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A REVIEW AND ANALYSIS OF THE INFLUENCE OF TECHNOLOGICAL PARAMETERS ON THE EFFICIENCY OF PROCESSING HARD-TO-MACHINE MATERIALS

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Abstract. The article analyzes modern technologies for machining workpieces of hard-to-machine materials with a hardness parameter higher than 45 HRC (Rockwell hardness). It is shown that the mechanics and thermodynamics of the forming process in such materials are subject to specific laws of cutting theory, which have systemic differences from the processing of traditional engineering materials. The advantages and disadvantages of machining chromium-nickel alloys using CNB inserts instead of grinding are analyzed. The influence of the cutting tool geometry during the machining of hard-to-machine materials is shown.

Keywords: cutting process, hard-to-machine material, tool geometry, chrome-nickel alloy, cutting force, shear zones, residual stress, surface roughness.

Introduction

The development of the mechanical engineering industry requires using new materials with significant advantages over traditional engineering materials in terms of improved performance, the ability to withstand higher power and thermodynamic loads, the longer service life of mechanical engineering products, and so on. However, despite all their advantages, the use of such materials creates new problems. First, all structural materials with improved performance characteristics are very expensive. Second, another problem is the complexity of their machining, which increases the cost of products, decreases the productivity of machining production, and can lead to negative profitability of the production process. Moreover, due to their high properties such as high strength, stiffness and hardness, manufacturing processes that can be easily applied to most engineering materials may not be effective when applied to advanced materials [1]. The most common problems in machining such materials are intensive tool wear, the need to use expensive equipment and tools, the possibility of using only low-power cutting modes, etc. For example, rapid tool wear is mainly caused by high temperatures and stresses, the abrasive structure of some of these materials, high hardness, and the need to combat high-frequency vibrations of the machine-tool-tool-part technological system [2]. Therefore, such materials are usually referred to as hard-to-cut or difficult-to-machine materials.

During machining, cutting energy is mainly generated in two main zones, the primary and secondary shear zones. Although the basic aspects of machining operations are almost the same, material properties significantly affect the mechanics of chip formation and heat generation, which in turn leads to the above problems [1]. Therefore, optimization of technological parameters of machining of hard-to-machine materials (such as cutting speed, feed rate and depth of cut), reasonable choice of geometric parameters of the cutting tool, tool material and its coating, lubricating and cooling fluids, and machining conditions is a top priority for researchers in the field of hard-to-machine materials. Production testing requires lengthy and very expensive research into machining conditions and machinability. In addition, even a small change in the machined material can cause significant errors and negate lengthy experimental testing. The knowledge gained by scientists allows tool manufacturers to develop suitable tool materials and coatings to withstand the harsh conditions encountered during machining. Despite significant progress and development in addressing many machinability issues, research in metal cutting is still ongoing and is likely to continue for a long time [1].

Problem-based analysis of mechanical properties of difficult-to-machine materials

Machining of materials with a hardness index higher than 45 HRC (Rockwell hardness) is subject to specific laws of cutting theory, which have systemic differences from the machining of traditional engineering materials [1–8]. Moreover, the 45 HRC tensile strength is only the lowest parameter for difficult-to-machine materials, as manufacturers often have to plan technological operations for machining products with values in the range of 58–68 HRC [2].

A group of heat-resistant alloys capable of maintaining their basic mechanical properties (strength, stiffness, and toughness) at very high operating and process temperatures. The main characteristics of these materials are their high resistance to oxidation and corrosion. These materials include high-alloy steels and alloys based on nickel, cobalt, tungsten, and molybdenum [1, 2]. Typical representatives of such materials are Inconel 600, AISI 600, EN 2.4816, DIN NiCr15Fe, ХН60ВТ, ХН78Т. Other technological characteristics of such materials are good weldability; resistance to chemically aggressive substances; neutrality to chlorine ions – resistance to stress corrosion damage; practical neutrality to magnetization; resistance to carburization and nitriding; good resistance to corrosion cracking at room and elevated temperatures; high resistance to hydrogen chloride.

Austenitic stainless steels are the most commonly used materials. Obviously, alloyed steels are significantly less expensive than alloys with a predominance of cobalt, tungsten, or nickel. Most stainless steels are strengthened by martensitic transformation, making them suitable for use at temperatures not exceeding 760 °C (1400 °F) [9]. The aforementioned property of corrosion and oxidation resistance is usually achieved by adding more than 10 % chromium. To stabilize the austenitic matrix, such iron-based alloys are typically alloyed with nickel in a mass composition of 25 to 60 % [10, 11]. The addition of molybdenum (Mo) and chromium (Cr) contributes to the development of the solid solution strengthening effect. Moreover, it is chromium that effectively increases the resistance to oxidation and sulfidation of this group of alloys within the operating temperatures [12]. The reason for this effect is the formation of a continuous thin and durable oxide layer enriched with chromium (over 9 % by weight) on the surface of the material. This layer forms a kind of barrier to protect stainless steel in aggressive environments [12]. To achieve high hardness, alloying materials with small atomic sizes such as carbon (C), nitrogen (N), and boron (B) are added to austenitic stainless steels. However, the high iron content still negatively affects the corrosion resistance of such materials [12].

Nickel-based alloys are another typical example of difficult-to-machine materials. Due to the dominant anticorrosive properties of nickel (even in aggressive environments [13]) combined with its high strength, this alloying element is effectively combined with iron, molybdenum, and copper. Nickel-based alloys can withstand higher temperatures than stainless steel (from 1050 to 1200 °C). Moreover, this range of operating temperatures can reach 70–90 % of the melting point of nickel, which is about 1455 °C [13]. This is the main reason for the widespread use of nickel alloys in high-performance gas turbine components. Most nickel-based alloys have a nickel-chromium-aluminum phase diagram. The single-phase gamma matrix of nickel alloys is dominated by carbide precipitates, which has a significant impact on heating and machining technology.

