

Research Article

Influence of Milling Parameters on Surface Roughness and Tool Wear During Milling of Composite Materials

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Abstract

Composite materials are widely used in aerospace, automotive, and mechanical engineering industries because of their excellent strength-to-weight ratio, high stiffness, corrosion resistance, and durability under demanding operating conditions. These advantages make them attractive for the production of lightweight and high-performance components. However, the machining of composite materials remains a challenging task due to their heterogeneous structure, anisotropic behavior, and abrasive characteristics. During milling operations, these properties can lead to unstable cutting conditions, increased cutting forces, rapid tool wear, and deterioration of surface quality. The present study investigates the influence of cutting parameters and tool wear on the machining quality of composite materials during CNC milling processes. Particular attention is paid to the effects of cutting speed, feed rate, and depth of cut on the cutting performance and the quality of the machined surface. Experimental investigations were conducted under various machining conditions to evaluate the relationships between process parameters, tool wear progression, and machining outcomes. The results of the study indicate that machining parameters significantly affect cutting force behavior, surface roughness, and tool life. Among the investigated factors, feed rate was found to have the most pronounced influence on cutting force fluctuations, surface finish quality, and the rate of tool wear. An increase in feed rate resulted in higher cutting loads and accelerated wear of the cutting tool, which negatively affected the quality of the machined surface. The findings of this research contribute to a better understanding of composite material machining and provide useful recommendations for selecting optimal CNC milling conditions to improve productivity, reduce tool wear, and achieve higher surface quality.

Keywords

Composite Materials, Milling Parameters, Surface Roughness, Tool Wear, Composite Milling, Finite Element Modeling

1. Introduction

Tool wear and surface roughness are critical factors directly governing the overall machining quality of composite materials. During the milling process, the highly abrasive nature of reinforcing glass fibers significantly accelerates the degradation of the cutting edge. This progressive tool wear elevates the frictional forces within the cutting zone, subsequently

leading to the severe deterioration of the machined surface topography. Experimental investigations have demonstrated that advancements in cutting speed, feed rate, and machining time drastically intensify flank wear, thereby yielding higher surface roughness values [1-4]. Consequently, the systematic optimization of cutting parameters is paramount to mitigating

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Received: 1 June 2026; Accepted: 10 June 2026; Published: 26 June 2026



tool wear, suppressing edge degradation, and maintaining an acceptable surface finish during the milling of composite structures [12-15].

2. Experimental Procedures

The contact interaction model between the workpiece and the cutting tool was considered based on a model that takes into account plastic deformation and cutting tool wear [5-7]. A hard-alloy cutting tool presented in Table 2 was used. The material was considered as a two-component composite consisting of epoxy resin and glass fiber, as shown in Table 1.

Table 1. Physical and mechanical properties of material.

Density. kg/m ³	2 000	2 000
Orthotropic Elasticity		
Young's Modulus X direction. Pa	45 000	4.5e+10
Shear Modulus XZ. Pa	5 000	5e+09
Poisson's Ratio XZ	0.3	0.30000
Young's Modulus Y direction. Pa	45 000	4.5e+10
Shear Modulus YZ. Pa	5 000	5e+09
Poisson's Ratio YZ	0.3	0.30000
Young's Modulus Z direction. Pa	10 000	1e+10
Shear Modulus XY. Pa	5 000	5e+09
Poisson's Ratio XY	0.3	0.30000
Orthotropic Stress Limits		
Tensile X direction. Pa	1100	1.1e+09
Compressive X direction. Pa	-675	-6.75e+08
Shear XY. Pa	80	8e+07
Tensile Y direction. Pa	1100	1.1e+09
Compressive Y direction. Pa	-675	-6.75e+08
Shear YZ. Pa	80	9e+07
Tensile Z direction. Pa	35	3.6e+07
Compressive Z direction. Pa	-120	-1.3e+08
Shear XZ. Pa	80	9e+07

Table 2. Physical and mechanical properties of VK8 cutting tool.

Stiffness. <i>MPa</i>	$2.8 \cdot 10^3$
Young's Modulus. <i>MPa</i>	$5.9 \cdot 10^5$
Coefficient of linear expansion. $10^6 (1/^\circ\text{C})$	5.1

Stiffness. <i>MPa</i>	$2.8 \cdot 10^3$
Density. <i>kg / m³</i>	$1.48 \cdot 10^4$

Surface roughness was measured using a GOYOJO GSR750 Surface Roughness profilometer and tool wear was evaluated using an MMI-2 microscope.

