SESSION C: PRODUCTION TECHNOLOGIES, CAE AND MANAGEMENT

Investigation of cutting parameters influence on vibration during milling of HDPE

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ABSTRACT

The paper analyzes the influence of spindle speed, feed rate and axial depth of cut on vibration acceleration in feed direction during peripheral milling of high-density polyethylene. Experimental research was planned and implemented using the response surface methodology in the Design-Expert software package. Based on the experimental results, a statistical analysis was performed and a mathematical model was developed to predict vibration acceleration. The research results showed that feed rate and axial depth of cut have a dominant influence on vibration acceleration, while the influence of spindle speed is less pronounced. A reduced quadratic mathematical model was developed to describe the dependence between process parameters and vibration acceleration in feed direction. Model diagnostics and validation results confirmed its adequacy and good predictive ability. The obtained results can serve as a basis for selecting process parameters in order to reduce vibrations and improve the stability of the peripheral milling of high-density polyethylene.

KEYWORDS

Peripheral milling, Vibration acceleration, Cutting parameters, Response Surface Methodology

1. INTRODUCTION

The main sources of vibration during milling operations are the cutting process itself, the machine structure, and the tool setup. These vibrations are generally categorized into free, forced, and self-excited vibrations (chatter). Cyclic tool engagement followed by interrupted cutting and varying chip thickness leads to forced vibrations. Regenerative chatter occurs when a cutting tooth engages a wavy surface generated by the previous tooth, while friction between the tool flank and the workpiece may further contribute to self-excited vibrations. Small or long tools bend easily under cutting forces, making them highly prone to snapping or vibrating. The natural shaking frequency of the machine frame can match the cutting frequency, amplifying the vibration.

Machining parameters, above all spindle speed, feed rate, depth of cut, and radial engagement are critical drivers of vibration and chatter in milling [1]. Spindle speed determines the frequency of the cut, feed rate dictates the chip load, radial and axial depth of cut directly influence the magnitude of cutting forces, tool path determines changes of tool engagement [2] which can lead to increased vibration. Researchers [3], [4] have reported correlations between machining parameters and vibration occurrence during milling processes.

Vibrations can be detected through the measurement of acceleration, velocity or displacement [5]. Piezoelectric, capacitive, and piezoresistive accelerometers are commonly employed for vibration measurements on machine tools. Vibration measurements are often used for direct chatter detection or indirect tool wear monitoring. Several studies have reported correlations between vibration levels, surface roughness, workpiece geometric accuracy, and cutting power consumption [6], [7]. It has also been shown that vibrations affect tool life, machine service life, and machining accuracy. Pimenov et al. [8] reviewed various indirect methods for tool condition monitoring, including vibration-based measurement techniques.

Although machining vibrations have been extensively investigated in metal cutting processes, comparatively less attention has been devoted to polymer machining, particularly in the case of HDPE (High-Density Polyethylene) materials. Existing studies primarily focus on cutting forces, tool wear, or surface quality, while the influence of machining parameters on vibration behavior remains insufficiently explored. Furthermore, the potential use of vibration signals as indirect indicators of process performance and surface quality has received limited attention. In addition, limited information is available regarding predictive modeling of vibration responses during HDPE milling under varying cutting conditions. The vibration signal acquired along the X-axis (feed direction) was selected for analysis. This direction is directly related to the process kinematics, as variations in feed rate and chip load are reflected through the cutting forces acting along the feed axis. Since the feed motion significantly influences the generation of the machined surface, vibrations measured in this direction are considered particularly representative of the machining process behavior and its response to changes in cutting conditions.

The aim of this study is to investigate the influence of spindle speed, feed rate, and axial depth of cut on vibration acceleration measured in the feed direction during CNC peripheral milling of HDPE using an high-speed steel (HSS) flat end mill. Statistical analysis and multiple linear regression modeling were employed to determine the significance of machining parameters and to develop predictive models for vibration in X-direction. Additionally, confirmation experiments were performed to validate the developed regression model.

