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Influence of processing parameters on tool life in machining the heat-resistant molybdenum-based MoTiC alloy

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ABSTRACT

Introduction. Modern mechanical engineering is characterized by the increasing application of heat-resistant alloys for critical components in aerospace and defense equipment. The machining of promising molybdenum alloys, such as *Mo-30TiC*, is particularly challenging due to their high heat resistance, abrasiveness, and the anomalous behavior of their mechanical properties at elevated temperatures. Existing technological solutions developed for nickel-based alloys often prove ineffective, highlighting the relevance of research in this area. ***Purpose of the work*** is *t*o develop rational machining conditions and strategies for the milling of the heat-resistant *Mo-30TiC* alloy, aimed at increasing tool life and ensuring the required surface quality. **Methodology.** Experimental studies were conducted on an *Okuma MB-46BE* machining center using carbide end mills from various manufacturers. The influence of geometric tool parameters (rake angle, cutting edge radius, and presence of a negative land) and cutting conditions (cutting speed, feed rate, depth of cut) on flank wear and surface roughness was investigated. Process monitoring was performed using optical microscopy and surface profilometry. **Results and discussion.** Optimal geometric tool parameters were determined: a rake angle of 0°, a cutting edge radius of 0.5–1 mm, and a negative land width of 0.05 mm. Two distinct machining strategies were developed: a standard cutting strategy (V_c = 50–72 m/min, f_z = 0.03–0.04 mm) for high-quality finishing, and a high-productivity power cutting strategy (V_c = 12–17 m/min, f_z = 0.08–0.1 mm). The *Karcan 99508003* and *CNCINS MS15.Z5.08.19.63.38.R05* end mills demonstrated superior tool life. It was shown that the progression of tool wear leads to an exponential increase in the variance of surface roughness parameters ***Ra*** and ***Rz***. ***Conclusions***. The proposed set of technological solutions enables effective machining of the *Mo-30TiC* alloy, providing control over tool wear and achieving the specified surface quality. The results of this work are of practical importance for manufacturing enterprises specializing in the machining of difficult-to-cut materials.

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Introduction

Modern mechanical engineering, especially in such knowledge-intensive industries as aircraft engine manufacturing, rocket engineering and space technology, is characterized by a steady trend towards an increase in the proportion of complex parts made of heat-resistant and difficult-to-machine alloys [1, 2].

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This is due to the requirements for improving the operating parameters of equipment (temperature, pressure, load), which, in turn, leads to the use of materials that retain high mechanical properties under extreme conditions. The widespread introduction of multi-axis *CNC* machining centers has allowed designers to virtually eliminate previous technological limitations on product geometry, but has shifted the main difficulty to the manufacturing stage [3].

The key problem in the machining of heat-resistant alloys is their low thermal conductivity compared to structural steels. As a result, most of the heat generated in the cutting zone is not removed with the chips, but rather accumulates in the surface layer of the workpiece and in the cutting tool, leading to considerable thermal stress in the process [1, 4]. This causes a number of negative phenomena: structural and phase transformations, the appearance of residual stresses, deformation of the part, and accelerated tool wear [5, 6]. To reduce these effects, in practice it is often necessary to significantly lower the cutting conditions, which directly reduces the productivity of machining on expensive equipment [7, 8].

Most fundamental and applied research in the field of cutting heat-resistant alloys focuses on nickel-based materials, such as Inconel alloys [9, 10]. At the same time, molybdenum-based alloys, which have a unique set of properties — high specific strength, melting point, and creep resistance — have not been sufficiently studied in the context of machining. In particular, the promising *Mo-30TiC* alloy is characterized not only by high heat resistance, but also by significant ductility and an anomaly in its mechanical properties — an increase in tensile strength when the temperature rises to a certain limit [11, 12].

The edge cutting machining mechanism of heat-resistant *MoTiC* alloy based on molybdenum has not yet been fully studied. Under the influence of force and heat, complex processes of softening and hardening occur in the cutting zone, leading to sharp changes in load during milling and sharp temperature fluctuations on the tool surface. These fluctuations accelerate tool wear or damage, ultimately reducing the quality of the machined part [13]. Solid carbide mills are often used in milling, so their wear attracts significant attention from researchers around the world.

Conventional milling generates significant heat during cutting, with peak temperatures exceeding 1,000°C. These extreme conditions alter the properties of the material in the cutting zone, create significant temperature gradients on the workpiece surface, and cause sudden cutting forces [6]. This results in residual deformations, induced stresses, and surface microcracks, which significantly affect the dimensional accuracy, surface integrity, and overall reliability of the final component.

