INFLUENCE OF CUTTING FORCES AND TOOL WEAR ON CHIP FORMATION DURING MILLING OF COMPOSITE MATERIALS

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Abstract: This study focused on the influence of cutting parameters on cutting force, tool wear and chip formation during milling of glass fiber reinforced composites. Experiment were conducted to determine the relationships between cutting conditions and tool wear. The results help to optimize milling parameters and improve machining efficiency of composite materials.

Keywords: Glass fiber reinforced polymer (GFRP), cutting force, tool wear, flank wear, chip formation, surface roughness, finite element modeling.

ВЛИЯНИЕ СИЛ РЕЗАНИЯ И ИЗНОСА ИНСТРУМЕНТА НА ОБРАЗОВАНИЕ СТРУЖКИ ПРИ ФРЕЗЕРОВАНИИ КОМПОЗИТНЫХ МАТЕРИАЛОВ.

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Аннотация: В данном исследовании изучалось влияние параметров резания на силу резания, износ инструмента и образование стружки при фрезеровании композитов, армированных стекловолокном. Были проведены эксперименты для определения взаимосвязи между условиями

резания и износом инструмента. Результаты помогают оптимизировать параметры фрезерования и повысить эффективность обработки композитных материалов.

Ключевые слова: Полимер, армированный стекловолокном (GFRP), сила резания, износ инструмента, износ боковой поверхности, образование стружки, шероховатость поверхности, конечно-элементное моделирование.

INTRODUCTION

Composite materials are heavily used in aerospace, automotive, and mechanical engineering industries because of their high strength-to-weight ratio and corrosion resistance [1,2,3,4]. Machining of glass fiber reinforced composites is connected with problems as tool wear, high cutting forces, and poor surface quality [5,6,7,8]. Investigating the influence of cutting parameters on machining performance is an important scientific task. This study analyze the relationships between cutting force, tool wear and chip formation during the milling process of composite materials.

MATERIALS AND METHODS

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

Table 1. Physical and mechanical properties of glass fiber composite material [9].

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	-6,76e+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	-1,4e+08
Shear XZ, Pa	80	9e+07

Table 2. Physical and mechanical properties of VK8 grade cutting tool [10]

Stiffnes, MPa	$2.8 \cdot 10^3$
Young's Modulus, MPa	$5.9 \cdot 10^5$
Coefficient of linear expansion, $10^6 (1/ {}^\circ C)$	5.1
Density, kg / m^3	$1.48 \cdot 10^4$

RESULTS

The signals obtained for evaluating the cutting force were processed and analyzed using a specially developed algorithm. To reduce system errors during calculations, average arithmetic values and coefficients for converting voltage into force values were applied. The processed results were then transferred to Microsoft Office Excel, and the obtained experimental data were summarized in Table 1.

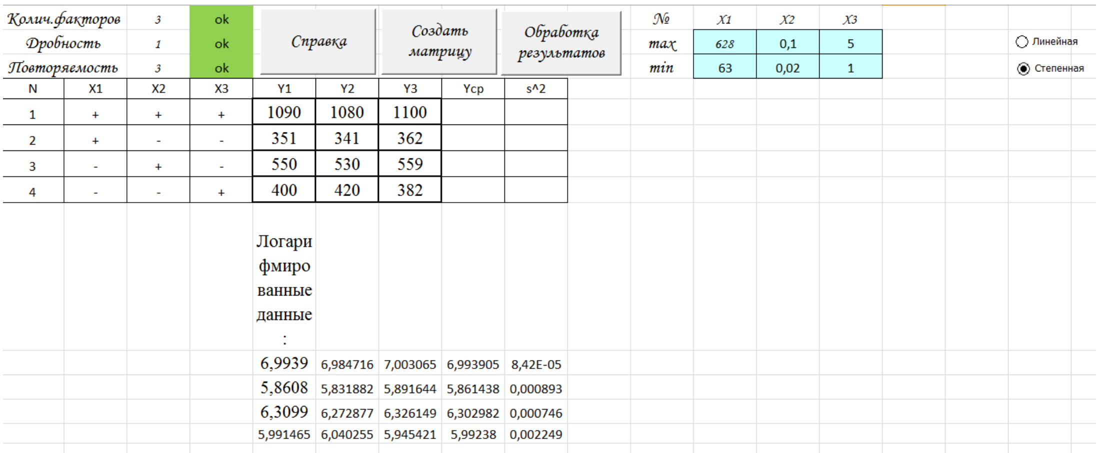
Table 3. Experimental values of forces generated during the cutting process [7]