2. MATERIALS AND METHODS

2.1. Workpiece Material

The workpiece material used in this study is HDPE, known for its exceptional strength-to-density ratio, outstanding chemical resistance, and high impact tolerance. The average density of the material is approximately 950 kg/m³, tensile strength typically ranging from 26 MPa to 38 MPa and melting point is between 120°C and 130°C [9]. HDPE has excellent machinability, rating as one of the easiest engineering plastics to cut, drill, turn, and mill. It produces minimal tool wear and creates smooth, clean surfaces when machined with sharp, high-speed tools. In this study, a box-shaped HDPE workpiece with dimensions of 50 × 50 × 35 mm was used. The peripheral milling process was performed as up-milling.

2.2. Machine Tool and Cutting Tool

Machining experiments were performed on a Unimat 4-Axis CNC Milling Machine configured as a 3-axis vertical milling machine. The machine positioning accuracy is 0.05 mm, while the maximum positioning speed is 300 mm/min. The spindle speed is adjustable between 2,000 and 15,000 rpm. The machine is intended for machining wood, plastics, wax and soft non-ferrous materials [10], [11]. Milling operations were carried out using a HSS two-flutes flat mill with a diameter of 2 mm.

2.3. Measurement Equipment

Vibrations generated during the machining process were measured using a four-channel vibration datalogger Extech VB500. The device enables simultaneous acquisition from four measurement channels and supports vibration acceleration, velocity, and displacement measurements. Measurements were performed in the frequency range from 10 Hz to 1 kHz using external piezoelectric accelerometers with magnetic mounting. The instrument accuracy is specified as ±(5% of reading + 2 digits), while acquired data are stored on an SD memory card for subsequent analysis. The device complies with the requirements of the ISO 2954 standard for mechanical vibration measurements.

2.4. Experimental Procedure

3Peripheral conventional milling was performed on polyethylene box shaped workpiece using an HSS flat mill on educational CNC milling machine. In this experiment the radial depth of cut was kept constant at 1 mm, corresponding to 50% tool engagement. The workpiece material and cutting tool also haven't been changed. The tool overhang length is set at 13 mm. Magnetic accelerometer is placed on clamping device fixed on the work table. Vibrations were measured in X direction (feed rate direction), when the tool is in full engagement with workpiece. An experimental setup and the accelerometer position is presented in Fig. 1.

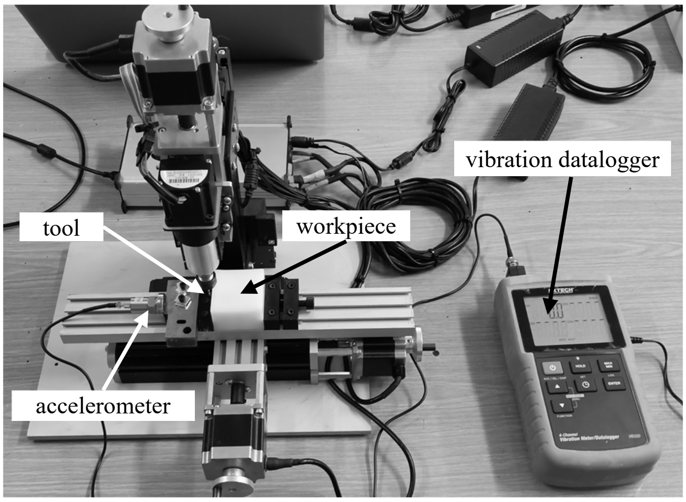

Figure 1: Experimental setup

2.5. Experimental Design

Input parameters (feed rate, spindle speed and axial depth of cut) were varied at three levels as shown in table 1. A full-factorial experimental design consisting of 27 experimental runs was employed.

