EXPERIMENTAL RESEARCH ON EFFECT OF TECHNOLOGY PARAMETERS ON VIBRATION DURING MILLING SKD11 STEEL

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ABSTRACT

A self-excited vibration is called chatter of components in technology systems. It occurs widely in cutting methods and significantly affects the manufacturing process efficiency and product quality. Vibration is the cause of dimensional accuracy, surface roughness, and tool life. In this paper, the input parameters of the milling process were studied including cutting speed (*V*), feed rate (*f*), and cutting depth (*t*). The Taguchi method was first used for experimental design. Then the ANOVA analysis of variance method was used to estimate the simultaneous influence of the input parameters on the vibration. The optimal set of technological parameters to achieve the smallest vibration is A3B1C1 corresponding to *V* = 280 m/min, *f* = 230 mm/min, and *t* = 0.5 mm. Finally, a mathematical regression function describing the influence of the input technological parameters on vibration amplitude is built and gives high accuracy when compared with experimental data.

NGHIÊN CỨU THỰC NGHIỆM ẢNH HƯỞNG CỦA CÁC THAM SỐ CÔNG NGHỆ ĐẾN RUNG ĐỘNG QUÁ TRÌNH PHAY THÉP SKD11

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TỪ KHÓA

Rung động
Thép SKD11
Chiều sâu cắt
Tốc độ chạy dao
Tốc độ cắt

TÓM TẮT

Dao động tự kích thích được gọi là rung động của các thành phần hệ thống công nghệ. Hiện tượng này xuất hiện hầu hết trong các phương pháp gia công và có ảnh hưởng đáng kể đến hiệu quả quá trình sản xuất và chất lượng sản phẩm. Rung động là nguyên nhân ảnh hưởng đến độ chính xác về kích thước, độ nhám bề mặt và tuổi thọ dụng cụ cắt. Trong bài báo này, các thông số đầu vào của quá trình phay được nghiên cứu bao gồm tốc độ cắt (*V*), tốc độ chạy dao (*f*) và chiều sâu cắt (*t*). Phương pháp Taguchi đầu tiên được sử dụng để thiết kế thực nghiệm. Sau đó, phương pháp phân tích phương sai ANOVA được sử dụng để phân tích mức độ ảnh hưởng đồng thời của các tham số đầu vào đến biên độ rung. Bộ thông số công nghệ phù hợp để đạt được biên độ rung động nhỏ nhất là A3B1C1 tương ứng với *V* = 280 m/phút, *f* = 230 mm/phút, *t* = 0,5 mm. Cuối cùng, hàm hồi quy toán học mô tả ảnh hưởng của các tham số công nghệ đầu vào đến biên độ rung động được xây dựng và có độ chính xác cao khi so sánh với dữ liệu thực nghiệm.

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1. Introduction

Predicting of chatter vibration during cutting is one of the essential tasks because vibration has a direct impact on the product quality. There are many studies that have forecasted chatter instability based on modeling the vibrations. A modeling of time-domain simulation was developed by Smith and Tlusty [1] for the chatter vibration during milling. Resolving instability in vibration when milling was proposed according to some analytical models [2] – [4]. Yasuhiro et al. [5] established a new method for detecting chatter vibrations during milling and verified its reliability by comparing with experimental data.

There are many factors affecting the vibration of the cutting process such as the geometry of the cutting tool, the cutting parameters and the rigidity of the technology system. In which, technological parameters play an important role. To improve the quality of the machining process, some researches have used optimization method to specify the cutting parameters which are the most suitable one [6], [7]. The method of statistical analysis like Taguchi, regression, and grey relational analysis (GRA) are effective to specify optimization parameters. Rajeswari et al. [8] studied on optimization of cutting tool geometry and cutting parameters for reducing chatter vibration during milling metal matrix composite. Szymon Wojciechowski et al. [9] studied the optimization of cutting force and vibration when ball end milling precisely of 55NiCrMoV6 steel. This was accomplished by minimizing process response with the application of signal-to-noise (S/N) ratio and grey relational analysis (GRA).

In this study, the simultaneous influence of the technological parameters on the vibration of the cutting process was analyzed by design of experiment Taguchi and analysis of variance ANOVA method. Besides, the suitable set of technological parameters to accomplish the minimum chatter vibration was built, and the mathematical equation describing the relationship of vibration amplitude and cutting parameters was also established.

