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Influence of Spindle Speed and Ratio of Variation Amplitude of Milling Process on Vibration and Surface Roughness

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ABSTRAK

Teknologi manufaktur menggunakan permesinan berbasis computer numerical control (CNC) sudah berkembang pesat, khususnya dalam proses milling. Dalam proses milling, getaran (chatter) merupakan salah satu permasalahan yang harus diatasi. Untuk mencegah terjadinya getaran, banyak metode yang digunakan antara lain metode pasif, aktif, dan spindle speed variation (SSV). Metode SSV ini mudah diterapkan karena tidak membutuhkan tambahan peralatan dan hanya menggunakan algoritma tertentu untuk mengatur kecepatan spindel. Paduan Aluminum dipilih sebagai material berbagai komponen mudah dalam proses permesinan, tahan korosi, bobot yang ringan, dan rasio kekuatan terhadap berat yang tinggi. Namun, paduan aluminum seri 5xxx memiliki machinability yang relatif rendah. Penelitian metode eksperimental yang menggunakan mesin slot milling ini bertujuan untuk memvalidasi sistem SSV yang diterapkan pada mesin milling Router 2600 Pro terhadap paduan Aluminum 5052 dan untuk mengetahui pengaruh amplitudo modulasi SSV terhadap kekasaran permukaan Aluminum 5052 dengan variasi RVA 0 % (atau tanpa SSV) sampai RVA 30 %. Selain itu, kecepatan spindel juga divariasikan di 3.000, 5.000, dan 9.000 rotasi per menit (RPM). Selama proses permesinan berlangsung, sensor akselero meter diletakkan di samping benda kerja untuk merekam data getaran. Hasil pengukuran kekasaran permukaan dan analisa getaran menunjukkan bahwa RVA terbaik didapatkan di 20 %. Saat RVA naik menjadi 30 % maka getaran meningkat dan kekasaran permukaan menjadi lebih jelek. Sementaraitu, kecepatan nominal spindel terbaik yang menghasilkan kekasaran permukaan rendah adalah 5.000 dan 9.000 RPM.

Kata Kunci : *kecepatan spindel, rasio variasi amplitudo,getaran, kekasaran permukaan.*

ABSTRACT

Manufacture technology by using a computer numerical control (CNC) based machine has developed rapidly, particularly in the milling process. This technology, however, still experiences challenges, one of which is chatter. To prevent chatter, several methods are used, i.e. passive, active and spindle speed variation (SSV) methods. The SSV method is easy to apply since it does not require additional tools and only uses a certain algorithm to control the spindle speed. Aluminum alloys are selected as materials for various components since it is easy to machine, corrosion resistant, lightweight, and has a high strength to weight ratio. However, series 5xxx aluminum alloys have relatively low machinability. This experimental method research using a slot milling machine aims to validate the SSV system applied to the Router 2600 Pro to Aluminum 5052 and to determine the effect of SSV modulation amplitude on the surface roughness of 5052 aluminum with RVA variations of 0 (or without SSV) to 30%. In addition, the spindle speed was also varied at 3,000; 5,000 and 9,000 rotations per minute. During the machining process, an accelerometer sensor was installed to record vibration data. The results of surface roughness measurement and vibration analysis show that the best RVA was at 20%. If the RVA increased to 30%, the vibration increased and the surface roughness worsened. Meanwhile, the best nominal spindle speeds that produce low surface roughness are 5,000 and 9,000 RPM.

Keywords: CNC machine, spindle speed variation, ratio of variation amplitude, vibration, surface roughness.

INTRODUCTION

Products, parts and components can be manufactured by several methods, e.g. casting, machining, forming, powder metallurgy, etc. Of those methods, the machining is widely used due to its several advantages, e.g. the advanced machining process by adding a computer numerical control (CNC) combined with a computer aided manufacturing (CAM) software enhances precision, quality, productivity, materials and energy efficiency as well as machining ability of complex geometries. By 2032, market of CNC machines is projected to achieve $195.59 billion [1]. Various types of machines have been equipped with CNC and CAM ranging from spindles that can rotate more than twenty thousand rotations per minute (RPM), two axes to five axes, and chisels with various types of geometry to address industrial requirements. Although the CNC-based milling process offers many benefits, defects can still be observed on the machined products. These defects can be due to misalignment, improper clamping, chatter and uncontrolled chip removal [2]. In addition, incorrect parameters setting, e.g. improper feed rate, excessively high cutting rate and incorrect installation of insert, also contribute to defects.

Chatter which occurs due to vibration between the cutting tool and workpiece in the machining process is a resonant phenomenon [3]. It can cause excessively loud noise and vibration during the machining. As a consequence, chatter decreases the quality of the machined product, creates excessive noise as well as shortens the service life of spindle bearing and chisel. For this reason, many works have been dedicated to investigating the chatter phenomenon and methods to suppress it, e.g. [4],[5]. Passive and active strategies are widely used to suppress chatter. The passive strategy controls the dynamic conditions of the machine through modification of mechanical system of the machine or installing any additional system to the machine which can dissipate energy caused by chatter or interfere any regenerative process. Commonly used passive methods include irregular cutting tool, regulated mass dampers, passive vibration absorbers, and mechanical vibration dampers [6]. High applicability is the advantage of the passive method. However, the passive method also has several restrictions, e.g. adjustment of the parameters of passive dampers requires a high-skill operator.

