

NUMERICAL MODELING AND EXPERIMENTAL EVALUATION OF MACHINING PARAMETERS FOR 2-DIMENSIONS ULTRASONIC-ASSISTED MICRO-MILLING AT LOW AND HIGH-SPEED MACHINING

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Abstract

Vibration assisted machining (VAM) is one of the hybrid machining processes for improving the machined surface quality. VAM performance is mainly influenced by the combination of machining and vibration control parameters, where surface roughness value (Ra) became the benchmarking indicator. It is difficult to determine the optimum parameter combination to produce high precision products, especially for micro-milling, due to the interconnected correlation among parameters. The benefits of high-speed machining with VAM are high material removal rate and shorter machining time than low-speed machining. VAM operation at high-speed machining is still limited due to the high possibility of chatter occurrence. Therefore, this research aims to evaluate the 2D VAM resonant performance at low-speed and high-speed machining, operated at ultrasonic vibration and amplitude below one μm . The mathematical model and experimental evaluate the vibration effect based on machining mode, amplitude, and spindle speed variation. The mathematical modelling and experiment result complement each other, where the mathematical model can characterize the effect of resonant vibration, amplitude, and spindle speed increment on the tool path trajectory. The 2D resonant vibration at the feed direction causes interrupting cutting and transforms the tool path trajectory from linear to wavy. The mathematical model and experiment result show the dominant influence of spindle speed and feed rate on the toolpath trajectory and Ra, where low spindle speed and feed rate result in better machine surface roughness. The low-speed machining with VAM results in Ra value between 0.1–0.155 μm , which is below the high-speed machining result, between 0.2–0.38 μm .

Keywords: high-speed machining, low-speed machining, micro-milling, toolpath trajectory, vibration assisted machining (VAM).

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1. Introduction

Micro components are high commodity goods in manufacturing which consists of a micro slot and belongs to the characteristics of modular products [1–3]. Thus, a micro-component must have high precision machining quality to promote an ease assembly process [4]. The manufacture of micro components through machining must use a specific technology because of the high demand for quality and the final specifications of the produced components [5]. Moreover, with the high demands for the fulfillment of sustainable manufacture and energy saving, the entire production process must be considered according to those aspects [6–8].

The application of micro-milling can be used as one suitable machining method to produce high precision and high-quality micro product [9]. To achieve the targeted quality of the end product, the utilization of Vibration Assisted Machining (VAM) onto the micro-milling process is advantageous. The benefit of the utilization of VAM is mainly on the improvements of the end product quality where the surface roughness value (R_a) is relatively low in comparison with conventional machining mode. The R_a value for machining with VAM can achieve a high precision requirement for micro products [10–12]. The challenge to produce a low R_a value in the milling process is proper parameter combination between machining and vibration control parameters. The combinations between machining and vibration parameters are still in the development phase because each aspect will affect the machining process about the changes of the workpiece quality. It makes further development for micro-milling still developing by adjusting the setting parameter under a different variation to obtain the appropriate combination according to the R_a value based on material and milling machine apparatus [13–15].

There are two classifications of VAM according to the position of induced vibration during the process that is 1-dimension (1D) and 2-dimensions (2D) VAM [16]. The main advantage of 1D-VAM is more compatible to be implemented onto the micro-milling machine since the vibration is induced only on the feed direction (x -axis). However, the reduction of R_a value through 1D-VAM tend to be uneven since the machining process is conducted on the x - y plane and the vibration is only induced in the feed direction (x -axis) [17]. To overcome this limitation, the utilization of 2D-VAM is highly reasonable for further development as it helps to provide a uniform effect on the product. In 2D-VAM mode, vibration is induced at the feed direction (x -axis) and tangential to the feed direction (y -axis) [18]. Theoretically, inducing the vibration in both directions (x - y plane) can significantly decrease the R_a value of the finished product [19]. Unfortunately, the actual application of 2D-VAM demands applicable combinations between machining parameters (spindle speed, depth of cut, and feed rate) and vibration control parameters (frequency and amplitude) [20]. The combination must consider the material properties for the processed workpiece and the applied tool for the micro-milling process. It makes the adjustment of parameter control on Vibration Assisted Micro-milling is complicated. Therefore, it has to be predicted before the machining to estimate the suitable parameter for the process to obtain the low R_a value of the processed product.