Research data on the variation of cutting tool wear and surface roughness depending on cutting parameters are presented in Tables 3-6.

Table 3. Cutting speed $V = 63 \text{ m/min}$, cutting depth $t = 5 \text{ mm}$ and feed rate $S = 0.02 \text{ mm/tooth}$ [8].

Time τ	Wear h. mm	Surface roughness Ra
3	0.05	2.09
6	0.07	2.29
8	0.08	2.88
13	0.09	2.88
16	0.09	3.06
21	0.10	4.35
28	0.11	4.83
32	0.12	5.58
38	0.13	5.68
42	0.13	5.5
45	0.14	5.16
47	0.17	5.49
51	0.19	5.49
54	0.20	5.76
56	0.21	5.95
60	0.21	5.95
63	0.22	5.96
67	0.23	5.94
69	0.23	6.05
72	0.25	5.94
74	0.27	6.27
78	0.28	6.49
81	0.31	7.04

Table 4. Cutting speed $V = 63$ m/min, cutting depth $t = 5$ mm and feed rate $S = 0.01$ mm/tooth [9].

Time τ	Wear h. mm	Surface roughness Ra
0.55	0.05	2.23
1.1	0.06	2.37
1.63	0.06	2.45
2.75	0.08	2.22
3.85	0.11	2.35
5.51	0.31	2.67

Table 5. Cutting speed $V = 628$ m/min, cutting depth $t = 5$ mm and feed rate $S = 0.1$ mm/tooth [10, 11].

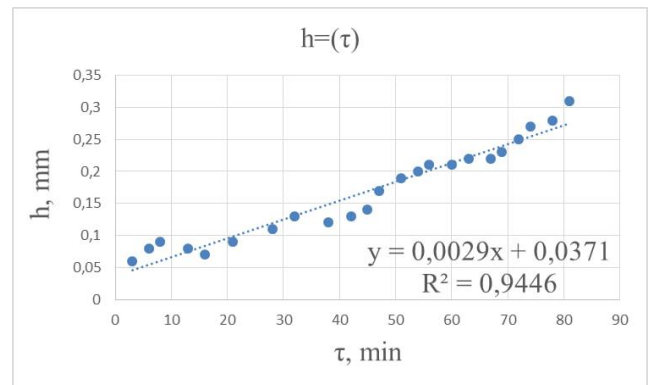
Time τ	Wear h. mm	Surface roughness Ra
0.18	0.11	5.52
0.38	0.14	5.73
0.56	0.22	7.11
0.93	0.28	7.73
1.34	0.32	7.52

Table 6. Cutting speed $V = 628$ m/min, cutting depth $t = 1$ mm and feed rate $S = 0.02$ mm/tooth.

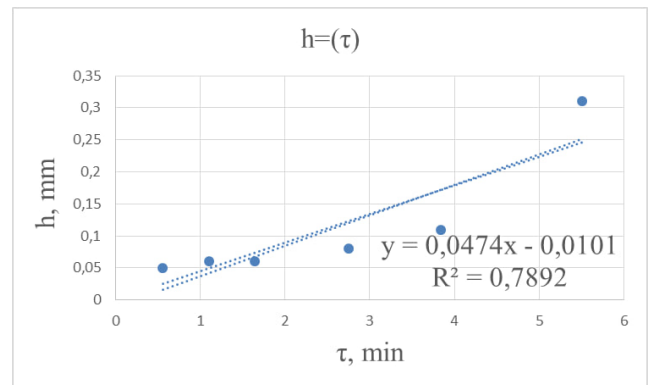
Time τ	Wear h. mm	Surface roughness Ra
0.98	0.02	2.023
1.98	0.04	2.35
2.94	0.07	3.424
4.95	0.11	2.84
6.93	0.12	3.352
8.95	0.15	2.816
10.87	0.21	2.68
13.89	0.26	4.536

Time τ	Wear h. mm	Surface roughness Ra
16.85	0.3	2.49

The dependence of cutting tool wear on machining time at cutting speed $V = 63$ m/min, cutting depth $t = 5$ mm, feed rates $S = 0.02$ mm/tooth and $S = 0.1$ mm/tooth are presented in Figures 1(a) and 1(b).