Among other factors affecting surface quality, machining stability, and tool life, cutting forces and temperatures in the machining zone are two key parameters [14]. Numerous studies have been conducted to quantitatively evaluate and analyze these parameters. When machining heat-resistant molybdenum-based alloys, it is noteworthy that the cutting edge radius significantly affects the magnitude and distribution of cutting forces [15]. A researcher [16] proposed an empirical model for predicting feed and main cutting forces, emphasizing the strong correlation between the edge radius and the resulting forces and offering valuable recommendations for optimizing cutting parameters to improve machining efficiency and part accuracy.

Solid carbide tools are widely used for milling molybdenum superalloys due to their relatively low cost compared to their ceramic competitors. However, high temperatures can alter the composition and mechanical properties of the tool material, increasing wear and reducing its performance [17]. In addition, cutting temperature directly affects the distribution of tangential stresses in the cutting zone, thereby influencing the stability of the machining process. Researchers have also used dynamic system modeling approaches, such as single-degree-of-freedom models, to predict dynamic cutting forces under various thermal conditions, highlighting the interrelated thermomechanical nature of the machining process [11–13].

Solid carbide cutters are widely used in semi-finishing and finishing operations. Tool wear significantly affects part quality, including surface roughness, residual stresses, surface chipping, and work hardening caused by machining [15]. Researchers [16] conducted experimental studies that revealed severe tool wear during the milling of heat-resistant alloys, identifying it as a key factor in surface quality deterioration. A thorough study of the milling process and surface analysis showed that as the tool wore, surface defects such as increased roughness, microcracks, and dimensional inaccuracies became more pronounced, highlighting the critical importance of effective wear management.

Several different wear mechanisms have been identified in the machining of molybdenum heat-resistant alloys, including flank wear, groove wear, abrasive wear, adhesive wear, and diffusion wear. Flank wear has received the most attention due to its direct impact on dimensional accuracy and surface quality [17–20]. Numerous studies have confirmed that flank wear is the dominant factor determining tool life and machining efficiency for these alloys [6, 21–23].

Despite their high hardness and heat resistance, carbide tools are still subject to rapid wear, frequent replacement, and reduced service life when machining molybdenum heat-resistant alloys using conventional methods. These factors highlight the need for precise control of machining parameters, in particular cutting speed, to optimize tool performance and extend tool life.

During cutting, carbide tools generate a significant amount of heat at the interface between the tool and the workpiece, with cutting temperatures often exceeding 800 °C. These elevated temperatures can significantly alter the mechanical properties and microstructure of carbide tools, reducing their cutting ability and service life. Researchers [24–26] made a significant contribution to the understanding of thermal effects in machining by analyzing heat distribution during milling. Through a combination of experimental and theoretical modeling, the authors [27] explained the relationship between heat distribution, cutting parameters, and tool wear behavior, offering valuable theoretical insights into thermal management and wear reduction strategies. Taken together, these studies have demonstrated that effective control of tool wear and heat generation during cutting not only improves machining efficiency but also significantly improves the quality and reliability of critical components in the aerospace, energy, and defense industries. Nevertheless, challenges remain, particularly those related to accurately predicting tool wear under complex cutting conditions, managing heat distribution during milling, and developing advanced carbide tools capable of maintaining structural integrity under extreme conditions. Research in these areas is crucial for improving machining technologies and enhancing results in high-performance manufacturing environments.

Existing process optimization strategies, including varying tool geometry parameters (rake angle, cutting edge radius), operating parameters (cutting speed, feed rate, depth of cut), and the use of modern cooling methods (including cryogenic media such as liquid nitrogen) have proven effective for nickel and titanium alloys. However, their direct transfer to the machining of the molybdenum alloy *Mo-30TiC* is incorrect due to fundamental differences in the physical and mechanical properties and behavior of materials in the cutting zone (Fig. 1). Thus, there is an obvious gap between the needs of modern production and the available scientific and technical database, which determines the relevance of this study.