Every combination in the machining parameter provides a different result to the workpiece. For example, VAM is ideal for low-speed machining combined with a low feed rate during machining [21]. The same approach is also recommended to reduce the R_a value for machining with VAM for low-speed machining and highlighted that the finished product's accuracy increased by 15 % [22]. The toolpath trajectory is highly influenced by the frequency of the induced vibration for the application of Ultrasonic-VAM and it can be observed through mathematical modeling and experimental [23]. The mathematical modeling can be used as a proper method to predict the toolpath trajectory, which helps to determine the chosen parameter is applicable for the machining process [24]. According to the previous studies, it can be said that the application of VAM improves the quality of the processed product and the importance of mathematical modeling to estimate the toolpath trajectory before the machining process.

Besides the machining mode based on VAM, machining parameters must be set accordingly, affecting the process of obtaining a low R_a value for the processed product. A comprehensive study through mathematical modeling can be conducted to predict the effect of machining parameters and machining mode (VAM) which each combination affects the R_a value of the product [25]. The effect of vibration in three levels (high, medium and low) varies the wear rate of the tool and workpiece where high vibration level allows to obtain low R_a value of the material [26]. Mathematical modeling can done through finite element analysis and recommends that low-speed machining is more applicable for VAM operational compared to high-speed machining where a high-quality end product is achieved by low-speed machining [27]. Depth of cut and feed rate in both machining mode (VAM and non-VAM) are considered important parameters aside from spindle speed, affecting the tool lifetime where it can fulfill the sustainable manufacturing principle [28]. The increase in the tool lifetime is mainly affected by the chosen parameter where it produces suitable cutting force during the machining process [29].

The above studies show the effect of machining mode and parameter process according to the end product quality. Unfortunately, no comprehensive study focuses on the mathematical modeling implementation based on the variation of machining mode and parameter process. Furthermore, a limited study compared the VAM application according to machining speed (low and high-speed machining) based on the toolpath trajectory and inhibited the recommended parameters for the machining process. The present study focuses on comparing machining mode (VAM and non-VAM) through mathematical modeling and experimental test to obtain the relation between toolpath trajectory and the quality of the milling process according to the Ra value. To provide more reliable results, the mathematical modeling is also done by varying the spindle speed and amplitude for VAM operational. More specific evaluation for the micro-milling process is expected to enhance the prediction of toolpath trajectory and its relation to the quality of the processed product. It can be used as a quick reference to determine the suitable combination of machining parameters.

2. Materials and methods

The cutting mechanism during the milling process can be predicted using numerical modeling to estimate the toolpath trajectory. Spindle speed, machining mode, the amplitude of piezoelectric transducer for Vibration Assisted Machining (VAM), feed rate and frequency influence the cutting process. In this study, the toolpath trajectory for the micro-end-milling process is set as the baseline for modeling the interaction between tooltip and workpiece. The toolpath trajectory for end-milling is formed as a trochoidal curve and can be predicted through (1), (2) for the x -axis and y -axis of non-VAM mode:

$$x_i = v_f \left(t + \frac{2\pi i}{z} \right) + r \sin(\omega t), \quad (1)$$

$$y_i = r \cos(\omega t). \quad (2)$$

Where v_f is feed rate, mm/second; t is machining time, second; z is the number of flutes; ω is the angular velocity of the spindle, rad/second; r is the tool radius, mm; n is spindle speed, rpm; i is the sequence number of the tooltip, for two-flute type, $i = 0$ and 1. The application of (1), (2) for four-flute type, $i = 0, 1, 2, 3$. The tooltip position in ordinate x and y are x_i and y_i , respectively, within the time frame; 1 second equals 360° rotation.

The use of VAM for the milling process makes the workpiece oscillates in two directions. Therefore, (1), (2) transforms to (3), (4) in order to plots the trajectory of the tooltip relative to the workpiece. The (3), (4) is needed since the vibration is induced in a sinusoidal wave with the same phase but having opposite direction at each axis. The modeling is taken by setting the changes in frequency and amplitude within the timeframe.

$$x_{i,2DVAM} = v_f \left(t + \frac{2\pi i}{z} \right) + A_x \sin \left(\lambda \omega \left(t + \frac{2\pi i}{z} \right) + \varphi_0 \right) + r \sin(\omega t), \quad (3)$$

$$y_{i,2VDAM} = r \cos(\omega t) + A_y \sin \left(\lambda \omega \left(t + \frac{2\pi i}{z} \right) + \varphi_0 \right). \quad (4)$$

So the toolpath trajectory with sinusoidal wave adds-on to the x -axis and y -axis, has amplitude displacement based on the tooltip rotation within specific timeframe. Where A_x and A_y are the amplitude at each axis; φ_0 is the phase angle; λ is the wavelength. The wavelength is the ratio of vibrational and spindle frequency.