2. Methodology

2.1. Material

SKD11 is steel of cold worked mold according to JIS-G4404. Its carbon content percentage is high (>1%). The chemical compositions and physical characteristics of the SKD11 steel are presented in Table 1 and Table 2, respectively.

Table 1. *The SKD11 steel' chemical compositions [10]*

Element code	**C**	**Cr**	**Mo**	**Si**	**Mn**	**Ni**	**V**
Content (%)	1.4 – 1.6	11 - 13	0.7 – 1.2	≤ 0.6	≤ 0.6	-	0.15 – 0.3

Table 2. *Physical characteristics of SKD11 steel [11]*

Mechanical properties	**Units**	**Value**
Density	Kg/m^3	8400
Specific heat	$J/kg.^oC$	461
Poisson's ratio	-	0.3
Young's modulus	MPa	208,000
Thermal conductivity	W/m.K	20.5
Melting temperature	^oC	1733

2.2. Experimental set-up

The MC500 CNC milling machine as shown in Figure 1 was used to carry out the experiments. The carbide milling inserts are coated with titanium made from Czech Republic, code 1604PDR – GM. The workpiece of SKD11 steel, size 70 x 31 x 81 (mm). After each test, the cutting insert is replaced to avoid the influence of tool wear on the vibration of the previous experiment on the cutting process.

The cutting vibration measuring device consists of the LAN – XI Data Acquisition Module with four inputs and two outputs at a frequency of 51.2 kHz from Bruel&Kjaer, Denmark; analysis module PULSE FFT 7770, 1-3 channels, PULSE FFT, Bruel&Kjaer, Denmark; Triaxial DeltaTron accelerometer, model TEDS 4525-B-001 with shell material made of Titanium. The vibration signal obtained on the computer is transformed from the real-time domain to the frequency domain (FFT - Fast Fourier Transformation). The vibration is presented by two components including frequency and amplitude. In which, the frequency symbolizes the rate of oscillation of the vibration, and the amplitude describes the degree of vibration.

