Influence of Lubrication on Vibration Response and Surface Roughness in Milling of Aluminum 6061

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Influence of Lubrication on Vibration Response and Surface Roughness in Milling of Aluminum 6061

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Abstract: Aluminum is used widely for components of renewable energy, such as wind and hydro turbines. Some of these components require a milling process to improve surface quality. This research presented the influence of lubrication on vibration and surface roughness in the milling process. The first step, the modal parameters data were obtained by the impulse response method using a hammering test with an impulse hammer, then the milling tests experiment were conducted in three different cutting conditions i.e. dry cutting, wet cutting with coolant and oil. The three-axis accelerometer was used to collect acceleration signals of milling test. The collected acceleration signals then were analyzed using Fast Fourier Transform (FFT) to first transform the signals into frequency domain and after that more phenomenon of the milling process in frequency domain were analyzed. Then, the surface roughness was measured using a surface roughness tester. The results showed that the amplitude of signal is lower in milling with lubricant than dry cutting. The cutting condition was stable in wet cutting for both types of lubricant while the chatter occurs in dry cutting. Then, the surface roughness for wet cutting is better than dry cutting and the best of roughness is wet cutting with lubricant of coolant in this experiment.

Keywords: Lubrication; Milling Process; Aluminum; Vibration Response; Surface Roughness

1. Introduction

Based on the General National Energy Plan, Indonesia has commitment to makes an energy transition towards new and renewable energy. The target of renewable energy implementation in Indonesia based on the General National Energy Plan is 25% of the total energy demand in Indonesia in 2025, increasing to 35% in 2050[1,2]. Indonesia has a potential energy mix from renewable energy to wind energy and hydro energy power generation. Indonesia has applied hydro energy for renewable energy mix with a value of 17.8% in 2018[3]. However, it still can be improved, which has extensive potential resources from the current capacity. Wind energy also has a high potential to be applied in Indonesia. Wind energy application is still low at 0,1% of the total energy used in 2018. Besides, the potential for wind energy and solar application is much greater than what has been applied at this time and can still be improved further[4].

Applying wind and hydro energy technology requires a precision milling process to produce suitable components. In the wind turbine and hydro energy components, the results of the milling process with smooth surface roughness are very necessary because it will affect the turbine performance[5]. One of the materials used for components of wind turbines and hydro turbines is aluminum alloy[6–8]. It is one of the materials that are easy to machines with a relatively lightweight[9,10]. Aluminum 6061 and Titanium 6Al-4V are usually used as material for gas turbines and has perform life prediction with good result[11]. Furthermore, aluminum 6061 is recommended as material for wind turbine edges since it has excellent erosion resistance, durable, high strength-to-weight ratio, and cannot react to air[12].

The milling process will meet the problem of excessive vibration or called chatter. The chatter that arises will cause productivity and quality to decline[13]. It causes the worst surface roughness, which will interfere with the function of the component[5]. In general, excessive vibration is a very dangerous phenomenon that also leads to tool wear[14]. There are several influencing parameters to avoid large vibrations in the milling, such as depth of cut (DoC), spindle speed, feed rate, lubrication, etc. It is significant to research the effect of changing these parameters[15].

From several studies that have been carried out, lubrication is one of the parameters that affect the roughness of the workpiece. Lubrication needs to diminish wear and excessive friction and also significantly affects the surface roughness of the milling process[16]. Lubrication in the milling process has a positive impact on preventing excessive vibration or chatter. It will also affect surface roughness results and dimensional accuracy[17]. To mitigate excessive vibration problems, machinists usually execute the operation in the milling process with conservative process parameters, such as reducing feed rate, cutting depth, and cutting width[18]. However, it will decrease the material removal rate, leading to a longer time and a less efficient milling process[19].

For monitoring milling operations based on spectral analysis, Fast Fourier Transform (FFT) can be used where this method transforms vibration signals in the time domain into signals in the frequency domain[20] FFT could be utilized to analyze cutting force signals that are used to detect chatter[21]. FFT is employed to analyze sound signals, which are obtained during the machining process[22]. FFT is also used to identify chatter vibration which uses acceleration signals[23,24].