Several works claimed that the active strategy is relatively low cost and can suppress chatter better since process parameters and external intervention can be online adjusted during the machining process to stabilize it [7],[8]. In addition to passive and active methods, there are many other methods to reduce vibration. Of those methods, the spindle speed variation (SSV) is also an alternative to minimize chatter. The SSV continuously modifies the cutting speed while the machining process is in progress. The SSV is effective particularly at low spindle speeds since the frequency and amplitude of speed variation can be adjusted during the machining process [9].Other SSV researches in the turning process have reported promising results but the SSV application in milling process needs to be further investigated [9]-[12].

To minimize the chatter, particular SSV properties can be modulated, i.e. ratio of variation amplitude (RVA), ratio of variation frequency (RVF) and nominal rotational speed [13]. The RVA compares the amplitude of the speed variation against the mean spindle speed. Meanwhile, the RVF is determined by dividing the variation frequency by the mean spindle speed. Many works developed the SSV to minimize chatter based on a particular algorithm, e.g. the method based on the Runge-Kutta approach [13], the semidiscretization method based on the Shannon standard orthogonal [14],[15], the method based on Legendre polynomial [16], the method based on Adams–Simpson formula [17], etc. Time delay exists when applying the SSV for continuously controlling the machining. Although an effective SSV application in minimizing chatter has been reported by many works, the optimization of SSV parameter still remains a challenge particularly under varied conditions, e.g. materials diversities, machine specification, varied sizes of workpiece and cutting tool properties. For this reason, this work is dedicated to investigating the influence of the RVA and the nominal spindle speed of Denford Router 2600 Pro vertical milling machine on the surface roughness of the Aluminum 5052.

MATERIALS AND METHODS

The materials used in this work were Aluminum 5052 whose Magnesium as its main alloy. Aluminum is used in engineering application due to its novel properties, i.e. high strength-to-

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weight ratio, good machineability, high castability, high recyclability, and good corrosion resistance [18]-[20]. Aluminum 5xxx series are widely applied in building, airplane, automotive and marine industries due to its novel corrosion, weldability and mechanical properties [21],[22]. For the 5xxx Aluminum series, Magnesium creates precipitates mainly at grain boundaries as a highly anodic phase which results in susceptibility to intergranular crack and stress-induced corrosion. The Aluminum 5052 has a yield strength at 90 MPa and an elongation at break at 46 % (Table 1) [23]. Dimension of the workpiece is depicted in Figure 1.

Table 1. Properties of aluminum 5052 used in this work [23]

Property	Value
Hardness	Brinell 47
Ultimate tensile strength	195 MPa
Yield strength	90 MPa
Elongation at break	46%
Young Modulus	69.3 GPa
Shear strength	125 MPa

This study used an experimental method at a CNC vertical milling machine Denford Router 2600 Pro (Figure 2). In this work, a variable frequency drive (VFD) regulated the spindle speed. In the VFD, an analog input received a signal as a voltage signal. The signal sent can be adjusted at the Arduino microcontroller by sending a digital signal using the pulse width modulation (PWM) method (Figures 3 and 4). The signal was then converted into an analog signal from the PWM to a voltage converter so that the VFD can read the analog input signal. This input signal was then translated into the desired spindle speed. An accelerometer read vibrations during the milling process and sent this vibration data via the Arduino Uno R3 as data acquisition to be processed with the Matlab-Simulink software. In addition to the vibration data, surface roughness was measured by using Mitutoyo SJ-301 roughness test. In this research, the RVA varied at 0, 10, 20 and 30 % while the spindle speed varied at 3,000; 5,000 and 9,000 RPM. Caliskan [24] used the RVA 20% in his work. Seguy *et al.* [25] still tolerated the RVA value up to 30 %. Therefore, the RVA values between 0 and 30 % were used in this work. For the controlled variables, the RVF was 0.3 %, depth of cut was 1 mm, feed rate was 50 mm/min. The RVA, depth of cut and feed rate in this work were selected to prevent failure of the cutting tool. The used cutting tool has 3 flutes. Meanwhile, its diameter is 4 mm.

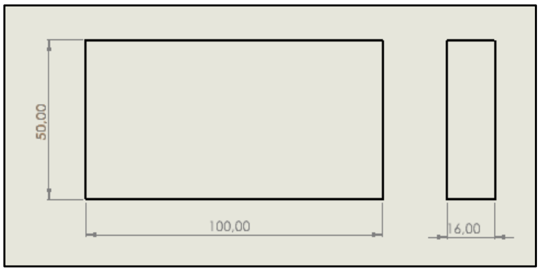

Figure 1. Dimension of workpiece in millimeters

Figure 2. The Denford Router 2600 Pro vertical milling machine

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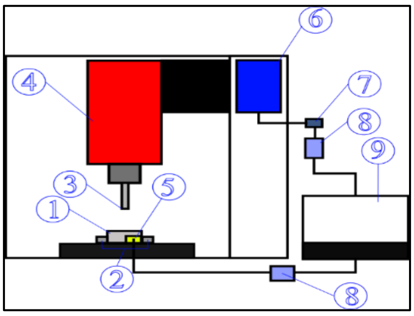

