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PRACTICAL RECOMMENDATIONS FOR STAINLESS STEEL TURNING

***Abstract**: The article discusses the current problem of increasing the efficiency of metalworking by choosing the optimal cutting modes and evaluating the wear resistance of indexable inserts during stainless steel turning. Austenitic stainless steels, with their high strength, toughness, and heat resistance, place increased demands on cutting tool, making their machining particularly important for modern production.*

The theoretical part of the work allowed us to reveal the physical and mechanical properties of stainless steel, determine the types and mechanisms of wear of the cutting tool, and analyze the influence of the design features of the indexable inserts and cutting conditions on the wear process. Special attention was paid to the effect of cutting speed, feed rate, and cutting depth on the intensity and nature of edge wear.

During the experimental part, specific cutting modes were selected, tests were conducted on a CNC lathe, and modern methods of wear measurement and analysis were used, including optical microscopy and digital indicators.

It has been established that the gentle mode provides maximum durability of the cutting tool, but it is characterized by low productivity. The intensive mode, on the other hand, produces high metal removal, but it is accompanied by rapid destruction of the cutting edge. The most effective mode was the medium mode, which provided an optimal balance between cutting tool durability and machining speed. Based on the data obtained, practical recommendations were formulated for production conditions, including requirements for cutting tool selection, cooling, and control conditions.

The paper also calculates the durability of the cutting tool using empirical models and justifies the intervals for replacing the tool in order to reduce downtime and increase the reliability of the process.

The obtained results can be applied in the practice of machine-building enterprises during the development and adjustment of technological processes for difficult-to-machine material turning. The proposed recommendations allow for increased production efficiency, extended cutting tool life, and reduced production costs.

Key words: *turning, stainless steel, wear, cutting tool, cutting modes, indexable insert.*
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1. Introduction

Metal cutting is one of the leading processes in engineering and metalworking enterprises. Among the materials that can be machined, stainless steel stands out for its high strength, corrosion resistance, and a number of specific characteristics that make it difficult to machine [1]. These features include increased viscosity, susceptibility to work hardening, and low thermal conductivity, which can lead to significant heat exposure on the cutting tool.

In practice, this results in rapid wear of the cutting edges, poor surface quality, increased energy consumption, and reduced equipment performance. In these conditions, it is especially important to choose the right cutting tool and optimal cutting conditions. The most widely used tool in modern practice is the indexable inserts, which allows you to quickly replace the cutting part of the tool without removing the tool holder from the machine. However, their effectiveness is largely determined by their resistance to wear under specific cutting conditions.

In this regard, the problem of increasing the wear resistance of cutting tools during stainless steel turning is relevant not only in terms of improving product quality, but also from the standpoint of economic efficiency, reducing equipment downtime, and rational use of cutting tool.

The relevance of this topic is due to the need for a systematic analysis of the wear processes of indexable inserts under various cutting conditions, which will allow for the development of practical recommendations for selecting optimal machining parameters and improving overall production efficiency. Modern research in this field confirms that cutting parameters (speed, feed, and depth), the geometry of the insert, and its coating have a significant impact on the intensity of wear, the nature of cutting edge failure, and the service life of the cutting tool [2-3].

The purpose of this work is to determine the wear patterns of indexable inserts during stainless steel turning, taking into account various cutting modes, as well as to establish optimal machining conditions that ensure minimal wear of the cutting tool while maintaining quality and productivity.

To achieve this goal, the following tasks are solved:

1. To study the features of stainless steel machining and analyze the main types of cutting tool wear;
2. Classify indexable inserts by material, geometry, and coating type;
3. To justify the choice of the machined material and experimental conditions;
4. To experimentally study the wear resistance of the inserts under various turning modes;
5. To conduct a comparative analysis of the results obtained;
6. To formulate the conclusions and recommendations for improving the durability of cutting tools.

The object of research is the process of stainless steel turning using indexable inserts.

The subject of the study is the wear of the cutting edge of the inserts, depending on the cutting mode parameters.

The methodological basis of the work is a set of theoretical principles in the field of metal cutting processes, tool science, and tribology, as well as experimental research that includes measurements and analysis of cutting tool wear [4-7].

The practical significance of the work lies in the possibility of using the obtained results to increase the durability of cutting tool in production, to select the most rational cutting modes for stainless steel turning, to reduce the cost of cutting tools, and to increase the stability of the technological process [8-10].

This research aims to solve an important problem: extending the service life of cutting tool without compromising the quality of machining, which is especially important in high-precision and mass production environments.

2. Theoretical foundations of stainless steel turning and cutting tool wear

2.1. Properties of stainless steel and their impact on the cutting process

Stainless steel is a broad group of iron-based alloys that are primarily alloyed with chromium (at least 10.5%) and other elements such as nickel, molybdenum, titanium, and others, which give it high corrosion resistance and strength. The main difference between stainless steels and carbon and low-alloy steels is their ability to form a thin but durable oxide film on their surface, which prevents corrosion even in aggressive environments. These advantages make this material widely used in the engineering, chemical, food, medical, and other industries.