This research compares several lubrication methods and various radial depths of cut to examine their effect on vibration and surface roughness in the milling process of aluminum 6061. This has several processes, firstly, we execute hammering tests to obtain modal parameters of workpieces. Next, we carry out a milling experiment on the workpieces which has set the milling conditions, dry and wet conditions with soluble oil and oil. This process is recorded by a 3-axis accelerometer and data storage acquisition then processed with FFT. To compare the roughness surface for each milling condition, we measure the machined surface using a roughness tester and take 100 times magnification photographs. Thus, we can conclude from those data, the influence of lubrication on vibration response and surface roughness in the milling of aluminum 6061. This research is conducted to find the relation between milling condition, vibration response, and surface roughness.

2. Methodology

2.1 Modal Parameters Using FRF

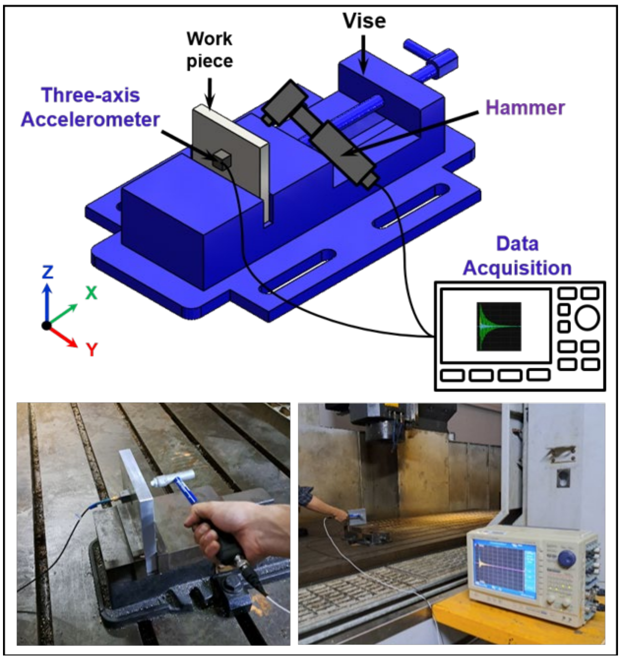


Fig. 1: Hammering Test Set Up

The impulse hammering test was carried out to collects the modal parameters of workpieces such as natural frequency, stiffness, and damping ratio. **Fig. 1** showed the illustration and the photograph of hammering test in this experiment, the hammer hit a workpiece in the X-axis, Y-axis, and Z-axis direction and the three-axis accelerometer sensor sticks on the workpiece. The hammering test is repeated three times in every axis direction. The data storage acquisition Yokogawa DL750 was used to collect the impulse force and the acceleration signals[23,25,26]. The sampling rate of data storage acquisition was set at 200 kHz. In this experiment, the type of hammer was Dytran 5800B3, and the three-axis accelerometer sensor was Dytran 3413A2[27,28].

The results of impulse force and the acceleration signals can be constructed to be a frequency response function (FRF) [29,30]. The FRF can be expressed as :

$$Hij\,(f) = \sum_{r=1}^{N} \frac{\varphi ir\ \varphi jr}{k_r(1-\lambda_r{}^2 + j2\xi_r\lambda_r)} \qquad (1)$$

Where K_r, ξ_r, and φ_r are the stiffness, damping ratio, and mode shape of the r-th mode, $\lambda_r = f/f_r$ and f_r is the natural frequency of the r-th mode. The natural frequency can be got as:

$$f_n = f_f \qquad (2)$$

Where f_f is the frequency at point f in the **Fig. 2**, and the damping ratio ξ could be expressed below:

$$\xi = (f_e - f_d)/2f_f \qquad (3)$$

Where f_d and f_e are the frequency at the amid points, between points d and e, the stiffness k could be expressed below :

$$k = 1/2\xi H_{if} \qquad (4)$$

Where H_{if} is the imaginary graph value at point f, the minimum value on the imaginary frequency function curve.