The aim of this work is to develop rational technological modes and strategies for edge cutting machining mechanism of the heat-resistant alloy *Mo-30TiC* on the *Okuma MB-46BE* machining center, aimed at increasing the durability of the cutting tool and ensuring the required surface quality. To achieve this goal, the following ***tasks*** must be solved:

– determination of the optimal geometric parameters of the cutting tool to minimize abrasive wear on the flank surface;

– development of a rational milling strategy that takes into account the characteristics of cutting forces and cutting speed;

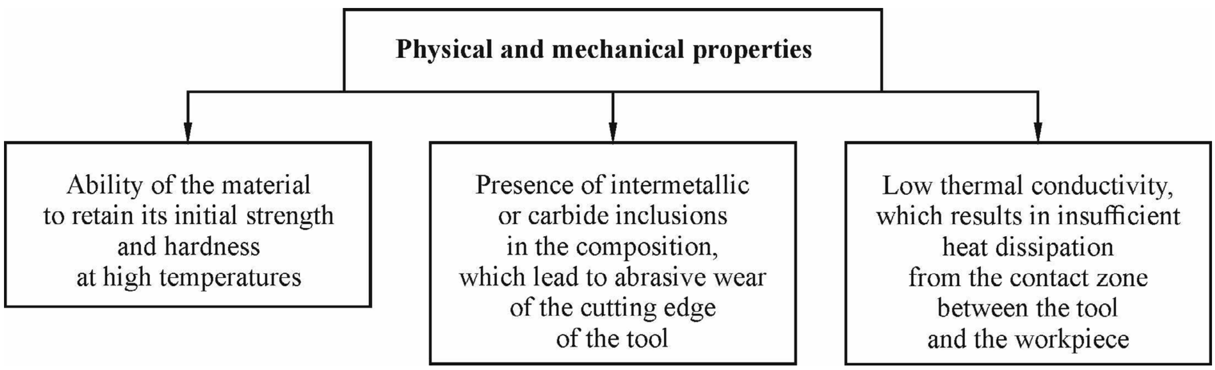

Fig. 1. Physical and mechanical properties

– search for and verification of cutting modes that ensure a balance between productivity and tool life;
– investigation of the dependence of the machined surface roughness on the technological parameters of the process.

Research methodology

The object of the study was a heat-resistant dispersion-strengthened alloy based on molybdenum – *Mo-30TiC*. The workpiece was a cylinder with a diameter of 20 mm and a length of 90 mm. For reliable clamping in the power vise of the machining center, a technological base in the form of a rectangular shank was formed on the end of the workpiece using a *Sodick VZ300L* electrical discharge machine (Fig. 2).

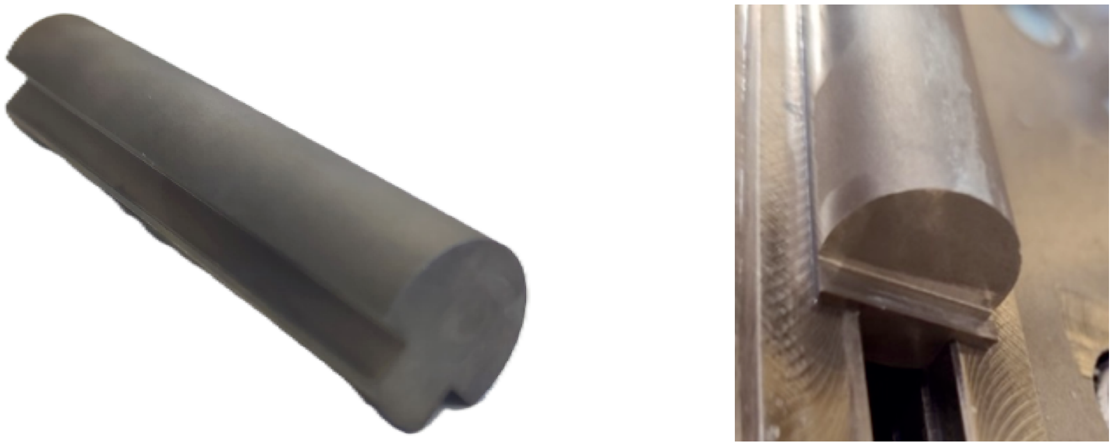

Fig. 2. Workpiece sample made of *Mo-30TiC* alloy with a technological shank

The chemical composition of the material is given in Table 1, and the main physical and mechanical properties that determine its difficult machinability are given in Table 2.

The experiments were conducted on a 5-axis *Okuma MB-46BE* machining center. Cooling was provided by *AdvaCut A2* water-emulsion coolant (7% concentration) at standard pressure.

The study used standard carbide tools from leading manufacturers: *Karcan Cutting Tools* (Turkey), *JJ Tools* (South Korea), and *CNCINS/InSistens* (China/Russia) (Table 3). End mills with a diameter of 8 mm and similar geometric parameters were selected to ensure comparability of results:

– relief angle (**α**): 12°;

Table 1

Chemical composition of *Mo-30TiC* alloy (wt.%).

