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Research Article

Using Taguchi method to investigate surface roughness in finishing with ultrasonic vibration-assisted machining (UVAM) on conventional machine tools

Nam Hai Tran[1,2,*], Lynh Huyen Duong[1,2], Son Anh Tran[1,2]

[1]Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

[2]Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam

Correspondence

Nam Hai Tran, Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam

Email: namth@hcmut.edu.vn

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ABSTRACT

Ultrasonic vibration-assisted machining (UVAM) has attracted considerable attention in recent years due to its potential to significantly enhance machining performance. This technique is particularly effective in extending tool life, minimizing surface roughness, and reducing cutting forces, which are critical factors in precision manufacturing. Unlike many previous studies that focus on high-speed spindles or specialized machining centers, the present research investigates the application of UVAM in finishing operations performed on conventional machine tools. The study specifically targets small, narrow surfaces with intricate profiles where the use of high-speed spindles is either impractical or unavailable. This approach broadens the scope of UVAM by demonstrating its feasibility in more common manufacturing environments. The ultrasonic vibration-assisted cutting tool used in this research is designed to be structurally similar to a conventional stand-alone cutting tool, allowing it to be integrated easily into traditional machining setups without requiring major modifications. To systematically evaluate the effects of key machining parameters on surface quality, the Taguchi method was employed as the experimental design framework. The parameters examined include vibration frequency (f), voltage supplied to the ultrasonic actuator (V), and spindle speed (n), which collectively influence the machining dynamics. The primary goal of the study was to achieve a surface roughness (Ra) below 1.6 μm while maintaining spindle speeds not exceeding 180 revolutions per minute, conditions relevant to conventional machine tool capabilities. Experimental results clearly indicate that vibration frequency exerts the most significant influence on surface roughness, followed by the voltage input to the ultrasonic actuator, while spindle speed within the tested range has a minor effect. Several experimental trials successfully achieved Ra values lower than the 1.6 μm target, confirming the effectiveness of UVAM under these constraints. These findings underscore the potential of ultrasonic vibration-assisted machining to improve surface finish quality on complex geometries even when using standard machining equipment. Ultimately, this work contributes valuable insights into expanding the practical application of UVAM, offering a promising solution for manufacturing scenarios where advanced high-speed machines are not accessible, thereby enhancing surface quality in resource-limited production settings.

Key words: Ultrasonic Vibration-Assisted Machining (UVAM), Taguchi, Surface roughness

INTRODUCTION

There are many studies on the application of ultrasonic vibration effects in machine part shaping[1–11]. In particular, some studies have directly applied ultrasonic vibrations to drill and form holes for materials with high hardness, such as glass, ceramics, etc., on specialized ultrasonic processing machines. Other studies have indirectly applied ultrasonic vibrations to common machining processes such as turning and milling to improve technological parameters, such as increasing tool durability, reducing roughness and machining force, etc. In these applications, ultrasonic vibrations are transmitted into the tool jig or workpiece. The research of Huy et al. has applied ultrasonic effects to machining tools for the process of turning 12-diameter holes on Cr12Mo mold steel with a hardness of 60 - 62 HRC[12]. The results have shown a reduction in cutting force of 20% to 30% and an improvement of at least one level of surface roughness compared with conventional turning without ultrasonic vibration.

A different approach involves finishing surfaces with small dimensions, such as narrow grooves 'A' with a diameter ϕD of less than 3 mm, as illustrated in Figure 1a[13,14]. Machining will be difficult when the tooltip (1) needs to produce a high enough finishing speed to achieve a surface roughness Ra below 1.6 μm. This requires the use of a high-speed spindle with a rotational speed n that can be over 10,000 rpm, which also causes rapid tool damage and increases fabrication costs. To reduce the need for high spindle speed

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n in these machining cases while still achieving the desired finishing-cutting speed as well as easy mounting on the holder of conventional machine tools without the need for specialized ultrasonic machine tools, the use of an Ultrasonic Vibration-Assisted Machining tool (UVAM) is a promising solution. Nam et al. have proposed designs of the UVAM tool for both 1D and 2D applications [13,14].

