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Investigation of Vibration in Micromilling with MQL: S/N Ratio Analysis

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Abstract:

Micromilling process equipped with minimum quantity lubrication (MQL) is proven to significantly reduce the cutting temperature during machining and improve the life of the cutting tool. However, undesired vibration known as chatter remains as an unsolved issue in micromilling especially with the presence of MQL. The objective of this research is to present the signal-to-noise (S/N) ratio analysis of the effect of MQL and micromilling parameters towards the vibration in micromilling. High-precision CNC machine tool (DT-110 Mikrotools, Singapore) was used to machine microchannels onto a copper workpiece (C1100) with a 500 µm diameter end milling tool lubricated with MQL system (Fuji-BC Engineering, Japan). Machining parameters spindle speed, depth of cut, oil flow rate, nozzle air pressure, and nozzle direction were experimentedusing Taguchi L16 Orthogonal Array design. The responses were spindle speed frequency (SSF) amplitudes and SSF chatter amplitude which were measured using an accelerometer (Dytran, USA) and a data acquisition system (Graphtec, Japan). From the amplitudes, chatter ratio was calculated and analysed using S/N ratio. The analysis showed that the spindle speed, nozzle direction, and nozzle air pressure have significant effect towards chatter followed by depth of cut and oil flow rate. The optimum parameter suggested by S/N ratio were found to be 20000 rpm spindle speed, 275° nozzle direction, 0.275 MPa nozzle air pressure, 50 µm depth of cut, and 3.75 ml/hr oil flow rate.

***Keywords:** Micromilling, MQL, vibration, chatter,Taguchi, S/N ratio*

I. INTRODUCTION

With the advancement of manufacturing engineering the requirement of precision machining and dimensional accuracy is becoming more important. This eventually made the fabrication of micro products to be greatly relies on the advancement of microfabrication technologies [1-2]. Microfabrication is known as the collection of techniques that is used to fabricate products in micrometer range [3]. In addition, micromilling has been recognized as the most flexible and suitable process. It has been known to have the capabilities of generating wide variety of microstructures [4]. Furthermore, micromilling also has the ability to fabricate parts directly from a three-dimensional (3D) computer-aided design (CAD) model. This gives micromilling a huge advantage of making micro sized prototypes easier and faster [5].

During machining process,the contact between the

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high-speed rotation ofthe cutting tool and the workpiecenormally introduces very high friction at the machining zone. This frictiongeneratedhigh cutting temperature which drastically reduces the lifespan of the cutting tool. In order to overcome this, lubricant is applied during the machining operation [6-7]. The most efficient method known to suitably lubricate micromilling zone is minimum quantity lubrication (MQL). This is because compared to flood lubrication, MQL uses less amount of lubrication fluid. The lubrication mist from the MQL system helps to dissipate the heat produced during the machining which then reduces the temperature at the machining zone [8-10].

Although, it was found that MQL is proven to help inreducing the cutting temperature produced by the friction of the cutting tool and the workpiece during micromilling process. However, MQL does not help in eliminating theuncontrolled vibration during the machining process. It is also known that by selecting the suitable MQL and micromilling parameters, the vibration can be controlledeffectively [11-12].Therefore, the objective of this research experiment is to investigate the effect of the MQL and micromilling parameters towards the vibration produced during the micromilling process of copper.

II. METHODOLOGY

A. Experimental Design

The experiment was conducted in order to collect data on vibration produced during micromilling with the presence of MQL. Taguchi L_{16} orthogonal array was used to design the experiment which consist of 5 factors and 4 levels.The list of controlled and fixed parameters used in this experiment isshown in Table 1.Three MQL parameters oil flow rate, nozzle air pressure, and nozzle direction and two micromilling parameters depth of cut, and spindle speed were selected as the factor in experimental design. This combination resulted in 16 experimental runs as shown in Table 2.