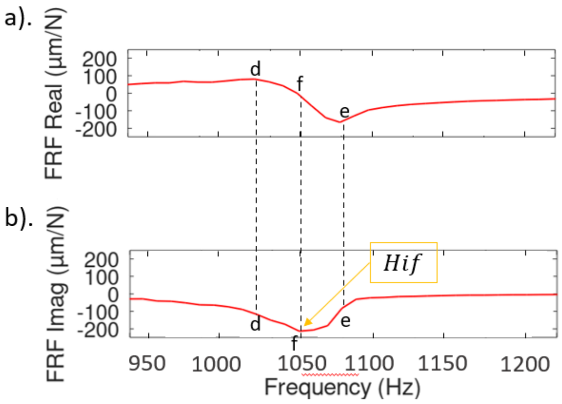


Fig. 2: The FRF on X-axis;
a) Real and b) Imaginary of a workpiece

In the hammering tests experiment, the values of FRF were determined on X-axis, Y-axis, and Z-axis direction, and then the value with the lowest stiffness was observed. The results showed that the lowest value of stiffness was found on the X-axis direction as can be seen in **Fig. 2**. Furthermore, the modal parameters such as stiffness, natural frequency, and damping ratio can be calculated using the curve of FRF. The values of modal parameters were listed in Table 1.

Table 1. Modal Parameters

Natural Frequency $f\ (Hz)$	Stiffness $k\ (\frac{N}{\mu m})$	Damping Ratio ζ (%)
1050	0,095	0,024

2.2 Fast Fourier Transform

The FFT is used to analyze the vibration response in the feature of vibration in the frequency domain. It will use to determine milling states. For the defined signal x(t) in a sampling period T, with the data length is N, the FFT is expressed below[30) :

$$X(n) = \sum_{j=1}^{N} x(j) e^{-i2\pi(n-1)\frac{j-1}{j}} \qquad (5)$$

FFT analysis was carried out to detect the chatter frequency (f_c), tooth-passing (f_T), natural frequency (f_n), and its harmonics are shown in **Fig. 6**, **Fig. 7**, and **Fig. 8**. For the tooth-passing frequency was calculated as follows[25,31) :

$$f_T = \frac{n}{60} Nt \qquad (6)$$

Where n and N_T are the spindle rotation and the number of flutes. The natural frequency is obtained from FRF.

2.3 Lubrication in Milling Process

Cutting fluid is used to improve milling capabilities so that the process is more efficient and better than without cutting fluid. Increased efficiency in milling will increase tool life, increase surface roughness, increase milling accuracy, reduce cutting forces, and reduce vibration in milling[14,31). Low vibration in the milling process will have a positive impact because vibration in the milling process will cause tool wear and worst surface roughness[14,32).

In this experiment, the influence of lubrication on vibration response and surface roughness in milling process was investigated. So that we choose the cutting conditions are dry cutting, wet cutting with coolant, and wet cutting with oil. In our experiment, coolant is a mixture of water and straight-cutting oil by comparison 50:50, or in some cases called soluble oil[16). The properties of coolant as shown in table 2. Then, the oil we used in this experiment is engine lubrication of SAE 0W-20 fully synthetic motor oil.

Table 2. Coolant Properties – Dromus Oil

Appearance	Dark Amber, Clear
Specific Gravity @20ºC	0.92
PH @5% Emulsion	8.9
Emulsion Type	Fine milky emulsion
Corrosion Test	30/1

2.4 Experimental Setup

Experiments were carried out on the KAFO K4122 CNC machine (dimensions of 4100 in length, 2200 mm in width, and 1000 mm in height) using Aluminum material to investigate the effect of lubrication and radial depth to vibration response and machined surface roughness of milling process. The type of aluminum used is 6061, which is one of the most commonly used due to its lightweight, durable, and functional properties[33). This material can also be used for wind turbine components[6,7) and hydro turbine components materials[8,10). A 12 mm of diameter end-mill with 4 flutes was used, the specifications related to the specifications of the tools and the milling conditions used are shown in Table 3 and 4 below.

Table 3. Tool Parameters

Tools Parameters	Value
Diameter of Tool	12 mm
Number of Flutes	4
Helix Angle	30 degree
Material	Carbide
Tool Length	90 mm
Overhang	45 mm

Table 4. Milling Conditions

Cutting Conditions	Value
Spindle Rotation ***n*** (min^{-1})	2000
Feed per Tooth f_z	0.066 mm/tooth
Feed Speed ***f***	500 mm/min
Axial DoC	12 mm
Radial DoC	1 mm, 2 mm, 3 mm