Table 1: Input parameters and their levels

Factor	Symbol	Levels		
Spindle speed	*n* (rpm)	3000	4000	5000
Feed rate	*f* (mm/min)	100	200	300
Axial depth of cut	*b* (mm)	3	6	9

The vibration acceleration measured along the X-axis was considered as the response variable.

3. RESULTS AND DISCUSSION

3.1. Experimental Results

Experimental studies were conducted to investigate the influence of spindle speed (*n*), feed rate (*f*) and axial depth of cut (*b*) on vibration acceleration (*Xvib*) in feed direction during peripheral milling of HDPE. Experiments were conducted for different combinations of process parameters, with three levels adopted for each factor. The obtained experimental values of *Xvib* are shown in Table 2.

Table 2: Experimental results

Exp. no	*n* (rev/min)	*b* (mm)	*f* (mm/min)	*Xvib* (m/s^2)
1	3000	9	100	3.38
2	3000	9	200	4.34
3	3000	9	300	5.11
4	4000	9	100	2.39
5	4000	9	200	2.80
6	4000	9	300	3.90
7	5000	9	100	2.78
8	5000	9	200	2.92
9	5000	9	300	4.43
10	3000	6	100	2.86
11	3000	6	200	3.68
12	3000	6	300	4.85
13	4000	6	100	2.81
14	4000	6	200	2.96
15	4000	6	300	3.46
16	5000	6	100	2.90
17	5000	6	200	2.80
18	5000	6	300	4.10
19	3000	3	100	1.66
20	3000	3	200	1.63
21	3000	3	300	3.20
22	4000	3	100	1.22
23	4000	3	200	1.67
24	4000	3	300	3.23
25	5000	3	100	1.64
26	5000	3	200	1.89
27	5000	3	300	4.19

Based on presented experimental results, it can be seen that the *Xvib* values are ranged from 1.22 m/s^2 to 5.11 m/s^2. The results indicate an increase in the *Xvib* value with increasing feed rate and axial depth of cut. On the other hand, the influence of the spindle speed is reflected in the tendency for the *Xvib* value to decrease at higher values of this parameter.

3.2. Statistical Analysis and Model Development

Statistical analysis of experimental results was carried out in the Design-Expert software package using the Response Surface Methodology [12], [13]. Linear, 2FI, quadratic and cubic mathematical models were considered to describe the influence of process parameters on *Xvib*. An overview of their statistical indicators is given in Table 3.

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Table 3: Summary statistical indicators of candidate models

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	0.5836	0.7220	0.6857	0.6178	10.77	
2FI	0.5668	0.7720	0.7036	0.5954	11.40	
Quadratic	**0.3454**	**0.9280**	**0.8899**	**0.8127**	**5.28**	**Suggested**
Cubic	0.2525	0.9774	0.9412	0.7676	6.55	Aliased

Based on shown statistical indicators, it can be concluded that the quadratic model most successfully describes the dependence between the process parameters and the *Xvib* value. High values of the adjusted coefficient of determination (Adj $R^2 = 0.8899$) and the predicted coefficient of determination (Pred $R^2 = 0.8127$), along with the lowest value of the Predicted Residual Error Sum of Squares parameter (PRESS = 5.28), confirm its good ability to describe and predict the response. Due to the appearance of the aliasing effect, the cubic model was not considered in further analysis, so the quadratic model was adopted for the development of the mathematical model. Analysis of variance (ANOVA) was applied to check the statistical significance of the developed model [14]. The results of this analysis are shown in Table 4.

