

INVESTIGATION OF VIBRATION IN MICROMILLING WITH MINIMUM QUANTITY LUBRICATION: PARAMETER SELECTION

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Abstract. *Micromilling using minimum quantity lubrication (MQL) is proven to reduce the cutting temperature and improve the cutting tool life. However, vibration remains as one of the critical issues. Thus, the objective of this research is to analyse the vibration produced during the process of micromilling with MQL. A high-precision CNC milling machine DT110 (Mikrotools Inc, Singapore) was used to machine microchannels with end milling tool (500 μm diameter, flat end, two flutes, 5 μm edge radius) on a C1100 copper alloy workpiece. The machining process was lubricated using MQL system (Bluebe FK, Fuji BC, Japan) with biodegradable vegetable-based oil. The parameters were the oil flow rate, nozzle air pressure, nozzle direction, spindle speed and depth of cut. Responses parameters were the spindle speed frequency (SSF) amplitudes and SSF chatter amplitudes. The accelerometer was attached onto the high-speed air bearing spindle (ABS-400, Nakanishi, Japan) installed onto the CNC machine DT110. The measured vibration data was recorded by the DAQ system and analysed using Graphtec GL-7000. This research showed that spindle speed, depth of cut, oil flow rate, nozzle pressure and nozzle direction are found to be influential in generating vibration in micromilling. Whereas, feed rate, tool overhang and nozzle distance are found to be not significant in generation vibration.*

Keywords: *Micromilling, vibration, chatter, design of experiment, MQL*

1. INTRODUCTION

The advancement of manufacturing engineering has increased the importance of precision machining and microfabrication technologies with high dimensional accuracy (Boswell et al., 2017; and Chavoshi and Luo, 2015). Micromilling is the most flexible and suitable process for microfabrication to generate wide variety of microfeatures (Chen et al., 2018). In addition, micromilling also has the ability to produce parts directly from a computer-aided design using multi-axis machining systems. Ultimately, this gives micromilling huge advantage of making micro-sized prototypes easier and also faster (Guckenberger et al., 2015).

In micromilling, the contact between the cutting tool and workpiece produces very high friction and generate high cutting temperature which directly reduces the life of the cutting tool. To overcome this problem, lubrication is applied during the machining to lower the cutting temperature (Koklu and Basmaci, 2017; Vazquez et al., 2015). The most efficient and cost-saving method of lubrication for the micromilling process is the minimum quantity lubrication (MQL) which uses a very small amount of lubrication which is mist-sprayed onto the machining zone (Sharma et al., 2016; Sharma et al., 2015). Whereas flood lubrication in micromilling is proven to be inefficient, increases the overall production cost, and also produces adverse health effect with long exposure of the fluid (Boubekri and Shaikh, 2014).

MQL is found to be proven in reducing the cutting temperature generated by the friction of the cutting tool and workpiece during micromilling process. However, uncontrolled vibration significantly affects the dimensional accuracy of the machined product. In addition, vibration in micromilling is still not fully investigated due to the complex behaviour of MQL mechanism. Hence, the vibration issues in micromilling with the presence of MQL are found to be a critical issue. It is known that by controlling the micromilling and MQL parameters, the vibration can be controlled and reduced (Carou et al., 2016; Guo and Huang, 2017). The objective of this research is to determine the micromilling and MQL parameters that significantly influence the vibration.

2. METHODOLOGY

This research is to identify the process parameters to control the vibration produced in micromilling with MQL. The selected workpiece material and cutting tool to be used in this investigation is copper (C1100) and two-flutes tungsten carbide micro end mill respectively. There are many other parameters to be used as the factors in the experimental design for the vibration investigation. However, to have an efficient experiment, only significant parameters are needed. Thus, investigation was done to identify and filter out the insignificant parameters. The schematic diagram of experimental procedure is shown in Figure 1. High-speed air bearing spindle (ABS-400, Nakanishi, Japan) installed onto the CNC machine DT110 and the accelerometer was attached onto the air bearing using magnet mount.