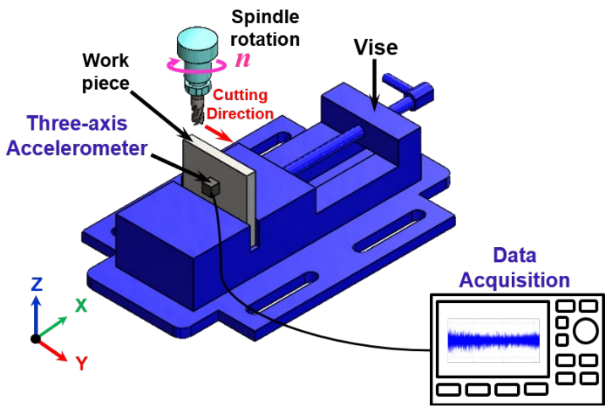


Fig. 3: Milling Test Experiment Setup

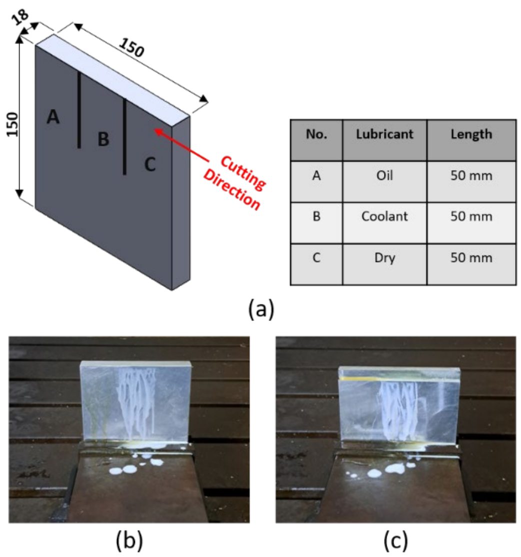


Fig. 4: Workpiece of Aluminum 6061 (a) illustration of lubrication method, (b) before milling, and (c) after milling

The dimension of the workpiece is 150 mm in length, 150 mm in height, and 18 mm in width. The rotation of spindle is clockwise and the direction is displayed in **Fig. 3**. The milling experiments perform continuously from dry cutting to wet cutting. The surface of the workpiece divides into three different lubrication parameters with a length of 50 mm as shown in **Fig. 4**. In this experiment, coolant and oil are rubbed onto the material surface. Then, the milling experiment is repeated three times for each milling condition.

3. Results and Discussion

3.1 Acceleration Signal

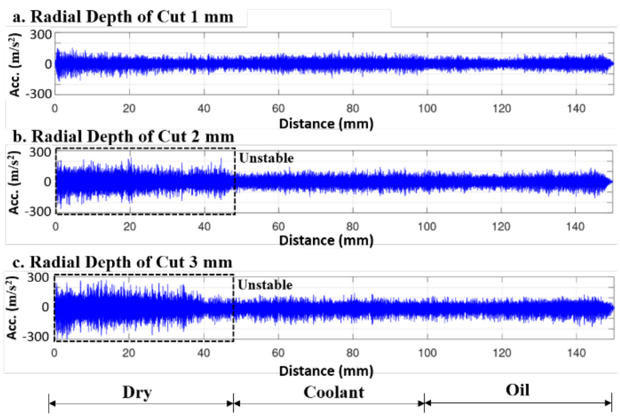


Fig. 5: Acceleration Signal acquired in milling test

As shown in the **Fig. 5**, the acceleration signal in milling test with 1 mm radial DoC has no significant difference. However, there was a significant difference for the 2 mm and 3 mm DoC, the signal amplitude was high in dry cutting but low in wet cutting. For dry cutting, it indicates an unstable condition of vibration. The existence of unstable vibrations will result in chatter. This chatter will cause the milling results to be worst[13,20].

3.2 FFT Spectra

Figs. 6, 7, and 8 show the frequency spectra by FFT for three variations of radial DoC 1 mm, 2 mm, and 3 mm, respectively. The FFT graph can identify the tooth-passing frequency (f_T), natural frequency (f_n), and chatter frequency (f_c). From Eq. 6, the value of tooth passing frequency (f_T) is 133 Hz. Then, the natural frequency can be obtained from the calculation of the FRF graph. The natural frequency f_n is 1050 Hz in this experiment as shown in Table 1.