Table 4: ANOVA analysis for reduced quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	26.02	7	3.72	32.81	< 0.0001	significant
A-*n*	0.5207	1	0.5207	4.60	0.0452	
B-*f*	12.20	1	12.20	107.71	< 0.0001	
C-*b*	7.62	1	7.62	67.23	< 0.0001	
AC	1.28	1	1.28	11.33	0.0032	
A^2	1.66	1	1.66	14.66	0.0011	
B^2	1.41	1	1.41	12.48	0.0022	
C^2	1.32	1	1.32	11.66	0.0029	
Residual	2.15	19	0.1133			
Cor Total	28.17	26				

The results of the ANOVA analysis show that the developed model is statistically significant, as confirmed by the high value of the F-statistic (F = 32.81) and the very low p-value ($p < 0.0001$). The analysis of individual factors showed that the greatest influence on *Xvib* is exerted by the feed rate (F = 107.71), followed by the axial depth of cut (F = 67.23), while the spindle speed has the smallest, but statistically significant, influence (F = 4.60). Also, the interaction of the AC factors was found to be statistically significant, indicating that the influence of the spindle speed depends on the selected depth of cut. The basic statistical indicators of the developed mathematical model are shown in Table 5.

Table 5: Statistical indicators of the developed model

Std. Dev.	0.3366	**R^2**	0.9236
Mean	3.07	**Adjusted R^2**	0.8954
C.V. %	10.98	**Predicted R^2**	0.8428
PRESS	4.43	**Adeq Precision**	21.6737

The statistical indicators confirm the reliability of the developed mathematical model. The value of the coefficient of determination ($R^2 = 0.9236$) shows that the model explains 92.36% of the total variability of *Xvib*. At the same time, the small difference between the values of Adj R^2 and Pred R^2 indicates a good predictive ability of the model. The value of the parameter Adeq Precision of 21.6737 exceeds the recommended minimum value of 4 by many times, which confirms an adequate signal-to-noise ratio. Based on the experimental results, a quadratic regression model for predicting *Xvib* was developed, shown in equation (1).

$$Xvib = 6.30265 - 0.003725 \cdot n - 0.011181 \cdot f + 1.27862 \cdot b - 0.000109 \cdot n \cdot b + 5.26143 \cdot 10^{-7} \cdot n^2 + 0.000049 \cdot f^2 - 0.052138 \cdot b^2 \quad (1)$$

where:

n – spindle speed (rev/min),
f – feed rate (mm/min),
b – axial depth of cut (mm).

3.3. Model Diagnostics

As part of the diagnostics of the developed model, the normality of the residual distribution and the need for response transformation were analyzed.

The normal residual distribution diagram shown in Figure 2 shows that the experimental points are located near the reference line, without significant deviations. Such a layout indicates an approximately normal distribution of the residuals and confirms the fulfillment of the basic assumptions necessary for conducting the ANOVA analysis.