3. EQUIPMENT AND MATERIALS

3.1 Cutting tools and workpiece

The micro cutting tool and workpiece are shown in Figure 2 and Figure 3 respectively and the detail specification are listed in Table 1. A two-flutes tungsten carbide tool with 500 μm diameter and edge radius of 5 μm has been selected. The size of the edge radius is selected in the consideration to increase the cutting-edge life by decreasing the cutting force and cutting temperature (Zheng, Liu, Chen and Wang, 2013) resistivity from chipping (Gupta and Laubscher, 2016). Next, the cutting tool helix angle is selected to be 40°. Both characteristics are important because as it have longer lifespan, it will be able to produce less variation in accuracies when multiple experiment run is done in an investigation process (Lu et al., 2016; Yang et al., 2011; Rahman et al., 2001).

Copper workpiece is considered as ideal for this investigation due to the intended fabrication of microchannel heat exchanger and the lack of investigation in micromilling with MQL using copper compared to other materials (Koklu and Basmacil, 2017; Kim, Kim and Lee, 2017; Aslantas and Cicek, 2018; Mathonsi, Laubscher and Gupta, 2018). Nevertheless, copper is the best choice to be used because it has the highest thermal conductivity value and ductile enough to be machined by micromilling.

3.2 Micro end milling machine

The machine used is a multi-process CNC DT110 (Mikrotools Inc., Singapore) as shown in Figure 4. It has the capability of machining by micro turning, micromilling, micro drilling, micro electrical discharge machining (micro-EDM), and micro wire EDM. The detail specification is listed in Table 2.

3.3 Micromilling accessory

3.3.1 Minimum quantity lubrication system

A near-dry lubrication method (MQL) is implemented in the micromilling machining process. An external MQL system (Bluebe FK, Japan) as shown in Figure 5a was used to supply the lubrication mist onto the machining zone. This MQL system enables the usage of different air pressure, oil flow rate, and nozzle direction to apply the lubricant during machining. The lubricant, Bluebe LB-1, is a vegetable-based oil and biodegradable. The detailed specifications of the system are listed in Table 3.

3.3.2 High speed air bearing spindle

This air bearing spindle (ABS-400, Nakanishi, Japan), as shown in Figure 5b, attachment was mounted onto the Mikrotools DT110. It is driven by compressed air and has the ability to provide spindle speed up to 57000 rpm. The specification of the air spindle is listed in Table 3.

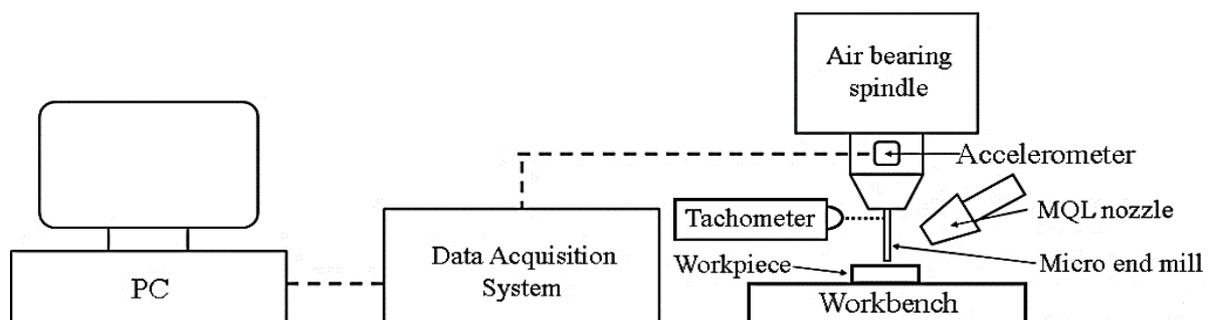


Figure 1. Schematic diagram for nozzle pressure and nozzle distance preliminary experiment