The experiment method is taken by using a specimen (3.3×18×18 mm) for each test. The setting parameters (**Table 1**) were used for the micro milling process. The specification of the machine was already reported in another study [30]. A piezoelectric transducer (PZT4) was used to produce vibration to induce a sinusoidal curve for the workpiece. The generator ultrasonic (USG-110 hybrid precision) was coupled to the piezoelectric at frequency 24 kHz with phase angle 90° oppositely. The VAM mechanism was assembled from Bolt-Clamped Langevin Transducer.

Table 1
Parameter control for the machining

Cutting Tool	
Category	End-Milling with two flute
Material properties	Titanium coated carbide
Tool diameter	1 mm
Axial rake angel	30°
Workpiece	
Material properties	Al6061-T6
Specimen dimension	18×18×3.3 mm
The applied machining parameter	
Feed rate	Low speed machining – 0.2; 0.5; 1 mm/s High speed machining – 2; 4; 6 mm/s
Spindle speed	Low speed machining – 3,000; 7,000; 15,000 rpm High speed machining – 30,000; 70,000; 80,000 rpm
Depth of cut	10 micro meters
The applied vibration parameter	
Amplitude at the feed direction	0.766 micro meters
Amplitude at the tangential to the feed direction	0.382 micro meters
The inducing frequency	24 kHz

Fig. 1 presents the VAM mechanism attached to the motor stage. The tool for the milling process was used end-milling tool with two-flute type made of carbide coated with TiAlN. The quality of the milling process was estimated according to the surface roughness value (Ra). The Ra was measured by Surfcom 2800SD3-12 with a cut-off value of 0.08 mm, length of measurement 4 mm and measuring the speed of 0.3 mm/s. The measurement was taken along the feed direction.

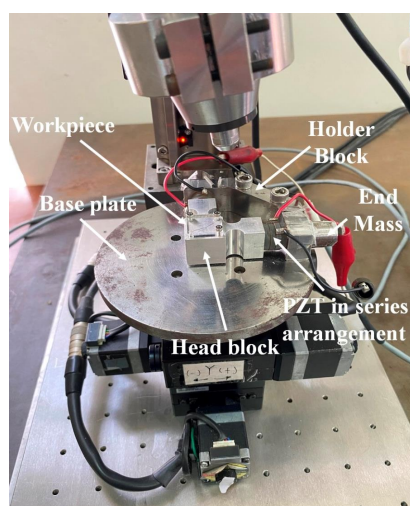


Fig. 1. The detailed components of the VAM mechanism

The detailed parameters for the experiment test are shown in **Table 1**. Since spindle speed, feed rate, and depth of cut are affecting the milling process performance. Thus each combination was set under two different machining modes, are VAM and non-VAM. The milling process was conducted to the workpiece according to the parameters combination in **Table 1**. Each parameter combination was tested three times to the workpiece.

3. Results

3.1. Results of the Effect of Vibration-Assisted Micro-milling

The application of Vibration Assisted Machining (VAM) during the micro-milling process shifts the toolpath trajectory. The model of the trajectory can be estimated by using numerical modeling where (1), (2) for non-VAM trajectory and (3), (4) for VAM. **Fig. 2** presents the result of mathematical modeling for machining mode with and without VAM according to feed direction (x -axis) and tangential direction from feed direction (y -axis).