However, despite its many advantages, stainless steel is a difficult material to work with. This is due to a number of its physical, mechanical, and thermochemical properties, which directly affect the cutting process and the intensity of wear on the cutting tool.

Firstly, stainless steels have a high viscosity. This leads to the formation of long continuous chips and worsens the conditions for evacuating the cut layer from the cutting zone. Violation of the chip breaker contributes to its secondary cutting and repeated contact with the cutting edge, increasing its thermal and mechanical stress.

Secondly, many stainless steel grades are prone to work hardening. When the surface layers of metal are deformed by the cutting force, the structure is compacted and the treated layer is hardened. This phenomenon leads to an increase in the hardness of the material in the cutting zone, creating additional stress on the cutting tool, accelerating its wear, and increasing the likelihood of microcracks appearing on the cutting edge.

The third important feature is the low thermal conductivity of stainless steels. During cutting, most of the heat is concentrated in the contact zone between the workpiece and the cutting tool. In the absence of sufficient heat dissipation, the temperature of the cutting edge increases, which can lead to thermal damage to the cutting layer, especially when using carbide or ceramic inserts without proper cooling.

In addition, the increased ductility of stainless steels makes them prone to build-up on the cutting edge. Such build-up impairs surface quality, destabilizes the cutting mode, changes the geometry of the cutting tool, and becomes one of the causes of irregular wear.

It is also worth noting the presence of abrasive inclusions in certain types of steel (such as those containing sulfur and manganese), which contribute to the abrasive wear of the cutting edge. This is especially important when machining steel produced by secondary melting.

2.2. Design and materials of indexable inserts

Indexable inserts are an integral part of modern metal cutting technology. Their use has significantly simplified the machining process, made it possible to standardize the cutting tool fastening system, and improve the operating and maintenance conditions of the cutting tool on the machine. The design of the insert allows you to avoid sharpening the cutting tool after each operation, but simply replace the worn-out insert with a new one or flip it to the other side, which is particularly effective in mass production.

From a design perspective, a indexable insert is a compact piece of hard material with multiple (usually 2 to 8) cutting edges. The insert is attached to the tool holder using a mechanical clamp, screw, or clamping wedge. The main types of fastening are screw, lever-cam, and spring. This system provides fast and reliable fastening, reduces the likelihood of vibrations, and allows the use of cutting tool in harsh environments.

The shape of the inserts varies depending on the application and includes square, rhombic, triangular, hexagonal, and octagonal options. The geometry of the cutting part also varies in terms of apex angles, tip radii, chamfers, grooves for chip breaking, and other elements. The design of the inserts is based on specific cutting conditions, such as turning, boring, finishing, or roughing, as well as intermittent or continuous cutting.

Modern indexable inserts are based on hard alloys, which are composite materials that combine the hardness and wear resistance of carbides with the strength of a metal binder. The most common alloys include tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC), and combinations thereof. Cobalt (Co) is traditionally used as a binding material, which provides the necessary plasticity and resistance to fracture under impact loads.

Modern trends in instrumental materials science have led to the development of coatings that are applied to the surface of inserts using CVD (chemical vapor deposition) or PVD (physical vapor deposition) methods. Coatings made of titanium nitride (TiN), aluminum nitride (AlN), aluminum oxide (Al_2O_3), and titanium carbonitride (TiCN) significantly increase the heat resistance and wear resistance of cutting tools. In addition, they reduce the coefficient of friction, facilitate easier chip removal, and protect the cutting tool from oxidation and thermochemical degradation.

Inserts designed for stainless steel machining are usually made of carbide compositions with increased heat resistance and chemical resistance. The properties of steel that is prone to hardening and build-up dictate the need for inserts with a special chip-breaking shape, improved heat dissipation, and a durable, wear-resistant coating.

The design of the indexable insert also takes into account the shape of the clearance angle and rake angle, which affect the cutting tool's resistance to vibrations, the nature of the chips, and the overall load on the cutting edge. The correct choice of cutting tool geometry angles is a crucial factor in machining stainless steels.

Thus, the design and materials of the indexable inserts are determined not only by their versatility, but also by their ability to withstand extreme cutting conditions. The successful operation of a cutting tool when stainless steel turning depends directly on the combination of geometry, fastening method, carbide structure, and coating properties. This is what makes the choice of indexable inserts a critical step in the machining technology design process.