The most commonly used nickel-based alloys are Inconel 600 and Inconel 718 [13]. However, both of these alloys have relatively low hardness at elevated temperatures (650–815 °C). In contrast to the aforementioned nickel-based materials, Inconel X-750 is characterized by three times the strength of Inconel 650 at 540 °C [14]. Important performance characteristics of nickel alloys include low-temperature toughness and very high corrosion resistance in aggressive environments. It should be noted that the specific thermal conductivity of nickel-based alloys is low, although the coefficients are approximately the same as those of low-alloy steels. This property leads to problems of significant deformation during welding, as heat is retained instead of being quickly dissipated through the depth of the welded parts [1, 15].

Another group of difficult-to-machine materials commonly used in machine building are cobalt-based alloys. It should be noted that the cost of such alloys is significantly higher than that of nickel alloys and even higher than that of high-alloy stainless steels. Cobalt-based alloys are strengthened, as in the case of nickel alloys, by the combination of carbides and solid solutions [15, 16]. The most common cobalt-based alloys are carbide inclusions of the M6C, M7C3, and M23C6 types. MC-type carbides cannot be formed in cobalt-based superalloys because they do not contain tantalum (Ta), titanium (Ti), zirconium (Zr), or hafnium (Hf) [15]. The performance characteristics of cobalt alloys are wear resistance, heat resistance, and corrosion resistance. Nickel alloys also have these properties, but it is cobalt alloys that exhibit higher strength at relatively higher operating temperatures in the range of 650–1150 °C [17]. Such properties are effective in terms of their serviceability, but these indicators create major problems during machining of such materials. This is due to the concentration of heat on the surface of the cutting tool, which causes its rapid wear and high cutting forces [1–6]. Ways to solve such problems and suggestions to improve their cutting efficiency are discussed below.

Machinability Characteristics of Hard-to-Machine Materials

As mentioned above, ensuring high productivity when machining difficult-to-machine materials is one of the main priorities of scientific research in the field of engineering as a science [1, 2]. However, to solve this problem it is necessary to ensure the production of tools with increased wear resistance at high cutting temperatures (which is typical for the machining of most difficult-to-machine materials), to use highly effective lubricating and cooling fluids, and to conduct comprehensive studies of the influence of technological cutting parameters on the formation of the stress-strain pattern and microgeometric state of machined surfaces. This encourages manufacturers to carry out experimental work to adjust the structure and parameters of technological processes according to the research results. However, the constant appearance of a new range of materials and cutting tools on the market makes this kind of work very inefficient. Often, new materials are created by adding alloying elements to existing materials to improve specific properties, such as wear resistance, fatigue strength, corrosion resistance, etc. New materials have specific metallurgical properties and present new machining challenges [2]. As noted in [1, 2, 3, 5], the main problems of poor machinability of high alloy steels and alloys are the presence of materials with an abrasive nature of added hard components or increased strength, toughness, corrosion or temperature resistance of the material being machined.

Therefore, the need for systematic scientific research and practical recommendations for the selection of design and technological support for machining operations is particularly important. This is what Sandvik Coromant is doing by selling tools with recommended cutting modes, material and geometry of carbide inserts, etc. to consumers [18]. In this case, however, this trading company primarily pursues its own commercial interests and (not without reason) lobbies for its products in the machine-building labor market. In addition, Sandvik Coromant catalogs do not provide any justification for the feasibility of proposed technological solutions, taking into account the material to be machined, but only make recommendations.

Grinding is often an alternative to edge machining of chrome-nickel, cobalt alloys, and heat resistant and stainless steels. Each of these machining techniques has its own advantages and disadvantages.

Typically, the cost of edge tools with superhard inserts is much higher than the cost of grinding wheels. It has been shown that machining significantly reduces machining time due to the flexibility of the process and high quality, and can be considered a less expensive alternative to grinding [19]. In addition, edge machining offers many more possibilities for correcting the microgeometric profile of the machined surface, the cyclicity and the integrity of the roughness parameters of the reference surfaces than grinding [2]. When deciding on the alternative of edge machining versus grinding, it is advisable to take into account their similarities and differences so that the chosen variant of the structure of the technological operation is technically and economically feasible:

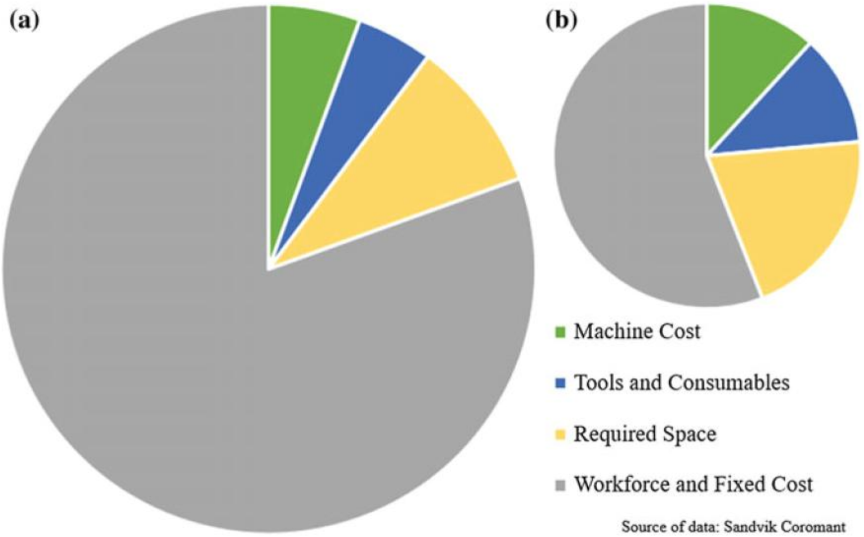
– circular grinding is used primarily as a finishing operation for machining hardened workpieces, while hard turning can be used effectively in both roughing and finishing operations;

– the negative rake angle of the tool during turning produces a zone of residual compressive stress, unlike grinding, which usually produces a zone of residual tensile stress on the machined surface of the workpiece due to the dominant temperature effect over the force factor;

– structural changes in the machined surface, which occur most often during edge machining (e.g. turning), similar to grinding;

– the length of contact between the tool and the workpiece is much shorter in edge machining than in grinding, resulting in higher average stresses in turning than in cylindrical grinding.

