SESSION C: PRODUCTION TECHNOLOGIES, CAE AND MANAGEMENT

Investigation of the influence of cutting parameters on noise emission during face turning of beech wood

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ABSTRACT

The paper presents the results of an experimental study of the influence of workpiece overhang length, feed rate and depth of cut on the equivalent sound pressure level during face turning of beech wood. Data analysis and mathematical model development were carried out using the Response Surface Methodology in the Design-Expert software package. The results of statistical analysis showed that the greatest influence on the equivalent sound pressure level is exerted by the depth of cut, followed by workpiece overhang, while the influence of feed rate is less pronounced. Based on the obtained data, a quadratic mathematical model was developed to predict the value of the equivalent sound pressure level. Additional experimental tests confirmed good agreement between the measured and model-predicted values. The obtained results can serve as a basis for selecting optimal process parameters in order to increase process quality and productivity during face turning of beech wood.

KEYWORDS

Face turning, Equivalent sound pressure level, Cutting parameters, Response Surface Methodology

1. INTRODUCTION

During machining processes, dynamic interactions between the machine tool, cutting tool and workpiece generate vibrations accompanied by characteristic sound emission. According to numerous studies, the main sources of vibration during turning operations on a lathe are the electric engine, the gearing between the engine and the gearbox, the existence of some worn parts inside the gearbox and the cutting process itself [1]. During the cutting process, the tool comes into contact with the material, resulting in chip removal which leads to the occurrence of vibrations [2]. Vibrations are frequently accompanied by characteristic noise pattern [1].

Several machining parameters, namely feed rate, depth of cut, cutting speed, workpiece diversity (material and hardness) and tool characteristics (tool material, cutting edge geometry, chip angle, etc.), affect sound pressure level in turning [3]. Besides the cutting parameters, the main factors that may influence the acoustic response during turning are the length of the workpiece zone which is not additionally supported or fixed, tool overhang length, the tool's active wear state, the type of tool tip and the the tool clamping method in the tool holder [1].

Some studies have reported the correlation of sound pressure level with surface roughness, accuracy of the workpiece part geometry and cutting power consumption [4]. Sound measurements are used in machine tools and in-process monitoring to detect and diagnose issues such as tool wear, tool breakage and chatter [5] - [9]. Monitoring changes in sound pressure level is proven useful for determining the optimal parameters of the cutting process and achieving maximum productivity, as it enables us to predict potential machine component failures and identify errors in the production process [10], [2]. Other studies [6] demonstrated the efficiency of using the sound generated during cutting by lathe for the adaptive metalworking control.

Mainly, the number of studies that considered sound pressure level as a criterion for machining operation is limited and focused on optimization of cutting parameters based on acoustic emissions in the field of metal processing industry. Keeping in mind economic and commercial importance and technical and technological complexity of wood processing industry, wood machining studies are not sufficiently represented, as in the case of metal processing industry.

Wood machining differs significantly from the machining of other materials. Wood is an anisotropic and heterogeneous material, so the machining responses largely depend on the direction of tool movement relative to the direction of wood grain. Studies have shown that adjusting cutting parameters can affect the surface quality of the processed wood [9].

Although numerous studies have investigated vibration and sound emission during metal cutting processes, considerably less attention has been devoted to *LAeq* analysis during wood turning operations, especially in the case of small-scale CNC machining systems and face turning configurations. Furthermore, the influence of machining parameters on *LAeq* during wood machining has not been sufficiently investigated, especially the influence of workpiece overhang length during face turning operations.

The aim of this study is to investigate the influence of feed rate, depth of cut and workpiece overhang length on *LAeq* during CNC face turning of beech wood using an HSS (high-speed steel) cutting tool. Statistical analysis and multiple linear regression modeling were employed to determine the significance of machining parameters and to develop predictive models for *LAeq* estimation. Additionally, confirmation experiments were performed to validate the developed regression models.

2. MATERIALS AND METHODS

2.1. Workpiece Material

The workpiece material used in this study is wood, which is a non-homogeneous and anisotropic material. Its mechanical and physical properties significantly depend on the grain orientation, density and moisture content. These characteristics strongly influence the cutting process, especially vibration behavior and sound emission.