2.3. The main types of cutting tool wear

During the cutting process, the cutting tool is subjected to intense impact from the material being machined, high temperatures, friction, and shock loads. Over time, these effects lead to a gradual deterioration of the cutting edge geometry and the functional properties of the cutting tool, a process known as wear. Wear of the cutting tool is an inevitable but highly undesirable phenomenon, as it negatively affects the quality of the machined surface, increases the cutting force, increases the temperature in the cutting zone, reduces the accuracy of machining, and causes premature failure of the cutting tool.

Wear is the result of a complex of mechanical, thermal, chemical, and tribological processes occurring at the tool-workpiece-shavings interface. Based on the nature of the manifestation and the location of the wear, there are several main types of cutting tool wear.

1. *Abrasive wear.* It occurs when the solid inclusions of the material being machined rub against the surface of the cutting tool. It is especially pronounced when machining steels with a high content of carbides or abrasive particles. Abrasive wear manifests itself in the gradual wear of the cutting tool material on the flank and rake faces. For carbide inserts with low bond strength, it can be critical even in the initial stages of cutting.

2. *Adiabatic (diffusion) wear.* It occurs as a result of atomic diffusion between the cutting tool material and the workpiece being machined at high temperatures. This is especially true when stainless steel turning, where the temperature in the cutting zone reaches 800-1000 °C, and the contact between the materials is prolonged. As a result, the cutting tool loses its alloying elements, the cutting layer structure is destroyed, and the edge loses its strength.

3. *Chemical (oxidative) wear.* It occurs when oxygen, coolant vapor, or aggressive steel components are exposed to the hot surface of the cutting tool. Oxidation zones form on the flank and rake faces, accelerating overall wear. It is especially dangerous when cooling is insufficient or when cutting without cutting fluid.

4. *Adiabatic shift and thermo-fatigue wear.* Turning with intermittent cutting or variable load causes cyclic temperature fluctuations in the cutting zone. These cycles lead to the accumulation of microcracks, fatigue damage, and edge chipping. This is typical when working with hard materials, including stainless steels.

5. *Adhesive wear.* It occurs when particles of the material being machined stick to the cutting edge. These particles are then detached along with fragments of the cutting tool itself, especially in areas of local overheating. This creates a so-called "edge build-up," which may temporarily improve cutting performance, but can lead to uneven wear and damage to the insert.

6. *Mechanical microchipping.* It is most often caused by insufficient strength of the cutting tool material, errors in cutting mode settings, or vibrations. It manifests itself in the form of chipping of the cutting edge. In carbide inserts, this can be caused by internal stress, uneven load distribution, or overheating.

7. *Plastic deformation of the cutting edge.* This occurs when working at high temperatures and significant loads, when the cutting tool loses its shape without breaking. This leads to changes in the edge geometry and a loss of cutting efficiency. This type of wear is more common in inserts that do not have a heat-resistant coating or operate at extreme temperatures.

In practice, these types of wear are rarely isolated. As a rule, the cutting tool experiences a combined effect, in which one mechanism prevails and the others accompany it. For example, when stainless steel turning, a combination of abrasive and adhesive wear, combined with a thermo-fatigue effect, is typical.

The degree and nature of wear are assessed visually and using measuring instruments such as microscopes, profilometers, and templates. The criterion for limiting wear is usually the width of the worn area on the flank face, at which point further use of the insert becomes impractical or dangerous for the workpiece and the machine.

Knowledge of the mechanisms and types of cutting tool wear allows you not only to choose the correct cutting modes, but also to predict the behavior of the cutting tool during machining, as well as to replace it in a timely manner, avoiding accidents and defects.

2.4. Influence of cutting modes on the wear resistance of the cutting tool

Cutting modes are a set of parameters that determine the conditions under which the cutting tool interacts with the material being machined. These include the cutting speed, feed rate, cutting depth, as well as the presence or absence of cooling (cutting fluid), the type of material being machined, and its condition. The quality of the resulting surface and the service life of the cutting tool depend largely on the correct modes. This is especially important when difficult-to-machine material turning, such as stainless steel.

Each cutting mode has a specific effect on the amount of wear and the nature of the cutting edge failure:

1. *Cutting speed.* This parameter has the greatest impact on the thermal condition of the cutting zone. As the cutting speed increases, the temperature in the tool-workpiece-shavings contact rises sharply. In case of insufficient thermal conductivity of the cutting tool material (or in the absence of cooling) this leads to the

intensification of thermal and diffusion wear. At high speeds, the insert coatings are particularly affected, as they lose their strength when overheated, which accelerates edge chipping. However, at very low speeds, the opposite is true, as build-up formation and unstable cutting become more likely. Therefore, in each case, there is an optimal range of speeds that ensures a balance between performance and durability.

2. *The feed rate.* The feed rate affects the amount of material cut per unit of time and, consequently, the mechanical load on the cutting edge. Increased feed values increase the cutting force, which can lead to chipping or plastic deformation of the cutting material, especially in finishing operations. On the other hand, if the feed rate is too low, the effect of work hardening increases, the chips become unstable, and the wear becomes chaotic. When stainless steel machining, it is especially important to avoid sudden reductions in feed rate to minimize work hardening and abrasion of the hardened layer.