The paper [2] presents comparative circular diagrams of turning and grinding as alternative methods in the implementation of finishing of difficult-to-machine materials (Fig. 1). Statistical data for the comparison were provided by comp. Sandvik Coromant [20]. The analysis of these indicators allows us to conclude that “hard turning” has greater capabilities, given its versatility, ability to provide an initial micro-profile of the workpiece with a stable micro-relief. However, in terms of technological costs, grinding is superior to turning of difficult-to-machine materials with tools made of superhard materials [7].



Source of data: Sandvik Coromant

Fig. 1. Comparison of the cost of turning and grinding as alternative methods in the implementation of finishing of hard-to-machine materials [2]

It is observed in references [1–7, 21–25] that the specifics of edge machining of basic difficult-to-machine materials (e. g., machining of chromium-nickel alloys) exhibit distinctive features that differentiate it from machining operations of traditional structural materials. It should be noted that these features have a systemic effect on the specific pattern of formation of the stress-strain state of the workpiece in the cutting zone, as well as on the physical (residual stresses and strains) and microgeometric state of the machined surface (parameters of roughness and waviness). Among the most characteristic features are the following:

– the formation of the so-called “sawtooth” chip shape is a consequence of the thermodynamic cutting pattern characteristic of machining chrome-nickel alloys;

– the geometry of cutting tools provides for the presence of a negative rake angle and the prevalence of rounding of cutting edges over chamfered transitions;

– the expediency of grinding and polishing the rake face of the tool is due to the need to reduce the friction component during chip flow along the cutting edge;

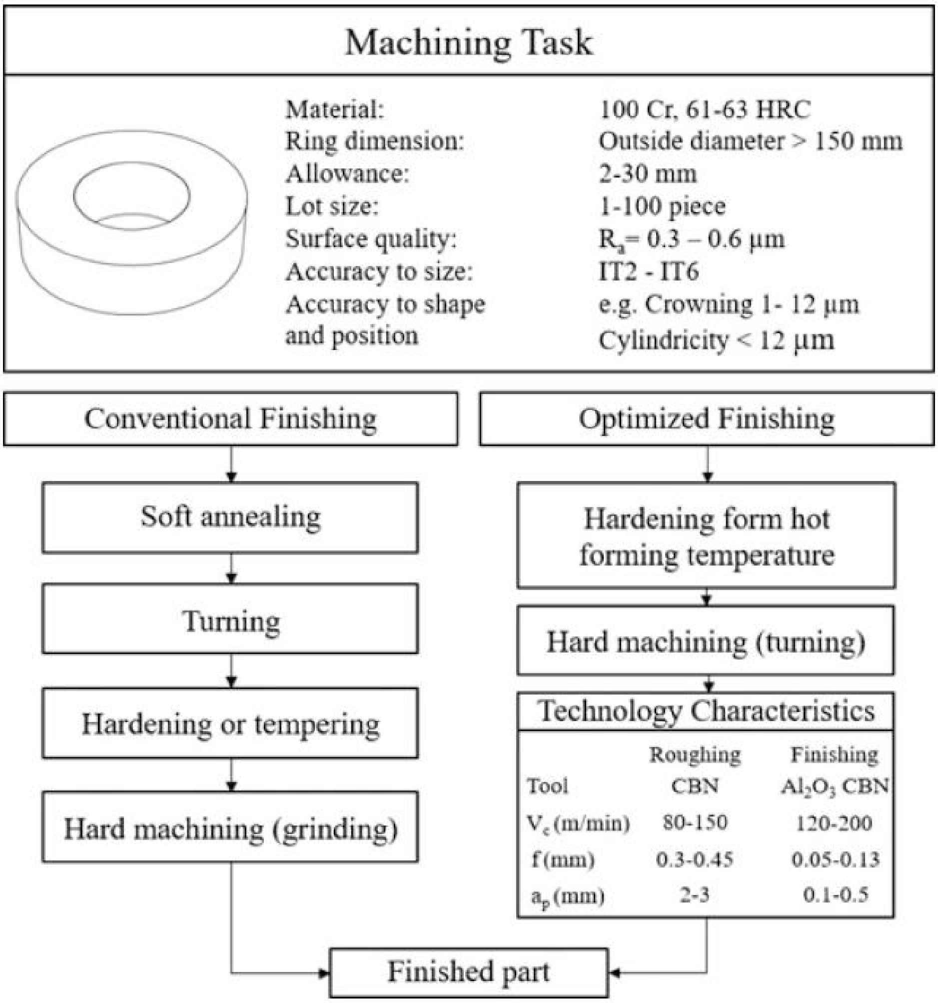
– the ratio between the longitudinal and transverse cutting forces is in the range of 1 to 5–7, which is caused by the ability of the workpiece material to maintain almost the original strength at high cutting temperatures;

– the specific energy consumed during the turning of a chrome-nickel alloy workpiece is much less than during the grinding of this material.