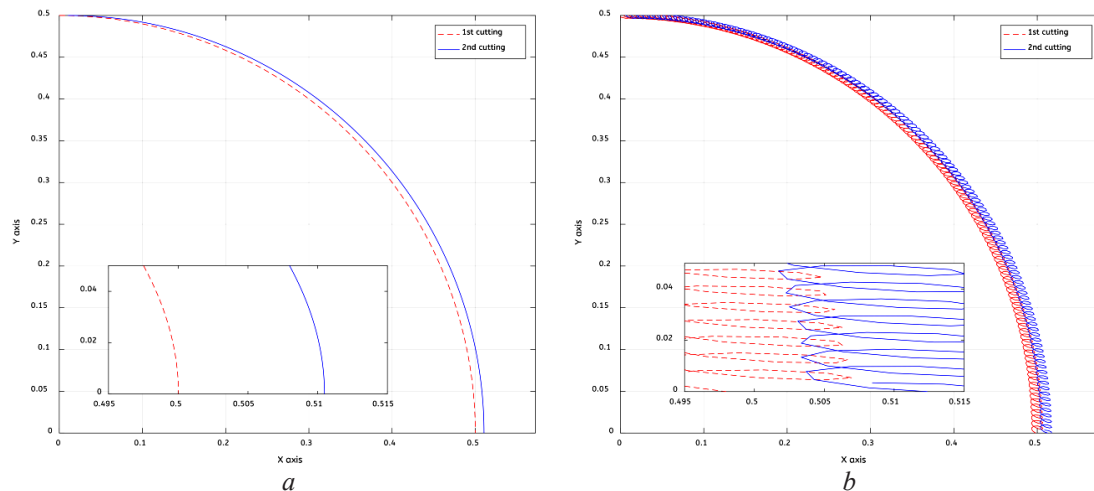


Fig. 2. Toolpath trajectory model for machining: *a* – without VAM; *b* – with VAM

As shown in **Fig. 2**, the changes in toolpath trajectory can be observed clearly. The trajectory for non-VAM displays a model curve pattern that indicates the tool and workpiece are always in contact along with the cutting process where there is an interval between 1st and 2nd cutting. The interval value is 0.11 mm, where during machining with VAM, the interval between 1st and 2nd cutting is not observed. As seen in **Fig. 2, b**, the trajectory for VAM shows a repeated circle path-like pattern with an intersection path between 1st and 2nd cutting. It demonstrates a repeated cutting process at the same surface on the workpiece.

3.2. Results for amplitude variation on tooltip trajectory

The variation of amplitude is affecting the toolpath trajectory for VAM. The modeling is done by varying the amplitude between 0.5–7.5 μm with interval 1 μm . The amplitude is set for the x -axis, where the amplitude of the y -axis is half of the x -axis amplitude. **Fig. 3** presents the trajectory model for each amplitude variation. As the amplitude increase, the interval between 1st and 2nd cutting becomes narrow. The repeated cutting process (circle path-like pattern) is started from an amplitude of 2.5 μm . The increment of amplitude after 2.5 μm affects the size of the peak and valley of the wave from the cutting trajectory. It is observed that there is an intersection between toolpath trajectories by using amplitudes of 6.5 and 7.5 μm . It indicates that increasing the amplitude for VAM can improve the quality of the machining process for micro-milling.

3.3. Spindle speed variation on tooltip trajectory

The spindle speed during the machining process has a critical influence on the machining duration. The machining duration is associated with the material removal rate from the workpiece. **Fig. 4** presents the effect of spindle speed during VAM with amplitude 0.7 and 0.35 μm . Under low-speed machining (ranging from 3,000–15,000 RPM), the peak and valley of the trajectory are getting wider as the spindle speed increase, which indicates the separation period between the tool and workpiece is shorter. High-speed machining (30,000–80,000 RPM) has a different pattern where the effect of VAM is not observed. The pattern shows a straight line with an interval between 1st and 2nd cutting is 0.11 mm.