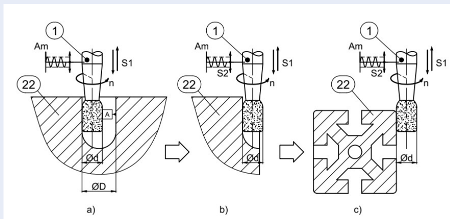


Figure 1: The principle of cutting speed conversion during finishing [13]

The principle of cutting speed conversion during finishing is illustrated in Figure 1, and the actual construction of the cutting tool used in this study is shown in Figure 2 [15]. It is worth noting that, since $\phi d < \phi D$, model B, as presented in Figure 1b, is employed as an intermediate step in transitioning from model A (Figure 1a) to model C (Figure 1c) in order to preserve the fundamental characteristics of the process. When machining the part surface (22), the mechanical vibration of the standard vibrating head (5) will be amplified to an amplitude of Am and transmitted to the tool head (1), which is a multipoint cutting tool as a group of interconnected abrasives, and it is integrated into the tool body (2). Under the multi-dimensional and multi-point machining capabilities of this group of interconnected abrasives, micro-cuts will occur on the machined surface in the direction of ultrasonic vibration S1 of the cutting tool head (1). Based on this machining effect, the spindle speed n can be reduced to a low level. A minimum low speed is acceptable when uniform wear of the tool-tip diameter (1) is ensured.

The purpose of this study is to present the process of surveying the roughness of small-sized surfaces in finishing using UVAM tools under the influence of technological parameters such as frequency f, voltage V of the vibrator, and spindle speed n of the machine tool. The Taguchi method was used to construct the experiment and analyze the results. In addition, an ANOVA (Analysis of Variance) statistic was performed to quantify the influence of the three technological parameters mentioned above on the measured surface roughness Ra.

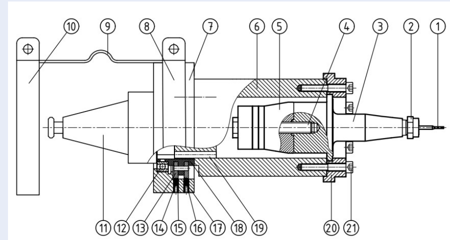


Figure 2: Ultrasonic vibration-assisted machining tool (UVAM) [15]

MATERIALS AND METHODS

Table 1: Technology parameters in experiences

No.	Factor	Note	Level		
			1	2	3
1	Vibration frequency (kHz)	f	38	40	42
2	Voltage level of Piezo (V)	V	200	-	240
3	Spindle speed (rpm)		120	150	180

The Taguchi method is used to set up the experimental process to investigate the influence of technological parameters, such as vibration frequency f (kHz), voltage level V (V), and spindle speed n (rpm), on the roughness criterion Ra of the machined surface when using the tool described in Figure 2. The target Ra should be achieved by not more than 1,6μm.

The goal of the Taguchi method is to design a process (or product) that is less susceptible to the factors that cause quality deviations. The goal is to adjust the factors to the optimum level so that the process (or product) is stable at the best quality level. The Taguchi method uses orthogonal series in experimental planning. The benefit of this method is that a minimal number of experiments are needed to study the effect of factors on a selected response of a process (or product) and, from there, quickly adjust the parameters for the fastest optimization.

Spindle speed is expected to be below 500rpm. However, to further reduce this speed enough to ensure even wear for the diameter of the cutting head, the initial study will be limited to the range of 120 to 180 rpm. This low spindle speed finishing condition is perfectly suitable for conventional machine tools. The three-speed levels of the n-factor (rpm) are selected as 120, 150, and 180, respectively. The survey range of the head vibration frequency will be limited to the range of 38 kHz to 42 kHz, with a center frequency of 40 kHz. This center frequency is the design frequency of the commercial standard vibrator (5) used in this study, as shown in Figure 2. The three frequencies of the f-factor (kHz) are, respectively, 38, 40, and 42. The voltage supplied to the vibrator varies in the range of 200 – 240 V. The two voltage levels of the V factor are selected as 200 and 240.

Table 1 lists the three controlling factors with different levels each, and an orthogonal array (L18) was used to design the various experimental combination are shown in Table 2. The roughness Ra data were obtained by Mitutoyo's SJ-210 roughness meter.

The experimental samples were made on 6063-T5 aluminum profile as shown in Figure 1c. The purpose of such sample selection is to facilitate easy setting and measurement of roughness values, but this still does not change the meaning of this study. The experimental set of samples is depicted in Figure 3.

The experiments are carried out on a common Bridgeport VMC 500-16 CNC milling machine. The tooling is shown in Fig. 2, and the machining system is shown in Figure 4. The positioner consists of components (8), (9), and (10) are used to fix the housing (7) of the power slip ring from (12) to (18) with the reciprocating part of the spindle to isolate the rotation of the milling machine spindle and transmit an electrical signal to the vibrator (5).

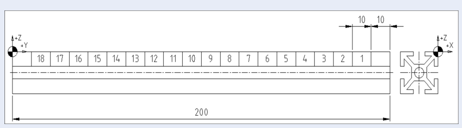


Figure 3: The experimental set of samples.