– the possibility of “dry” turning offers a technological method of eliminating the use of coolant, which makes it an environmentally friendly process.

– turning is considered a more economical machining method because it reduces machining time and allows for the concentration of different processing operations within a single CNC machine.

Fig. 2 presents a comparative analysis of the conventional finishing technique for hardened steel rings, namely grinding, and the optimized finishing approach utilizing hard turning. As illustrated in Fig. 2, the optimized process not only reduces processing time but also eliminates the necessity for certain heat treatment processes, thereby reducing the environmental impact.



Material: 100 Cr, 61-63 HRC
Ring dimension: Outside diameter > 150 mm
Allowance: 2-30 mm
Lot size: 1-100 piece
Surface quality: $R_a = 0.3 – 0.6$ µm
Accuracy to size: IT2 - IT6
Accuracy to shape and position: e.g. Crowning 1- 12 µm
Cylindricity < 12 µm

	Roughing	Finishing
Tool	CBN	Al_2O_3 CBN
V_c (m/min)	80-150	120-200
f (mm)	0.3-0.45	0.05-0.13
a_p (mm)	2-3	0.1-0.5

Fig. 2. Comparison of conventional and optimized finishing technology for hardened steel rings [29]

The main tools for turning workpieces made of difficult-to-machine materials with hardness in the range of 45–70 HRC are prefabricated cutters with inserts made of polycrystalline superhard material based on cubic boron nitride (CBN) [27–32]. There are studies that have linked the influence of the mechanism and geometric parameters of chip formation on the process of stability and frictional components of cutting forces [34–37]. Important studies have also been carried out to ensure the wear resistance of tools when machining difficult-to-machine steels and nickel and cobalt-based alloys [38–40], as well as the influence of the properties of the machined material, tool geometry, and cutting conditions on the functional properties of the machined surfaces [41–45]. At the same time, most researchers have emphasized the difficulty of formalizing the mutual influence of technological and design factors on the initial cutting parameters of these difficult-to-machine materials, such as the microgeometry of the machined surfaces, residual stresses and strains, and so on. The main parameters that determine the relationship between technological factors are shown in Fig. 3. The parameters above the horizontal dashed lines are considered as input data for the turning process. All other parameters located below these dashed lines are considered as performance indicators or results of the turning process using superhard cutting inserts. In [46] it has been proved that almost all the parameters shown in this diagram have a significant influence on both the productivity of the hard turning process and the quality indicators of the machined layer (mainly roughness, accuracy, hardness and residual stresses).

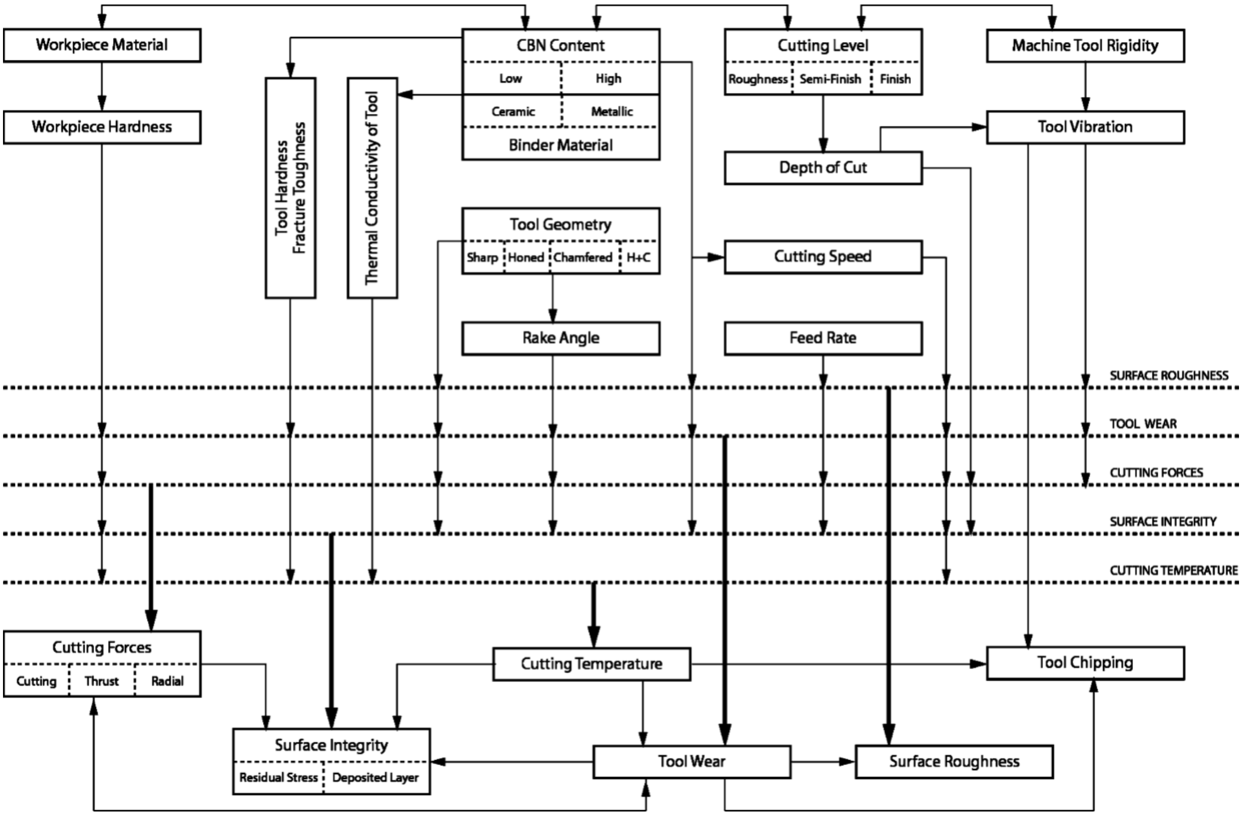


Fig. 3. Diagram of the mutual influence of technological parameters of machining hard-to-machine materials with CBN tools [46]