3. *Cutting depth.* The cutting depth determines the volume of the removed layer and the contact area between the cutting tool and the workpiece. As the depth increases, the load on the cutting tool, including its lateral and support faces, increases. This contributes to an increase in temperature, vibrations, and plastic deformation of the cutting tool. However, in rough operations, using a moderately high depth can be cost-effective if it reduces the overall number of passes.

4. *Application of cooling and lubricating fluids.* The use of cutting fluid helps to reduce the temperature in the cutting zone, reduces friction, prevents the build-up formation, and slows down chemical wear. When stainless steel turning, the use of emulsions and synthetic compounds with active additives is particularly effective. However, in some high-speed modes (for example, dry cutting on modern machines), the use of cutting fluid may be limited or replaced by a minimal dosing system. In these cases, high-quality insert coatings are required.

5. *The combined effect of the modes.* It is important to understand that speed, feed, and cutting depth do not operate in isolation. Changing one parameter leads to a redistribution of loads and thermal balance, which affects the behavior of the cutting tool. For example, increasing the feed rate while maintaining the speed can cause a sharp increase in cutting forces, while simultaneously reducing the depth can partially compensate for this effect.

To increase the wear resistance of the cutting tool in real conditions, it is necessary to select cutting modes by trial and error, taking into account the type of steel being machined, the characteristics of the machine, and the conditions of fastening. The geometry of the insert, the presence or absence of a micro-chamfer, the type of chip breaker, and the coating of the cutting tool also play an important role.

The wear resistance of the cutting tool during stainless steel turning is largely determined by the choice of an optimal combination of cutting modes. Proper adjustment of these parameters not only extends the service life of the cutting element, but also ensures stable process performance, high productivity, and minimal defective parts.

3. The methodology of research and testing of indexable inserts

3.1. Description of the machined material and its characteristics

In this study, AISI 321 stainless steel, one of the most common austenitic steels used in mechanical engineering, chemical and food industries, construction, and the production of equipment operating in aggressive environments, was selected as the material to be machined. This steel grade is widely used in industry due to its high level of corrosion resistance, good weldability, and satisfactory mechanical properties.

AISI 321 stainless steel belongs to the category of heat-resistant and high-temperature materials. It is alloyed with chromium (approximately 17-19%), nickel (9-11%), and also contains titanium (up to 1%), which stabilizes the structure and prevents intergranular corrosion. Due to its austenitic structure, this alloy retains its strength and ductility over a wide temperature range, up to 600 °C.

Below are the main physical and mechanical characteristics of AISI 321 stainless steel:

1. Density: ~7.9 g/cm³;
2. Tensile strength: 500-750 MPa;
3. Yield strength: 200-300 MPa;
4. Relative elongation: at least 40%;
5. Brinell hardness: 170-200;
6. Coefficient of thermal conductivity: 14-16 W/(m×K);
7. Coefficient of linear thermal expansion: 16-18×10^{-6} 1/°C;
8. Melting point: 1400-1450 °C.

One of the features of this steel that makes it difficult to process is its low thermal conductivity. During cutting, heat is not dissipated into the workpiece or chips, but is concentrated in the cutting zone, leading to overheating of the cutting tool. This is especially critical in high-speed machining, where the cutting edge temperature can reach 800 °C or higher.

Another important factor is the high plasticity and tendency to work hardening, which means that the surface layer of the workpiece becomes harder during the cutting process. The hardened layer provides additional abrasive and mechanical impact on the cutting edge, increasing its wear rate. Machining without proper cooling also increases the risk of build-up formation on the cutting tool edge, which can disrupt the stability of the cutting process.

In addition, this steel grade has a high chemical activity at high temperatures, which can contribute to the diffusion destruction of the cutting layer of the tool, especially when using cutting tools based on carbide alloy without a resistant coating.

Due to its properties, AISI 321 stainless steel is considered a difficult-to-process material, which makes its use in research justified and practically significant. Studying the behavior of a cutting tool during the turning of this particular steel allows us to simulate conditions that are close to the most difficult conditions in real production.

In this work, AISI 321 stainless steel samples were prepared as cylindrical workpieces with a diameter of 45 mm and a length of 150 mm. The workpieces were annealed and pre-machined to ensure stability during subsequent finishing turning.

The choice of this steel grade as the object of machining is due to its relevance for industrial tasks, as well as its pronounced properties that significantly affect the wear resistance of the cutting tool. This creates the necessary conditions for an objective assessment of the durability of indexable inserts under various cutting conditions.

3.2. Selection of cutting tools and cutting modes

The selection of the cutting tool and its operating modes is one of the key stages of the turning process. The correct selection of the cutting tool not only affects the productivity and quality of the machining, but also the service life of the indexable insert, especially when working with difficult-to-process materials such as stainless steel.