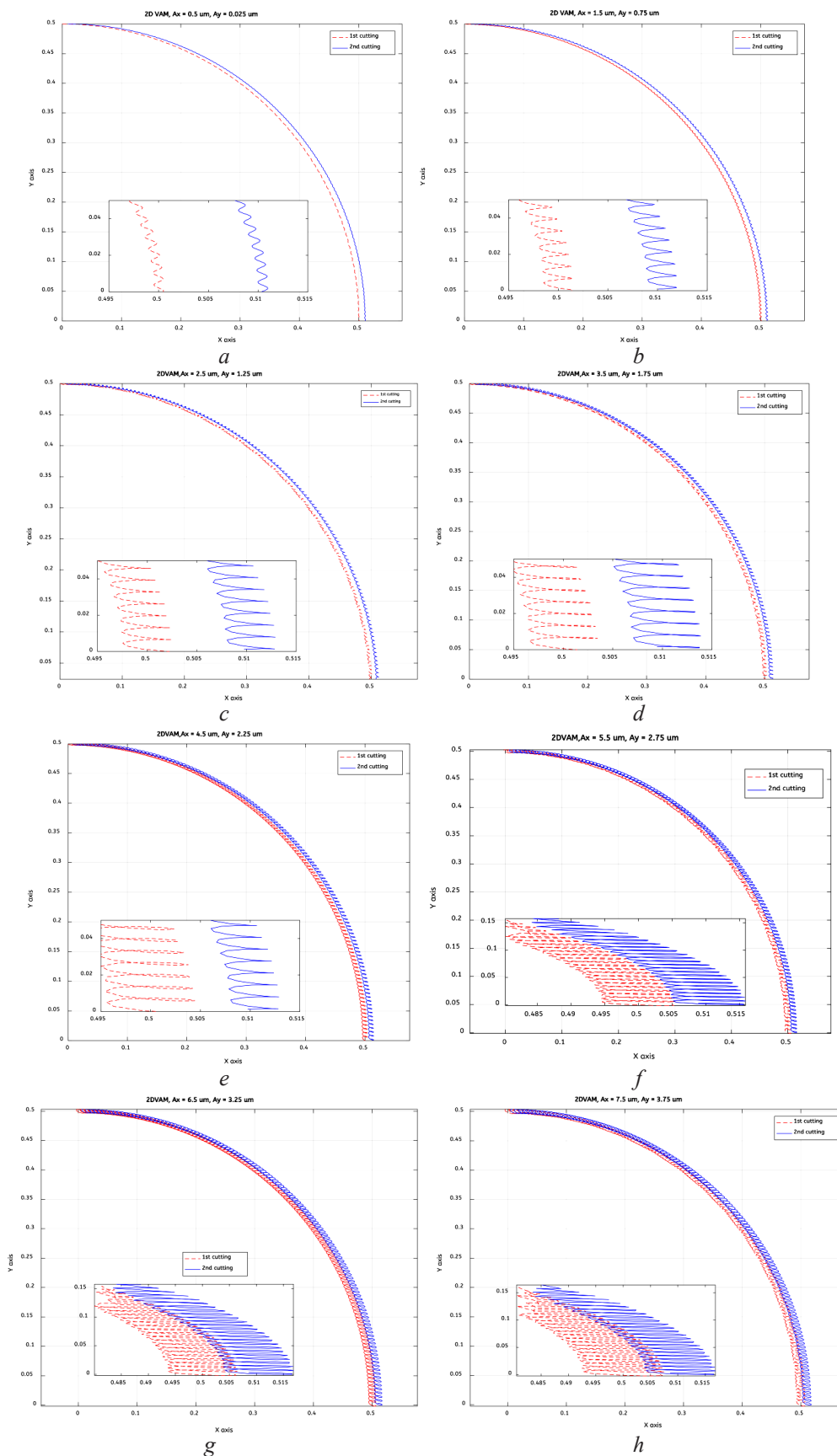


Fig. 3. The effect of amplitude on toolpath trajectory for VAM:
a – 0.5 μm; *b* – 1.5 μm; *c* – 2.5 μm; *d* – 3.5 μm; *e* – 4.5 μm; *f* – 5.5 μm; *g* – 6.5 μm; *h* – 7.5 μm