In the FFT analysis, we separate the signals became three groups of cutting conditions: dry cutting, wet cutting with coolant, and wet cutting with oil. As shown in **Fig. 6**, the tooth-passing frequency, its harmonics, and the natural frequency were identified for DoC cut 1 mm and the amplitude is almost similar for three conditions. However, there is a large difference in amplitude between the dry cutting and wet cutting for DoC 2 mm and 3 mm as shown in **Figs. 7** and **8**. For DoC 2 mm in dry cutting (**Fig. 7**), it is found that the slightly chatter frequency begins to occurs at a frequency of 1000 Hz. Commonly, chatter occurred close to the natural frequency[20,31]. And, the results of FFT spectra showed that the chatter frequency identified before and has a lower amplitude than the natural frequency at 1050 Hz for DoC 2 mm. Furthermore, the chatter frequency amplitude become higher than the natural frequency for DoC 3 mm in dry cutting as shown in **Fig. 8**. Besides, for wet cutting with the same DoC, the chatter frequency was not found.

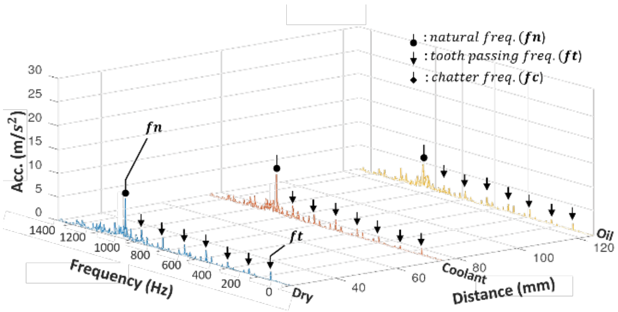


Fig. 6: Frequency spectra by FFT with Radial DoC 1 mm

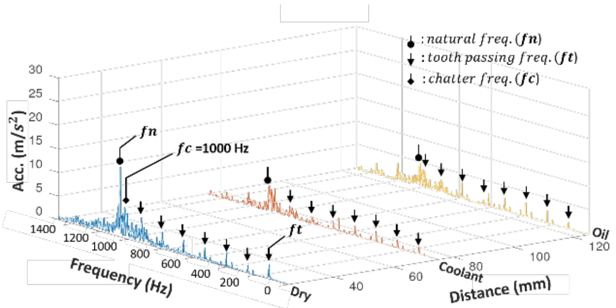


Fig 7: Frequency spectra by FFT with Radial DoC 2 mm

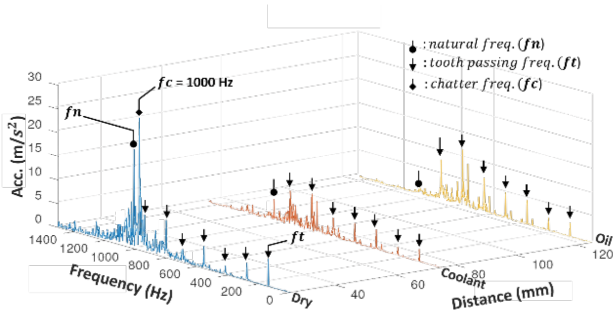
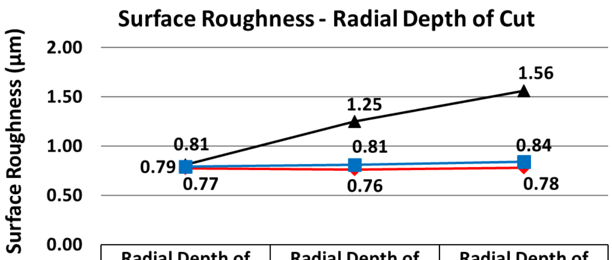


Fig. 8: Frequency spectra by FFT with Radial DoC 3 mm

3.3 Surface Roughness

Fig. 9 showed the roughness of the machined surface for dry cutting and wet cutting with coolant and oil. The surface roughness test is executed with portable surface roughness tester Mitutoyo SJ-301[34,35]. The test is repeated three times for each milling condition. The photograph of the machined surface is taken using Keyence VHX 7000 with 100 times zooming[36,37]. As shown in the **Fig. 9**, the roughness increases with radial DoC for dry cutting while it is almost constant with radial DoC for wet cutting. From these results, roughness in wet cutting tends to be stable than dry cutting. This shows that there is correlation between the increase in chatter frequency amplitude to surface roughness.