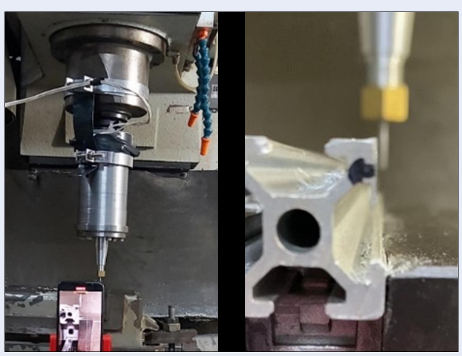


Figure 4: The machining system.

Test samples are pre-machined with the same condition of roughing or finishing before the experiments to get a similar initial roughness for comparison purposes. Furthermore, to remove the effect of initial roughness in the results and reduce the cutting steps of pre-finishing, the smaller value of initial Ra than the desirable experiments is chosen. The initial roughness is chosen about 0,8μm while the desirable value is 1,6μm. The dry-cutting method without cutting fluid is also used to remove the effect of cutting fluids in the test samples. These experimental conditions help to show the pure cutting effect of ultrasonic machining. The relationships between the frequency of vibration, the flow rate of the cutting fluid, and the cavitation phenomenon are also not concerned here, which will be discovered in other experiments in the future.

RESULTS

Since a smaller roughness is desired in this study, the equation$S/N = -10\log\left[\frac{1}{n}\left(\sum y_i^2\right)\right]$was used to calculate the Signal-to-noise ratio (S/N). The experimental results with the surface roughness value Ra of the corresponding numbered test specimens after measurement are described in Table 2 and Figure 6. The product of the test sample after machining is described in Figure 5 which is based on the design in Figure 3. In Table 2, the test samples No. 4, 6, 10 and 15 have obtained surface roughness results below 1.6μm and have input parameters in bold rows.

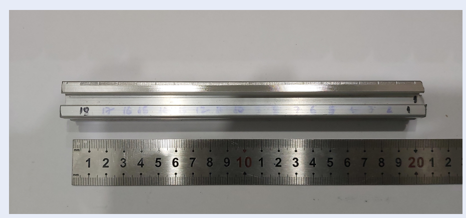


Figure 5: The product of the test sample after machining.

DISCUSSION

To understand the influence of each factor with different levels on the surface roughness Ra, the average S/N ratios at each level were calculated and listed in Table 3 by using Minitab 19 software. The average S/N ratios in Table 3 are plotted in Figure 7. In Table 3, the range of each factor (delta) is defined as the difference between the highest and the lowest average S/N ratios. The larger the range, the larger the influence of the corresponding factor on the surface quality.

Table 2: Experimental Results

No.	Voltage level of Piezo (V)	Vibration frequency (kHz)	Spindle speed (rpm)	Surface Roughness Ra (μm)
1	200	38	120	2.182
2	200	38	150	2.244
3	200	38	180	1.754
4	200	40	120	1.596
5	200	40	150	1.912
6	200	40	180	1.553
7	200	42	120	2.540
8	200	42	150	1.857
9	200	42	180	2.826
10	240	38	120	1.515
11	240	38	150	1.886
12	240	38	180	2.208
13	240	40	120	4.019
14	240	40	150	2.237
15	240	40	180	1.321
16	240	42	120	3.893
17	240	42	150	4.031
18	240	42	180	3.618

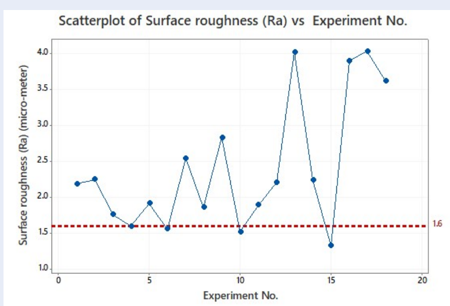


Figure 6: Diagram depicting surface roughness (Ra) values of 18 experiments.

Table 3: Response table for signal to noise ratios (smaller is better).