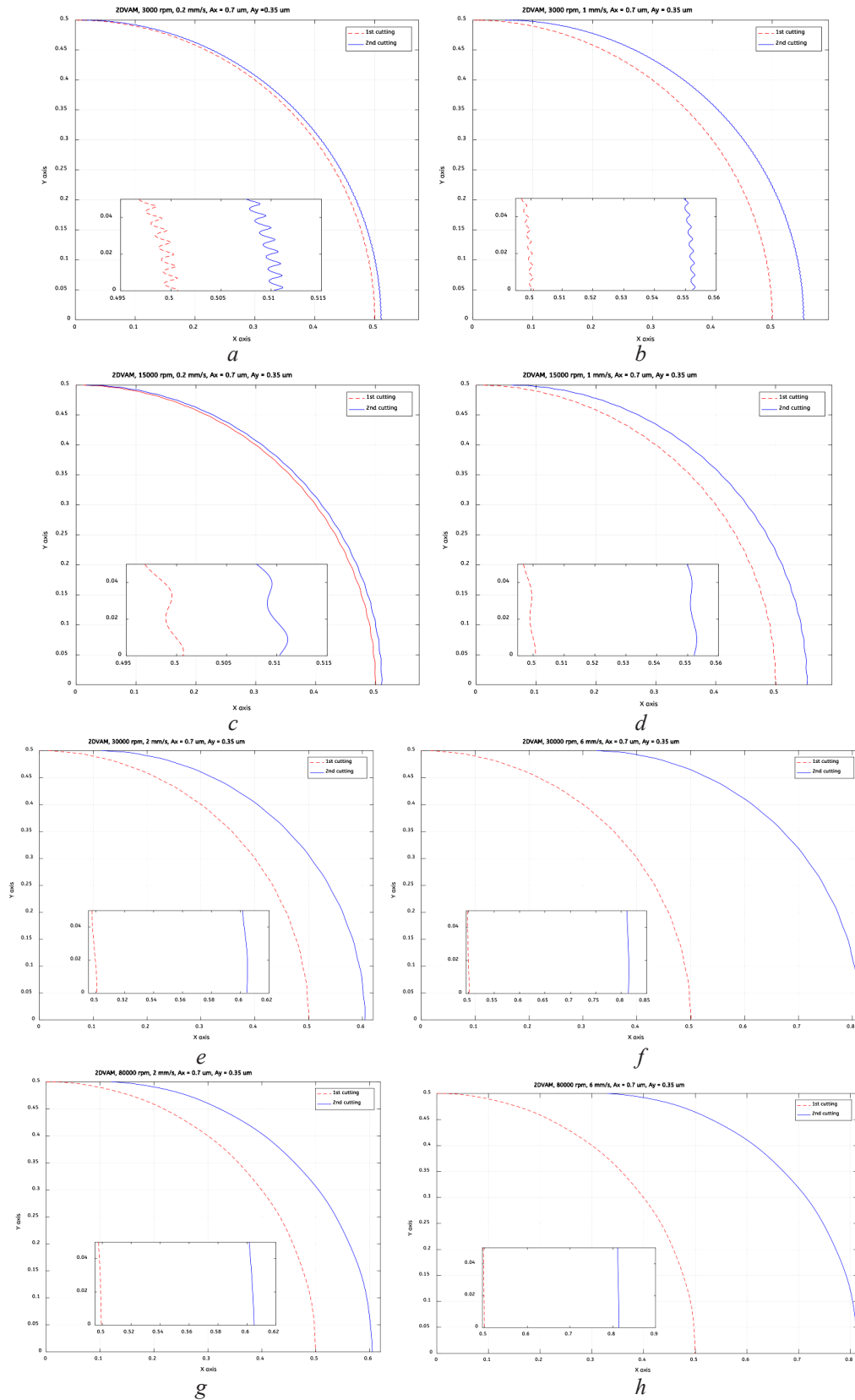


Fig. 4. The effect of spindle speed on toolpath trajectory for VAM: *a* – 3000 RPM $f=0.2$ mm/s; *b* – 3000 RPM $f=1$ mm/s; *c* – 15000 RPM $f=0.2$ mm/s; *d* – 15000 RPM $f=1$ mm/s; *e* – 30000 RPM $f=2$ mm/s; *f* – 30000 RPM $f=6$ mm/s; *g* – 80000 RPM $f=2$ mm/s; *h* – 80000 RPM $f=6$ mm/s

3. 4. Resonant Vibration Assisted Micro-Milling Performance

The surface roughness value (Ra) from the workpiece after the milling process is the critical parameter that should be addressed carefully, particularly for a micro-component that requires high accuracy. According to the parameter, micro-milling performance can be determined by measuring the surface roughness of the end product. The micro-milling process with and without VAM is compared according to the surface roughness. Since the milling speed also affects the surface roughness, let's compare the surface roughness of the tested specimen with and without VAM under different milling speeds. **Fig. 5** presents the surface roughness (Ra) at the different slot of the specimen under low and high-speed milling process with and without VAM (Ra_{VAM} and $Ra_{NON-VAM}$, respectively).