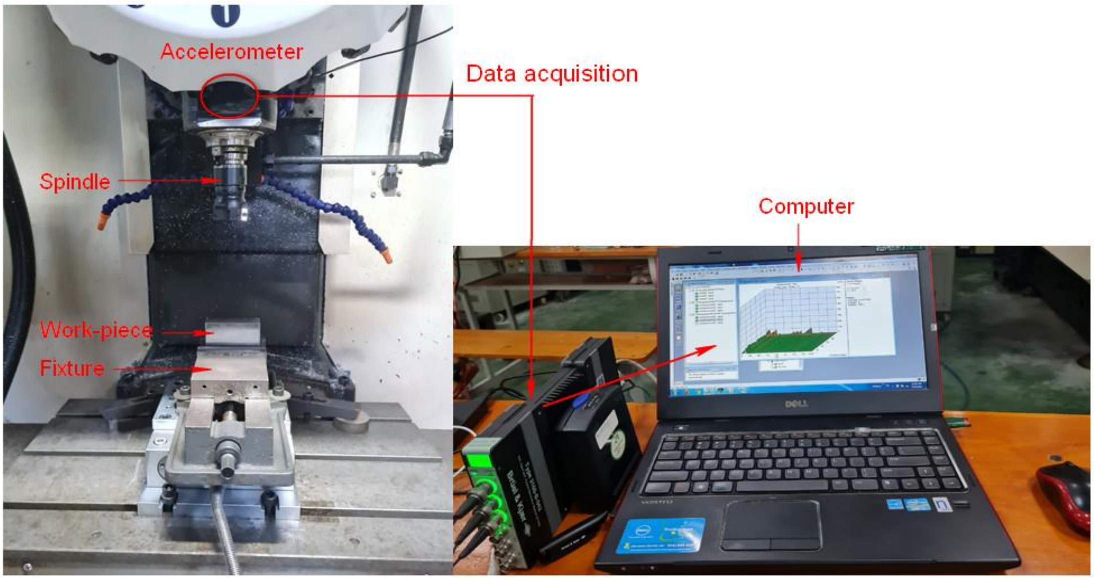


Figure 1. *Experimental design of end milling SKD11 steel*

2.3. Taguchi method

The Design of Experiment (DOE) following Taguchi's approach was standardized from the experimental design technique (known as classical DOE) introduced by British R.A. Fisher in the early 1920s. Some of the outstanding advantages of the Taguchi method are effective experimental design, easy application, and data analysis. The signal-to-noise ratio (S/N ratio) is used to measure the sensitivity and control the quality characteristic under investigation to uncontrollable external factors. The objective of the experiment is always to determine the highest possible S/N ratio for the evaluation criterion. A high S/N value means that the signal is much higher than the random effects of noise factors. Design the product or process to operate in accordance with the highest S/N that always yield optimum quality with minimal variance. The conversion of a set of observations into a single number, the S/N ratio is performed in two steps. Firstly, the squared deviation (MSD) is calculated. Then the ratio S/N is determined from the MSD by the formula:

$$S/N = -10\log\left(MSD\right) \tag{1}$$

The quality characteristic of cutting vibration is “smaller is better”, the *MSD* is determined by the following equation:

$$MSD = \frac{1}{r}\sum_{i=1}^{r} y_1^{\,2} \tag{2}$$

Where y_i is all test values of the experiments, r is the number of tests in each experiment.

2.4. Experimental design

In this study, the input technological parameters of the cutting process including *V*, *f*, and *t* were analyzed and evaluated for their influence on the output parameter, which is the vibration amplitude. Table 3 presents control parameters and their study levels. With input data from 3 control parameters and 3 levels, the L9 orthogonal array designed by the Taguchi method is showed in Table 4.

Table 3. *Control parameters and levels*

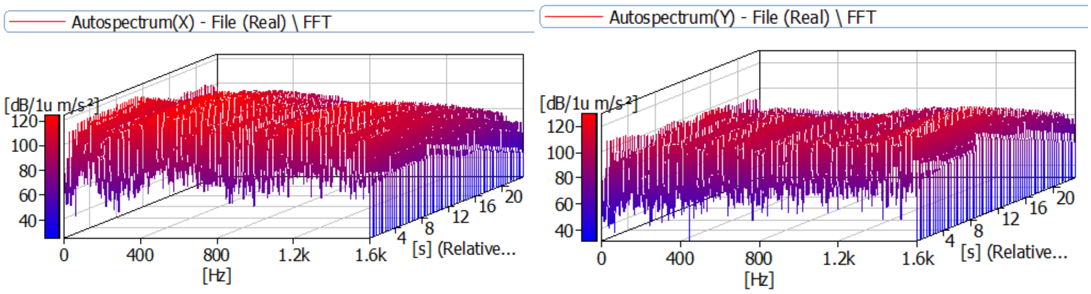
Symbol	Control parameters	Unit	Level		
			1	2	3
A	*V*	m/min	190	235	280
B	*f*	mm/min	230	305	380
C	*t*	mm	0.5	1.0	1.5

Table 4. *The L9 orthogonal array*

Experiment No.	V (m/min)	f (mm/min)	t (mm)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3. Results and discussions

3.1. Effect of the cutting speed, feed rate, and cutting depth on the vibration amplitude of the cutting process



a) b)

Figure 2. *Vibration in the X (a) and Y (b) directions when milling at V = 190 m/min, f = 380 m/min, t = 1.5 mm*

The experiment matrix and vibration amplitude' results of the cutting process are presented in Table 5. Each experiment is performed three times, and the average vibration amplitude results of those three experiments are taken. The vibration amplitude is the sum of the vibration amplitudes in the two directions X and Y determined by the equation (3). Vibration image of the cutting process in 2 directions X and Y when milling SKD11 steel with cutting mode: V = 190 m/min, f = 380 m/min, t = 1.5 mm is presented in Figure 2. Based on analysis of vibration data when machining combined with separate vibration data and no-load vibration showed that the obtained vibration results do not have resonance phenomenon.

$$A_{XY} = \sqrt{A_X^{\ 2} + A_Y^{\ 2}} \qquad (3)$$

Table 5. *Experimental matrix and vibration amplitude results when milling steel SKD11*

Exp. No.	*V* (m/min)	*f* (mm/min)	*t* (mm)	A_{XY} (dB)	S/N
1	190	230	0.5	158.386	-43.9943
2	190	305	1	174.741	-44.8479
3	190	380	1.5	176.233	-44.9218
4	235	230	1	158.354	-43.9926
5	235	305	1.5	174.080	-44.8150
6	235	380	0.5	163.347	-44.2622
7	280	230	1.5	157.329	-43.9362
8	280	305	0.5	150.093	-43.5272
9	280	380	1	166.246	-44.4150

Experimental research on the vibration amplitude when milling SKD11 steel with an L9 orthogonal array designed by the Taguchi method has the results as shown in Table 5. The ratio S/N of the experiment gives the evaluation criteria of the vibration amplitude that is "smaller is better", and is calculated according to formulas (1) and (2).