In this work, cutters with mechanical fastening of indexable inserts were used as a cutting tool. This is due to the versatility of such cutters, their high positioning accuracy, the ease of replacing a worn-out insert without removing the tool holder, and their widespread use in industrial practice.

Characteristics of the cutting tool used:

1. Tool holder type: external turning cutter with a square cross-section of 20×20 mm;
2. Fastening system: screw;
3. Insert model: CNMG 120408-PM (ISO standard);
4. Geometry: a rhombic insert with an apex angle of 80°;
5. Insert material: WC-Co-based hard alloy;
6. Coating: multi-layer PVD coating based on TiAlN + Al_2O_3;
7. Manufacturer: Sandvik Coromant (similar products: Walter, Seco, Iscar).

The choice of this geometry and coating is based on the following reasons:

1. The CNMG shape allows for even distribution of loads during turning with variable feeds and depths;
2. The presence of eight cutting edges makes the insert cost-effective and convenient for mass production;
3. The TiAlN + Al_2O_3 coating effectively protects the insert from oxidation, diffusion, and thermal wear at high temperatures;
4. The optimal hardness and strength of the carbide alloy ensure reliable operation on stainless steels with minimal risk of chipping.

The cutting modes were selected based on the properties of AISI 321 stainless steel, the manufacturer's recommendations for the cutting tool, and the requirements for experimental reliability. All modes were divided into three groups: minimum (gentle), medium (nominal), and maximum (intensive), which allowed us to evaluate the impact of parameter changes on cutting tool wear.

Mode I (minimum): cutting speed of 80 m/min; feed rate of 0.15 mm/rev, and cutting depth of 0.5 mm.

Mode II (medium): cutting speed of 120 m/min; feed rate of 0.25 mm/rev, and cutting depth of 1.0 mm.

Mode III (maximum): cutting speed of 180 m/min; feed rate of 0.35 mm/rev, and cutting depth of 1.5 mm.

In all modes, external longitudinal machining was used on a numerically controlled (CNC) lathe of the Haas TL-1 model, using an emulsion as a cooling and lubricating fluid. The cutting fluid was sprayed directly into the cutting zone to provide cooling and prevent build-up formation.

Thus, the selected cutting tool and cutting parameters allow for an objective assessment of the cutting edge's durability when varying the modes. During the analysis, special attention was paid to the wear pattern, the rate of wear accumulation, the stability of cutting, and the nature of insert failure.

This method of selecting cutting tools and modes is widely used in mass and small-scale production, as well as in laboratory tests, which makes the research results suitable for generalization and further practical interpretation.

3.3. Equipment and methods of wear measurement

In order to accurately assess the wear resistance of indexable inserts during the stainless steel machining, it is important not only to ensure stable cutting conditions, but also to use precise and reliable methods for measuring the amount and nature of wear on the cutting tool. This study used a set of equipment that provides control over machining parameters and objective measurement of wear on the inserts.

The main machining of workpieces was carried out on the Haas TL-1 CNC lathe, which is characterized by stable operation and the ability to adjust the required range of modes. To ensure an optimal thermal regime during the cutting process, a centralized supply of water emulsion was used to maintain a stable temperature and pressure in the area where the cutting tool contacted the workpiece. The coolant also helped to remove shavings, reduced friction, and prevented overheating of the cutting edge.

An optical microscope, MBS-10, was used to monitor the condition of the cutting tool, allowing for visual assessment of the cutting edge for cracks, chips, wear, and other defects. Wear measurements were carried out using a measuring system with a digital indicator, the ICH-10, which provides high accuracy in determining the width of the wear zone on the flank face and the depth of wear on the rake face. In addition, a digital microscope with a magnification of up to 1000 times was used to capture small defects and document the cutting area.

The geometry of the cutting tool was measured before and after operation using calipers and micrometers. During the experiment, after each turning pass or at regular intervals, the cutting tool was removed and the wear was measured with an accuracy of 0.01 mm. According to industrial standards, the limiting wear value at which a insert is considered unsuitable for further use is 0.3 mm. This value was adopted as the boundary criterion for durability.

In addition, the rank face of the cutting tool was studied, with special attention paid to the formation of craters, traces of thermal damage, changes in the geometry of the chip breaker, and other features that indicate the type of wear – abrasive, adhesive, diffusion, etc. In addition to quantitative measurements, a visual analysis of cutting edge damage was performed, including spalling, microcracks, and signs of plastic deformation. Each insert was individually marked, and all data was recorded and compared with the cutting conditions in which it was used.