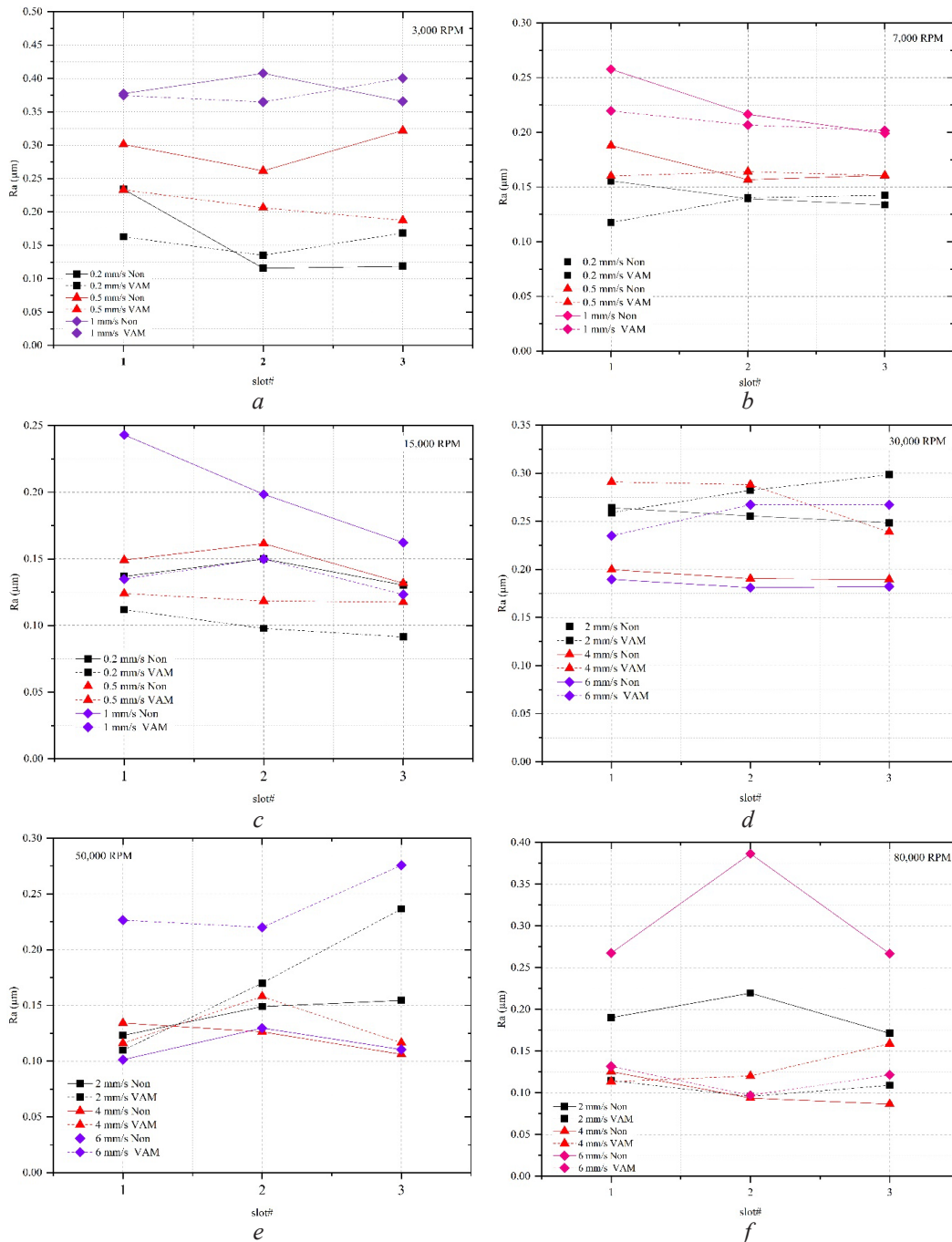


Fig. 5. Surface roughness value after machining: *a* – 3000 RPM; *b* – 7000 RPM; *c* – 15000 RPM; *d* – 30000 RPM; *e* – 50000 RPM; *f* – 80000 RPM

All specimens processed by VAM have a relatively lower surface roughness than those processed without VAM during low-speed machining. For high-speed machining, the specimens processed with VAM tend to have a higher surface roughness than those without VAM. However, for machining with spindle speed 80,000 RPM, a specimen processed without VAM has a higher surface roughness value, contrary to VAM, where the surface roughness is lower.

4. Discussion

The application of Vibration Assisted Machining (VAM) affects the cutting mechanism for the workpiece in the micro-milling process. According to the mathematical modeling as shown in **Fig. 4**, it can be observed significantly that the superimpose vibration to the toolpath trajectory. The trajectory model shows the effect that occurs on the workpiece where machining with VAM can improve the quality of machining because of the separation period between the tooltip and workpiece. It is advantageous for machining with VAM because the interval between 1st and 2nd cutting can be narrowed down. Thus the tooltip conduct repeated cutting on the same surface from the workpiece. Therefore, the repeated circle path-like pattern within one machining cycle proves that the machining with VAM can reduce the surface roughness of the workpiece.