(a)



(b)

Figure 1. Dependence of cutting tool wear on machining time.

The dependence of cutting tool wear on machining time at cutting speed $V = 628$ m/min, cutting depths $t = 5$ mm and $t = 1$ mm, feed rates $S = 0.1$ mm/tooth and $S = 0.02$ mm/tooth is presented in Figures 2(a) and 2(b).

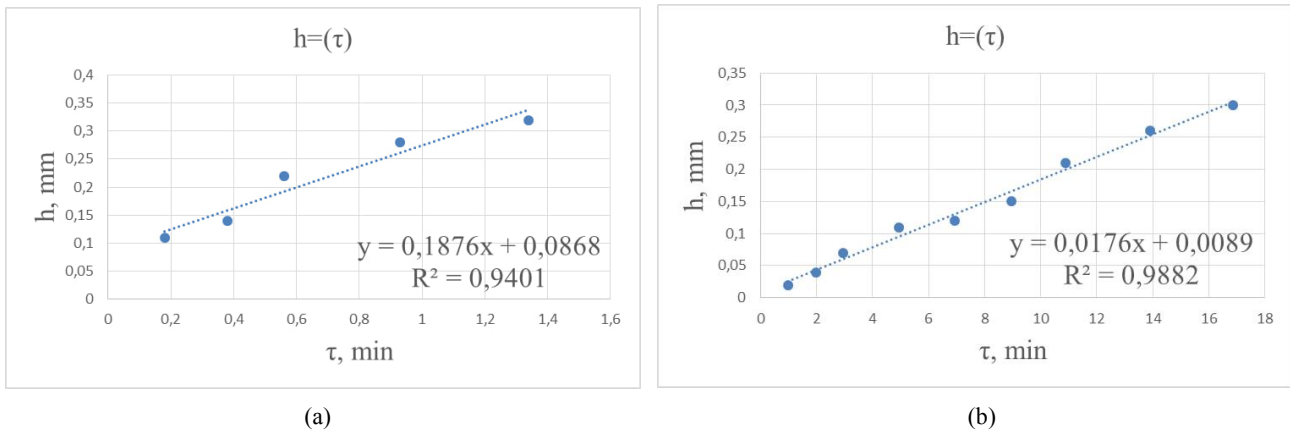


Figure 2. Dependence of cutting tool wear on machining time.

Using the standard algorithm in Microsoft Excel, the coefficients of the mathematical relationship were analyzed. The calculation of coefficients A and B for the relationship: $h = A+B \cdot \tau$.

№ эксп.	V	S	t	A	B	A~	a	
1	69	0,02	10	0,0325	0,003	0,0325	-0,0451	
2	69	0,1	1	-0,0148	0,0493	-0,0148	0,00022	
3	200	0,1	10	0,0688	0,2064	0,0688	0,08813	
4	200	0,02	1	0,0074	0,0178	0,0074	0,00604	
							S=	2,4E-34
Определение k-ов a								
	1	69	0,02	10		0,0325		
A=	1	69	0,1	1	B=	-0,0148		
	1	200	0,1	10		0,0688		
	1	200	0,02	1		0,0074		
	0,8328	0,69391	-0,9439	0,4172			-0,0451	
A^(-1)=	-0,0038	-0,0038	0,00382	0,00382			0,00022	
	-6,25	6,25	6,25	-6,25			0,08813	
	0,05556	-0,0556	0,05556	-0,0556			0,00604	

№ эксп.	V	S	t	A	B	B~	b	
1	69	0,02	10	0,0325	0,003	0,003	-0,1507	
2	69	0,1	1	-0,0148	0,0493	0,0493	0,00066	
3	200	0,1	10	0,0688	0,2064	0,2064	1,46813	
4	200	0,02	1	0,0074	0,0178	0,0178	0,00791	
							S=	2,5E-33
Определение k-ов b								
	1	69	0,02	10		0,003		
B=	1	69	0,1	1	B=	0,0493		
	1	200	0,1	10		0,2064		
	1	200	0,02	1		0,0178		
	0,8328	0,69391	-0,9439	0,4172			-0,1507	
A^(-1)=	-0,0038	-0,0038	0,00382	0,00382			0,00066	
	-6,25	6,25	6,25	-6,25			1,46813	
	0,05556	-0,0556	0,05556	-0,0556			0,00791	