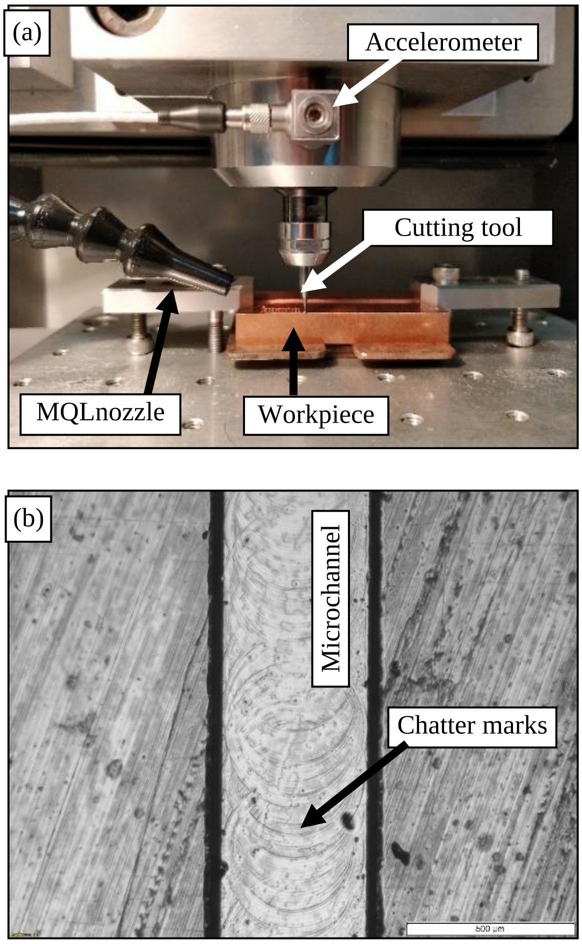


Figure 1. (a) Experimental setup of MQL micromilling and, (b) optical image machined microchannel with chatter marks.

B. Equipment and Workpiece

The workpiece material selected for this experiment was the copper (C1100) and machined using a multi-process CNC machine (DT-110 Mikrotools, Singapore). The workpiece was initially milled using conventional end milling in order to obtain a flat surface of the workpiece which mitigates the unevenness and irregularities while it is being micromilled. Copper is one of the commonly used material in the fabrication of microchannel heat exchanger [13]. A two-flutes tungsten carbide micro end milling tool with the diameter of 500 µm, helix angle of 40° and edge radius of 50 µm was used as the cutting tool. The specification of the cutting tool was selected in order to have longer tool life [14-15], and higher resistivity from chipping [16-17]. The lubricant supplied to the MQL system (Fuji-BC Engineering, Japan) was Bluebe LB-1, which is a vegetable based oil andbiodegradable. Experimental setupis shown in Fig. 1(a).

C. Vibration Data

During the micromilling process, an accelerometer (Dytran, USA) connected to data acquisition system (Graphtec, Japan) was used to measure the vibration produced. The accelerometer was attached onto the high-speed air bearing spindle, Nakanishi ABS-400 (Nakanishi, Japan). After the measurement have been recorded, the analysis of the vibration data was done in a frequency domain graph.Taguchi's "smaller-the-better" signal-to-noise (S/N) ratio approach was used to analyse the results and rank the significance of the parameters and its selected values towards the production of vibration.

III. RESULTS AND DISCUSSIONS

By examining the results of the vibration data in frequency domain, it was seen that the significant frequency occurs at the spindle speed frequency (SSF) and at its harmonics. It was also observed that when comparing the chatter frequency results and optical images of the machined microchannel surface, there were chatter marks left by the cutting tool as shown in Fig. 1(b). Machined microchannel surface with less chatter marks is considered as smooth surface, where as surface with chatter marks is considered as chattered surface. It is also worth to be mentioned that, different chatter marks, were produced by different chatter frequency characteristics.