1. Workpiece
2. Vise
3. Chisel
4. Spindle motor
5. DF Robot Accelerometer 6-Axis
6. Optidrive E2
7. PWM to Voltage Converter
8. Arduino Uno R3
9. Laptop

Figure 3. An illustration of the experimental set up

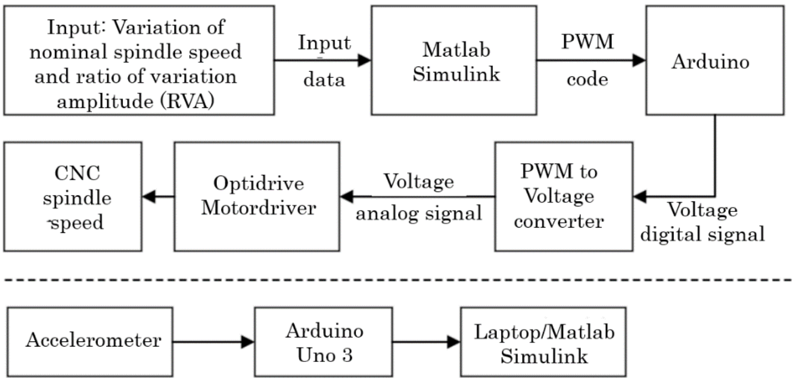

Figure 4. A block diagram for CNC control and data processing

RESULTS AND DISCUSSION

Influence of Spindle Speed and RVA on Vibration

Initially, the influence of spindle speed and RVA on vibration was investigated. Figure 5 depicts the influence of varied RVA at 0, 10, 20 and 30% when the spindle speed was 3,000 RPM. Unlike for the RVA 0 %, the spindle speed fluctuates when RVA variations were applied. The actual spindle speed depends on the set-up value and the corresponding RVA. For example, the actual spindle speed varied between 2,700 and 3,300 RPM when the spindle speed was set at 3,000 and the RVA 10%. The peak and valley measured from the nominal spindle speed setting depend on the RVA variations. For example, the distance between peak and valley from the nominal spindle speed setting is ± 350 RPM for the RVA 10 %.

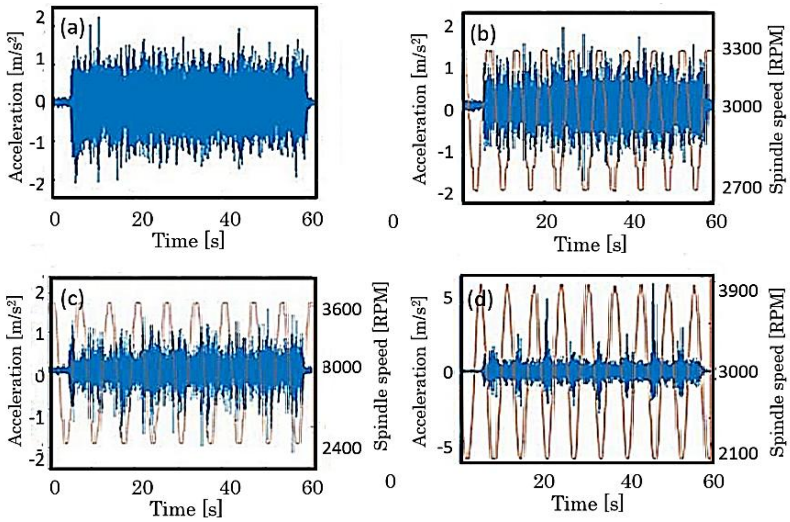

Figure 5. Influence of RVA on vibration at a constant nominal spindle speed 3,000 RPM: a) RVA 0%, b) RVA 10%, c) RVA 20%, d) RVA 30 %

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For the RVA 0%, the vibration signal fluctuated from -2 to 2 m/s^2. When the RVA was 10 and 20 %, most of the vibration fluctuated between -1 and 1 m/s^2. However, vibration fluctuated more significantly for the case of RVA 30%, i.e. the vibration signal fluctuated from -3 to 3 m/s^2 for a particular time period. Ding *et al.* [26] outlined that an increase of vibration, which leads to system instability, occurs when the RVA surpasses the spindle speed limit. This may explain the higher vibration amplitude for the RVA 30 % in this current work. Figure 6 exhibits the influence of spindle speed on vibration for a constant RVA 20 %. For the spindle speed 5,000 RPM, the vibration fluctuated less than that of 3,000 and 9,000 RPM. For a low spindle speed, i.e. at 3,000 RPM in this research, an increase of feed rate lead to a higher vibration. Unlike the cases of 3,000 and 9,000 RPM, the vibration for 5,000 RPM never achieved 2 m/s^2. Due to this low vibration fluctuation, the spindle speed at 5,000 RPM may result in better surface roughness compared to 3,000 and 9,000 RPM.

