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The Analysis of Response Surface Methodology-Based Optimization of Surface Roughness in Vibration-Assisted Micro-Milling of Aluminium T6061

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Abstract: This study investigates the application of response surface methodology (RSM) to optimize machining parameters for minimizing surface roughness in vibration-assisted micro-milling. Experimental trials were designed and conducted using Taguchi's experimental design approach. The primary machining parameters considered include spindle speed, feed rate, vibration amplitude, and vibration frequency. The influence of these parameters on surface roughness was systematically analysed, and the optimal cutting conditions for achieving minimum surface roughness were identified. A second-order regression model was developed using RSM to describe the inherent relationship between the machining parameters and surface roughness. Experimental findings indicate that vibration amplitude is the most influential factor affecting surface roughness, followed by feed rate. A close agreement between the predicted and experimental results demonstrates the reliability and accuracy of the proposed model. Validation experiments further confirm that the developed RSM model is effective in predicting surface roughness in vibration-assisted machining of aluminium T6061 workpieces.

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Keywords: Response surface methodology, vibration assisted machining, vibration amplitude, vibration, frequency.

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1. Introduction

Vibration assisted machining (VAM) integrates conventional precision machining with small-amplitude tool or workpiece vibration to enhance the overall fabrication process. This technique has been widely implemented across various machining operations and applications The incorporation of vibration into manufacturing processes has been extensively reported in the literature for more than five decades [1].

In VAM, the cutting edge is subjected to controlled vibration at a prescribed frequency, which has been shown by numerous studies to improve material removal rate, surface finish, and tool life. Chern and Lee introduced a vibrating worktable capable of generating vibrations of up to 10 kHz from the workpiece side for vibration-assisted drilling of aluminum [9]. Their findings demonstrated that increasing vibration frequency and amplitude significantly reduced hole center displacement and surface roughness of the drilled walls. In the present study, a horizontal micro-milling configuration equipped with a two-dimensional piezoelectric actuator is employed, in which vibration is applied directly to the workpiece during machining. Vibration-assisted milling is among the most widely adopted metal cutting processes for machining materials such as metals, glass, and ceramics in industrial applications. A fundamental characteristic of vibration cutting is the periodic separation of the tool face from the workpiece, which reduces cutting forces and improves machining stability. This technique was first applied in the precision drilling of wood [1]. Subsequently, Adachi et al. [4] developed an electro-hydraulic servo system capable of inducing vibrations up to 1,000 Hz in the spindle of a CNC vertical milling machine. Their experimental investigations on aluminum drilling revealed a substantial reduction in burr formation under low-frequency vibration conditions. The present research aims to optimize the key parameters governing vibration-assisted machining of aluminum T6061 within a low-frequency range of 1 kHz to 3 kHz. Aluminum T6061 was selected due to its favorable machinability, making it suitable for investigating the fundamental mechanisms of vibration-assisted milling at this exploratory stage. The primary objective of this study is to determine the optimal machining parameters and to evaluate their effects on surface roughness using Taguchi design and response surface methodology (RSM). Four critical process variables—feed rate, vibration amplitude, vibration frequency, and spindle speed—are considered. The machining experiments focus on applying low-frequency vibration (1–3 kHz) to the workpiece rather than the cutting tool. The surface quality of the machined slot sidewalls is quantitatively assessed using a Zygo 3D optical profiler.

2. Materials & Methodology

A Horizontal desktop micro-milling machine as shown in figure 1a is used to carry out the experimental trial at a spindle speed of up to 15,000 rpm, 50mm/min federate, 1µm to 5µm vibration amplitude and up to 3,000 Hz vibration frequency. The fundamental design was followed by mounting XY stage to drive the vibration excitation. In addition, a jig was designed to hold a workpiece in horizontal axis to perform slot milling operation. This was taken into consideration to give optimum cutting conditions during the cutting process. The experimental trials aim to investigate aluminum T6061 as a workpiece being cut with several slots on horizontal milling orientation. The size of the workpiece is 30mm × 30mm × 6mm which was securely clamped with 5 screws inside the jig slot.