The workpiece material used in this study was European beech wood (*Fagus sylvatica*), classified as a hardwood material. Beech wood is characterized by relatively high density, good machinability and relatively homogeneous structure [11]. The average density of the material is approximately 720 kg/m³ under air-dried conditions.

In this study, wooden bar blank with diameter of 8 mm is used. During the face turning operation, cutting was predominantly performed perpendicular to the grain direction.

2.2. Machine Tool and Cutting Tool

Machining experiments were performed on a UNI-DREH CNC lathe equipped with two CNC-controlled axes and stepper drives (2A, 1.8°). The machine positioning accuracy is 0.05 mm, while the maximum positioning speed is 300 mm/min. The spindle speed is constant and its value is 3333 rpm. The machine is intended for machining wood, plastics, wax and soft non-ferrous materials [12], [13]. Face turning operations were carried out using a high-speed steel (HSS) cutting tool with a shank size of 3.5 × 3.5 mm.

2.3. Measurement Equipment

Sound pressure measurements were performed using a Brüel & Kjær Type 2270 dual-channel sound level meter and analyzer. The device is a Class 1 measurement system intended for high-precision acoustic measurements in industrial and environmental applications. The analyzer supports broadband frequency measurements in the range from 4.2 Hz to 22.4 kHz using the Brüel & Kjær Type 4189 microphone [14]. The microphone was placed at a height of 1.5 m and at a distance of 1 m from the sound source.

In this study, the equivalent continuous A-weighted sound pressure level (*LAeq*) was used as the response parameter.

2.4. Experimental Procedure

Face turning operation of wooden bar blank with diameter of 8 mm was performed using an HSS cutting tool on educational CNC lathe.

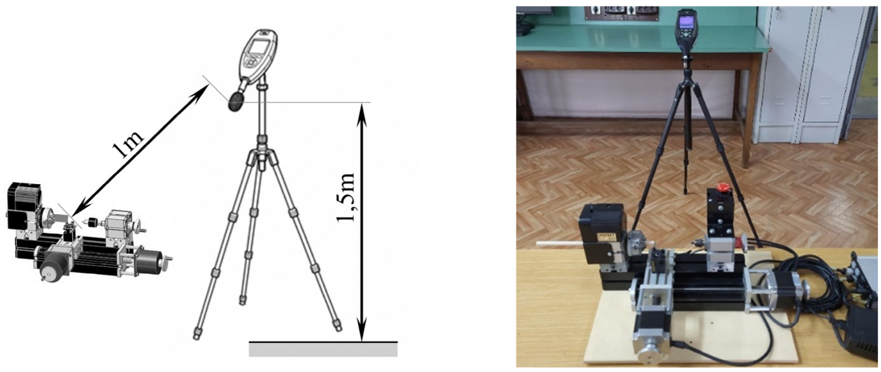

Figure 1: Experimental setup

Constant cutting parameters in this experiment were: spindle speed (3333 rpm) and workpiece diameter (8 mm). Workpiece material, tool and method of tool clamping in the tool holder also haven't been changed.

Sound pressure measurements were performed using sound level meter during each cutting processes including time when tool is approaching to workpiece and exiting from cutting zone. Each measurement was repeated three times.

2.5. Experimental Design

Input parameters (feed rate, depth of cut and overhang length) were varied at three levels, chosen according to trial experiments and to equipment limitations, which are shown in Table 1.

Table 1: Input parameters and their levels

Factor	Symbol	Levels		
Overhang length of workpiece	*l* (mm)	15	25	35
Feed rate	*f* (mm/min)	50	100	150
Depth of cut	*a* (mm)	0,5	1	1,5

3. RESULTS AND DISCUSSION

3.1. Experimental Results

Experiments were conducted for different combinations of workpiece overhang, feed rate and depth of cut, with three levels adopted for each parameter. Each experimental combination was repeated three times to increase the reliability of the measurements and reduce the influence of random deviations. The obtained experimental *LAeq* values are shown in Table 2.