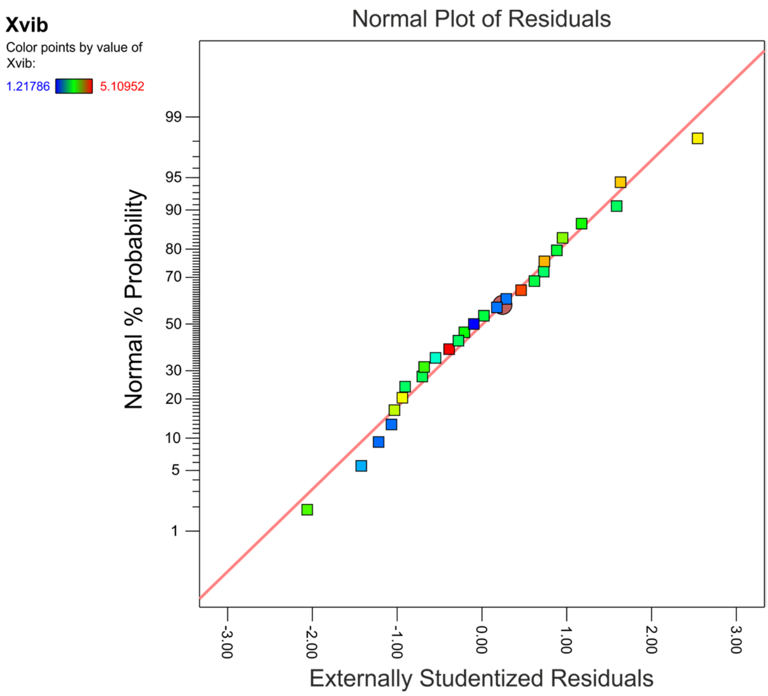


Figure 2: Normal probability plot of residuals

The Box–Cox analysis shown in Figure 3 indicated that no transformation of the response variable was required while the current value of the parameter λ is within the confidence interval. Based on the obtained results, it can be concluded that the experimental data were suitable for direct statistical processing without applying additional transformations.

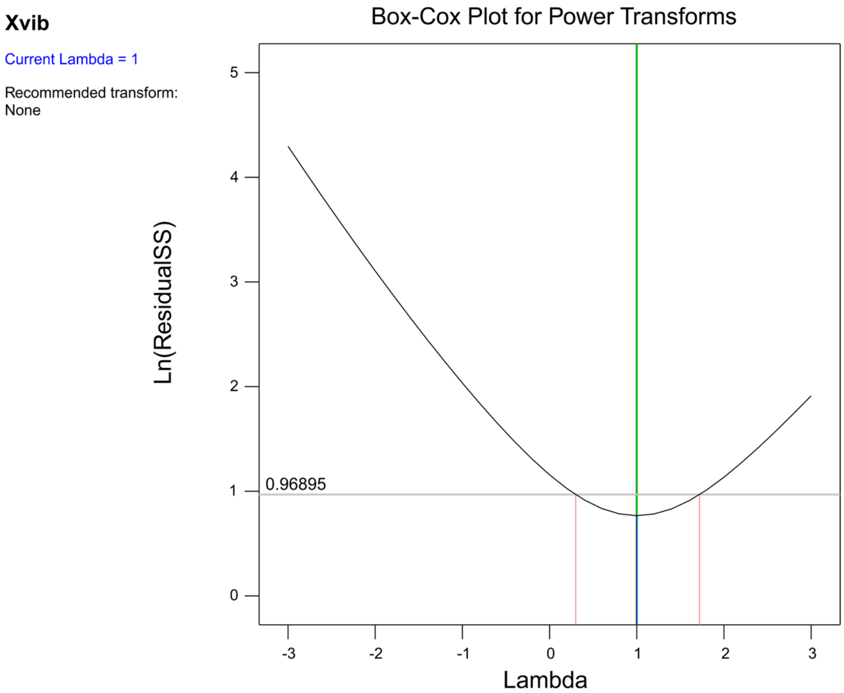


Figure 3: Box–Cox plot for response transformation

3.4. Response Surface Analysis

The mutual influence of spindle speed, feed rate and axial depth of cut on *Xvib* was analyzed using the response surfaces shown in Figure 4.

Based on the presented response surfaces, it can be seen that increasing the axial depth of cut leads to an increase in the *Xvib* value for most of the analyzed combinations of spindle speed and feed rate. At the same time, increasing the feed rate additionally intensifies *Xvib*, with this effect being more pronounced at higher axial depths of cut. In contrast, increasing the spindle speed tends to decrease the *Xvib* value, which indicates more favorable conditions for the milling process. The observed changes in the response surfaces confirm the results of the statistical analysis and indicate the dominant influence of feed rate and axial depth of cut on *Xvib*.

3.5. Model Validation

In order to assess the predictive ability of the developed mathematical model, additional experimental measurements were conducted for five combinations of process parameters that were not used during model development. The validation points and corresponding experimentally determined *Xvib* values are shown in Table 6.