The condition of the cutting tool was monitored regularly, as the cutting length accumulated, which allowed for the construction of a wear curve as a function of operating time and the identification of the rate of wear under different operating conditions. All the data obtained, including wear values, cutting modes, machining time, and photos of wear zones, were recorded as observations were made. This ensured a high degree of accuracy when comparing the inserts with each other and made it possible to perform a statistically sound analysis of the cutting tool's behavior.

The methods used in the experiment are based on the requirements of GOST 19265-73, as well as on modern approaches to assessing the durability of cutting tools in industrial production. The use of both visual inspection and numerical measurements allows for a comprehensive understanding of wear, taking into account both quantitative and qualitative changes in the cutting edge, and drawing conclusions about the impact of cutting conditions on the service life of the cutting tool.

The use of reliable measuring equipment, combined with a consistent control methodology, ensured the objectivity and reproducibility of the results, allowing for an effective assessment of the wear resistance of the cutting tool.

3.4. Conditions and procedure of the experiment

The experimental part of the work was aimed at determining the effect of various cutting modes on the wear resistance of indexable inserts during stainless steel turning. To achieve objective results, stable and reproducible machining conditions, a sequence of actions, and a fixed procedure for monitoring the wear of the cutting tool were provided.

Before the experiment, the workpieces were pre-machined and degreased to eliminate the influence of surface contaminants and residual stresses on the test results.

The cutting tool used was an external turning cutter with a mechanical fastening of CNMG 120408-PM indexable inserts made of TiAlN + Al_2O_3 hard alloy. Each insert was used in only one mode until it reached its wear limit.

An aqueous emulsion was used to cool and lubricate the cutting area, which was continuously supplied through a centralized cutting fluid system. Maintaining a constant pressure and jet direction ensured stable temperature conditions and improved the evacuation of shavings.

The experimental procedure included the following steps:

1. Fixing the workpiece in the machine chuck and mounting the cutting tool at the height of the rotation axis;
2. Setting the selected cutting mode;
3. Turning for a length of 150 mm with continuous supply of cutting fluid;
4. Stopping the machine, removing the insert, and measuring it;
5. Recording wear values and visual defects using a microscope and digital measuring equipment;
6. Repeat the machining with a new insert using the same mode (at least three times for statistical reliability);
7. Transition to the next cutting mode as the measurement series is completed.

Three sets of parameters specified in section 3.2 were used to evaluate the effect of cutting modes.

Wear measurement was performed after each machining of a 150 mm long workpiece. When the wear limit of 0.3 mm was reached, the insert was decommissioned. During each measurement, not only the wear width was recorded, but also the nature of the damage: uniform wear, crater formation, spalling, and thermal cracks.

Since high experimental accuracy requires statistical reliability, each test was repeated at least three times on new inserts under identical conditions.

This allowed us to average the data and eliminate the influence of random factors.

The experiment was organized according to the principles of comparability, repeatability, and reproducibility, which ensured the high quality of the collected data. The obtained results formed the basis for subsequent analysis and allowed us to establish the patterns of wear under various cutting conditions.

4. Analysis of the experimental results

4.1. Dynamics of cutting tool wear under different cutting conditions

Based on the conducted experimental studies, it was found that cutting modes have a significant impact on the nature and rate of wear of indexable inserts during stainless steel turning. The main criterion for assessing wear resistance was the wear width on the flank face of the cutting tool, measured at regular intervals during machining. The wear dynamics were monitored by the cutting length at each mode, which allowed for the analysis of comparative dependencies and the identification of characteristic features of the cutting tool behavior.

The average wear width values (in mm) after each 150 mm pass are as follows:

a) Pass number – 1; cutting length – 150 mm; wear (mode I) – 0.05 mm; wear (mode II) – 0.08 mm; wear (mode III) – 0.12 mm.

b) Pass number – 2; cutting length – 300 mm; wear (mode I) – 0.09 mm; wear (mode II) – 0.15 mm; wear (mode III) – 0.21 mm.

c) Pass number – 3; cutting length – 450 mm; wear (mode I) – 0.13 mm; wear (mode II) – 0.21 mm; wear (mode III) – 0.29 mm.

d) Pass number – 4; cutting length – 600 mm; wear (mode I) – 0.18 mm; wear (mode II) – 0.28 mm; wear (mode III) – 0.36 mm (limiting wear).

e) Pass number – 5; cutting length – 750 mm; wear (mode I) – 0.23 mm; wear (mode II) – 0.34 mm (limiting wear).

f) Pass number – 6; cutting length – 900 mm; wear (mode I) – 0.28 mm.

g) Pass number – 7; cutting length – 1050 mm; wear (mode I) – 0.32 mm (limiting wear).

As can be seen from the data, wear increases slowly and evenly when the machine is operated in a gentle mode (mode I). At the same time, the cutting tool remains operational up to 1050 mm of cutting length, which corresponds to the highest durability. The wear is mostly uniform, with no pronounced chipping or thermal damage, and the coating structure lasts longer than in other modes.