Table 2: Experimental results

Exp. no	*l* (mm)	*f* (mm/min)	*a* (mm)	*LAeq* (dB)		
				1st measurement	2nd measurement	3rd measurement
1	15	50	0,5	73	72,4	73,3
2	15	50	1	75,7	75,8	75,8
3	15	50	1,5	78	77,8	77,5
4	15	100	0,5	74,3	73,7	73,3
5	15	100	1	76,9	75,8	76,1
6	15	100	1,5	78,2	78,2	77,8
7	15	150	0,5	74,5	72,3	72,5
8	15	150	1	75,1	74,8	76,2
9	15	150	1,5	76,2	76,5	75,8
10	25	50	0,5	74,2	73,6	73,6
11	25	50	1	76,3	76	76,2
12	25	50	1,5	78,3	77,7	78,3
13	25	100	0,5	74,1	74,6	75
14	25	100	1	76,7	75,4	76,4
15	25	100	1,5	77,9	77,3	77,9
16	25	150	0,5	73,3	72,6	74,8
17	25	150	1	75,2	76,9	75
18	25	150	1,5	76,3	76	76,6
19	35	50	0,5	75,2	76,4	75,4
20	35	50	1	78,6	79,9	79,3
21	35	50	1,5	80,2	80,1	80,1
22	35	100	0,5	75,3	76,2	76,5
23	35	100	1	77,8	77,4	77,8
24	35	100	1,5	79,9	79,7	78
25	35	150	0,5	72,1	76,2	76,2
26	35	150	1	77,3	76,8	75,6
27	35	150	1,5	78,2	76,1	79

Experimental results show that the *LAeq* values are ranged from 72.1 dB to 80.2 dB. The presented data show a tendency for the value of *LAeq* to increase with an increase in the depth of cut and overhang of the workpiece. On the other hand, the influence of the feed rate on the change in *LAeq* is less significant.

3.2. Statistical Analysis and Model Development

The experimental results were processed in the Design-Expert software package using the Response Surface Methodology (RSM) [15], [16], [17]. Linear, 2FI, quadratic and cubic mathematical models were considered to describe the dependence between process parameters and *LAeq*. Their statistical indicators are given in Table 3.

Table 3: Summary statistical indicators of candidate models

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	0.8969	0.7991	0.7911	0.7759	68.18	
2FI	0.8120	0.8418	0.8288	0.8092	58.04	
Quadratic	**0.6669**	**0.8977**	**0.8845**	**0.8639**	**41.41**	**Suggested**
Cubic	0.6697	0.9071	0.8836	0.8462	46.80	Aliased

Based on the presented results, it can be seen that the quadratic model achieves the best statistical characteristics. The values of the adjusted coefficient of determination (Adj $R^2 = 0.8845$) and the predicted coefficient of determination (Pred $R^2 = 0.8639$), along with the lowest value of the Predicted Residual Error Sum of Squares parameter (PRESS = 41.41), indicate that this model most adequately describes the dependence between process parameters and *LAeq*. The cubic model was not considered due to the appearance of the aliasing effect, so the quadratic model was adopted for further analysis.

In order to assess the statistical significance of the developed model, an analysis of variance (ANOVA) was performed [18]. Analysis of results for the developed quadratic model are shown in Table 4.

Table 4: ANOVA analysis for quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	273.14	9	30.35	68.24	< 0.0001	significant
A-l	59.26	1	59.26	133.25	< 0.0001	
B-v	13.41	1	13.41	30.15	< 0.0001	
C-a	165.57	1	165.57	372.30	< 0.0001	
AB	2.13	1	2.13	4.79	0.0319	
AC	1.85	1	1.85	4.16	0.0452	
BC	8.80	1	8.80	19.79	< 0.0001	
A^2	9.70	1	9.70	21.82	< 0.0001	
B^2	4.21	1	4.21	9.46	0.0030	
C^2	2.97	1	2.97	6.67	0.0119	
Residual	31.13	70	0.4447			
Lack of Fit	7.28	17	0.4281	0.9511	0.5230	not significant
Pure Error	23.85	53	0.4501			
Cor Total	304.27	79				

The results of the ANOVA analysis show that the developed model is statistically significant, which is confirmed by the high value of the F-statistic (F = 68.24) and the very low p-value ($p < 0.0001$). The value of the Lack of Fit test was p = 0.5230, which indicates that the deviations between the experimental and model-predicted values are not statistically significant, i.e., that the model adequately describes the observed process. The analysis of individual factors showed that the greatest influence on *LAeq* is the depth of cut (F = 372.30), followed by the workpiece overhang (F = 133.25), while the feed rate has the smallest, but still statistically significant, influence (F = 30.15). Also, all interactions of the factors (AB, AC and BC) were statistically significant, which confirms the mutual dependence of the process parameters during the machining process. The basic statistical indicators of the developed mathematical model are given in Table 5.