The paper [1] emphasizes the complexity of machining non-rigid parts made of difficult-to-machine materials because they cannot resist the cutting forces during machining. This encourages designers to pay special attention to the manufacturability of products in terms of the ratio of overall dimensions within acceptable limits. A similar requirement is placed on machine tools and machine tools themselves. For example, to achieve the highest productivity, a machine used for turning a difficult-to-machine workpiece material with CBN tools must have a rigid frame structure, be equipped with spindles with a collet system to place the spindle bearing as close to the workpiece as possible, and so on. The authors of [47] consider the use of small-pitch ball screws to be an effective way of reducing vibration.

Another factor in the effective implementation of the functionally oriented technological process of machining products from difficult-to-machine materials is ensuring a qualitative (in the operational sense) microstructural change in the treated surface layer of the workpiece [48]. As a rule, this feature is a consequence of austenitic-martensitic transformations, resulting in the formation of the so-called “white layer”. In addition, the depth of the “white layer” can vary widely, from a few microns to tens of microns. The formation of a white film is not very detrimental from an operational point of view, especially under conditions of high functional contact stresses or fatigue loads. Fig. 5 shows an electron microscope photograph of the microstructure of a 52100 steel billet, which is the result of a large plastic deformation that causes rapid grain recovery, especially when a wear zone is formed along the side surface. In addition, microstructural residual stresses of the 2nd type occur as a result of structural phase transformations due to rapid heating and cooling of the treated surface layer and chemical interaction of the workpiece material with the tool and the environment [2].

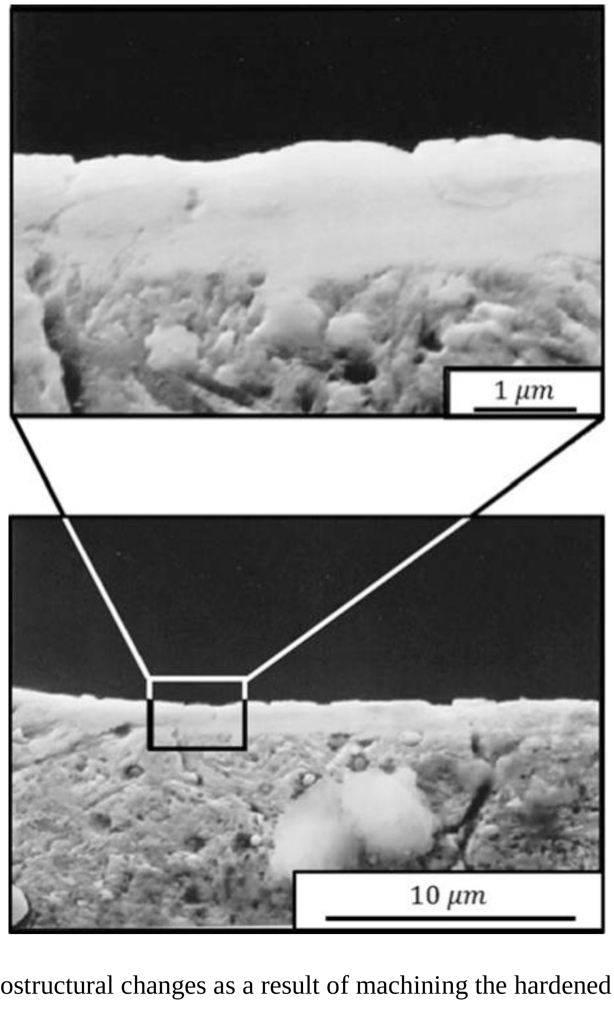


Fig. 4. An example of microstructural changes as a result of machining the hardened surface of steel 52100 [49]

Another equally important operational factor resulting from the mechanical and thermal loads occurring during the chip formation process is the residual stress of type 1. When analyzing the occurrence of different types of such stresses, it should be noted that tensile residual stresses are the most harmful due to their negative impact on the fatigue characteristics and service life of the machined part. Fig. 4 shows that cutting speed has a dominant influence on the distribution of residual stresses. In addition, a higher cutting speed not only contributes to the growth of tensile residual stresses as a result of an increase in cutting temperature but also increases the thickness of the surface residual stress layer [48].

Another important parameter that significantly influences the set of functionally dependent parameters of the machined surface layer of the workpiece is tool vibration. It is known that vibrations and macro-vibrations of the cutting tool are important factors that affect the stability of the cutting process and have a significant impact on the quality of the part and the productivity of the technological operation [50]. Classically, it is believed that the main way to reduce tool and workpiece vibrations is to ensure high rigidity of the "Machine-Device-Tool-Workpiece" (MDTW) system. It is the radial component of the cutting force that is the most significant parameter that forms the force on the elastic deformation parameters of cutting during edge machining of difficult-to-machine materials [51]. However, the theory of optimal stiffness of the MDTW technological system is widespread. It substantiates the possibility of damping vibrations in the technological system of the machine tool by introducing an element with variable dynamic characteristics. It is also important to develop a dynamic model of the cutting process by a tool with variable stiffness parameters [52] and to obtain analytical dependencies for the calculation of machining accuracy. Such models take into account the effect of tool stiffness deviations from the average value and establish dependencies to determine the zone of stable operation of the cutter, as well as the relationship between the amplitude of tool oscillations and cutting modes. In the paper [53], the relationship between cutting modes and the design parameters of the surfaces of the component holders is substantiated. The technological limits of the modes associated with the design features of the tool were determined.