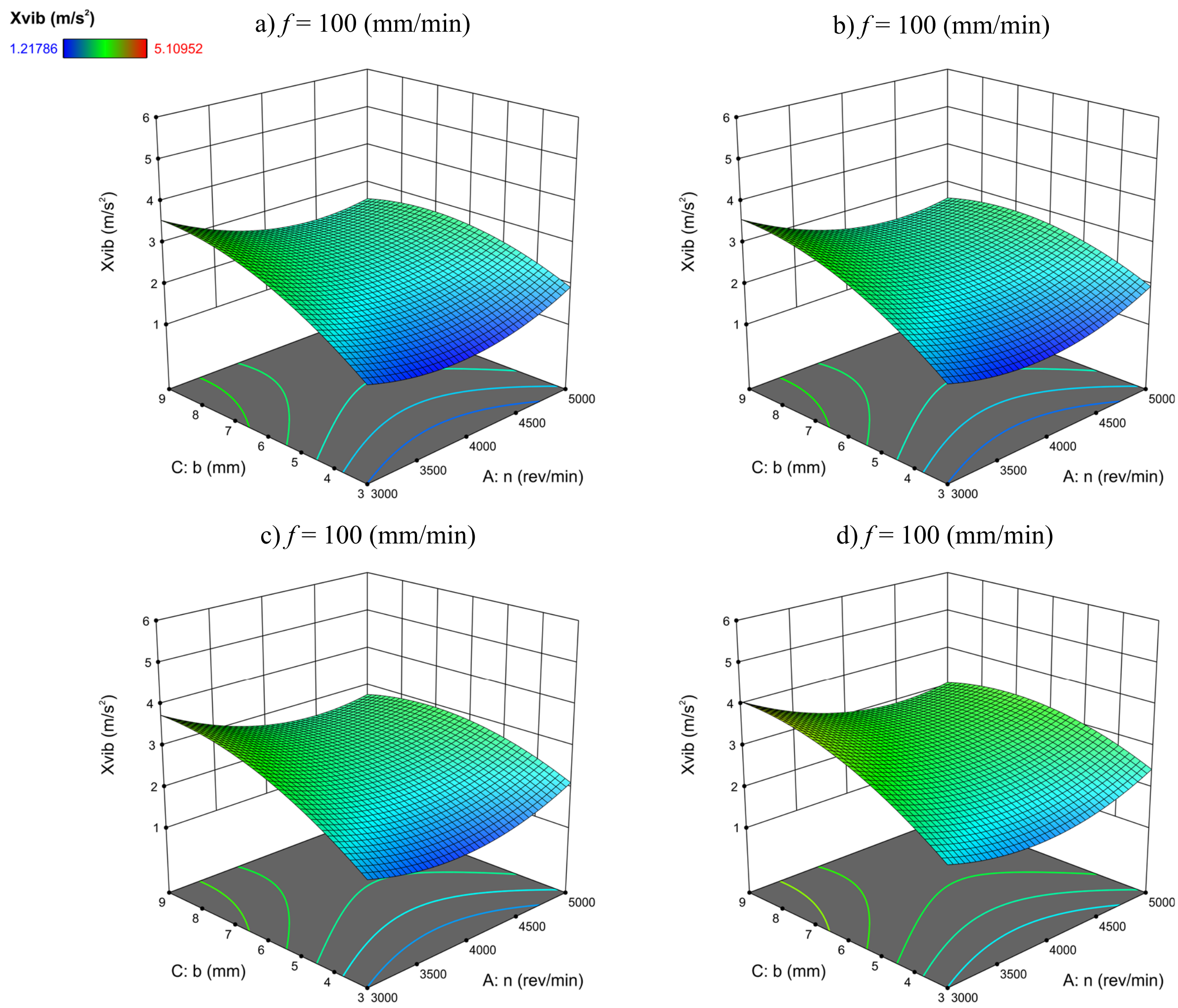
Table 6: Validation experiments and measured *Xvib* values

Exp. no	*n* (rev/min)	*f* (mm/min)	*b* (mm)	*Xvib* (m/s²)
1	3500	180	7.5	3.24
2	3800	210	6.0	2.63
3	4750	250	5.5	2.74
4	4100	110	4.0	2.31
5	3150	118	3.5	2.34

The results of the mathematical model validation obtained in the Design-Expert software package are shown in Table 7.