Table 5: Statistical indicators of the developed model

Std. Dev.	0.6669	**R^2**	0.8977
Mean	76.29	**Adjusted R^2**	0.8845
C.V. %	0.8742	**Predicted R^2**	0.8639
PRESS	41.41	**Adeq Precision**	30.3647

The presented statistical indicators confirm the adequacy of the developed model. The value of the coefficient of determination ($R^2 = 0.8977$) shows that the model explains 89.77% of the total variability of the response, while the small difference between the values of Adj R^2 and Pred R^2 confirms its good predictive ability. Also, the value of the parameter Adeq Precision (30.3647) significantly exceeds the recommended minimum value of 4, which indicates a favorable signal-to-noise ratio. Based on the experimental results, a quadratic regression model was developed for predicting the *LAeq* value, shown in Equation (1).

$$LAeq = 67{,}83448 - 0{,}167001 \cdot l + 0{,}061220 \cdot f + 9{,}96358 \cdot a - 0{,}000495 \cdot l \cdot f - 0{,}046084 \cdot l \cdot a - 0{,}020106 \cdot f \cdot a + 0{,}007369 \cdot l^2 - 0{,}000194 \cdot f^2 - 1{,}62999 \cdot a^2 \quad (1)$$

where:

l – workpiece overhang length (mm),
f – feed rate (mm/min),
a – cutting depth (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. Based on the normal residual distribution diagram shown in Figure 2, it can be seen that the experimental points largely follow the reference line. This arrangement confirms that the residuals are approximately normally distributed and that the basic assumptions of the ANOVA analysis are met.

The Box–Cox analysis indicated that no transformation of the response variable was required while the current value of the parameter λ is within the confidence interval. The obtained results confirm that there was no need for additional response transformation before statistical analysis.

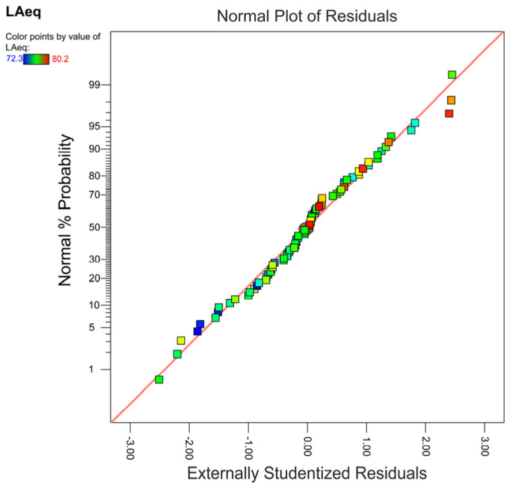

Figure 2: Normal probability plot of residuals

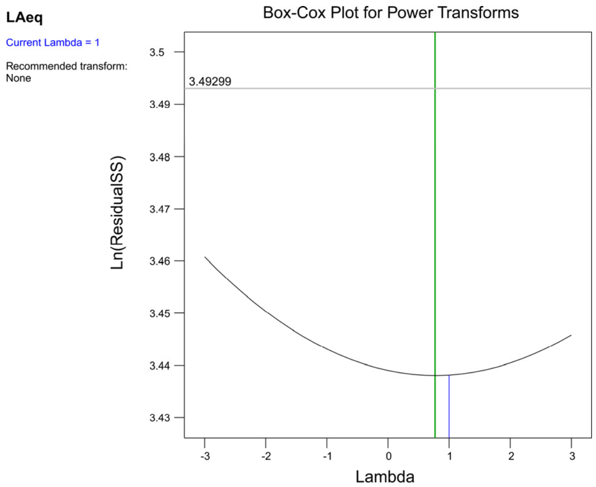

Figure 3: Box–Cox plot for response transformation

3.4. Response Surface Analysis

The effect of workpiece overhang length and feed rate on *LAeq* for different values of depth of cut was analyzed using the response surfaces shown in Figure 4.