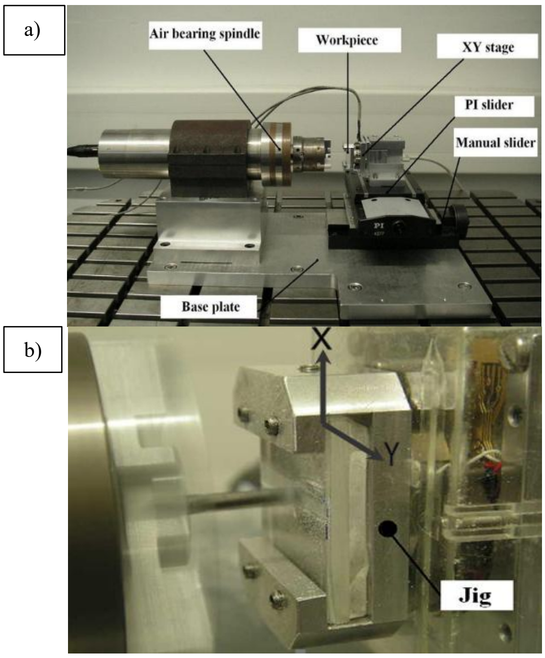


Fig. 1 - (a) Horizontal desktop micro-milling machine; (b) Workpiece position and jig designed

3. Experimental Setup

Piezoelectric actuators are characterized by high positioning accuracy, rapid dynamic response, and relatively large actuation force. In this study, piezoelectric actuators are employed to generate two-dimensional vibration through a purpose-designed mechanical structure. The first stage involved the development of a two-dimensional vibration system comprising two pairs of piezoelectric actuators and two linear guideways, as illustrated in Fig. 1(b). The vibration jig and fixture serve dual functions: (i) securing the workpiece, and (ii) generating controlled vibrations along the X and Y directions.

The experimental setup for machining aluminum T6061 is shown in Fig. 1(a). Surface roughness (Ra) measurements were obtained from the side walls of the machined slots in the direction where vibration was applied. The tool trajectory follows an elliptical locus, which is governed by the superposition of vibrations along the two orthogonal axes combined with the feed motion of the workpiece. Four machining parameters—vibration amplitude, vibration frequency, feed rate, and spindle speed—were selected for investigation. Each parameter was examined at three levels, resulting in a multi-level experimental design. Owing to the multi-level nature of the selected factors, their combined effects on surface roughness exhibit nonlinear behavior. A total of 81 preliminary cutting experiments with coded values and factor levels are presented in Table. Experiments were conducted using three coded levels for each parameter.

Table 1 - Machining parameter and their coded levels

Process Variables	Levels		
	L1 (L)	L2(M)	L3(H)
Vibration amplitude, A (μm)	1	3	5
Vibration frequency, F (Hz)	1000	2000	3000
Feed, f (mm/min)	1	4	6
Spindle Speed, s (rpm)	4000	7000	10000

The experimental trials were carried out using a horizontal desktop micro-milling machine with the following specifications. The end mill was clamped with an overhang length of 12 mm from the chuck to the tool tip in order to minimize tool deflection during machining. The spindle speed was varied within a range of 1,000 to 15,000 rpm, while the vibration frequency was set between 1,000 Hz and 3,000 Hz. The vibration amplitude ranged from 1 μm to 5 μm with a resolution of 0.05 μm, and the feed rate was varied from 1 to 6 mm/min.

The vibration amplitude was calibrated and continuously monitored using displacement sensors throughout the cutting process to ensure accuracy and stability. All machining experiments were performed under dry cutting conditions, with compressed air supplied to effectively remove chips from the cutting zone.

4. Results and Discussions

4.1 Taguchi Analysis on The Effect of Parameters R_a

To reduce the number of experimental runs while maintaining statistical reliability, a three-level Taguchi orthogonal array L27 was employed to design the cutting trials for the four selected factors. The four control parameters considered in this study were feed rate (A), vibration amplitude (B), vibration frequency (C), and spindle speed (D). The influence of these control parameters on the arithmetic surface roughness (Ra) is illustrated in Figure 2.

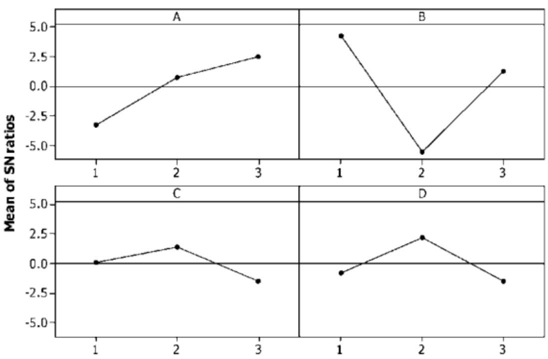


Fig. 2 - Mean of S/N ratios for arithmetic surface roughness (R_a).

Since achieving a lower surface roughness is desirable in machining operations, the "smaller-the-better" quality characteristic was adopted for the analysis. The calculated responses of the different control parameter combinations on surface roughness are summarized in Table 2.

Table 2 - Response of different parameters on surface roughness (R_a)

Level	A	B	C	D
1	-3.24262	4.28410	0.08216	-0.79412
2	0.74382	-5.57921	1.41207	2.22696
3	2.48378	1.28010	-1.50925	-1.44786
Delta	5.72640	9.86331	2.92132	3.67481
Rank	2	1	4	3

To evaluate the statistical significance of each control parameter on the machined surface roughness, an analysis of variance (ANOVA) was performed based on the signal-to-noise (S/N) ratios, and the corresponding results are presented in Table 3.