Factors Affecting the Efficiency of the Chip Formation Process when Machining Hard-to-Machine Materials

It is considered that the most significant factor in the force analysis of the cutting process is the hardness of the material being machined. However, it is argued in [1, 2, 54] that the value of cutting forces when machining difficult-to-machine materials (and in particular chromium-nickel alloys) cannot be significantly high for some reasons:

– taking into account the peculiar mechanical characteristics of these materials and, in particular, their relatively low ductility, chip formation is carried out as a result of cracking rather than plastic deformation;

– the friction force during edge machining of most chrome-nickel alloys is significantly lower than during machining of other structural materials The reason for this is the relatively small contact area between the tool and the chip.

A number of authors [1, 3, 23, 28] contend that the hardness of the material being machined is not the most significant factor influencing the magnitude of the cutting force. They posit that the cutting force can be diminished by enhancing the material's hardness. A more significant indicator is the thermal resistance of the material, particularly the potential for and extent of thermal softening. An additional crucial factor influencing the generation of cutting force parameters is the plasticity of the material undergoing processing. It is established that the cutting force increases markedly when the hardness exceeds 50 HRC, which correlates with the onset of toothed chip formation. This pattern of chip formation can be attributed to an imbalance between the longitudinal and transverse cutting forces. In other words, the processes of compression and shear are separated in time. In this instance, the process is influenced by two contradictory factors. Concurrently, the yield strength of the workpiece material rises in conjunction with heightened hardness, necessitating augmented force to induce deformation and chip formation. Conversely, the workpiece material experiences a reduction in its yield strength as a consequence of the generation of excessive heat during the machining process. In the case of difficult-to-machine materials, such as chrome-nickel steels, if the workpiece hardness exceeds a certain chip formation limit, the dominant phenomenon is crack initiation rather than plastic deformation. In other words, plastic deformation is inferior to brittle fracture, similar to machining, for example, cast iron. Because of this phenomenon, the strain energy, which is subsequently converted into heat, decreases and the material softens, practically, does not occur. This phenomenon should be taken into account both when setting the machining modes and when selecting the tool material or its coating.

Influence of Technological Factors and Cutting Tool Geometry on the Machinability of Chrome-Nickel Steels and Alloys

The technology of machining hard-to-machine materials, which undoubtedly includes high-alloy steels and chromium- and nickel-based alloys, offers some advantages over traditional abrasive machining methods, particularly in the context of round and surface grinding operations for finishing. Among the most significant advantages, researchers have identified greater flexibility (facilitating the adaptation of the process to complex products), the speed of changeover to other types of parts, the ability to combine several operations into one as a result of the versatility of the forming movement of the edge tool compared to the abrasive one, higher productivity, and relatively low technological cost [42, 46, 53, 55]. The technology of machining hard-to-machine materials, which undoubtedly includes high-alloy steels and chromium- and nickel-based alloys, offers several advantages over traditional abrasive machining methods, particularly in the context of round and surface grinding operations for finishing. Among the most significant advantages, researchers have identified greater flexibility (facilitating the adaptation of the process to complex products), the speed of changeover to other types of parts, the ability to combine several operations into one as a result of the versatility of the forming movement of the edge tool compared to the abrasive one, higher productivity, and relatively low technological cost [42, 46, 53, 55].

For this purpose, many studies have been conducted using various computational methods for modeling and optimizing the hard-turning process, such as:

It is well known that it is the geometry of the cutting edge that shapes the thermal pattern in the chip formation zone. Tugrul Ozel and other authors [46, 53] studied the effect of cutting-edge geometry on surface roughness and cutting forces during the turning of various difficult-to-machine materials and concluded that cutting-edge geometry has the greatest impact on surface roughness and cutting forces when machining high-alloy steels based on chromium, nickel, and vanadium. In turning, tool geometry also affects tool wear, surface roughness, chip shape, residual stress, cutting forces, heat generation, white layer, and machined layer residual deformation parameters, as shown in Fig. 5.

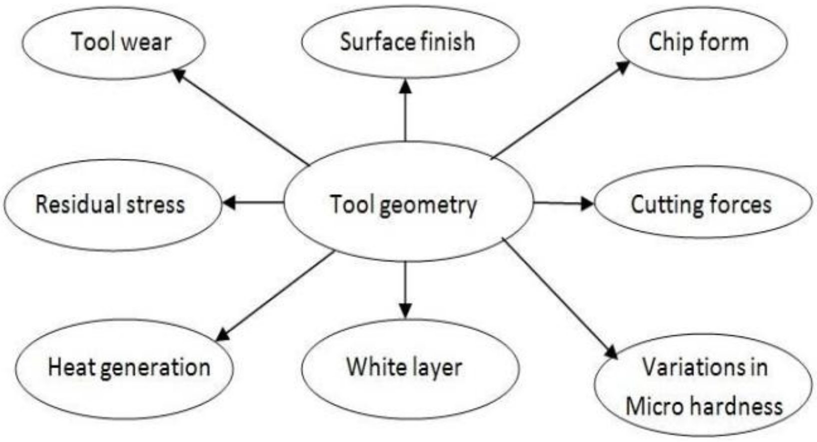


Fig. 5. Factors influencing the geometry of the cutting tool on the machinability of hard-to-machine material

A significant element in the generation of the force and thermodynamic field is the geometry of the cutting tool, including the radius at the tip of the cutter, the rake, and rear angles, the radius of curvature of the cutting nose, and other pertinent characteristics.