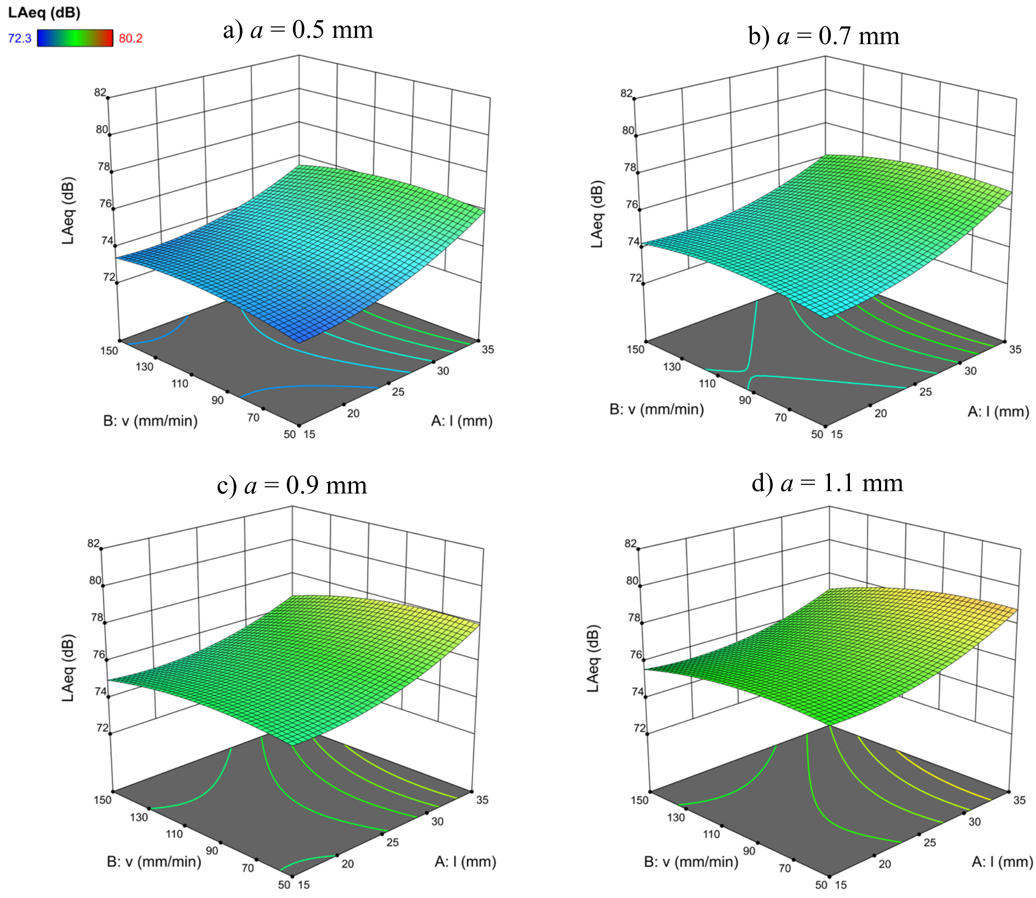

Figure 4: Response surfaces showing the influence of workpiece overhang length and feed rate on *LAeq* at different depths of cut

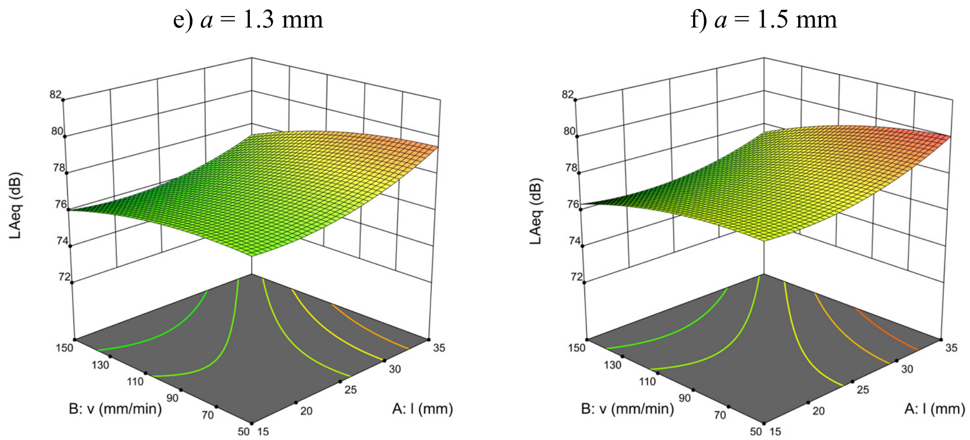

Figure 4: Response surfaces showing the influence of workpiece overhang length and feed rate on *LAeq* at different depths of cut