Level	Voltage level of Piezo	Vibration frequency	Spindle speed
1	-6.077	-5.780	-7.739
2	-8.064	-5.834	-7.107
3		-9.597	-6.366
Delta	1.988	3.817	1.373
Rank	2	1	3

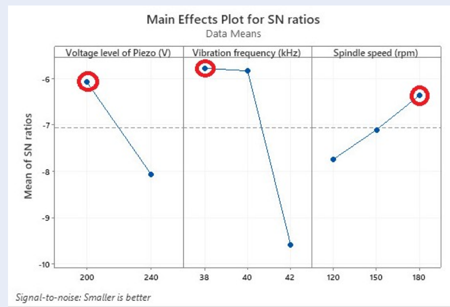
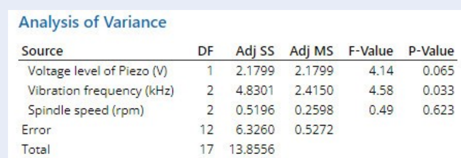


Figure 7: The graph shows the influence of technological parameters according to the survey values on the surface roughness index Ra.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Voltage level of Piezo (V)	1	2.1799	2.1799	4.14	0.065
Vibration frequency (kHz)	2	4.8301	2.4150	4.58	0.033
Spindle speed (rpm)	2	0.5196	0.2598	0.49	0.623
Error	12	6.3260	0.5272		
Total	17	13.8556			

Figure 8: Analysis of Variance for Ra in Minitab 19

Table 4: Level of impact of factors on Ra

Factors	DOF	Adj SS	Adj SS (%)
Voltage level of Piezo	1	2.1799	15.73
Vibration frequency	2	4.8301	34.86
Spindle speed	2	0.5196	3.75
Error	12	6.3260	
Total	17	13.8556	

Besides, the results of the ANOVA with roughness Ra are presented in Figure 8 and Table 4. The results of this analysis are performed at a significance level of α = 0.05, i.e., with a confidence level of 95%. The combination data of Figure 7, Figure 8, Table 3 and Table 4 clarifies the influence of factors related to surface roughness (Ra) measured.

In this study, vibration frequency f is the most influential factor (34.86%), and the change in roughness Ra takes place very strongly in the frequency range from 40 to 42 kHz. Voltage is the second most influential factor with a 15.73% influence on roughness Ra. Spindle speed has the smallest range of 1.373 and has the smallest influence (3.75%) on the Ra.

By following the criteria of smaller roughness with a larger S/N ratio, Figure 7 with marked red circles can be used to determine the optimal factors to achieve minimal roughness. The combination to achieve the smallest roughness is the voltage level of 200V (level 1), the vibration frequency of 38kHz (level 1), and the spindle speed of 180 rpm (level 3). However, with the goal of the study, the result of Ra only needs to be less than 1.6μm to be satisfactory, so the selection of parameters is also extended; for example, the points below the red dashed line in Figure 6.

Test samples No. 4, 6, 10, and 15 show the potential of the study is clearly with the below 1.6μm of surface roughness. Using the proposed Ultrasonic Vibration-Assisted Machining tool in case of these input parameters will help to reduce the need for high spindle speed n while still achieving the desired finishing-cutting speed on conventional machine tools. It is possible to finish machining of small-sized dimension surfaces at a low cost and without the need for specialized ultrasonic machine tools.

CONCLUSIONS

In this study, the Taguchi method was applied to investigate the influence of technological parameters such as frequency f, voltage V of the vibrating head, and spindle speed n on surface roughness in finishing with an ultrasonic vibration-assisted machining (UVAM) tool on conventional machines. The results show that at low spindle speeds up to 180 rpm, the frequency factor f has the largest influence, followed by the voltage V, and finally, the spindle speed n of the machine tool, which is the least influential. With the obtained roughness value Ra less than 1,6μm in experiments 4, 6, 10, and 15, the small influence of the rotation speed n of the spindle has satisfied the proposed goal. It is possible to finish machining a small-sized dimensional surface at a low cost and without the need for specialized ultrasonic machine tools.

The limitation of this study is that the minimum roughness value has not been written out. However, to solve this problem, in the next studies, the scope of investigating the influence of rotational speed will be expanded. The relationships between the frequency of vibration, the flow rate of the cutting fluid, and the cavitation phenomenon are also not concerned here, which will be discovered in other experiments in the future.

ABBREVIATIONS

UVAM: Ultrasonic Vibration-Assisted Machining
S/N: Signal-to-noise ratio
ANOVA: Analysis of Variance

CONFLICT OF INTEREST

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

AUTHORS' CONTRIBUTIONS

The first and second authors conceived of the study participated in its design and coordination and helped to draft the manuscript. The third author read and approved the final manuscript.