Table 3 - ANOVA for S/N ratios of control parameters on surface roughness (R_a).

Source	DoF	SS	MS	F	P
A	2	1.7166	0.8583	38.92	0.000
B	2	7.6854	3.8427	178.23	0.000
C	2	1.2370	0.6185	28.04	0.000
D	2	0.7568	0.3784	17.16	0.000
Error	18	0.3970	0.0221		
Total	26	11.7927			

The results of the ANOVA analysis indicate that the calculated F-values for all control parameters exceed the critical tabulated values of F0.05,2,18=3.5546 F0.05,2,18 =3.5546 and F0.01,2,18=6.013, F 0.01,2,18 =6.013. Accordingly, it can be concluded that all selected parameters have a statistically significant effect on surface roughness at the 99% confidence level. Consequently, all four control parameters should be incorporated in the subsequent development of the response surface model. Based on the parameter ranking presented in Table 2, vibration amplitude is identified as the most influential factor affecting surface roughness, followed by feed rate, spindle speed, and vibration frequency. According to the maximum signal-to-noise (S/N) ratio criterion, the optimal machining conditions correspond to a low vibration amplitude (1 μm), high feed rate (6 mm/min), medium vibration frequency (2,000 Hz), and spindle speed of 7,000 rpm

4.2 Response surface modelling (RSM)

The Box–Behnken design (BBD) was employed with factors coded at three levels, namely −1, 0, and +1 [17]. A single replicate with one block was constructed, incorporating three center points. Based on the F-values calculated for each factor as presented in Table 4, factor D (spindle speed) consistently exhibited the lowest F-value, indicating its relatively minor contribution to the response surface formulation. To improve the statistical significance and robustness of the RSM regression model, factor D was therefore excluded from further analysis. Consequently, only three significant factors were considered in the response surface design, each evaluated at three levels within a single block. The resulting quadratic response surface model is expressed in Eq. (1), and the corresponding ANOVA results for the fitted response surface are summarized in Table 4. The RSM regression model is found to be statistically significant at the 95% confidence level, as evidenced by an F-value of 7.27, which exceeds the critical value of $F_{0.05,9,5} = 4.7725$.

$$Y = 0.562333 - 0.371250A + 0.0782500B - 0.0490000C + 0.414583A^2 + 0.0900833B^2 + 0.0300833C^2 - 0.151500AB + 0.20400AC + 0.0280000BC \quad (1)$$

Table 4 - ANOVA table for response surface of arithmetic surface roughness (R_a).

Source	DoF	SS	MS	F
Regression	9	2.07956	0.231062	7.27
Error	5	0.15891	0.031782	
Total	14	2.23847		

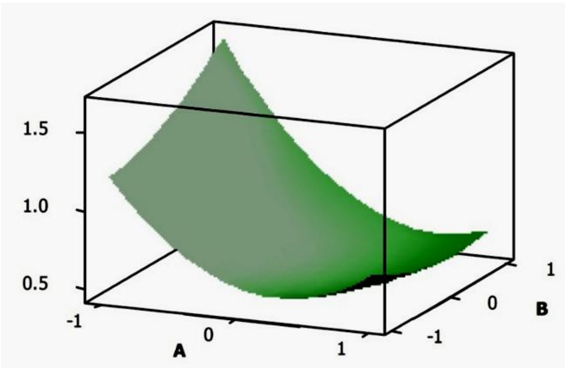


Fig. 3 - 3D plot of response surface of R_a (in µm) for factors A and B, with C=0.

The three-dimensional response surface plot constructed using the coded factors is presented in Figure 3. The plot indicates that minimum surface roughness is attained at higher values of factor A. However, the influence of factor B varies depending on the level of factor C, highlighting the interaction effect between these parameters. This observation is consistent with the findings from the Taguchi orthogonal array analysis, which demonstrated that a higher feed rate (factor A) tends to produce an improved surface finish. Based on the developed response surface model (Eq. 1), the optimal combination of machining parameters is estimated as A = 0.5211, B = 0.5902, and C = −1.0, resulting in a minimum surface roughness (Ra) of 0.4687 µm.