№	*S (mm/tish)*	*V (m/min)*	*t (mm)*	*P (N)*
1	0,1	63	1	596
2	0,02	63	5	475

The obtained experimental data, adapted to the experimental design, made it possible to determine the mathematical relationship between cutting force and cutting parameters, where: V is the cutting speed (m/min), S is the feed rate (mm/tooth), and t is the cutting depth (mm).

$$P = 926 \cdot V^{0,12} \bullet S^{0,43} \cdot t^{0,25}$$

This relationship was obtained as a result of processing the experimental data using the “Least Squares Method” software package on a computer (Figures 1–2).



Колич.факторов	3	ok
Дробность	1	ok
Повторяемость	3	ok

№	X1	X2	X3
max	628	0,1	5
min	63	0,02	1

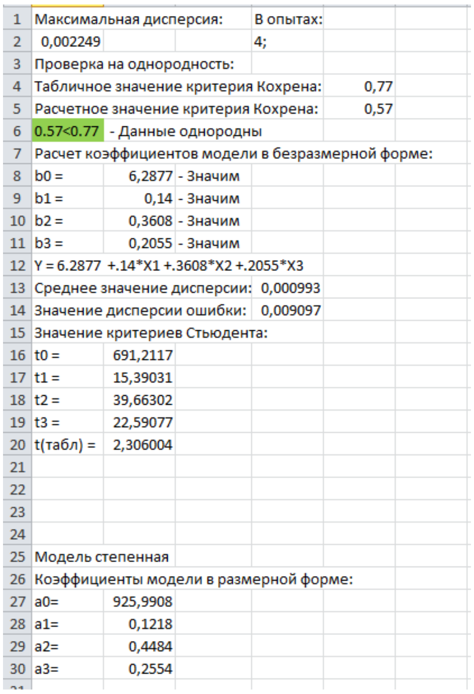
○ Линейная
● Степенная

N	X1	X2	X3	Y1	Y2	Y3	Ycp	s^2
1	+	+	+	1090	1080	1100		
2	+	-	-	351	341	362		
3	-	+	-	550	530	559		
4	-	-	+	400	420	382		

Логарифмированные данные:

6,9939	6,984716	7,003065	6,993905	8,42E-05
5,8608	5,831882	5,891644	5,861438	0,000893
6,3099	6,272877	6,326149	6,302982	0,000746
5,991465	6,040255	5,945421	5,99238	0,002249

Figure 1. Program working window



Максимальная дисперсия:		В опытах:	
0,002249		4;	
Проверка на однородность:			
Табличное значение критерия Кохрена:			0,77
Расчетное значение критерия Кохрена:			0,57
0.57<0.77	- Данные однородны		
Расчет коэффициентов модели в безразмерной форме:			
b0 =	6,2877	- Значим	
b1 =	0,14	- Значим	
b2 =	0,3608	- Значим	
b3 =	0,2055	- Значим	
Y = 6.2877 +.14*X1 +.3608*X2 +.2055*X3			
Среднее значение дисперсии:		0,000993	
Значение дисперсии ошибки:		0,009097	
Значение критериев Стьюдента:			
t0 =	691,2117		
t1 =	15,39031		
t2 =	39,66302		
t3 =	22,59077		
t(табл) =	2,306004		
Модель степенная			
Коэффициенты модели в размерной форме:			
a0=	925,9908		
a1=	0,1218		
a2=	0,4484		
a3=	0,2554		

Figure 2. Program operating state

The experimental data were processed using the least squares method, and a linear relationship was obtained (2).

Table 4. Experimental data obtained during the study: stresses (σ) and cutting force (P).

№	*S (mm/tish)*	*V (m/min)*	*T (mm)*	*P (N)*	σ*(MPa)*
3	0,1	63	1	597	1800
4	0,02	63	5	476	1350

$P = 5{,}2 + 0{,}28\cdot\sigma$

The relationship graph is presented in Figure 3.