Figure 3. Calculation of coefficients A and B.

$$H = A+B \cdot \tau$$

where:

$$A = 0.0325 \cdot V - 0.0148 \cdot S + 0.0688 \cdot t + 0.0074$$

$$B = 0.003 + V \cdot 0.0493 + S \cdot 0.0178 + t \cdot 0.0178$$

The experiments confirmed a linear relationship between the cutting force and the amount of cutting tool wear at $V = 63$ m/min, $S = 0.1$ mm/tooth and $t = 5$ mm, the following relationship was obtained:

$$P = 1576 \cdot h - 8.142$$

where P is the cutting force (N) and h is the flank wear of the cutting tool (mm). Similar relationships can also be obtained for other cutting conditions.

Investigation of the dependence of surface roughness Ra on cutting conditions. The obtained experimental data made it possible to determine two types of relationships:

- 1) The relationship between the arithmetic mean deviation of the machined surface profile Ra, machining time (τ) and cutting conditions;
- 2) The relationship between the flank wear of the cutting tool (h) and the arithmetic mean deviation of the machined surface profile Ra.

The relationships obtained at cutting speed $V = 63$ m/min, cutting depth $t = 5$ mm and feed rate $S = 0.02$ mm/tooth are presented in Figure 4.

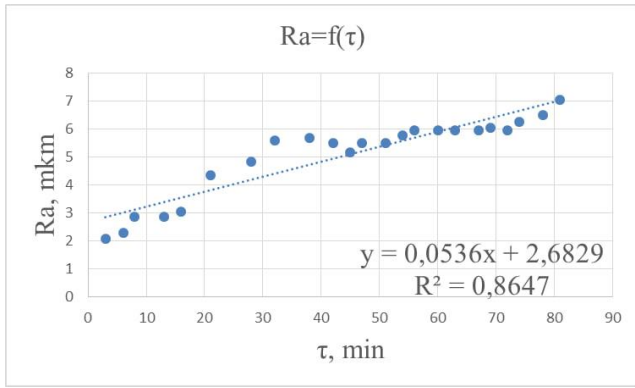


Figure 4. Dependence of surface roughness on time.

The relationships obtained at cutting speed $V = 628$ m/min, cutting depth $t = 5$ mm and feed rate $S = 0.1$ mm/tooth are presented in Figure 5.

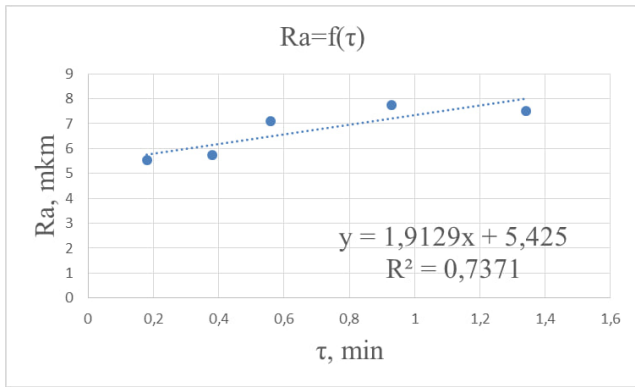


Figure 5. Dependence of surface roughness on time.

The relationship between the arithmetic mean deviation of the machined surface profile and time has the following form:
 $Ra = A + B \cdot \tau$

№ эксл.	V	S	t	A	B	A~	a	
1	69	0,02	10	2,6685	0,0537	2,6685	-0,24884	
2	69	0,1	1	2,2235	0,0631	2,2235	0,011714	
3	200	0,1	10	5,3893	1,9548	5,3893	14,82813	
4	200	0,02	1	2,5718	0,0488	2,5718	0,18125	
							S=	9,86E-31
Определение k-ов a								
A=	1	69	0,02	10				2,6685
	1	69	0,1	1	A~=			2,2235
	1	200	0,1	10				5,3893
	1	200	0,02	1				2,5718
A^(-1)=	0,832803	0,693914	-0,94391	0,417197				-0,24884
	-0,00382	-0,00382	0,003817	0,003817				0,011714
	-6,25	6,25	6,25	-6,25				14,82813
	0,055556	-0,05556	0,055556	-0,05556				0,18125