Figure 2. HPMT (NiTiCo 30) micro end mill (HPMT, 2019)

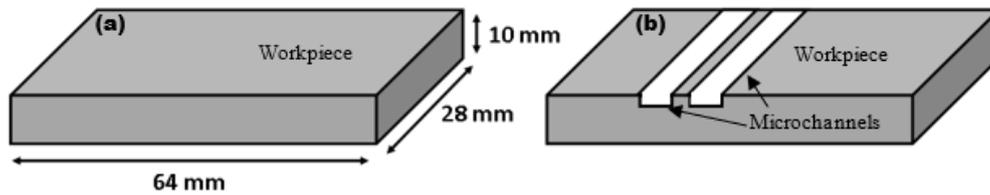


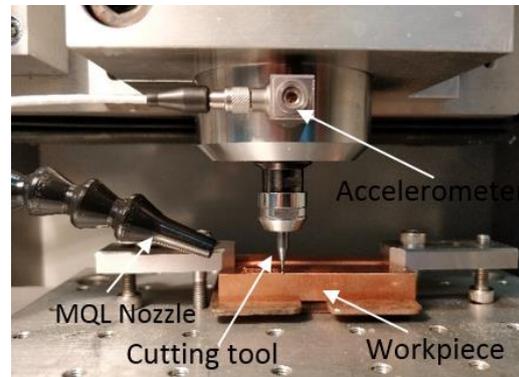
Figure 3. Copper workpiece with dimensions, (a) before machining and (b) after micromilling machining.

Table 1. Specifications of the micro end mill and workpiece

Characteristics	Descriptions
Cutting Tool	
Tool material, coating	Tungsten carbide, aluminum chromium nitride
Cutting diameter (μm), Edge radius (μm)	500, 5
No. of flutes	2
Helix angle ($^\circ$)	40
Tool length (mm)	2.0 effective, 50.0, overall
Workpiece	
Dimension (mm)	64 x 28 x 10
Melting point ($^\circ\text{C}$)	1083
Thermal conductivity (W/mK)	391.1
Density (gm/cm^3), Specific heat (J/kgK)	8.96, 393.5
Toughness (MPa), Mohr's hardness	369, 2.5-3



(a)



(b)

Figure 4. (a) Multi-process CNC machine tool DT110 (Mikrotools Inc., Singapore) (b) details of the machining zone

3.3.3 Accelerometer

The vibration signal was measured using an accelerometer (Dytran 3097a2, USA), as shown in Figure 5c. It is a lightweight miniature integrated electronics piezo electric accelerometer which is intended to be used for modal and structural analysis, including vibration measurement. Its specifications are listed in Table 3.

Table 2. Selected specification of Mikrotools DT110

General Features	Description and/or Specification
Machine configuration	Granite table machine base. Y axis mounted on the granite base. X and Z axes are on high stiffness gantry structure mounted on the granite base.
Machine travels (mm)	X = 200, Y = 100 , and Z = 100
Position accuracy (μm)	+/- 1
Position feedback system	Optical linear scale with resolution 100 nm RS422 (TTL) compromise



(a) MQL system (Bluebe FK, Japan)



(b) Air bearing (Nakanishi ABS-400, Japan)



(c) Accelerometer (Dytran 3097a2, USA)

Figure 5. High speed micro end milling accessories

3.3.4 Data acquisition (DAQ) system

The DAQ system (Graphtec GL7000, Japan) used in this investigation to process the vibration signal from accelerometer. The specifications are listed in Table 3. The data collected can easily be viewed using Graphtec’s dedicated software “GL-Connection” which enables statistical calculation of the data. The analysis was done in a frequency domain rather than time domain. For this to happen, time domain data have to undergo Fast-Fourier Transform (FFT) first, and this is handled by the software itself.