Mo / Mo	*Ti / Ni*	*C / C*	Other elements
Base	28–32	0.8–1.2	< 0.5

Table 2

Physical-mechanical properties of *Mo-30TiC* alloy

Property	Value	Note
Hardness	45–47 HRC	
Ultimate strength, $\boldsymbol{\sigma}_u$	450–460 MPa (at 20°C)	Increases to ~600 MPa at 600°C
Relative elongation, **δ**	0.5–1.0%	
Modulus of elasticity, ***E***	~320 GPa	
Thermal conductivity	Low	Intense heat localization in the cutting area

Table 3

Tools used in the study

Parameter	*Karcan 99508003* mill	*JJ Tools 4SUE080120S08* mill	*CNCINS MS15.Z5.08.19.63.38.R05* mill
Manufacturer	*Karcan Cutting Tools* (Turkey)	*JJ Tools* (South Korea)	*CNCINS / InSistence* (China / Russia)
Designation	99508003	*4SUE080120S08*	*MS15.Z5.08.19.63.38.R05*
Diameter (mm)	8	8	8
Number of teeth, z	4	4	4
Rake angle, γ°	5°	5°	5°
Clearance angle, α°	12°	12°	12°
Angle of helical flute, ω°	40°	40°	40°
Design features	Reinforced core for enhanced rigidity	Special chip-breaking geometry	Cutting edge radius R0.5 mm
Material / Coating	Carbide / Wear-resistant coating (*TiAlN*)	Carbide / Wear-resistant coating (*TiAlN*)	Carbide / Wear-resistant coating (*TiAlN*)

– rake angle (γ): 5°;
– helix angle (ω): 40°;
– number of teeth (z): 4.

The tool was mounted in a *SCHUNK* hydraulic chuck with the minimum possible overhang (no more than 1.5 times the diameter of the cutter) to maximize the rigidity of the machine–fixture–tool–workpiece system (Fig. 3).

Modern practice in the machining of heat-resistant alloys offers two fundamentally different technological approaches.

The first approach involves the use of a sharp tool with reduced feed rates per tooth (0.05–0.1 mm). This strategy allows for high-quality machined surfaces but is characterized by relatively low productivity. The efficiency of machining is assessed in different ways: for roughing operations, the key indicator is the volume of chips removed during the tool's life, while for finishing operations, it is the area of the machined surface during the same time interval.

Fig. 3. Tool mounted in a *SCHUNK* hydroplastic holder

An alternative strategy is based on the use of a tool with a hardened cutting edge, featuring a negative chamfer or an edge rounding radius of about 0.05 mm. This geometry promotes the formation of a hardened layer of the machined material in the adjacent area, which performs a protective function and reduces the intensity of abrasive wear on the cutting edge. This allows the feed per tooth to be increased by approximately three times compared to the first approach and significantly increases the volume of material removed. The compromise is the need to reduce the cutting speed to minimize heat generation. Despite a slight decrease in productivity, the main benefit is achieved by a multiple increase in tool life and a reduction in tool consumption, which is confirmed by preliminary tests.

The ranges of variation of the main technological parameters, selected on the basis of literature analysis and manufacturers' recommendations, are presented in Table 4.

Table 4

Recommended and experimental cutting conditions

Tool		***n*** (rpm)	f_z (mm)	A_p (mm)	A_e (mm)	***T*** (s)	***V*** (mm^3)
1	*Karcan 99508003*	2875	0.05	12	1	2	393.6
		2875	0.03	12	2	5	787.2
		2000	0.05	12	1.2	55	4920.2
2	*Karcan 111408002*	3500	0.05	12	1	3	393.6
3	*Karcan 101408002*	3000	0.05	12	1	4	393.6
4	*JJ Tools 4SUE080120S08*	1600	0.04	12	1	8	393.6
		200	0.15	12	3	21	1180.8
		400	0.15	12	2	15	1180.8
		600	0.15	12	2	3	393.6
5	*CNCINS MS15.Z5.08.19.63.38.R05*	955	0.01	12	1	25	393.6

To evaluate the effectiveness of each approach, two key parameters were monitored: tool wear and the quality of the machined surface.

The main criterion for tool wear was the width of the wear land on the flank surface (***VB***). Measurements were taken for each cutter tooth using a UIM-21 optical microscope. The maximum *VB* value was recorded, and the criterion for the end of tool life was taken as *VB* = 0.3 mm or the onset of catastrophic chipping of the cutting edge.

Surface quality was measured by the ***Ra*** parameter (arithmetic mean deviation of the profile) using a *MAHR MarSurf PS1* portable profilometer. Measurements were taken at five points along the feed direction. The presence or absence of defects such as chipping, burrs, and thermally affected areas (heat tints) was also visually assessed.