By analyzing the response surfaces, it can be seen that with an increase of the depth of cut, there is an increase in the value of *LAeq* for almost all combinations of workpiece overhang and feed rate. Also, increasing the workpiece overhang leads to an increase in *LAeq*, where this effect is more pronounced at larger depths of cut. On the other hand, the change in feed rate causes smaller changes in the *LAeq* value, which is in agreement with the results of the ANOVA analysis. The response surfaces additionally confirm the increasing trend of *LAeq* with increasing depth of cut and workpiece overhang length.

3.5. Model Validation

To verify the predictive ability of the developed mathematical model, additional experimental measurements were performed for three combinations of process parameters that were not used during model development. The adopted validation points and the corresponding experimentally measured *LAeq* values are shown in Table 6.

Table 6: Validation experiments and measured *LAeq* values

Exp. no	*l* (mm)	*f* (mm/min)	*a* (mm)	*LAeq* (dB)		
				1st measurement	2nd measurement	3rd measurement
1	30	125	1.25	76.56	77.06	76.65
2	20	60	1.40	76.55	77.71	76.46
3	17	140	0.60	74.02	73.17	73.97

The results of the validation of the mathematical model 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 (dB)**	**Predicted Median (dB)**	**Std. Dev.**	**n**	**SE Pred**	**95% PI Low (dB)**	**Data Mean (dB)**	**95% PI High (dB)**
LAeq	77.2592	77.2592	0.666874	3	0.418486	76.4246	76.7567	78.0939
LAeq	77.5980	77.5980	0.666874	3	0.423888	76.7525	76.9067	78.4434
LAeq	73.9464	73.9464	0.666874	3	0.429894	73.0890	73.7200	74.8038

Based on the presented results, it can be observed that there is a very good agreement between the model-predicted and experimentally determined *LAeq* values for all analyzed combinations of process parameters. In all cases, the experimentally determined mean values are within the 95% prediction interval, which confirms the adequacy of the developed model and its good predictive ability. The obtained results confirm that the developed model can reliably predict *LAeq* values for new combinations of process parameters within the analyzed experimental domain.

4. CONCLUSIONS

The results showed that all analyzed process parameters have a statistically significant effect on *LAeq* during face turning of beech wood. ANOVA analysis showed that the greatest impact is exerted by the depth of cut, followed by the workpiece overhang, while the impact of the feed rate is less pronounced.

Based on the experimental results, a quadratic regression model was developed to predict the *LAeq* value. Statistical analysis and validation results confirmed the adequacy of the model for describing the observed process and reliably predicting *LAeq* values within the analyzed experimental domain. The obtained results indicate that *LAeq* is sensitive to changes in machining parameters and may be considered a useful indirect indicator of machining conditions during face turning of beech wood. The developed methodology and regression model provide a basis for future research aimed at using acoustic measurements for process monitoring, machining quality assessment and parameter optimization. The applied methodology can also be extended to future studies involving different workpiece materials, cutting tools and machining conditions.

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REFERENCES

[1] S.-C. Olaru, L. Slătineanu, M. Silitră, A.-M. Mihalache, and M. Coteață, “Investigation of the sound intensity level in the case of a universal lathe”, MATEC Web of Conferences, Vol. 112, Article 01025, https://doi.org/10.1051/matecconf/201711201025, (2017)

[2] T. Miodragović, B. Radičević, S. Pajović, N. Kolarević, and V. Grković, “Identification of noise source based on sound intensity in vertical CNC milling machine”, Proceedings of XI International Conference “Heavy Machinery – HM 2023”, Vrnjačka Banja (Serbia), 21–24 June 2023, pp. C.45–C.50, (2023)

[3] A. Şahinoğlu and M. Rafighi, “Investigation of tool wear, surface roughness, sound intensity, and power consumption during hard turning of AISI 4140 steel using multilayer-coated carbide inserts”, Journal of Engineering Research, Vol. 9(4B), pp. 377–395, https://doi.org/10.36909/jer.8783, (2021)