Three levels of control parameters with their S/N ratios are presented in Table 6. Figure 3 presents the effect of the S/N ratio of technological parameters on the cutting process's vibration amplitude when milling SKD11 steel. The results show that the cutting depth (*t*) has the most significant influence with an influence percentage of 37.1% on the A_{XY} of the cutting process. The cutting speed (*V*) is less affected with an influence percentage of 34.2%. The feed rate (*f*) has the lowest influence on the vibration amplitude at 28.7%. The technological parameters suitable for the smallest A_{XY} is A3B1C1 corresponding to $V = 280$ m/min, $f = 230$ mm/min, and $t = 0.5$ mm.

Table 6. *ANOVA results for vibration amplitude*

Parameters	Mean S/N ratio of each level			Sum of squares	Contribution
	1	2	3		
A	-44.588	-44.357	-43.959*	0.606	0.342
B	-43.974*	-44.397	-44.533	0.509	0.287
C	-43.928*	-44.419	-44.558	0.657	0.371

**) Optimal value*

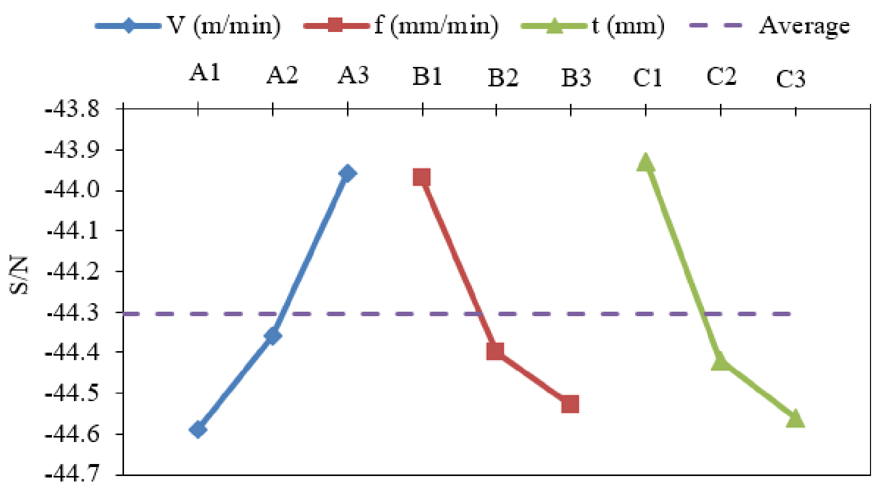


Figure 3. *Mean of S/N ratios of the factors considering A_{XY}*

3.2. Effect of the cutting speed, feed rate, and cutting depth on the vibration amplitude of the cutting process

The model of the vibration amplitude during milling SKD11 steel depends on the technological parameters (V, f, t) of the form:

$$A_{XY} = a \cdot V^{b} \cdot f^{c} \cdot t^{d} \tag{4}$$

where *a*, *b*, *c*, and *d* are corresponding coefficients and exponents determined from the experiment.

To construct a model of A_{XY} when milling SKD11 steel, the research uses the Gauss-Newton nonlinear regression function method. This method is integrated into the Nonlinear Regression tool of Minitab 17 software. The L9 orthogonal array and the resulting vibration amplitudes presented in Table 5 are used as input data for the method. With the data of 9 test points when milling SKD11 steel, the coefficients and exponents of equation (4) are determined as shown in Table 7. The vibration amplitude nonlinear regression function depends on technological parameters presented in equation (5).