Results and Discussion

The first stage of the experiment was devoted to a preliminary assessment of the behavior of various tools when machining Mo30TiC alloy at the settings recommended by the manufacturers. The results of the visual and auditory analysis are presented in Table 5 and Figs. 4–6.

All tested cutters demonstrated stable segmented chip formation without signs of thermal impact (scuffing), which indicates the absence of critical overheating in the cutting zone. An important result is the complete absence of chipping at the edges of the machined areas, which confirms the suitability of the selected modes for finishing with high edge quality requirements.

Table 5

Results of preliminary tool testing

Tool	*Karcan 99508003*	*JJ Tools 4SUE080120S08*	*CNCINS MS15. Z5.08.19.63.38.R05*
Visual chip analysis	Segmented, no signs of overheating	Segmented, no signs of overheating	Segmented, without signs of overheating
Part edge integrity	No chipping	No chipping	No chipping
Vibroacoustic characteristics	Within acceptable range	Slight vibrations present	Minor vibrations present

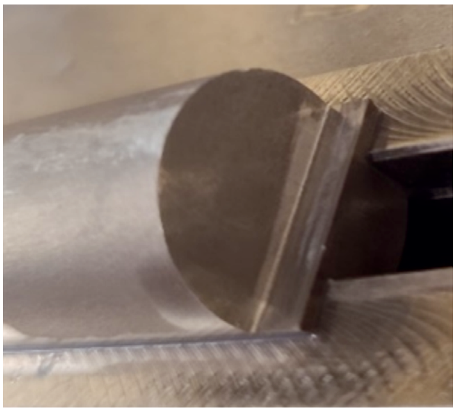

Fig. 4. Sample surface after machining with *Karcan 99508003*

Fig. 5. Sample surface after machining with *JJ Tools 4SUE080120S08*

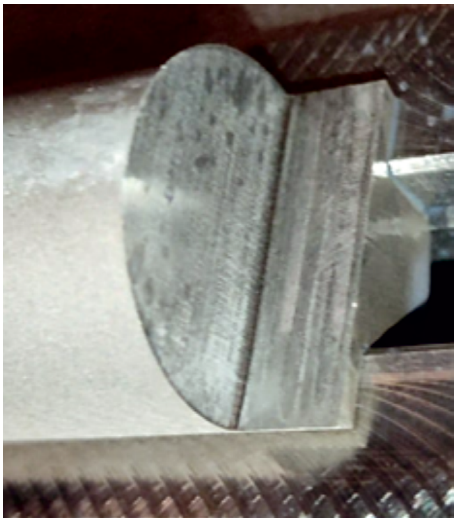

Fig. 6. Sample surface after machining with *CNCINS MS15.Z5.08.19.63.38.R05*

The *Karcan 99508003* mill demonstrated the highest vibration resistance, which is probably due to the optimal combination of its geometry and the dynamic rigidity of the entire technological system. Visual analysis of the tool after machining (Figs. 7–9) did not reveal any catastrophic damage, but subsequent stages were aimed at quantitative assessment of wear.

For in-depth research, the *JJ Tools 4SUE080120S08* mill was selected to study the effect of power milling with increased feed and cutting depth at critically low speeds (200, 400, 600 rpm). In this test, the feed per tooth and the cutting depth in the axial direction were increased, as shown in Table 6.

Fig. 7. Karcan 99508003 end mill:
top – before machining, bottom – after machining

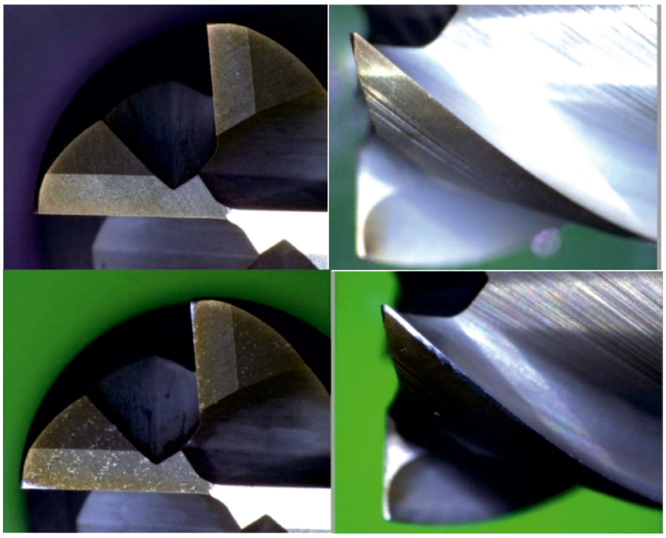

Fig. 8. JJ Tools 4SUE080120S08 end mill:
top – before machining, bottom – after machining