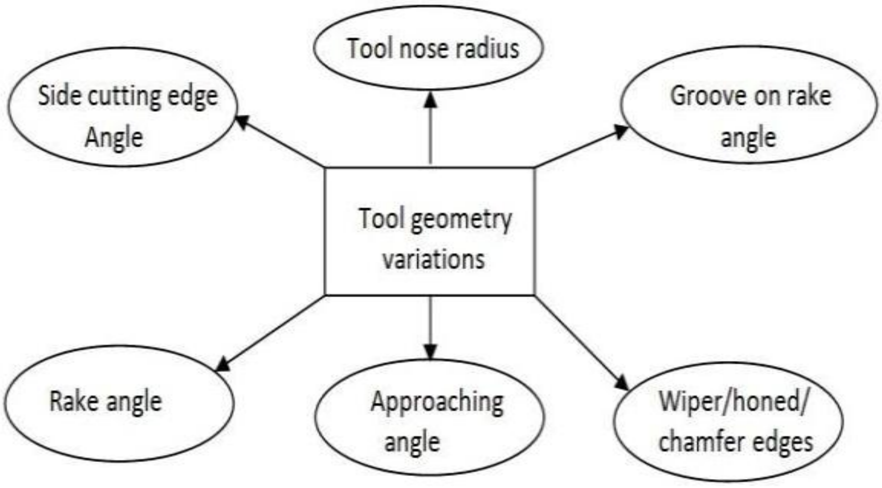


Fig. 6. Variation of cutting tool geometry

Among all these parameters, the radius of the rake part of the cutting tool is of dominant importance. It significantly changes the chip morphology. The images of the chips (Fig. 7) collected after orthogonal turning of hardened AISI 1550 steel (58–60 HRC), magnified 100 times, do not show any notches in the chip cross-section. However, similar images of chips obtained during machining with a tool with a 0.1 mm radius of sharpening or a round insert show a completely different picture. In the case of a significant radial rounding of the tool or the use of a round insert, it is already possible to note the presence of significant serration along the flank edge of the chip.

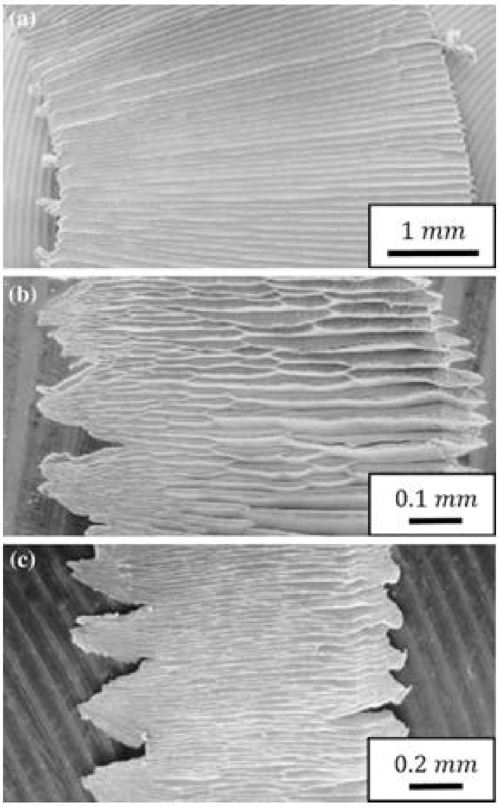


Fig. 7. Enlarged (×100) image of chips (workpiece material – AISI 1550 steel) produced by cutting tools with different geometries: a – orthogonal cutting with a rake angle of $\gamma = 6°$; b – oblique cutting with a rake angle $\gamma = 6°$ and a nose radius $r = 1.2$ mm; c – orthogonal cutting with a rake angle of $\gamma = 6°$ using a round insert

The saw-toothed chip can be explained by a change in chip thickness, as shown in Fig. 8 [1]. As can be seen from the diagram, in the absence of a shank radius, the chip thickness remains constant along the cutting edge (section A-B) (*a*). However, the presence of a significant rounding of the tool edge or the use of a round cutter produces a pattern of chip thickness that varies along the line (A-B) (*b*). The chip is the thinnest at point A, which causes a significant stress concentration and is a consequence of the high temperature in this chip formation zone. It can also be noted that the radius of the cutting edge affects the chip flow rate, which varies with chip thickness. This leads to an uneven displacement along the chip width and forms a toothy transverse chip surface

Special conditions for choosing the microgeometry of a cutting tool when machining chromium-nickel alloys are put forward in the case of using tools with CBN inserts. Such tools are characterized by significantly lower toughness to prevent chipping [46, 53]. The specifics of the geometry of such tools is the priority use of inserts with a negative rake angle and a rounded or Wiper design of the cutting edge [56]. Moreover, the productivity of the cutting process with CBN tools significantly depends on the cutting parameters, i. e., speed, feed rate, feed rate, and depth (thickness) of cut [57]. Cutting speed and depth of cut are particularly important factors in tool life when machining difficult-to-machine materials such as chrome-nickel alloys.. An increase in cutting speed and depth of cut leads to an increase in temperature in the cutting zone. Since CBN is a ceramic material, the chemical nature of wear becomes the most dangerous at high temperatures, which is often the main cause of sudden and unpredictable destruction (chipping) of the tool edge. In addition, the authors in [43] concluded that at high feed rates and machining speeds of chrome-nickel (and other difficult-to-machine materials), compressive residual stresses change to tensile stresses. This can be explained by the priority of the effect of heat over the effect of force..

Changes in the rake angle mainly cause changes in the inclination angle and intermediate rake angle, respectively, at each point (each element of the cutting edge) of the radius cutting edge of the tool's nose. Moreover, the angle of inclination of the cutting edge has the least influence on the formation of the thermodynamic cutting pattern at a shallow depth of cut, which corresponds to finishing turning.