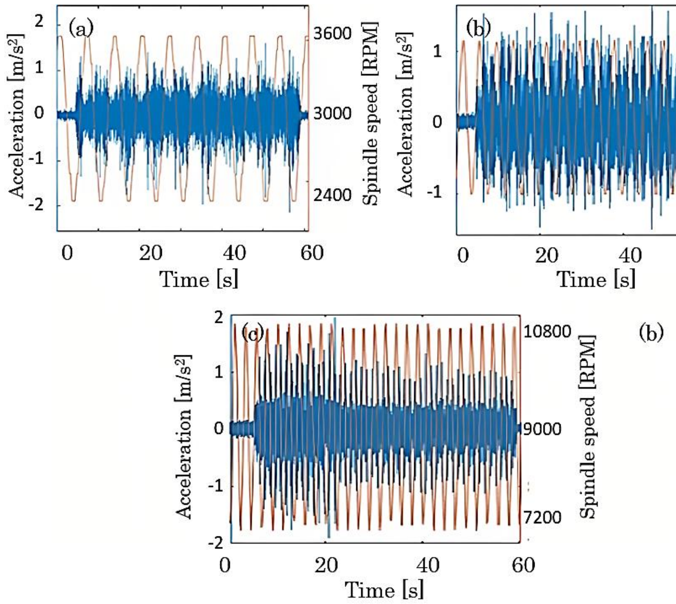

Figure 6. Influence of nominal spindle speed on vibration at a constant RVA 20 %: a) 3,000 RPM, b) 5,000 RM, c) 9,000 RPM

Influence of Spindle Speed and RVA on Surface Roughness

Table 2 and Figures 7-10 show the result of surface roughness measurement for all spindle speeds and RVA variations. The surface roughness properties outlined in this work are roughness average (Ra), root mean square average of the profile heights over the evaluation length (Rq), average maximum height of the profile (Rz), maximum profile peak height (Rp) and maximum profile valley depth (Rv). The evaluation length and cut-off for all cases were 1.00 mm and 0.25 mm, respectively. In addition, number of peaks and valleys over the evaluation length are also outlined. For the spindle speed of 3,000 RPM, the RVA 0 and 20% resulted in a poor surface roughness. As explained in the previous chapter, higher vibration occurs for a low spindle speed. This vibration worsens the surface condition. It can be observed that for the case RVA 0%, increasing spindle speed from 3,000 RPM to 5,000 RPM and 9,000 RPM decreased all parameters of surface roughness, i.e. Ra, Rq, Rz, Rp and Rv. For the case of RVA 20% and the nominal spindle speeds of 5,000 and 9,000 RPM, the Ra, Rq, Rz, and Rp achieved the lowest value. As depicted in Figure 4, the RVA 20 % generated less vibration which then contributed to a better surface roughness. Subsequently, the surface roughness worsened when the RVA increases to 30%. Based on these data, it can be concluded that the RVA 20 % and the spindle speed of 5,000 and 9,000 RPM generated the best surface condition. Increasing spindle speed from 5,000 RPM to 9,000 RPM only slightly changed the surface roughness parameters for the case RVA 20 %.

The best RVA at 20 % in this work slightly differs from Seguy *et al.* [25] where they still tolerated the RVA value up to 30 %. Meanwhile, the number of peaks and valleys in the evaluated sample length, which shows the roughness frequency in the corresponding evaluated length, increased with increasing RVA for all spindle speed cases. However, number of peaks did not significantly

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differ for the spindle speeds of 5,000 and 9,000 RPM. The best RVA in this work at 20 % may differ to other works since every vertical milling machine has its own properties, i.e. a clamping force to the cutting tool, an axis linearity between spindle and cutting tool, a vibration damping system, etc. The discrepancy may exist also due to different cutting tool used since each cutting tool has its own value for hardness, elasticity modulus, yield point, etc.

Table 2. Result of surface roughness measurement for all nominal spindle speed and RVA variations

Spindle speed	RVA	Ra	Rq	Rz	Rp	Rv	Number of	
				[µm]			Peak	Valley
3,000 RPM	0%	5.273	6.752	36.623	20.663	15.960	6	6
	10%	2.725	3.383	18.969	9.369	9.600	9	8
	20%	2.526	3.009	15.447	8.629	6.818	10	10
	30%	1.443	1.708	8.933	4.403	4.531	10	9
5,000 RPM	0%	2.807	3.626	20.582	8.800	11.782	9	9
	10%	2.630	3.172	12.597	6.262	6.335	11	10
	20%	1.200	1.490	7.770	3.489	4.281	12	11
	30%	1.937	2.438	13.834	6.506	7.328	10	10
9,000 RPM	0%	1.467	1.823	7.982	4.277	3.705	10	10
	10%	2.114	2.464	10.481	5.260	5.221	9	10
	20%	1.290	1.611	8.600	3.542	5.057	12	11
	30%	1.577	2.400	13.743	10.835	2.908	11	12