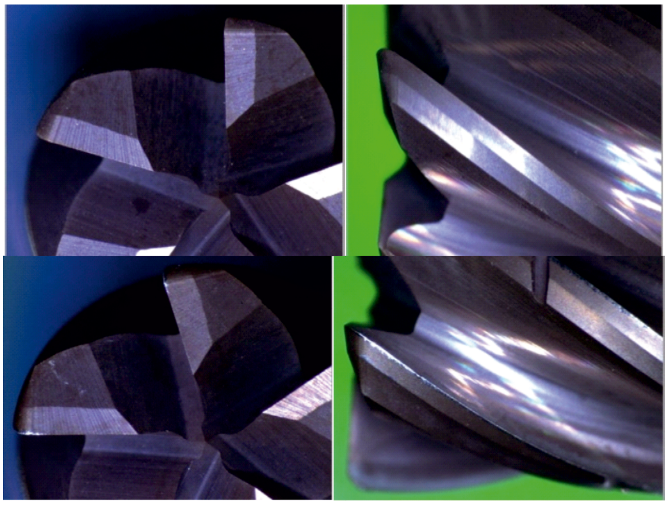

Fig. 9. CNCINS MS15.Z5.08.19.63.38.R05 end mill:
top – before machining, bottom – after machining

The results (Table 6) revealed common problems for this mode:

– the appearance of chips at the edges of the material removal zone on the cutting side, caused by impact loads;

– the formation of an additional edge at the mill exit, indicating plastic flow of the material and high contact pressures;

– clearly pronounced vibrations and impact effects.

Table 6

Effect of cutting parameters on tool wear and surface quality

Tool	*JJ Tools 4SUE080120S08*		
Spindle speed	200 rpm (fig. 10)	400 rpm (fig. 11)	600 rpm (fig. 12)
Visual chip analysis	Segmented, no signs of overheating	Segmented, no signs of overheating	Segmented, no signs of overheating
Part edge integrity	Chipping along the edges of the machined area on the entry side	Chipping along the edges of the machined area on the entry side	Chipping along the edges of the machined area on the entry side
Vibroacoustic characteristics	Vibrations present. Impact loads during tool entry	Vibrations present	Vibrations present. Impact loads during tool entry
Tool edge integrity	Burr formation at the tool exit from the material	Burr formation at the tool exit from the material	Burr formation at the tool exit from the material

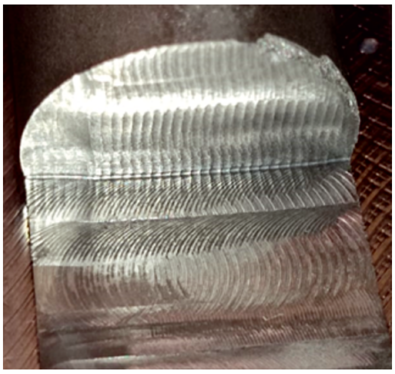

Fig. 10. Sample surface after machining with *Karcan 99508003*

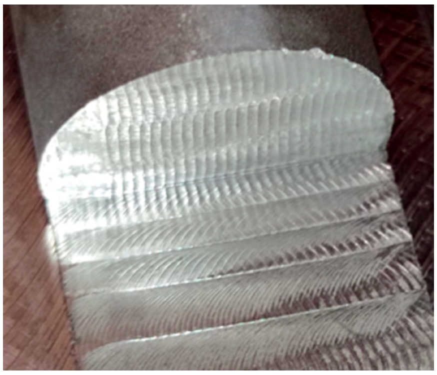

Fig. 11. Sample surface after machining with *JJ Tools 4SUE080120S08*

Fig. 12. Sample surface after machining with *CNCINS MS15.Z5.08.19.63.38.R05*

Despite these negative phenomena, wear on the flank surface remained insignificant, confirming the effectiveness of the strategy of working with a strengthened cutting edge to combat abrasive wear. However, impact loads limit the applicability of this approach for machining critical contours.

At the final stage, testing of the *Karcan 99508003* mill in the middle range of modes (Table 7) allowed a compromise to be found. The work was carried out in the middle ranges of cutting speed and feed rate, but with the recommended milling steps in the axial and radial directions being maintained. Only minor chipping was noted, while favorable vibroacoustic characteristics were maintained. This allows us to recommend this tool and these modes for rough machining.