The superimpose vibration on VAM is dependent on the produced amplitude by a piezoelectric transducer which significantly affects the toolpath trajectory between the tooltip and workpiece. The amplitude directly increases the peak and valley of the toolpath trajectory, where a higher amplitude causes the interval between 1st and 2nd cutting to decrease. It can be noticed distinctly according to the trajectory model in **Fig. 5**, where the intersection between 1st and 2nd cutting appears at amplitude 5.5 μm . The amplitude 6.5 and 7.5 μm cause the intersection area between 1st and 2nd cutting to become wider, making the separation period during cutting more extended, which help to increase the cooling time for the product before the subsequent cutting. An extended cooling time is highly recommended where the lifetime of the tool can be prolonged. Unfortunately, producing high amplitude requires high energy consumption for the piezoelectric transducer where it is undesirable for sustainable manufacturing.

In order to improve the quality of the end product for the micro-milling process with VAM under a lower amplitude, it should be combined with the spindle speed of the machining. It can be seen in **Fig. 5** where the effect of spindle speed at amplitude 0.5 μm at x -axis and 0.25 μm at y -axis shifts the toolpath trajectory. At high-speed machining, the effect of spindle speed in VAM micro-milling is not observed, which means a cutting mechanism similar to without VAM. The effect of spindle speed during low-speed machining is observed where the interrupting cutting occurs. The interval between 1st and 2nd cutting becomes narrower when the workpiece oscillates under a certain spindle speed. Therefore, it emphasizes that the application of VAM for the micro-milling process should be accompanied by compatible spindle speed, especially when the VAM is using low amplitude. The feed rate also has to be considered to maintain the quality of the end product for VAM with low amplitude.

The combination of spindle speed, feed rate, and machining mode has significantly affected the quality of the micro-milling process, which can be measured through the surface roughness value (R_a) of the end product. The increment of feed rate at specific spindle speed for low-speed machining with VAM escalated the surface roughness value where the R_a for feed rate 0.2 mm/s and 1 mm/s range between 0.1–0.155 μm and 0.136–0.379 μm , respectively. The same result is also shown for machining without VAM, where the increment of feed rate at a specific spindle speed increases the R_a value. The main difference between the two-mode is that the R_a value for VAM is lower than without VAM, which has a R_a value at feed rate 0.2 mm/s and 1 mm/s are ranging from 0.139–0.156 μm and 0.2–0.38 μm , respectively. The result proves that machining with VAM under the same parameter with non-VAM for low-speed machining reduces the surface roughness value of the end product, which indicates a better-quality product can be obtained.

High-speed micro-milling has no clear-cut trend or pattern where each parameter independently affects the result. It can be observed according to the R_a value for VAM and non-VAM without significant differences. Further, the mathematical modeling as shown in **Fig. 2** emphasizes the pattern of surface roughness value in **Fig. 5** where changes one parameter milling process

will transform the Ra value fluctuate. The mathematical model can predict the cutting mechanism according to each parameter process. Thus the effect of each parameter can be estimated before the milling process and help determine the quality of the process. The experiment result presents the effect of each milling process where one single parameter will significantly affect the quality of the end product, particularly for high-speed micro-milling. During low-speed machining, the effect of machining mode by using Vibration Assisted Machining (VAM) results in a better milling process quality where the workpiece's low surface roughness value can be achieved compared to non-VAM machining.

The limit of this study is that the evaluation of VAM performance is reviewed from only the tool path trajectory and its influences on the surface roughness value achievement. Therefore this numerical model in this study can be developed into the surface generation modelling. Also, the experimental results can be used as a baseline for further investigation in the influence of VAM application at high-speed milling on the accuracy dimension achievement and tool wear rate.

5. Conclusions

Vibration Assisted Machining (VAM) micro-milling changes the toolpath trajectory so the interrupting cutting can be obtained, which is desirable to decrease the surface roughness value of the workpiece. The interrupting cutting starts at amplitude 5.5 μm at feed direction and 2.75 μm tangential to the feed direction. Machining with VAM under spindle speed more than 30,000 RPM causes the toolpath trajectory similar to non-VAM machining. Feed rate 0.2 mm/s has a better surface roughness value compared to feed rate with 1 mm/s for low-speed machining. The effect of VAM is not observed for high-speed machining since the surface roughness value of the end product cannot be predicted precisely and tends to have a higher surface roughness value than low-speed machining.

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