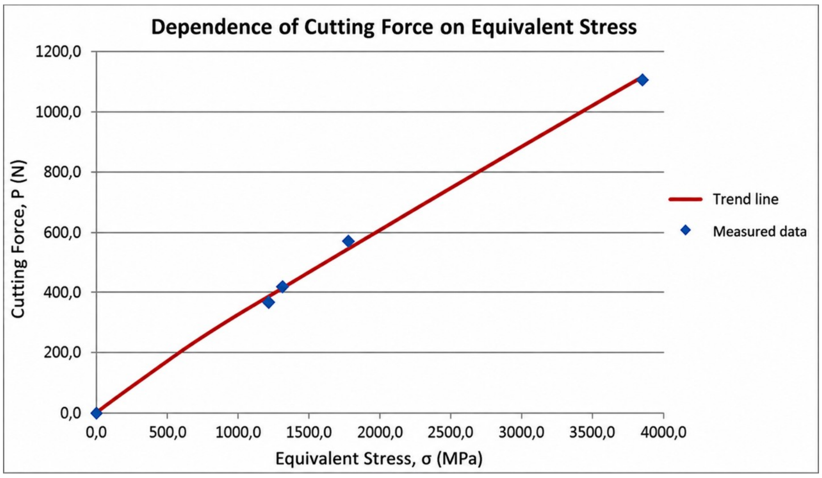


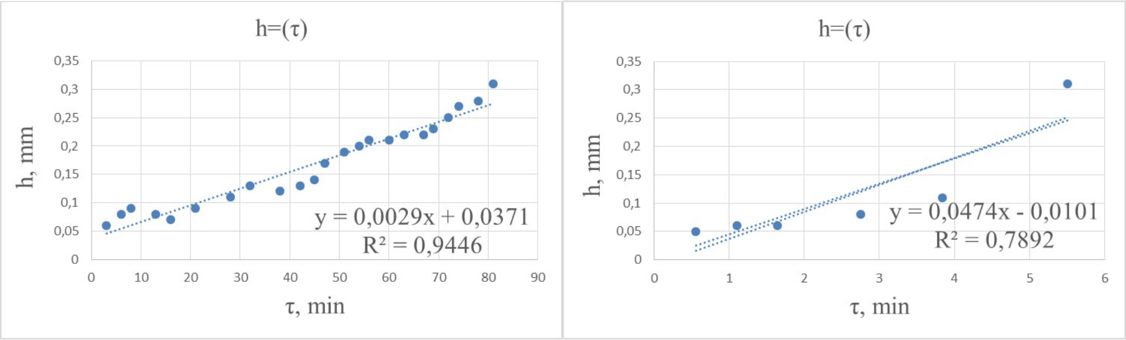
Figure 3. Relationship between the results obtained during the milling process

The dependence of tool wear on cutting parameters Table 5.

Time t, min	**Wear h, mm**	**Roughness Ra**
Cutting speed V = 63 m/min, cutting depth t = 5 mm, Feed rate S = 0,02 mm/tooth		
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	5,17
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	5,86
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
h correlation coefficient		0,87
t correlation coefficient		0,93

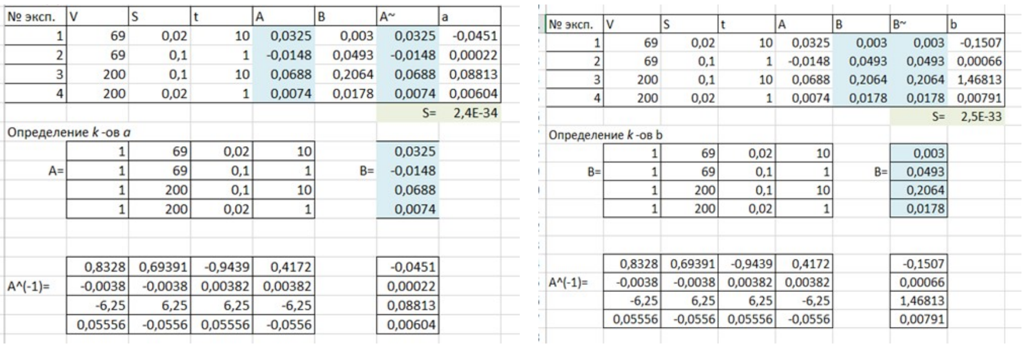
The dependence of cutting tool wear on machining time at cutting speed V = 63 m/min, cutting depth t = 5 mm, feed rates S = 0.02 mm/tooth and S = 0.1 mm/tooth are presented in Figure 4 (a), (b).