Table 7

Performance assessment in the medium parameter range

Tool	Karcan 99508003
Visual chip analysis	Segmented chips, no signs of overheating
Part edge integrity	Minor chipping along the edges of the machined area
Vibroacoustic characteristics	Vibroacoustic parameters within acceptable range

The dependence of ***Ra*** roughness parameters on feed and tool geometry was investigated (Table 8). The direction of rotation (***S***) and feed direction (f_z) of the cutter is shown in Fig. 13.

Table 8

Machined surface roughness results

A tool with a preset cutting angle of 12°					
Feed per tooth, f_z (mm/tooth)	Surface roughness (***Ra***) for standard cutting				
	Measurement number				
	1	2	3	4	5
0.03	2.42	2.35	2.42	2.23	2.32
0.04	4.01	3.98	4.11	4.13	3.94

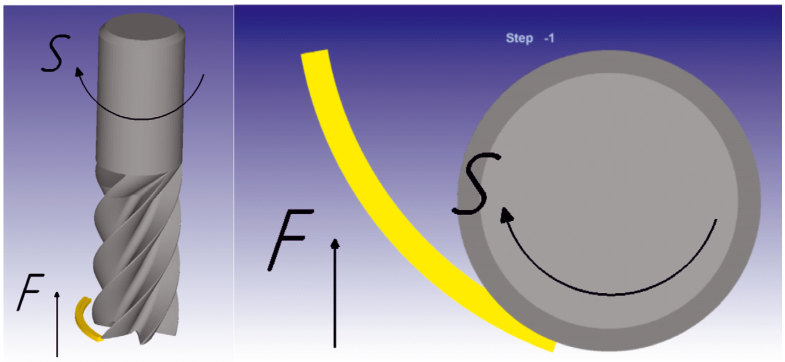

Fig. 13. Cutter rotation direction (*S*) and feed direction (*F*)

Analysis of the obtained profiles and the 3D surface model constructed on their basis (Fig. 14) revealed a pattern: with an increase in feed per tooth, the pitch of irregularities increases regularly, which leads to an increase in the ***Rz*** parameter. However, the use of a tool with a hardened edge (*JJ Tools*) even at increased feeds allowed for a more predictable and uniform micro-relief compared to a sharp tool under similar conditions, where there was a tendency for micro-scratches to occur.

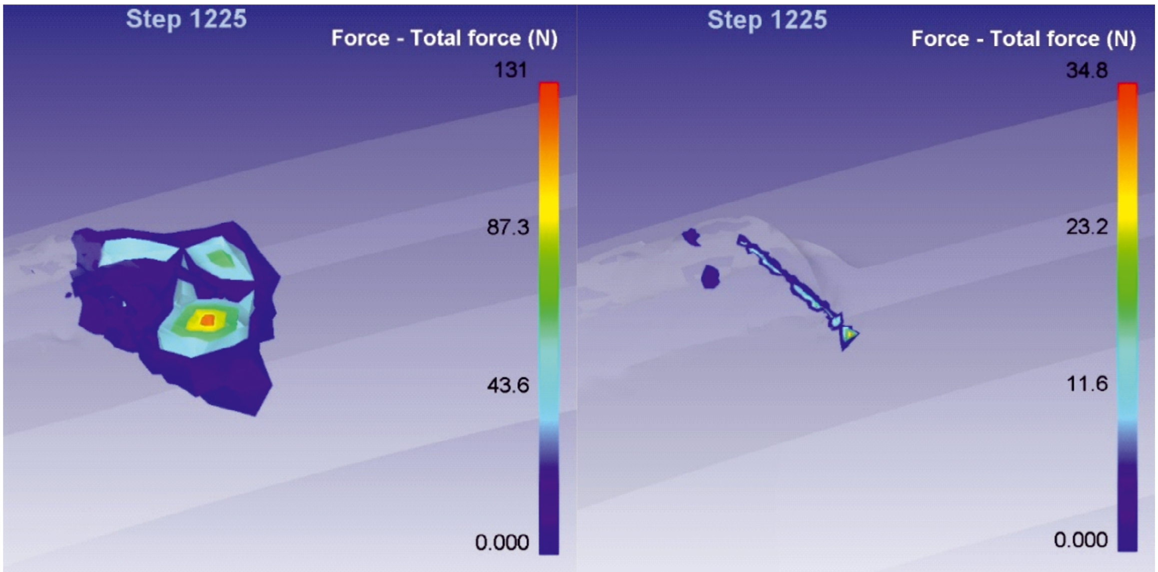

Fig.14. Initial 3D surface model

Analysis of the graph (Fig. 15) showing the dependence of wear on machining time at different cutting speeds revealed the following patterns. The most intense wear is observed at a speed of 50 m/min (curve **1**), where the critical value of the wear land width of 0.1 mm is reached after only 5–7 minutes of machining. Reducing the speed to 35 m/min (curve **2**) allows the tool life to be increased to 15–17 minutes, and at a speed of 25 m/min (curve **3**), the tool remains operational for 25 minutes with minimal wear.