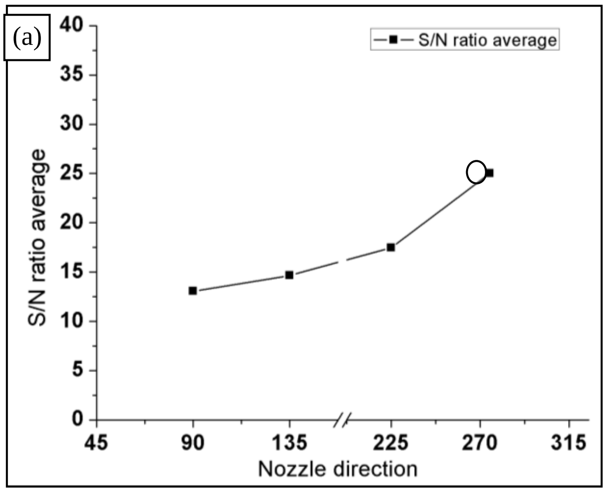
However, the value of the chatter amplitude and SSF amplitude does not accurately reflect the actual severity of the chatter marks produced by the vibration during machining. Thus, a chatter ratio value calculated from the chatter amplitude and SSF amplitude was used to determine the severity and stability of the machining [18]. Calculated chatter ratio is shown in Table 2.

It was found that the higher the S/N ratio value, the better the machining which also means that the chatter produced was reduced. Machined microchannel surface has lesser severity of chatter marks [19]. In order to realise the effect of each of the factor, the averages of S/N ratio of the different level of the factor is calculated and tabulated in Table 2. For easier and simpler viewing, a graph depicting the effect of the MQL and micromilling factors towards chatter marks is shown in Fig. 2 and Fig. 3 respectively.

From the results based in Fig. 2(a) and 2(b), MQL parameter that are highly affecting the chatter marks is the nozzle direction, followed by nozzle air pressure. In order to reduce the chatter marks on the microchannel surface, nozzle direction and nozzle air pressure needs to be set to 270° and 0.275 MPa respectively. This is because that the position of the nozzle at 270° and higher nozzle air pressure will have a higher penetration towards the cutting tool edge which accomplish the actions of cooling and lubrication of the machined surface [20]. Fig. 2(c) shows that oil flow rate is found to be having very low effect towards the chatter marks. Nevertheless, a low setting of oil flow rate resulted in the reduction of vibration during machining process.

Based on the results in Fig. 3(a) and 3(b), it is found that both depth of cut and spindle speed parameters are highly significant towards the chatter marks. Higher depth of cut during machining does reduce the chatter marks. On the other hand, a setting of low spindle speed such as 20000 rpm does reduce the chatter marks. However, using a highest spindle speed such as 50000 rpm also manage to reduce the chatter marks but less significant compared to using spindle speed of 20000 rpm. This is due to the higher spindle speed rotation formed an invisible 'wall' that obstruct the penetration of MQL lubricant towards the cutting tool center [20].

Finally, in order to rank the significance of the parameters towards the chatter marks, the delta of the highest and lowest averages of S/N ratio of each level has been calculated as listed in Table 3.



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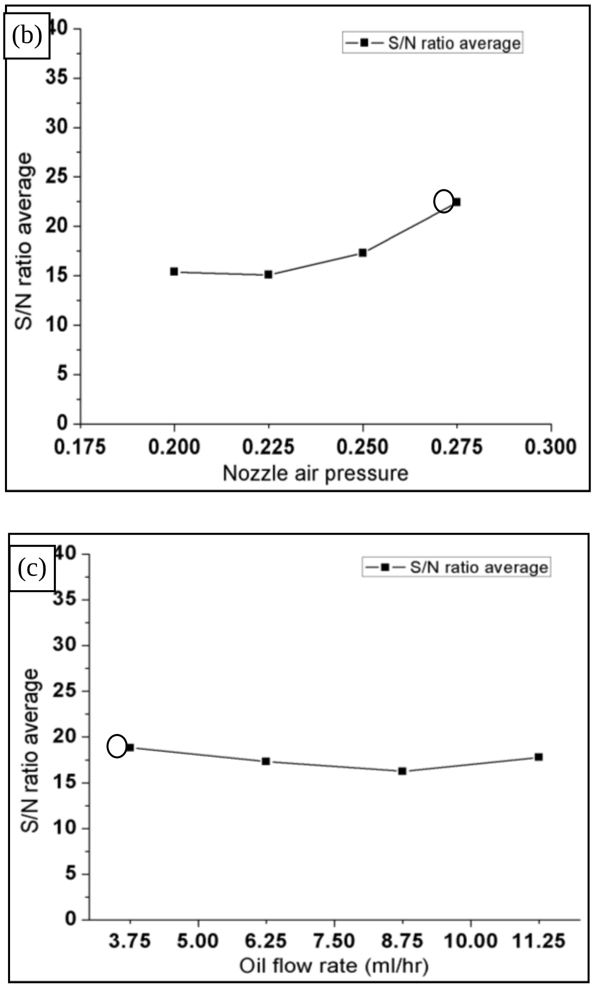

