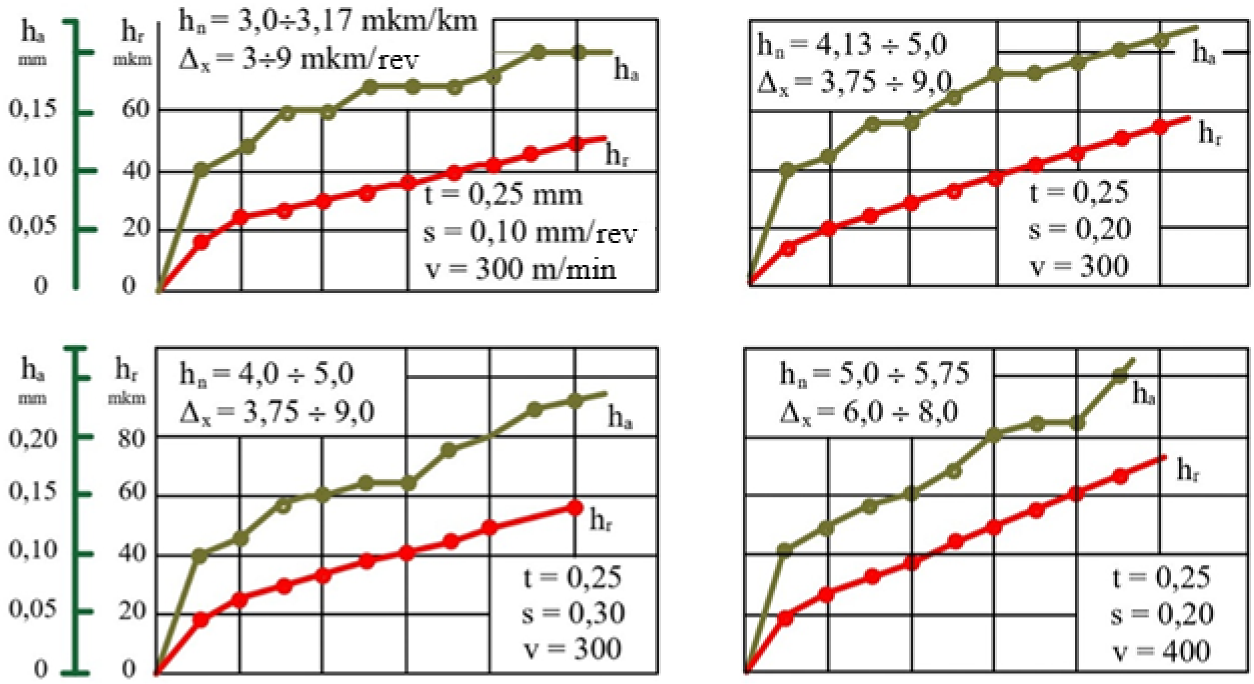


Fig. 6. Dependence of the radial wear and the width of the flank wear land on the cutting path length for a turning tool with a T30K4 alloy insert during the machining of a Steel 45 workpiece [27].

In this case, a more distinct pattern is observed in the $h_r = f(l)$ curves compared to the $h_a = f(l)$ curves.

In all experiments, the break-in period is completed at a distance of l_i = 2000 m. When values of l = 3000, 4000, 6000, 8000, and 10000 m are substituted into formula (6), the value of the linear relative wear ($h_{lin.rel.}$) varies within a very narrow range. Relative wear can be determined most accurately when l = 3000–4000 m.

When the values of cutting time (T) corresponding to cutting lengths of 3000, 4000, 6000, 8000, and 10000 m are substituted into formula (7), Δ_x varies over a much wider range. For example, when t = 0.50 mm, s = 0.10 mm/rev, and v = 300 m/min:

- Relative wear varies from 3.63 to 4.0 µm/km,
- Specific wear varies from 3.75 to 6.0 µm/min.

The presented data indicate that as the cutting path length varies, relative wear, which characterizes the intensity of dimensional wear, is more stable than specific wear, which characterizes the rate of change in the flank wear land width.

The constancy of the slope of the radial wear curve, $h_r= f(T)$, has also been observed by a number of other researchers [25, 28, 29, 30]. Thus, the methodology presented in this paper will enable cutting conditions to be determined more efficiently and reliably in practical manufacturing processes.

Conclusions.

1. Toolpath strategy plays a fundamental role in the optimization of the machining process on CNC machine tools. A well-planned toolpath facilitates the reduction of machining times, minimizes cutting tool wear, and ensures the achievement of high surface quality.
2. The research shows that types of cutting tool wear (particularly radial and specific wear) directly affect the technological and economic efficiency of the machining process. Radial wear indicators are more stable and reliable, and therefore can be adopted as a primary criterion for determining cutting conditions.
3. The selection of optimal cutting conditions has a significant impact on increasing machining productivity and extending cutting tool life. The analysis of cutting tool wear, particularly in its radial form, allows for a more precise determination of these conditions.
4. The efficiency of technological processes on multitasking CNC machine tools can be significantly increased through technical approaches such as optimizing tool motion schemes, executing passes in parallel, and reducing machine time.
5. The optimal structure of multi-pass machining cycles not only enhances the efficiency of process planning but also facilitates the more targeted development of control programs.
6. In the context of the application of advanced CNC systems and low-waste production technologies, toolpath and cutting condition strategies serve as key factors that create a technological advantage for manufacturing enterprises in the modern competitive environment.

The results obtained demonstrate the importance of a comprehensive approach—which considers the toolpath, cutting conditions, and cutting tool wear in combination—to ensure productive and high-quality machining on CNC machine tools.

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