	Radial Depth of Cut 1 mm	Radial Depth of Cut 2 mm	Radial Depth of Cut 3 mm
Dry	0.81	1.25	1.56
Coolant	0.77	0.76	0.78
Oil	0.79	0.81	0.84

Fig 9: Surface Roughness of Aluminum Workpiece Surface

Figs. 10, 11, and **12** show the photographs of machined surfaces for aluminum workpieces after the milling process with 100 times magnification. Based on the photograph of the machined surface for Radial DoC 1 mm (**Fig. 10**), the pattern of cutting in the machined surface is nearly uniform and smooth for dry cutting, and wet cutting with coolant and oil. This is a similar trend with surface roughness values as shown in **Fig. 9**. For the Radial DoC 2 mm, the pattern of the machined surface for dry cutting looks rougher compared to wet cutting as shown in **Fig. 11**. The wet cutting with coolant has the best pattern in this experiment. Furthermore, for the Radial DoC 3 mm, the pattern of machined surface in milling under dry cutting shows the roughest surface in this experiment. The pattern of surface in milling under wet milling using coolant looks consistent with the three variations of Radial DoC and corresponds to the roughness values which tend to be stable as shown in **Fig. 9**. Milling process under wet cutting with coolant produces a smoother surface compared to milling under dry cutting[16,31].

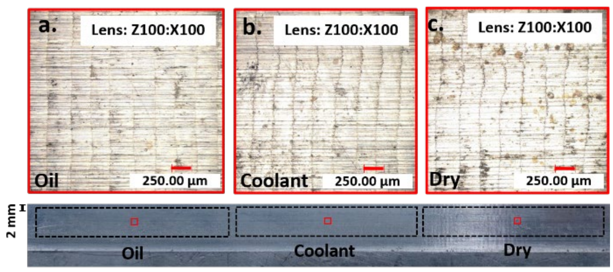


Fig 10: Photographs of Machined Surface for Radial DoC 1mm and 100 Times Magnification Image of the machined surface on (a) Wet Cutting with Oil, (b) Wet Cutting with Coolant, (c) Dry Cutting

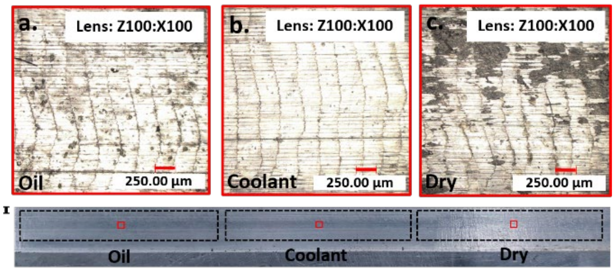


Fig. 11: Photographs of Machined Surface for Radial DoC 2mm and 100 Times Magnification Image of the machined surface on (a) Wet Cutting with Oil, (b) Wet Cutting with Coolant, (c) Dry Cutting

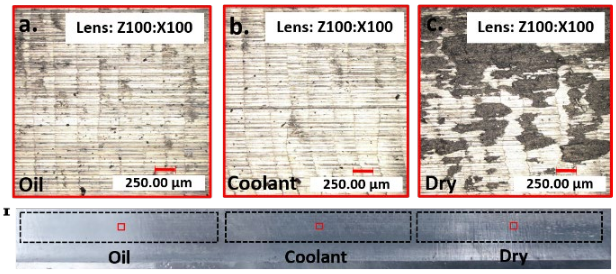


Fig 12: Photographs of Machined Surface for Radial DoC 3mm and 100 Times Magnification Image of the machined surface on (a) Wet Cutting with Oil, (b) Wet Cutting with Coolant, (c) Dry Cutting

4. Conclusion

In this paper, the influence of lubrication on vibration and surface roughness in milling process of aluminum 6061 was analyzed. The amplitude of acceleration signal for dry cutting is higher than wet cutting at every radial depth of cut. Based on vibration analysis by FFT, the chatter frequency occurs for dry cutting at radial depth of cut 2 and 3 mm while for wet cutting no chatter occurs at the same radial depth of cut. The radial depth of cut also affects the vibration, the greater the radial depth of cut causes an increase in vibration. The surface roughness results showed that wet cutting tends to be stable than dry cutting. For dry cutting, the roughness increases with radial depth of cut while for wet cutting it is almost constant with radial depth of cut. The results of the photograph, wet cutting has a better pattern of work surface than dry cutting, and the best of pattern is wet cutting with lubrication using coolant.

We conclude that the lubrication in milling of aluminum 6061 reduces the vibration response both in time and frequency domain, while no chatter detected. The surface roughness produced from wet cutting was smoother than dry cutting for every experiment depth of cut.

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