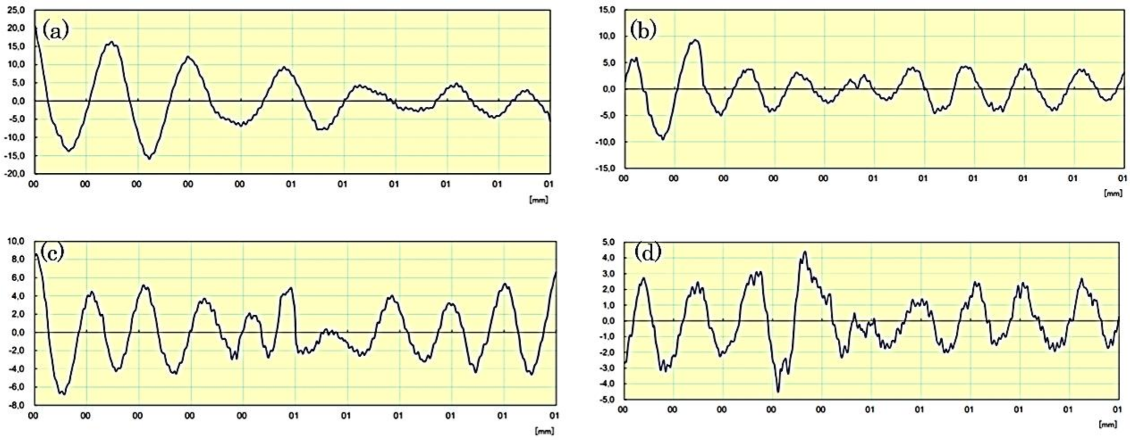

Figure 7. Surface roughness for the spindle speed 3,000 RPM and RVA variations: a) RVA 0 %, b) RVA 10 %, c) RVA 2 0%, d) RVA 30 %
(Y-axis: surface roughness, X-axis: the evaluation length from 0 to 1 mm)

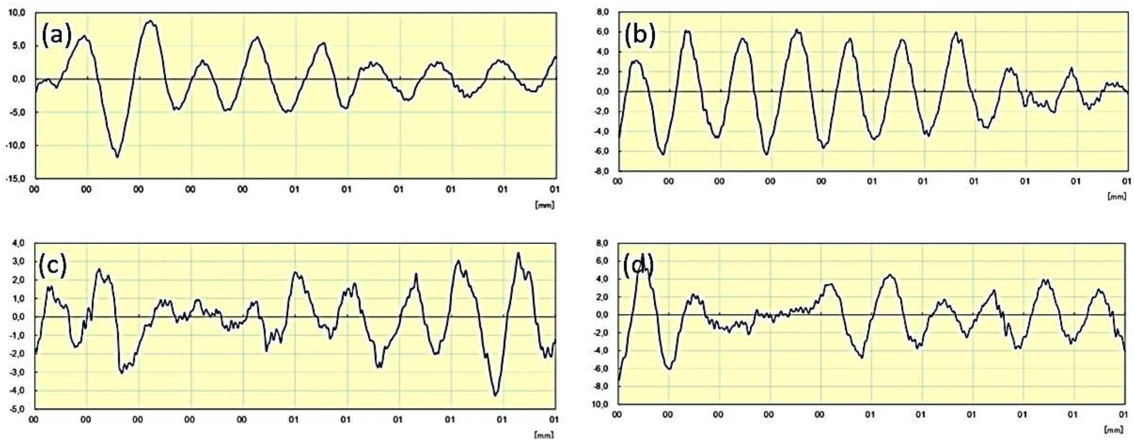

Figure 8. Surface roughness for the spindle speed 5,000 RPM and RVA variations: a) RVA 0%, b) RVA 10 %, c) RVA 20 %, d) RVA 30 %
(Y-axis: surface roughness, X-axis: the evaluation length from 0 to 1 mm)

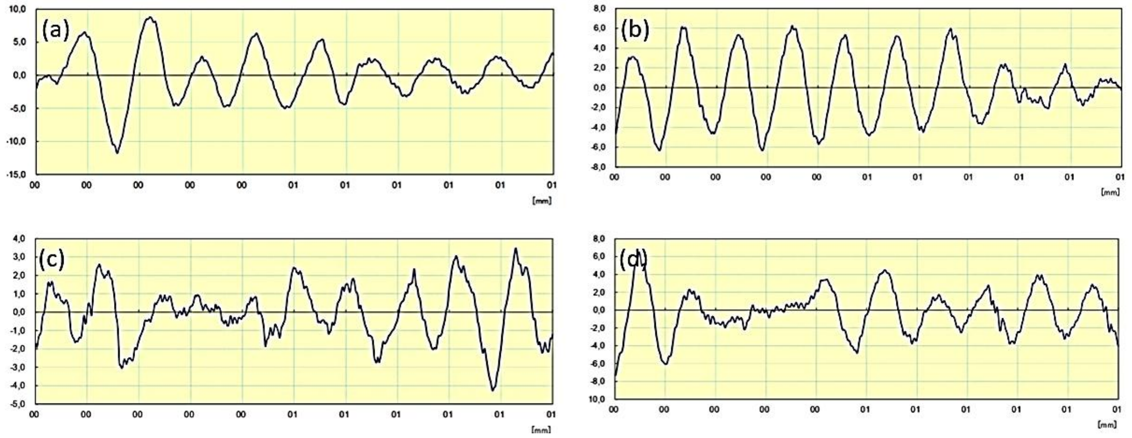

Figure 9. Surface roughness for the spindle speed 9,000 RPM and RVA variations: a) RVA 0 %, b) RVA 10 %, c) RVA 20 %, d) RVA 30 %
(Y-axis: surface roughness, X-axis: the evaluation length from 0 to 1 mm)