Table 7. *The coefficients and exponents of the vibration amplitude model when milling steel SKD11*

Coefficients/ exponents	a	b	c	d
Value	212.165	-0.78	0.126	0.066

$$A_{XY} = 212.165 \cdot V^{-0.178} \cdot f^{0.126} \cdot t^{0.066} \tag{5}$$

Table 8. *Deviation of vibration amplitude model at various experiments*

Exp. No.	A_{XY-E}	A_{XY-M}	ΔA_{XY} (%)	Exp. No.	A_{XY-E}	A_{XY-M}	ΔA_{XY} (%)
1	158.386	158.214	0.11	6	163.347	162.310	0.63
2	174.741	171.631	1.78	7	157.329	158.761	0.91
3	176.233	181.249	2.85	8	150.093	153.015	1.95
4	158.354	159.468	0.7	9	166.246	164.688	0.94
5	174.080	169.737	2.5	-	-	-	-

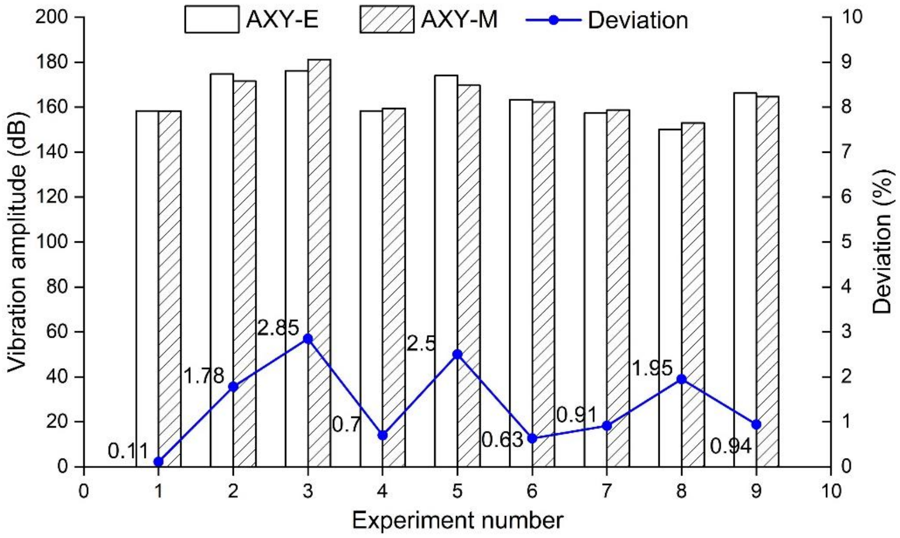


Figure 4. *The vibration amplitude determined from equation and experiment*

The accuracy of the vibration amplitude model when milling SKD11 steel is estimated by the deviation when compared with experimental data as shown in Table 8 and Figure 4. In which, the deviations of vibration amplitudes calculated from equation (5) compared with experiment results are calculated according to the following formula:

$$\Delta A_{XY}\left(\%\right)=\left|\frac{A_{XY-M}-A_{XY-E}}{A_{XY-E}}\right|\times 100 \tag{6}$$

where $A_{XY\text{-}M}$ and $A_{XY\text{-}E}$ are the vibration amplitude values determined from the equation and experiment, respectively.

The results of Table 8 and Figure 4 showed that the maximum deviation of vibration amplitude determined from the model when compared with the experimental value was 2.85% in experiment number 3. Thus, the vibration amplitude model was constructed during the milling of SKD11 steel as equation (5) had high reliability.

From equation (5), using the tool of Maple software, the graph representing the relationship between the vibration amplitude and the technological parameters (*V*, *f*, *t*) when processing SKD11 steel is shown in Figure 5. Figures 5a, 5b, and 5c are the graphs of vibration amplitudes when fixed *V*, fixed *f*, and fixed *t*, respectively. The amplitude of vibration is proportional to *f* and *t*, but inversely proportional to *V*.