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Bài Nghiên cứu

Ứng dụng phương pháp Taguchi để khảo sát độ nhám của bề mặt trong gia công tinh bằng dụng cụ gia công có hỗ trợ rung động siêu âm (UVAM) trên máy công cụ truyền thống

Hải Nam Trần[1,2,*], Huyền Lynh Dương[1,2], Anh Sơn Trần[1,2]

[1]*Khoa Cơ khí, Trường Đại học Bách Khoa Thành phố Hồ Chí Minh (HCMUT), 268 Lý Thường Kiệt, Quận 10, TP. Hồ Chí Minh, Việt Nam*

[2]*Đại học Quốc gia Thành phố Hồ Chí Minh, Phường Linh Trung, Thành phố Thủ Đức, TP. Hồ Chí Minh, Việt Nam*

Liên hệ

Hải Nam Trần, Khoa Cơ khí, Trường Đại học Bách Khoa Thành phố Hồ Chí Minh (HCMUT), 268 Lý Thường Kiệt, Quận 10, TP. Hồ Chí Minh, Việt Nam

Đại học Quốc gia Thành phố Hồ Chí Minh, Phường Linh Trung, Thành phố Thủ Đức, TP. Hồ Chí Minh, Việt Nam

Email: namth@hcmut.edu.vn

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TÓM TẮT

Gia công có hỗ trợ rung siêu âm (UVAM - Ultrasonic Vibration-Assisted Machining) đã thu hút sự chú ý đáng kể trong thời gian gần đây nhờ khả năng nâng cao hiệu suất gia công. Kỹ thuật này đặc biệt hiệu quả trong việc tăng tuổi thọ dụng cụ cắt, giảm độ nhám bề mặt và lực cắt – các yếu tố then chốt trong gia công chính xác. Khác với các nghiên cứu trước đây, vốn chủ yếu triển khai UVAM trên các máy chuyên dụng hoặc các máy sử dụng trục chính tốc độ cao, nghiên cứu này tập trung vào việc ứng dụng UVAM trong nguyên công hoàn thiện (gia công tinh) trên các máy công cụ thông thường. Đối tượng gia công là các chi tiết có bề mặt hẹp, kích thước nhỏ với biên dạng phức tạp, nơi việc sử dụng trục chính tốc độ cao không khả thi hoặc không sẵn có. Phương pháp này mở rộng khả năng ứng dụng của UVAM trong các môi trường sản xuất phổ thông. Dụng cụ UVAM được thiết kế với cấu trúc tương tự dao cắt truyền thống, cho phép tích hợp dễ dàng vào các hệ thống gia công hiện có mà không đòi hỏi cải tiến đáng kể về trang thiết bị. Để đánh giá một cách hệ thống ảnh hưởng của các thông số công nghệ đến chất lượng bề mặt, nghiên cứu sử dụng phương pháp thiết kế thí nghiệm Taguchi. Ba thông số công nghệ chính được khảo sát bao gồm: tần số dao động siêu âm (f), điện áp cung cấp cho bộ kích siêu âm (V) và tốc độ quay trục chính (n), vốn tác động tổng hợp đến cơ chế cắt. Mục tiêu là đạt được độ nhám bề mặt (Ra) dưới 1,6 μm trong điều kiện tốc độ quay trục chính không vượt quá 180 vòng/phút, phù hợp với khả năng của các máy tiện thông thường. Kết quả nghiên cứu chỉ ra rằng tần số dao động siêu âm là yếu tố ảnh hưởng lớn nhất đến độ nhám bề mặt, tiếp theo là điện áp siêu âm, trong khi tốc độ quay trục chính có mức độ ảnh hưởng thấp hơn trong phạm vi khảo sát. Nhiều thí nghiệm đã đạt được giá trị Ra nhỏ hơn 1,6 μm, đáp ứng mục tiêu đề ra. Điều này khẳng định hiệu quả của UVAM ngay cả trong điều kiện thiết bị hạn chế. Nghiên cứu chứng minh rằng UVAM là một giải pháp hiệu quả để cải thiện chất lượng bề mặt của các chi tiết có biên dạng phức tạp, ngay cả khi sử dụng các máy công cụ tiêu chuẩn. Kết quả này góp phần mở rộng phạm vi ứng dụng thực tiễn của công nghệ UVAM, đặc biệt phù hợp với các cơ sở sản xuất không có khả năng tiếp cận các hệ thống máy móc hiện đại.

Từ khoá: Gia công có hỗ trợ rung siêu âm (UVAM), Taguchi, Độ nhám bề mặt

Trích dẫn bài báo này: Trần H N, Dương H L, Trần A S. **Ứng dụng phương pháp Taguchi để khảo sát độ nhám của bề mặt trong gia công tinh bằng dụng cụ gia công có hỗ trợ rung động siêu âm (UVAM) trên máy công cụ truyền thống**. *Sci. Tech. Dev. J. - Eng. Tech.* 2025; 8(4):2663-2669.