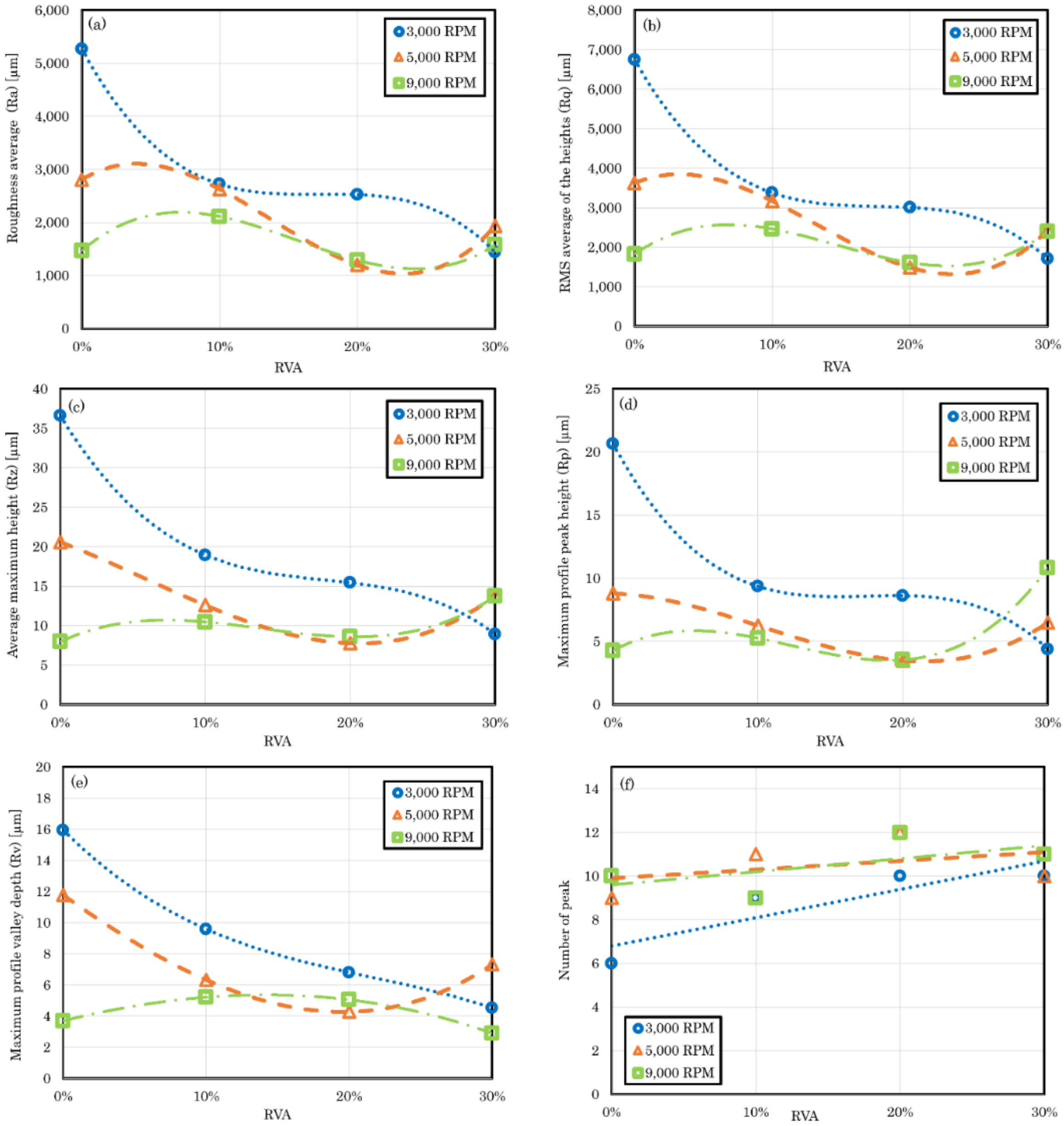

Figure 10. Influence of spindle speed and RVA variation on surface roughness parameters: a) Ra, b) Rq, c) Rz, d) Rp, e) Rv, f) Number of peaks

For the case of spindle speed 3,000 RPM, the surface roughness continually decreased with increasing RVA. For the spindle speeds of 5,000 RPM and 9,000 RPM, the lowest surface roughness also occurred for the RVA 20%. For these spindle speed, the surface roughness worsened when the RVA increases to 30%. Unlike the case of spindle speed 3,000 RPM, the surface roughness for the spindle speeds 5,000 and 9,000 RPM showed a sinusoidal value with an increasing RVA. For this sinusoidal case, the amplitude at 9,000 RPM was higher than that of 5,000 RPM. Although the RVA can result in different surface roughness, the RVA is not the only parameter to generate low surface roughness. This finding slightly differs from Alberteli, *et al.* [27] since they reported that the RVA is effective in controlling the surface roughness and neglecting the influence of the spindle speed.