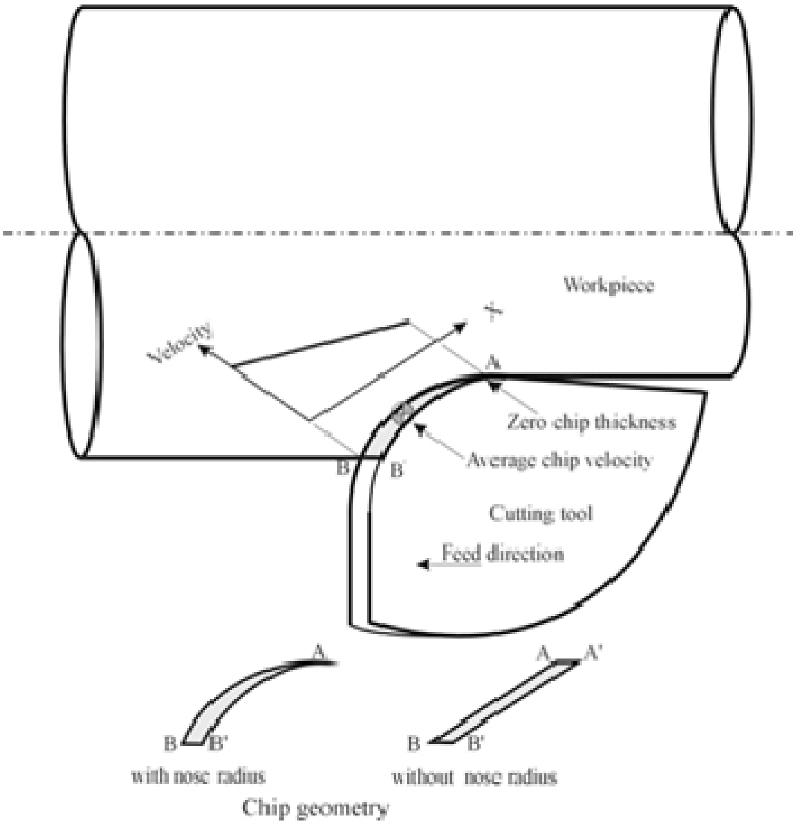


Fig. 8. Influence of the tool nose's rounding radius on the resulting chips' morphology [1]

As evidenced by statistical analysis [58], the primary angle of the cutter plan exerts the most significant influence on surface roughness, accounting for 32.5 % of the total effect. The rake and rear angles also contribute to the roughness, with effects of 9.9 % and 11.9 %, respectively. Furthermore, it was determined that an increase in surface roughness is associated with negative rake angles and minimal rear angles. Conversely, the plan angle is also the primary factor influencing the wear of the side surface of the cutter, with a 60.1 % impact, while the rake angle exerts a 23.37 % influence, and the rear angle has a negligible effect on this parameter (4.2 %). The findings of the experimental studies indicate that the specific wear of the tool exhibits a decline with a reduction in the rake angle and the angle in the plan. The same work [58] provides a fundamental analysis of the influence of cutting tool microgeometry and cutting conditions (cutting speed and feed) on surface roughness during the turning of high-alloy steel AISI 52100 (58 HRC). The authors employed the RSM and GA methodologies to construct a surface roughness regression function and to optimize the machining process. The findings indicated that a reduction in the rake angle and cutting speed was associated with an increase in surface roughness. This assertion is inconsistent with the findings of some scientific studies, as reported in [46, 53]. Conversely, the results corroborate the widely accepted tenet that an increase in the radius at the top of the tool and cutting speed is associated with a reduction in the roughness of the machined surface. The results of experimental studies have demonstrated that the radius at the top of the tool exerts the most significant influence on surface roughness, followed by the main angle in the plan, and the rear and rake angles of the cutting edge in the sequence of influence. However, a notable increase in the radius (exceeding 1.5 mm) of the tool, resulting in rounding, has been observed to initiate an increase in surface roughness. This finding challenges the prevailing theoretical perspectives on cutting theory.

The results of experimental studies on the turning of AISI 4140 (52HRC) steel indicate that the influence of cutting speed and depth of cut on tool edge wear is more pronounced than that of feed, with a ratio of 27 % to 14 %, respectively. Furthermore, at a cutting speed of 170 m/min, a build-up edge is formed, and subsequently, the roughness increases with rising cutting speed. A comparable investigation into the impact of these variables on the power and thermo-deformation processes of machining challenging materials was conducted by A. Zerti [59] during the turning of martensitic stainless steel. To model the output characteristics, the response surface methodology (RSM) and artificial neural networks (ANN) were employed. The results demonstrated that the RSM and ANN models adequately represent the experimental results.

Conclusions

1. Machining hard-to-machine materials is an economical way to achieve a high-quality machined surface. This type of machining refers to the turning of parts with a hardness of more than 45 HRC. Due to the higher rate of metal removal and the ability to eliminate several production steps, turning is considered to be a cost-effective alternative to grinding.

2. Despite the great number of experimental and theoretical studies in the theory of cutting difficult-to-machine materials, it should be noted that there are significant differences and conflicting views of scientists on the formation of stress-strain, the thermodynamic state of the workpiece during machining, the effect of cutting modes and tool geometry on the state of the surface layer of the machined component (residual stresses, distortions, micro-relief, roughness and waviness, and so on).

3. A promising area of research in the field of the theory of cutting of difficult-to-machine materials is the methodology of simulation modeling of the cutting process and multicriteria optimization of technological parameters. The main goals of machining are surface quality and its operational possibilities, wear resistance, fatigue strength, corrosion resistance, and economic efficiency or cutting performance.

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