[4] A. Şahinoğlu and M. Rafighi, “Investigation of vibration, sound intensity, machine current and surface roughness values of AISI 4140 during machining on the lathe”, Arabian Journal for Science and Engineering, Vol. 45(2), pp. 765–778, https://doi.org/10.1007/s13369-019-04124-x, (2020)

[5] D. Yu. Pimenov, M. K. Gupta, L. R. R. da Silva, M. Kiran, N. Khanna, and G. M. Krolczyk, “Application of measurement systems in tool condition monitoring of milling: a review of measurement science approach”, Measurement, Vol. 199, Article 111503, https://doi.org/10.1016/j.measurement.2022.111503, (2022)

[6] A. Shokrani, H. Dogan, D. Burian, T. D. Nwabueze, P. Kolar, Z. Liao, A. Sadek, R. Teti, P. Wang, R. Pavel, and T. Schmitz, “Sensors for in-process and on-machine monitoring of machining operations”, CIRP Journal of Manufacturing Science and Technology, Vol. 51, pp. 263–292, https://doi.org/10.1016/j.cirpj.2024.05.001, (2024)

[7] V. Nahornyi, A. Panda, J. Valíček, M. Harničárová, M. Kušnerová, I. Pandová, S. Legutko, Z. Palková, and O. Lukáč, “Adaptive control of the metalworking process with using sound generated during cutting”, Research Square, https://doi.org/10.21203/rs.3.rs-986998/v1, (2021)

[8] A. Petrović, M. Rasinac, V. Grković, and M. Ivanović, “An experimental plan for noise analysis and chatter detection in milling depending on the cutting parameters”, Proceedings of the 26th International Conference “Noise and Vibration”, Niš (Serbia), 6–7 December 2018, pp. 41–44, (2018)

[9] M. Rasinac, B. Radičević, M. Kolarević, A. Petrović, and M. Bjelić, “Frequency analysis of noise at different milling parameters of steel”, Proceedings of X International Conference “Heavy Machinery – HM 2021”, Vrnjačka Banja (Serbia), 23–25 June 2021, pp. B.35–B.38, (2021)

[10] R. A. Kazeem and E. T. Akinlabi, “Experimental investigation of machine vibration rate and machine sound level in MQL turning of AISI 1525 steel employing mango oil as lubricant”, International Journal on Interactive Design and Manufacturing, Vol. 19, pp. 4379–4394, https://doi.org/10.1007/s12008-024-02077-6, (2025)

[11] M. Najafian Ashrafi, H. Shaabani Asrami, Z. Vosoughi Rudgar, M. Ghorbanian Far, A. Heidari, E. Rastbod, H. Jafarzadeh, M. Salehi, E. Bari, and J. Ribera, “Comparison of physical and mechanical properties of beech and walnut wood from Iran and Georgian beech”, Forests, Vol. 12(6), Article 801, https://doi.org/10.3390/f12060801, (2021)

[12] UNIMAT, “TVET – CNC – 1”, Product Catalog, The Cool Tool Education, (2017)

[13] UNIMAT, “TVET – CNC – 2”, Product Catalog, The Cool Tool Education, (2017)

[14] Brüel & Kjær, “Hand-held analyzers – Type 2250 and Type 2270 with Building Acoustics Software BZ-7228, Dual-channel Building Acoustics Software BZ-7229 and Qualifier Type 7830”, Product Data, Brüel & Kjær, Nærum (Denmark), (2008)

[15] R. H. Myers, D. C. Montgomery, and C. M. Anderson-Cook, Response surface methodology: process and product optimization using designed experiments, John Wiley & Sons, Hoboken, NJ (USA), (2009)

[16] M. Kolarević, D. Minić, M. Rajović, V. Grković, and Zv. Petrović, “Selection of the optimal mathematical model of multiple regression in the ternary mixture experiments”, IMK-14 – Research & Development in Heavy Machinery, Vol. 20(2), pp. 55–60, (2014)

[17] S. Pajović, M. Bjelić, V. Grković, and J. Perić, “Acoustic properties of standard low density polyurethane lime foam S 2535”, Proceedings of 27th International Conference “Noise and Vibration”, Niš (Serbia), 20–21 October 2022, pp. 137–142, (2022)

[18] D. C. Montgomery, Design and analysis of experiments, John Wiley & Sons, Hoboken, NJ (USA), (2012)