№ эксл.	V	S	t	A	B	B~	b	
1	69	0,02	10	2,6685	0,0537	0,0537	-1,7363	
2	69	0,1	1	2,2235	0,0631	0,0631	0,007202	
3	200	0,1	10	5,3893	1,9548	1,9548	11,97125	
4	200	0,02	1	2,5718	0,0488	0,0488	0,105367	
							S=	6,38E-32
Определение k-ов b								
B=	1	69	0,02	10				0,0537
	1	69	0,1	1	B=			0,0631
	1	200	0,1	10				1,9548
	1	200	0,02	1				0,0488
A^(-1)=	0,832803	0,693914	-0,94391	0,417197				-1,7363
	-0,00382	-0,00382	0,003817	0,003817				0,007202
	-6,25	6,25	6,25	-6,25				11,97125
	0,055556	-0,05556	0,055556	-0,05556				0,105367

Figure 6. Calculation of coefficients A and B.

where:

$$A = 2.6685 + V \cdot 2.2235 + S \cdot 5.3893 + t \cdot 2.5718$$

$$B = 0.0537 + V \cdot 0.0631 + S \cdot 1.9548 + t \cdot 0.0488$$

Experimental data describing the relationship between cutting tool wear and the arithmetic mean deviation of the machined surface profile are presented graphically in Figures 7 and 8. A fragment of the calculation of coefficients A and B for this relationship is shown in Figure 9.

The dependence of surface roughness Ra on tool wear at cutting speed $V=63$ m/min, cutting depth $t=5$ mm and feed rate $S=0.02$ mm/tooth

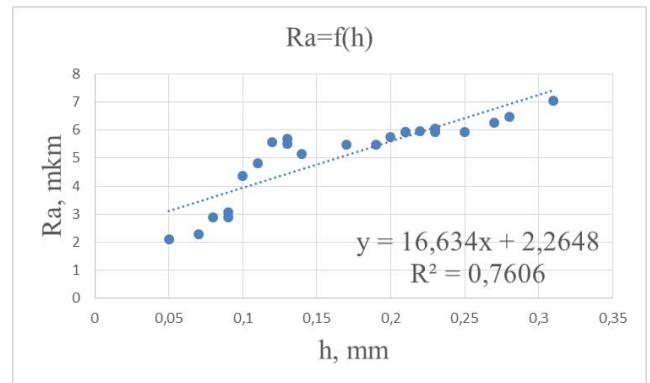


Figure 7. Dependence of cutting tool wear on surface roughness.

The dependence of surface roughness Ra on tool wear at cutting speed $V = 628$ m/min, cutting depth $t = 5$ mm and feed rate $S = 0.1$ mm/tooth.

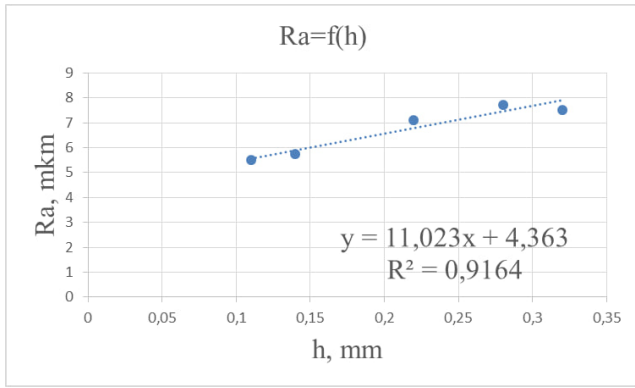


Figure 8. Dependence of cutting tool wear on surface roughness.