This work shows that the spindle speed strongly influenced the surface roughness. At a lower spindle speed, the centrifugal force of the cutting tool is lower compared than at a higher spindle speed due to a lower angular speed of the cutting tool (ω) which equals to the spindle speed since both share the similar rotation axis (eq. 1). The effect of angular speed of the cutting tool is strong due to the quadratic role in determining the centrifugal force (Fc). In addition, the centrifugal force of the cutting tool is also influenced by the mass of the cutting tool (m) and the diameter of the cutting tool (d). The centrifugal force of the cutting tool is an important factor in the milling process.

$$Fc = m\,\omega^2\,(d/2) \qquad (1)$$

The discrepancy between Alberteli, *et al.*[8] and this work could also be due to discrepancies on machine specification, materials properties and cutting tool properties. As an example, a strong and hard cutting tool experiences no difficulties when used for any materials with a high hardness and a high yield point, unlike a low-quality cutting tool. At last, the machine condition is also a very important factor since many works in this topic are based on the experimental research at a particular milling machine. Predictive and preventive maintenances are therefore substantial to achieve a high overall effective equipment (OEE) value of the milling machine [28], since a bad maintenance schedule of milling machine can increase the chatter.

CONCLUSION

A CNC-based machining has been widely used due to its advantages, i.e. enhanced precision, quality, productivity, materials and energy efficiency as well as machining ability of complex geometries. However, challenges remain. Of these challenges, chatter is one substantial challenge since it can decrease the service life of the machine, decrease product quality. In this work, an effort to minimize chatter is worked out by varying RVA and nominal spindle speed. The RVA varied between 0, 10, 20 and 30 %. The nominal spindle speed was varied at 3,000; 5,000 and 9,000 RPM. The experiment shows that the best RVA for the particular Denford Router 2600 Pro vertical milling machine is 20%. Meanwhile, vibration analysis and the result of surface roughness measurement show that the appropriate nominal spindle speeds are 5,000 and 9,000 RPM. The vibration analysis and measurement of surface roughness for both speeds do not differ significantly. However, the result of this work may differ from other machines since every vertical milling machine has its own properties, i.e. a clamping force to cutting tool, an axis linearity between spindle and cutting tool, a vibration damping system, etc. The discrepancy may also exist due to different cutting tools used since each cutting tool has its own value for hardness, elasticity modulus, yield point, etc.

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REFFERENCES

[1] Fortune business inside, CNC (Computer Numerical Control) machine market size, share & industry analysis, https://www.fortunebusinessinsights.com/industry-reports/computer-numerical-controls-cnc-machine-tools-market-101707, retrieved in May 2025

[2] C. Kulkarni and G. Bagale "Defect identification in CNC manufactured products and their control measure", *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 6, no. 7, 2017, doi:10.15680/IJIRSET.2017.0607169

[3] A. Basit, N.B. Khan, S. Ali, and R. Muhammad, "Chatter detection and suppression in machining processes: A comprehensive analysis", *International Journal on Interactive Design and Manufacturing*, vol. 18, no. 6, pp. 1-21, 2024, doi:10.1007/s12008-023-01716-8

[4] Y. Altintas and M. Weck, "Chatter stability of metal cutting and grinding", *CIRP Annals Manufacture Technology*, vol. 53, no. 2, pp. 619–642, 2004, doi: 10.1016/S0007-8506(07)60032-8

[5] G. Quintana and J. Ciurana, "Chatter in machining processes: A review", *International Journal of Machine Tools and Manufacture*, vol. 51, no. 5, pp. 363–376, 2011, doi: 10.1016/j.ijmachtools.2011.01.001

[6] B. Liu, C. Liu, X. Yu, Y. Zhou, and D. Wang, "Prediction, detection, and suppression of regenerative chatter in milling", *Advances in Mechanical Engineering*, vol. 14, no. 10, pp. 1-26, 2022, doi: 10.1177/168781322211297

[7] D. Longyang, Y. Sun, and Z. Xiong, "Online chatter suppression in turning by adaptive amplitude modulation of spindle speed variation," *Journal of Manufacturing Science and Engineering*, vol. 140, no. 2, pp. 1-11, 2018, doi: 10.1115/1.4041248

[8] C. Wang, X. Zhang, Y. Liu, H. Cao, H., and X. Chen, "Stiffness variation method for milling chatter suppression via piezoelectric stack actuators", *International Journal of Machine Tools and Manufacture*, vol. 124, no. 1, pp. 53–66, 2018, doi: 10.1016/j.ijmachtools.2017.10.002

[9] P. Albertelli, S. Musletti, M. Leonesio, G. Bianchi, and M. Monno, "Spindle speed variation in turning: Technological effectiveness and applicability to real industrial cases", *The International Journal of Advanced Manufacturing Technology*, vol. 62, pp. 59–67, 2012, doi: 10.1007/s00170-011-3790-8

[10] S. Seguy, T. Insperger, L. Arnaud, G. Dessein, and G. Peigné, "On the stability of high-speed milling with spindle speed variation", *The International Journal of Advanced Manufacturing Technology*, vol. 48, pp. 883–895, 2010, doi:10.1007/s00170-009-2336-9