Table 7: Results of the validation of the mathematical model

Analysis	**Predicted Mean (m/s²)**	**Predicted Median (m/s²)**	**Standard Deviation**	**n**	**SE Pred**	**95% PI Low (m/s²)**	**Data Mean (m/s²)**	**95% PI High (m/s²)**
Xvib	3.065	3.065	0.3366	1	0.3681	2.295	3.24	3.835
Xvib	2.846	2.846	0.3366	1	0.3765	2.058	2.63	3.634
Xvib	3.325	3.325	0.3366	1	0.3662	2.558	2.74	4.092
Xvib	1.724	1.724	0.3366	1	0.3674	0.955	2.31	2.493
Xvib	1.780	1.780	0.3366	1	0.3681	1.010	2.34	2.551



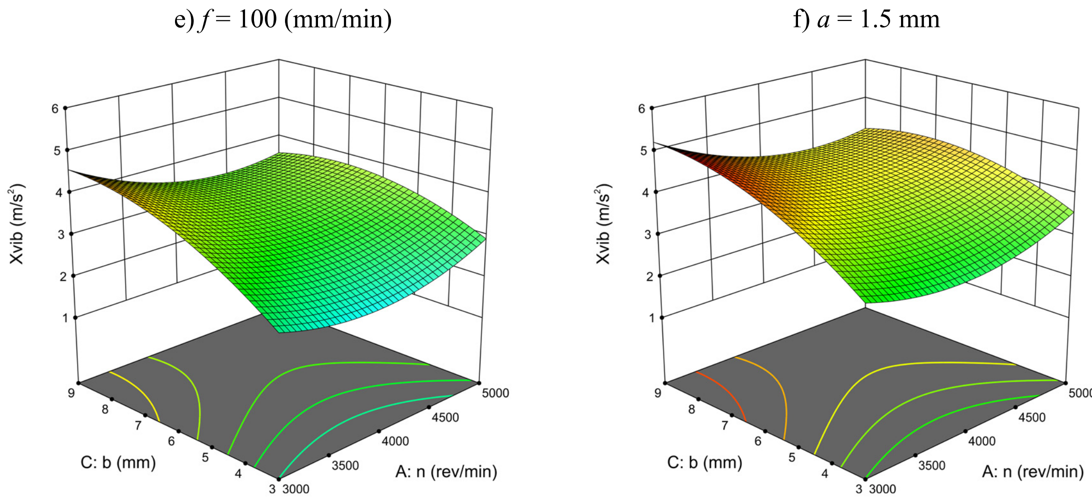


Figure 4: Response surfaces showing influence of the spindle speed and depth of cut on *Xvib* at different feed rates

By comparing the experimentally determined and model predicted values shown in Table 7, a good agreement of the results can be observed for all analyzed validation points. In all cases, the experimental values are within the corresponding 95% prediction intervals, which confirms the adequacy of the developed mathematical model. The obtained results indicate that the model has a satisfactory predictive ability and can be used to estimate the *Xvib* values for new combinations of process parameters within the analyzed experimental domain.

4. CONCLUSIONS

The conducted research showed that the spindle speed, feed rate and axial depth of cut affect *Xvib* during CNC peripheral milling of HDPE materials. Analysis of the results indicated that the feed rate and axial depth of cut have the greatest influence, while the influence of the spindle speed is less pronounced.

Based on the experimental data, a reduced square mathematical model was developed to predict the *Xvib* value. The results of statistical analysis, diagnostics and validation confirmed the adequacy of the model and its satisfactory predictive ability within the analyzed experimental domain.

The developed model can be a useful tool for estimating *Xvib* and selecting process parameters with the aim of reducing vibrations and improving the stability of the peripheral milling of HDPE materials.

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