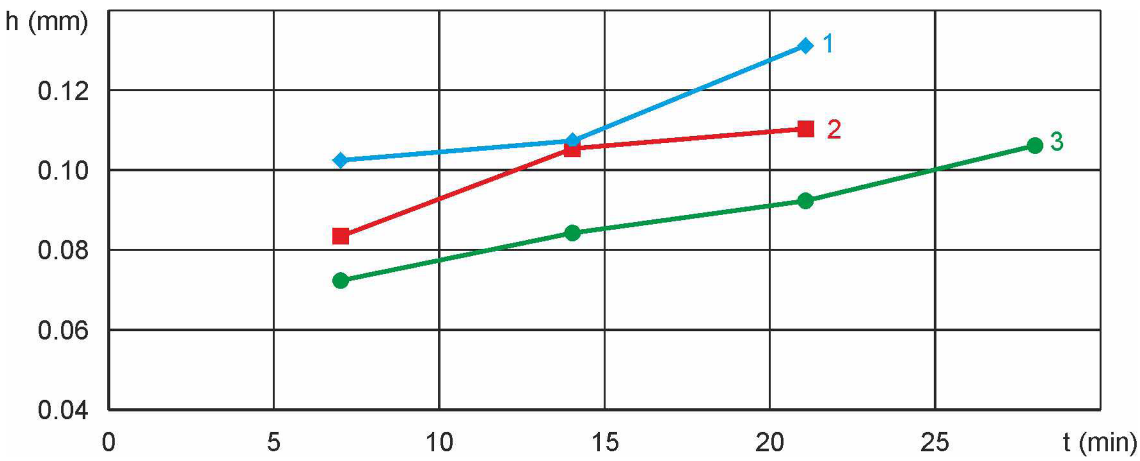

Fig. 15. Tool wear as a function of machining time

The data obtained convincingly demonstrate the inverse relationship between cutting speed and tool life. Reducing the speed from 50 to 25 m/min increased the tool's life by more than three times. The best results when machining the heat-resistant alloy *Mo-30TiC* are achieved at cutting speeds of 25–35 m/min, which provides an optimal balance between productivity and tool life.

Conclusions

As a result of the study, the purpose of the work was achieved: rational technological modes and strategies for machining the heat-resistant alloy *Mo-30TiC* were developed, ensuring increased tool life and the required surface quality. The tasks set were solved as follows:

1. The optimal geometric parameters of the cutting tool were determined, minimizing abrasive wear on the flank surface. The best results were shown by the geometry with a rake angle of 0°, a cutting edge

rounding of 0.5–1 mm, and a negative chamfer of 0.05 mm with an angle of 18°–20°. The tool must have at least four teeth to ensure rigidity and productivity. Among the tested samples, the *Karcan 99508003* and *CNCINS MS15.Z5.08.19.63.38.R05* mills have the most suitable geometry.

2. A rational milling strategy has been developed, taking into account the characteristics of power cutting. The strategy involves the use of a reinforced shank, a milling depth of 1–1.5 times the cutter diameter, and a radial overlap of up to 40%. A key requirement is the elimination of variable contact load to ensure a constant chip cross-section, which prevents vibrations and shock loads.

3. Cutting modes have been found and verified that provide a balance between productivity and tool life:

– for standard cutting (optimized for surface quality): cutting speed (V_c) = 50–72 m/min, feed per tooth (f_z) = 0.03–0.04 mm.

– for power cutting (optimized for productivity): cutting speed (V_c) = 12–17 m/min, feed per tooth (f_z) = 0.08–0.1 mm.

4. The dependence of roughness on technological parameters was investigated. It was established that tool life is a system-forming factor. Wear accumulation leads to an exponential increase in the dispersion of ***Ra*** and ***Rz*** parameters, increasing the amplitude of high-frequency components in the surface profile. Maintaining the tool in a state of stable wear is critical not only for productivity but also for ensuring predictable surface parameters necessary for subsequent operations, such as surface plastic deformation (smoothing).

Thus, the set of proposed solutions – from the choice of tool geometry and machining strategy to specific cutting modes – allows for the effective edge cutting machining of the difficult-to-machine heat-resistant alloy *Mo-30TiC*, controlling tool wear and forming the specified surface quality.

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Conflicts of Interest

The authors declare no conflict of interest.

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