[11] M. Zatarin, I. Bediaga, J. Munoa, and R. Lizarralde, "Stability of milling processes with continuous spindle speed variation: Analysis in the frequency and time domains, and experimental correlation", *CIRP Ann*, vol. 57, no. 1, pp. 379–384, 2008, doi: 10.1016/j.cirp. 2008.03.067

[12] M. Leonesio, "Spindle speed variation in turning: technological effectiveness and applicability to real industrial cases", *The International Journal of Advanced Manufacturing Technology*, vol. 62, no. 1, pp. 59–67, 2012, doi: 10.1007/S00170-011-3790-8

[13] X. Dong and W. Zhang, "Stability analysis in milling of the thin walled part considering multiple variables of manufacturing systems", *The International Journal of Advanced Manufacturing Technology*, vol. 89, no. 1-4, pp. 515–527, 2017, doi: 10.1007/s00170-016-9072-8

[14] X. Dong, W. Zhang, and S. Deng, "The reconstruction of a [1semi-discretization method for milling stability prediction based on Shannon standard orthogonal basis," *The International Journal of Advanced Manufacturing Technology*, vol. 85, no. 5-8, pp. 1501–1511, 2016, doi: 10.1007/s00170-015-7719-5

[15] L. Shujie and Z. Yang, "Stability of milling process with variable spindle speed using Runge–Kutta-based complete method", *Mathematical Problems in Engineering*, pp. 1-10, 2021, doi: 10.1155/2021/6672513

[16] Y. Ding, X. J. Zhang, and H. Ding, "A Legendre polynomials based method for stability

analysis of milling processes", *Journal of Vibration and Acoustics*, vol. 137, no. 2, pp. 1-7, 2015, doi: 10.1115/1.4029460

[17] C. Qin, J. Tao, and C. Liu, "Stability analysis for milling operations using an Adams-Simpson-based method", *The International Journal of Advanced Manufacturing Technology*, vol. 92, no. 1–4, pp. 969–979, 2017, doi: 10.1007/s00170-017-0186-4

[18] V.Y. Risonarta, J. Anggono, and G.R. Aditya, "The influence of iron concentration on the mechanical properties of A356 Al alloy for car rims application", *Rekayasa Mesin*, vol. 11, no. 1, pp. 61-68, 2020, doi: 10.21776/ub.jrm.2020.011.01.7

[19] P.A. Soetjipto, J. Anggono, and V.Y. Risonarta, "Studi pengaruh cat serta pemisahan tutup dan badan kaleng minuman dalam proses peleburan pada kadar Aluminum", Bachelor thesis, Petra Christian University, Surabaya, Indonesia, 2017

[20] W. Suprapto, V.Y. Risonarta, and A.S. Widodo, "Investigation of microstructure and corrosion resistance of Silumin after Nickel and Copper addition", *EUREKA: Physics & Engineering*, vol. 21, no. 3, pp. 137-147, 2024, doi: 10.21303/2461-4262.2024.003086

[21] A. V. Jebaraj, K.V.V. Aditya, T. S. Kumar, L. Ajaykumar, and C.R. Deepak, "Mechanical and corrosion behaviour of aluminum alloy 5083 and its weldment for marine applications", *Materials Today: Proceeding*, vol. 22, no. 4, pp. 1470-1478, 2020, doi: 10.1016/j.matpr.2020.01.505

[22] C. R. Song, B. X. Dong, S. Y., Zhang, *et al.*, "Recent progress of Al–Mg alloys: Forming and preparation process, microstructure manipulation and application", *Journal of Materials Research and Technology*, vol. 31, no. July–August, pp. 3255-3286, 2024, doi: 10.1016/j.jmrt.2024.07.051

[23] Premiumalu, 5082 Aluminum Alloy, https://premiumalu.com/product/5082-aluminum-alloy/, retrieved in May 2025

[24] H. Caliskan, "Real-time milling chatter detection and control with axis encoder feedback and spindle speed manipulation", *Journal of Manufacture and Materials Processing*, vol. 8, no. 4, pp. 1-21, 2024, https://doi.org/10.3390/jmmp8040173

[25] S. Seguy, G. Dessein, L. Arnaud, and T. Insperger, "Control of chatter by spindle speed variation in high-speed milling", *Advanced Materials Research,* vol. 112, no. 5, pp. 179-186, 2010, doi: 10.4028/www.scientific.net/AMR.112.179

[26] L. Ding, Y. Sun, and Z. Xiong, "Online chatter suppression in turning by adaptive amplitude modulation of spindle speed variation", *Journal of Manufacturing Science and Engineering*, vol. 140, no. 12, pp. 1-14, 2018, doi: 10.1115/1.4041248

[27] P. Albertellia, V. Mussib, C. Ravasioc, and M. Monnoa, "An experimental investigation of the effects of spindle speed variation on tool wear in turning", *Procedia CIRP*, vol. 4, pp. 29-34, 2012, doi: 10.1016/j.procir.2012.0.006

[28] V. Y. Risonarta and A.K. Wardhani, "Increasing profitability of a manufacturing company by using the total productive maintenance approach: A review", *International Journal of Mechanical Engineering and Application,* vol. 4, no.1, pp. 39-50, 2023, doi: 10.21776/MECHTA.2023.004.01.5