a) b)

Figure 4. Dependence of cutting tool wear on machining

Part of the calculations is presented in Figure 6, and the empirical relationship coefficients were determined by analyzing the data using a standard algorithm in Microsoft Excel..



№ 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 5. Calculation coefficient A, B

The dependence of wear on time can be expressed as:

$h=A+B\cdot\tau$

where:

$A=0.0335-V\cdot 0.0148+S\cdot 0.0688+t\cdot 0.0074$

$B=0.003+V\cdot 0.0393+S\cdot 0.0178+t\cdot 0.0178$

The experiments established a linear relationship between cutting force and cutting tool wear at cutting conditions of V=63 m/min, S=0.1 mm/tooth, and t=5 mm:

$P=1576\cdot h-8.143$

where P is the cutting force (N), and h is the flank wear of the cutting tool (μm).]

One of the important characteristics of the cutting process is the nature of chip formation. Analysis of chip formation makes it possible to evaluate cutting force, generated heat, as well as the quality and accuracy of the machined surface. During the machining of composite materials, different chip forms can be observed, including elemental and fragmented chips.

An increase in flank wear of the cutting tool leads to a reduction in the bonding strength between chip elements. As a result, the chips are formed as fine fragmented particles. Experimental studies showed that cutting tool wear significantly affects both chip formation behavior and variations in cutting force.

$P=1576\cdot h\text{-}8{,}142$

Where: P is the cutting force (N), and h is the flank wear of the cutting tool (μm).

During the initial wear stage, when the wear value is within the range of 0.05–0.15 mm, long chips with a length of 5–10 mm are observed, as shown in Figure 7(a). When the wear increases to 0.15–0.25 mm, smaller fragmented chips are formed, as presented in Figure 7(b). At the allowable wear limit, powder-like chips are generated, as shown in Figure 7(c).

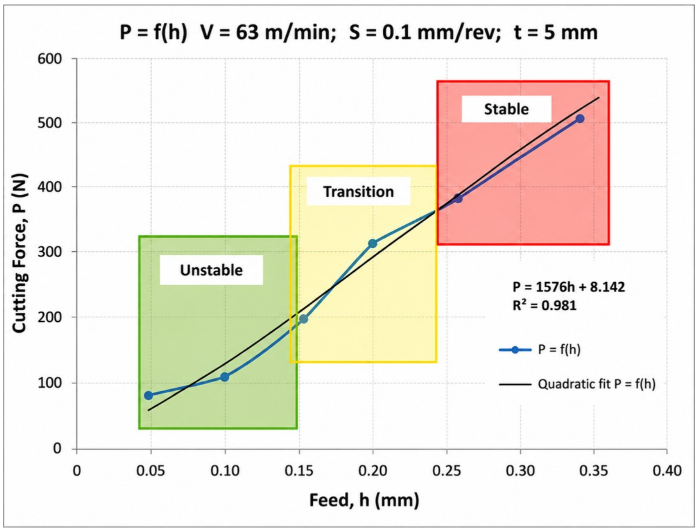


Figure 6. Effect of tool wear and cutting force on chip formation

Flank wear in the range of 0.15–0.25 mm (b, c); sharpened cutting tool

(a)

a) b) c)

Figure 7. Effect of tool wear on chip formation

CONCLUSION

The conducted experimental studies confirmed the existence of stable relationships between cutting parameters, cutting force and tool wear during milling of composite materials. Empirical models describing the influence of cutting conditions on cutting force and tool wear were developed. The results showed that increasing tool wear significantly affects chip formation, cutting force and surface quality. The experimental approach can be effectively applied for optimizing milling parameters and improving machining efficiency of composite materials

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