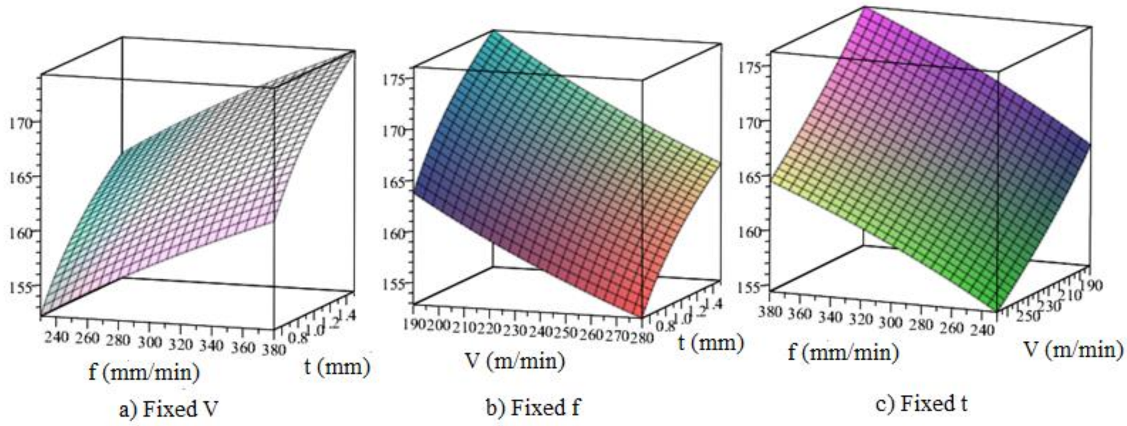


Figure 5. *The relationship between the vibration amplitude of the cutting process and the technological parameters when milling steel SKD11*

4. Conclusions

The research has studied the relationship of technological parameters including the cutting speed, feed rate, cutting depth, and vibration amplitude when milling SKD11 steel. Some of the salient conclusions are listed below:

- The cutting depth has the most significant effect on vibration with a percentage of 37.1%. Meanwhile, the cutting speed and feed rate have less influence with the influence percentage of 34.2% and 28.7%, respectively;
- The appropriate set of technological parameters to reach the smallest vibration amplitude is A3B1C1 respectively to $V = 280$ m/min, $f = 230$ mm/min, and $t = 0.5$ mm;
- A mathematical model describing the relationship between the vibration amplitude of the cutting process and the technological parameters *V, f, t* has been built and gives high accuracy when compared with experimental data.

REFERENCES

[1] S. Smith and J. Tlusty, "Efficient Simulation Programs for Chatter in Milling," *Annals of the CIRP*, vol. 30, no. 1, pp. 21–25, 1993.

[2] I. Minis and T. Yanushevshky, "A New Theoretical Approach for the Prediction of Machine Tool Chatter in Milling," *ASME Journal of Engineering for Industry*, vol. 115, pp. 1–8, 1993.

[3] Y. Altintas and E. Budak "Analytical Prediction of Stability Lobes in Milling," *Annals of the CIRP*, vol. 44, no. 1, pp. 357–362, 1995.

[4] E. Shamoto and K. Akazawa, "Analytical prediction of chatter stability in ball end milling with tool inclination," *CIRP Annals – Manufacturing Technology*, vol. 58, pp. 351-354, 2009.

[5] Y. Kakinuma, Y. Sudo, and T. Aoyama, "Detection of chatter vibration in end milling applying disturbance observer," *CIRP Annals – Manufacturing Technology*, vol. 60, pp. 109-112, 2011.

[6] T.-B. Mac, V.-C. Dinh, T.-L. Banh, and D.-T. Nguyen, "Cutting force model for thermal-assisted machining of tool steel based on Taguchi method," *Metals*, vol. 8, no. 12, pp. 1-18, 2018.

[7] A. K. M. N. Amin, M. H. B. Saad, and M. D. Arif, "Modeling & Optimization of Surface Roughness & Vibration Amplitude in Heat Assisted End Milling of SKD 11 Tool Steel using Ball Nose Tool," *Advanced Materials Research*, vol. 541, pp. 799–803, 2012.

[8] R. Sridhar, S. P. Subramaniyan, and S. Ramesh, "Optimization of machining and Geometrical parameters to reduce vibration while milling metal matrix composite," *Transactions of the Indian Institute of Metals*, vol. 72, pp. 3179-3189, 2019.

[9] S. Wojciechowski, R. W. Maruda, G. M. Krolczyk, and P. Niesłony, "Application of signal to noise ratio and grey relational analysis to minimize forces and vibrations during precise ball end milling," *Precision Engineering*, vol. 51, pp. 582-596, 2018.

[10] C. Wang, F. Ding, D. Tang, L. Zheng, S. Li, and Y. Xie, "Modeling and simulation of the high-speed milling of hardened steel SKD11 (62 HRC) based on SHPB technology," *International Journal of Machine Tools and Manufacturing*, vol. 108, pp. 13-26, 2016.

[11] D. W. Tang, C. Y. Wang, Y. N. Hu, and Y. X. Song, "Constitutive equation for hardened SKD11 steel at high temperature and high strain rate using the SHPB technique," *Proceedings of Fourth International Conference on Experimental Mechanics*, vol. 7522, pp. 1-12, 2009.