In the medium cutting mode (mode II), wear increases more rapidly. By the fourth pass (600 mm), the wear reaches a critical value of 0.28 mm, and by the fifth pass (750 mm), it exceeds the permissible limit. Signs of diffusion and thermal wear were detected: local areas of darkening of the coating, areas of crater formation on the rake face, and small chips at the edges.

The most intensive wear was recorded at the maximum cutting mode (mode III). After the second pass (300 mm), the wear value reaches 0.21 mm, and after the third pass, it approaches the critical level. After 450 mm of cutting, the tool fails: the edge breaks, chips off, and the cutting part loses its shape. In some cases, the edge was chipped to a length of up to 0.5 mm, which confirms that prolonged operation at extreme parameters is not allowed.

Analysis of the experimental data suggests a non-linear increase in cutting tool wear. There is a sharp increase in wear, especially in the medium and maximum modes. This is due to the accumulation of heat, the activation of diffusion processes, and the degradation of the hard coating on the cutting tool.

It has been established that an increase in cutting speed, feed rate, and depth leads to accelerated wear of the cutting tool. The gentle mode allows for the greatest durability, but requires more machining time. The medium mode provides a reasonable compromise between performance and cutting tool life. The intensive mode provides maximum material removal speed, but it drastically reduces the service life of the insert, increasing the risk of emergency failure and part defects.

The obtained data allow for the reasonable selection of cutting modes depending on the technological requirements and the resource of the cutting tool, as well as for the formation of recommendations for practical application in mass or small-scale production.

4.2. Comparative analysis of the durability of indexable inserts

Based on the experimental data obtained during the AISI 321 stainless steel turning using CNMG 120408-PM inserts, a comparative analysis of their durability under various cutting conditions was conducted. In this study, durability refers to the total amount of cutting that the cutting edge can withstand before reaching a wear limit of 0.3 mm.

The comparison was based on the following criteria:

1. Cutting path length before critical wear;
2. Rate of wear increase (mm per 100 mm of machining);
3. The visual nature of insert destruction;
4. Overall stability of the cutting process.

a) Cutting mode – I (gentle); total cutting length before limiting wear – 1050 mm; average durability – 7 passes; wear pattern – uniform, without chips; overall behavior of the cutting tool – stable operation, slow wear.

b) Cutting mode – II (medium); total cutting length before limiting wear – 750 mm; average durability – 5 passes; wear pattern – moderately pronounced crater, edge cracks; overall behavior of the cutting tool – acceptable load, accelerated wear.

c) Cutting mode – III (intensive); total cutting length before limiting wear – 450 mm; average durability – 3 passes; wear pattern – chipping, fractures, thermal erosion; overall behavior of the cutting tool – instability, risk of cutting tool breakage.

When operating in a gentle mode, the cutting edge remains functional up to 1050 mm of cutting length, which is the best result. Wear increases slowly, mainly due to uniform abrasive wear on the flank face. The cutting edge surface maintains its shape until the last passes, and the coating damage is minimal. This indicates that the coating and cutting tool alloy can withstand limited heat loads.

In medium mode, the cutting tool demonstrates stable operation up to 750 mm of cutting length. However, at the end of the cycle, there are signs of a crater forming on the rake face, as well as cracks along the edge. This indicates an increase in temperature in the cutting zone and the activation of diffusion and thermo-impact processes. Nevertheless, the durability remains satisfactory and suitable for industrial applications.

Under heavy cutting conditions, the durability of the cutting tool decreases dramatically. Critical wear is detected after 3 passes (450 mm). In addition to accelerated edge wear, there is material chipping, coating peeling, and partial chipping of the insert tip. Surface cracks and thermal erosion indicate overheating and loss of the hard alloy's strength properties.

The analysis of the results shows that the service life of the indexable inserts decreases by more than two times when the cutting intensity increases. The difference in wear resistance between the gentle and intensive modes was more than 130%, which highlights the sensitivity of the cutting tool to temperature and mechanical loads.

It should be noted that even when the values are visually identical (for example, 0.3 mm), the nature of the edge damage differs significantly. In one case, there is uniform wear, in another, there is coating destruction, and in the third, there is fragmentation of the cutting part. This is of direct importance for the production reliability and suitability of the cutting tool for further use.

Thus, the optimal cutting mode in terms of durability and stability was the medium cutting mode, which provided a balance between productivity and preserving the cutting tool's resource. The gentle mode is effective for high requirements of accuracy and repeatability, while the intensive mode is only suitable for short-term machining or in a limited production cycle.

The obtained data confirm the need for individual selection of cutting modes depending on the machining tasks, material characteristics, and requirements for the cutting tool resource.

4.3. Determining the optimal machining mode

Based on the analysis of the cutting tool wear dynamics and the comparative assessment of its durability under different cutting conditions, it is possible to formulate reasonable recommendations for selecting the optimal cutting mode for AISI 321 stainless steel turning using indexable inserts.