4.3 Experiment Verification

Based on the ANOVA results presented in Table 4 and the analysis of the mean signal-to-noise (S/N) ratios shown in Figure 3, factor A (feed rate) is identified as a statistically significant parameter, with its higher level being more favourable**.** This finding is further supported by the response surface contour plots for factor A**,** which consistently indicate that higher feed rate values are preferred across all three levels of factor C (vibration frequency)**.** These results collectively demonstrate that an increase in feed rate leads to a reduction in surface roughness (Ra)**.**

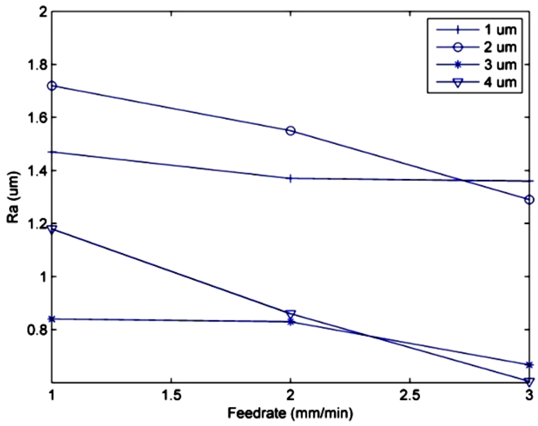
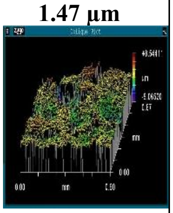
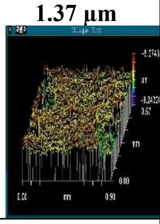
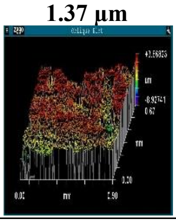
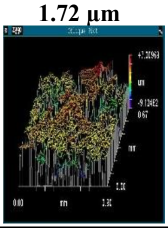
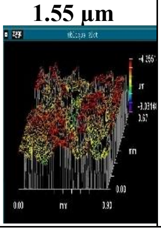
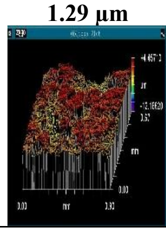


Fig. 3 - Relationship between surface roughness and feed rate at various depths of cut.

In addition to the designed experiments listed in Table 2, an independent set of validation experiments was conducted using the same machine configuration but with different machining parameters to verify the optimization results obtained from response surface methodology (RSM) and Taguchi's approach. In these verification experiments, the depth of cut was selected as an independent variable to further investigate the relationship between surface roughness and feed rate.

The experimental results are summarized in Table 5 and illustrated in Figure 4. As observed in Figure 4, for all tested depths of cut, the surface roughness (Ra) decreases with increasing feed rate. These findings confirm that a higher feed rate is preferable for achieving minimum surface roughness, thereby validating the optimization results predicted by the RSM and Taguchi analyses.

Table 5 - Effect of feed rate on surface roughness at different depths of cut

D. O. C. (µ m)	Surface roughness (R_a)		
	Feedrate = 1 mm/min	Feedrate = 2 mm/min	Feedrate = 3 mm/min
1.00	1.47 µm 	1.37 µm 	1.37 µm 
2.00	1.72 µm 	1.55 µm 	1.29 µm 

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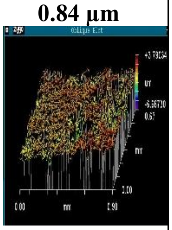
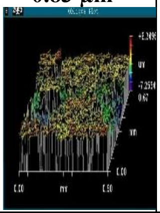
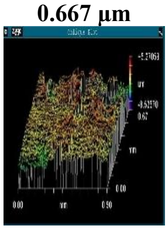
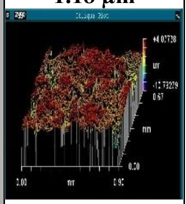
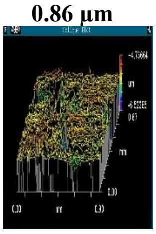
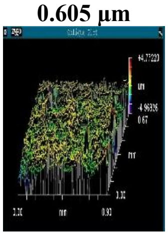
3.00	**0.84 µm** 	**0.83 µm** 	**0.667 µm** 
4.00	**1.18 µm** 	**0.86 µm** 	**0.605 µm** 

5 Conclusion

The surface roughness in vibration-assisted machining of aluminium T6061 under various cutting conditions was evaluated using Taguchi design and response surface methodology (RSM). Based on the experimental results and analytical findings, the following conclusions can be drawn:

The influence of machining parameters on surface roughness was systematically evaluated using the Taguchi method, and the optimal machining conditions for minimizing surface roughness were successfully determined.

The results indicate that vibration amplitude is the most significant parameter affecting surface roughness, followed by feed rate. In contrast, vibration frequency and spindle speed exhibit comparatively minor effects on surface generation.

The optimal machining conditions identified in this study correspond to a low vibration amplitude (1 µm), high feed rate (6 mm/min), medium vibration frequency (2,000 Hz), and spindle speed of 7,000 rpm.

The application of vibration-assisted machining significantly improves surface finish in the machining of aluminium T6061. Validation experiments confirm that the optimized parameter combination is effective and satisfies practical machining requirements in desktop vibration-assisted micro-milling of aluminium T6061.

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