Figure 2. Graph of S/N ratio for MQL parameters (a) nozzle direction, (b) nozzle air pressure, and (c) oil flowrate.

The highest delta shows the most significant parameter which affects the vibration [21]. It was found that by comparing the three MQL parameters, nozzle direction has the highest significant delta compared to nozzle air pressure and oil flow rate. This shows that vibration produced during the machining process can be reduced significantly by changing the positioning of the nozzle direction compared to nozzle air pressure and oil flow rate.

Then, by comparing the remaining two micromilling parameters, depth of cut is found to be more significant towards of vibration compared to spindle speed. Similar results are also shown by the previous researchers [22-23]. By comparing all of the parameters; MQL and micromilling parameters, it was found that depth of cut is the more significant in affecting the vibration during machining process followed by nozzle direction.

On the other hand, it is also seen that the least significant parameter in affecting vibration is the oil flow rate, followed by spindle speed and nozzle air pressure.

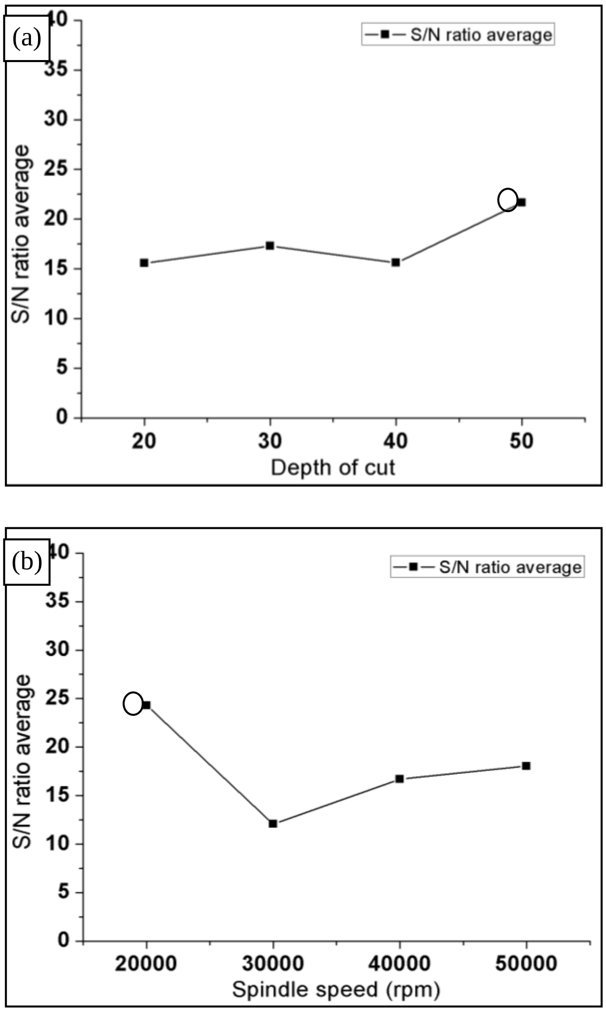

Figure 3. Graph of S/N ratio for micromilling parameters (a) depth of cut and (b) spindle speed