№ эксп.	V	S	t	A	B	A~	a	
1	69	0,02	10	2,3439	16,427	2,3439	0,181646	
2	69	0,1	1	2,2309	1,3843	2,2309	0,009788	
3	200	0,1	10	4,6263	10,001	4,6263	12,50188	
4	200	0,02	1	2,513	3,0194	2,513	0,123683	
							S=	3,16E-30
Определение k-ов a								
	1	69	0,02	10			2,3439	
A=	1	69	0,1	1	A~=		2,2309	
	1	200	0,1	10			4,6263	
	1	200	0,02	1			2,513	
	0,832803	0,693914	-0,94391	0,417197			0,181646	
A^(-1)=	-0,00382	-0,00382	0,003817	0,003817			0,009788	
	-6,25	6,25	6,25	-6,25			12,50188	
	0,055556	-0,05556	0,055556	-0,05556			0,123683	

№ эксп.	V	S	t	A	B	B~	b	
1	69	0,02	10	2,3439	16,427	16,427	6,460641	
2	69	0,1	1	2,2309	1,3843	1,3843	-0,01829	
3	200	0,1	10	4,6263	10,001	10,001	-50,3819	
4	200	0,02	1	2,513	3,0194	3,0194	1,223572	
							S=	5,18E-30
Определение k-ов b								
	1	69	0,02	10			16,427	
B=	1	69	0,1	1	B~=		1,3843	
	1	200	0,1	10			10,001	
	1	200	0,02	1			3,0194	
	0,832803	0,693914	-0,94391	0,417197			6,460641	
A^(-1)=	-0,00382	-0,00382	0,003817	0,003817			-0,01829	
	-6,25	6,25	6,25	-6,25			-50,3819	
	0,055556	-0,05556	0,055556	-0,05556			1,223572	

Figure 9. Fragment of calculation of coefficients A and B.

The relationship between the arithmetic mean deviation of the machined surface profile and flank wear of the cutting tool has the following form: $Ra = A + B \cdot h$ where:

$$A = 2.3439 + V \cdot 2.2309 + S \cdot 4.6263 + t \cdot 2.513$$

$$B = 16.427 + V \cdot 1.3843 + S \cdot 10.001 + t \cdot 3.0194$$

3. Conclusions

The study investigated the influence of milling parameters

on tool wear and surface quality during machining of composite materials. The experimental results confirmed that cutting conditions significantly influence flank wear, cutting force and surface roughness during milling of composite materials. Increasing machining intensity accelerated tool wear and deteriorated the machined surface quality. Mathematical relationships describing the dependence between machining time, tool wear and surface roughness were obtained. The developed models can be used for predicting machining quality and selecting rational cutting conditions for efficient milling of materials.

Abbreviations

- τ Machining Time
- h Flank Wear of the Cutting Tool

Author Contributions

Fayzimatov Shukhrat: Conceptualization, Formal Analysis, Methodology, Supervision, Validation, Writing – review & editing

Rustamov Bannobjon: Data curation, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing, Investigation

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Fayzimatov Shukhrat is a Doctor of Technical Sciences and a professor in the field of mechanical engineering and manufacturing technology. He has made significant contributions to research on machining processes, composite material processing, cutting tool performance and manufacturing systems. He is the author of numerous scientific articles, educational materials and methodological works devoted to machining technology and modern manufacturing methods. Currently, he works at the Department of Mechanical Engineering of Fergana State Technical University, where he actively participates in scientific research and supervises graduate students and young researchers. His scientific interests include CNC machining, composite material processing, cutting tool wear, surface quality improvement, and optimization of machining parameters. Throughout his academic career, Professor Fayzimatov has supervised numerous postgraduate researchers and has played an important role in the development of engineering education and advanced manufacturing research in Uzbekistan.



Rustamov Bannobjon is a PhD candidate and assistant lecturer at the Department of Mechanical Engineering, Fergana State Technical University, Uzbekistan. He completed advanced professional training abroad and actively collaborates with foreign professors and researchers in the field of advanced manufacturing technologies and composite material processing. He is actively involved in scientific research related to modern machining technologies and intelligent manufacturing systems.

Research Field

Fayzimatov Shukhrat: Machining Technologies, Composite Material Processing, Cutting Tool Design, High-Speed Machining, Cutting Force Analysis, Tool Wear and Surface Integrity, CNC Manufacturing Systems, Adaptive Control in Machining Processes, Modeling of Technological Processes, Intelligent Manufacturing Technologies.

Rustamov Bannobjon: Composite Material Machining, Milling of GFRP Composites, Cutting Force Stabilization, Tool Wear Analysis, Surface Roughness Formation, Finite Element Modeling of Machining Processes, High-Speed Milling Technologies, Adaptive Control of Machining Processes, CNC Manufacturing Technologies, Intelligent Manufacturing Systems.