During the experiment, it was found that under a gentle machining mode, the cutting tool demonstrates the highest durability, up to 1050 mm of cutting length before reaching a limiting wear of 0.3 mm. However, the low productivity of this mode makes it ineffective for mass production. It is suitable for cases where the priority is given to surface quality, minimum roughness, and precise geometry of the parts.

The maximum mode is characterized by a high metal removal rate, but it drastically reduces the service life of the cutting tool. After 450 mm of machining, critical wear is recorded, accompanied by coating destruction, cutting edge chipping, and loss of process stability. This mode is only suitable for rough operations on workpieces with low requirements for accuracy and roughness, or for short-term work on powerful machines with automatic tool change.

The medium cutting mode showed the most balanced results. The cutting tool remained operational up to 750 mm of cutting length, demonstrating moderate wear growth and a predictable wear pattern. The surface of the machined parts met the requirements for cleanliness, the chip shape was stable, and the cutting tool worked without vibration or overheating. At the same time, the productivity level was significantly higher than in the gentle mode, and the insert's resource remained acceptable for production tasks.

Taking into account all the factors – wear rate, cutting stability, machining quality, and cost-effectiveness – the optimal mode for stainless steel turning in this study is the medium mode. It provides the best balance between productivity and cutting tool durability. In addition, the TiAlN + Al_2O_3 coating of the insert works most effectively in this mode, demonstrating its thermal protection properties without overloading the cutting edge.

When developing a technological process for stainless steel turning, the use of the selected mode allows for the following:

1. Increasing the cutting tool's service life by 40-50% compared to intensive cutting;

2. Reducing the likelihood of emergency destruction of the cutting tool;

3. Ensuring stable quality of the machined surface;

4. Reducing the cost of insert replacement and equipment downtime.

The choice of the optimal machining mode should be based not only on the calculated productivity, but also on a comprehensive assessment of the cutting tool's behavior during long-term cutting.

This approach improves the efficiency of metalworking and extends the service life of cutting tools, especially when working with stainless steels that are subject to high levels of thermomechanical loads.

5. Conclusion

The results obtained during the study allow us to develop reasonable recommendations for selecting cutting modes and conditions for using indexable inserts when AISI 321 stainless steel turning in production conditions. The practical implementation of these recommendations is aimed at increasing the durability of the cutting tool, reducing the cost of replacing it, and ensuring stable machining quality.

The analysis showed that the optimal machining mode is the medium-intensity mode, with a cutting speed of 120 m/min, a feed rate of 0.25 mm/rev, and a cutting depth of 1.0 mm. This mode ensures a balanced relationship between process performance and cutting edge life. The cutting tool maintains a stable shape, wears evenly without chipping, and the surface of the part meets the requirements for roughness. These conditions are preferred for most finishing and semi-finishing operations on stainless steel turning.

In production practice, it is extremely important to choose the right type of cutting tool and its geometry. The use of TiAlN + Al_2O_3-coated carbide inserts significantly increases the heat resistance of the cutting edge and reduces wear during high-temperature machining. The geometry of the insert should include a positive back rake angle and the chip breaker that promotes efficient chip removal from the cutting zone. These design features improve cutting conditions and prevent the formation of build-up.

It is recommended to use a directed supply of coolant, such as emulsions or synthetic cutting fluids suitable for stainless steel machining. The presence of cooling in the contact area significantly reduces the thermal load on the cutting tool, prevents surface oxidation, and extends the coating's service life. It is also necessary to regularly monitor the concentration and purity of the cutting fluid, as a deterioration in its properties can cause instability in the process.

An important part of the machining process is monitoring the condition of the cutting tool. Regular visual inspection and measurement of wear after a certain cutting path allow you to detect a critical approach to the wear limit and replace the insert in time. This prevents accidents and ensures smooth machining. If possible, especially on CNC machines, a vibration monitoring system, cutting force monitoring, or temperature monitoring system can be implemented to automate control and improve the accuracy of wear tracking.

From the point of view of economic efficiency, transition from an intensive cutting mode to a medium one allows you to increase the durability of the cutting tool by more than 60% with a slight decrease in the machining speed. This reduces the cost of replacing inserts, reduces the time spent reconfiguring the equipment, and reduces the amount of defective products. In batch or mass machining, the effect of such improvements can be quite significant.

You should also consider the rigidity of the machine equipment, the method of fixing the workpiece, and the characteristics of the material being machined. All of these parameters can affect the behavior of the cutting tool, so the process modes should be adapted to the specific production conditions.

The use of reasonable machining modes and appropriate tooling solutions can significantly improve the efficiency of stainless steel turning. The practical implementation of these recommendations at enterprises not only improves the quality of products, but also optimizes the costs of cutting tools and equipment.

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