IV. CONCLUSIONS

In this experimental research, the investigation of vibration in micro milling with MQL was performed. S/N ratio was used in analyzing the influences of the MQL and micromilling parameters towards the vibration produced during machining which resulted in chatter marks onto the machined surface. MQL and micromiling parameters such as oil flow rate, nozzle air pressure, nozzle direction, depth of cut, and spindle speed were tested for its significance towards the vibration produced during the machining process. This experimental investigation showed:

1) The severity of the vibration produced during machining can be determined by calculating the

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chatter ratio which is the ratio between the chatter amplitude and the SSF amplitude.

Table 1. Experimental control and fixed parameters

Controlled Parameters		**Experimental Conditions**			
		Level I	**Level II**	**Level III**	**Level IV**
MQL parameters	Oil flow rate (ml/hr)	3.75	6.25	8.75	11.25
	Nozzle air pressure (MPa)	0.200	0.225	0.250	0.275
	Nozzle direction (°)	90	135	225	270
Micro milling parameters	Spindle speed (rpm)	20000	30000	40000	50000
	Depth of cut (µm)	20.0	30.0	40.0	50.0
Fixed Parameters					
Micro milling parameters	Feed rate (mm/min)	15.0			
	Tool overhang (mm)	20.0			
MQL parameters	Nozzle distance (mm)	20.0			

Table 2. Taguchi L_{16} experimental runs and responses (chatter ratio and S/N ratio)

Exp.	**Factors**					**Responses**	
	Oil flow rate (ml/hr)	**Nozzle air pressure (MPa)**	**Nozzle direction (°)**	**Depth of cut (µm)**	**Spindle speed (rpm)**	**Chatter ratio (Chatter amplitude ÷ SSF amplitude)**	**S/N ratio (dB)**
1	3.75	0.200	90	20.0	20000	0.1413	16.997
2	3.75	0.225	135	30.0	30000	0.4095	7.754
3	3.75	0.250	225	40.0	40000	0.1633	15.742
4	3.75	0.275	270	50.0	50000	0.0181	34.861
5	6.25	0.200	135	40.0	50000	0.3202	9.892
6	6.25	0.225	90	50.0	40000	0.2080	13.640
7	6.25	0.250	270	20.0	30000	0.1397	17.096
8	6.25	0.275	225	30.0	20000	0.0370	28.627
9	8.75	0.200	225	50.0	30000	0.2331	12.650
10	8.75	0.225	270	40.0	20000	0.0497	26.075
11	8.75	0.250	90	30.0	50000	0.2876	10.826
12	8.75	0.275	135	20.0	40000	0.1695	15.417
13	11.25	0.200	270	30.0	40000	0.0793	22.016
14	11.25	0.225	225	20.0	50000	0.2274	12.865
15	11.25	0.250	135	50.0	20000	0.0529	25.529
16	11.25	0.275	90	40.0	30000	0.2899	10.756

Table 3. Ranking of S/N ratio mean

Parameters	**S/N Ratio mean**				**Delta**	**Rank**
	Level I	**Level II**	**Level III**	**Level IV**		
Oil flow rate	18.839	17.314	16.242	17.792	2.597	5
Nozzle air pressure	15.389	15.083	17.298	22.415	7.332	3
Nozzle direction	13.055	14.648	17.471	25.012	11.957	2

Spindle speed	15.594	17.306	15.616	21.670	6.076	4
Depth of cut	24.307	12.064	16.704	18.048	12.243	1

2) S/N ratio ranking shows that nozzle direction and depth of cut were the most significant parameter affecting the chatter marks produced, followed by the nozzle air pressure, spindle speed, and oil flow rate.
3) The level of chatter can be minimized if 3.75 ml/hr oil flow rate, 0.275 MPa nozzle air pressure, 270° nozzle direction, 50 µm depth of cut, and 20000 rpm of spindle speed are used.

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