Table 3. Specification of Micro End milling accessories

General Features	Description and/or Specification
MQL system	Bluebe FK, Japan)
Oil flow rate (ml/hr)	0-170
Nozzle air pressure (MPa)	0.8
Supported lubricant	FUJI-BC genuine lubricant
Lubricant reservoir (ml)	300-4000
Nozzle type	Copper
Operating temperature (°C)	5-50
Air bearing	ABS-400, Nakanishi, Japan
Max spindle speed (rpm)	57000
Spindle accuracy (µm)	1
Air pressure (MPa)	Turbine: 0.3-0.4, Bearing: 0.5
Bearing load capacity (N)	Radial: 14 N, Thrust: 30 N
Accelerometer	Dytran 3097a2, USA
Sensitivity (mV/g, ±5 %)	10
Frequency range (Hz, ±5 %)	0.3 to 5000
Resonance frequency (Hz)	35000
Operating temperature (°C)	-51 to 82
DAQ System	Graphtec GL7000, Japan
Sampling speed (s ⁻¹)	1000
Measurement range	100, 200, 500 mV, 1, 2, 5, 10, 20, 50, 100 V
Measurement accuracy	± 0.25 %
Frequency response	DC to 1 kHz (at +1/-3 dB)
Filter (Low pass)	Off, Line (1.5 Hz), 5, 50, 500 Hz (-3 dB, 6dB/oct)

4. EXPERIMENTAL INVESTIGATION AND DISCUSSIONS

In this experimental investigation, several parameters were tested in order to have the first insight on the vibrational signal produced by each of the parameters. The parameters were selected based on the literature review and the capability of the machine (Ali, Banu and Bakar, 2018). The response for this investigation is harmonics amplitude, overall amplitude, spindle speed frequency (SSF), and peak amplitude. The responses from the vibrational signal were used to indicate the significance level of the tested parameters. It is also used to determine the suitable range of parameter values to be used in the vibration investigation experiment design. The listed parameters in Table 4 consist of two different groups: micromilling and MQL which are controlled separately by the Mikrottool DT110 CNC machine and Bluebe FK

MQL system respectively. The most significant parameters and suitable range of values will be used for experimental studies and to develop mathematical models.

The machining experiments were conducted using a multi-process CNC machine tool together with a high-speed air bearing. This equipment provides a high-accuracy and high-precision movement of the workbench up to 1 μm and a spindle that capable of achieving maximum speed of 57000 rpm (Cheng and Huo, 2013). New microtool was used for each of the experiments for consistency. The MQL system used for this investigation is an external applicator Bluebe FK Model (Fuji-BC Engineering, Japan). This MQL system have the capability in producing a maximum lubricant mist of 60 l/min to discharge. The lubricant, Bluebe LB-1, is a vegetable-based and biodegradable oil that is specifically formulated for high lubricity and moderate to heavy duty machining.

Figure 1 shows the complete schematic diagram of micromilling process with MQL. The first setup used is for the spindle speed parameters selection was the high-speed air bearing spindle together with the cutting tool where the spindle spins in dry condition. A tachometer and an accelerometer were used to measure the spindle speed and to record the vibrational signal respectively. The overall experimental setup is shown in Figure 4b. Based on literature review, values of experimental parameters were estimated as listed in Table 4. Then the micromilling was performed to estimate parameters values more precisely.

4.1 Spindle speed selection

One of the sources of vibration is the air bearing. By running several experiments on the different spindle speed value, individual characteristics of the vibration signal produced by each of the spindle speed can be studied. The schematic diagram and machining setup as shown in Figure 1 and 4b respectively. To measure the vibration signal that solely produced by spindle, a dry-run method (spinning of spindle speed without any contact on workpiece) was used. The spindle speed used for this first experiment is between 20000 to 50000 rpm. The results are tabulated in Table 5. SSF is the frequency generated by the spinning of the cutting tool itself, it is the vibration produced by the complete rotation of one of the teeth during spinning. Next, each of the SSF that is visible in the graph have its own amplitude. The recorded vibration signal is then exported into the personal computer equipped with the Graphtec GL7000 dedicated software; "GL-Connection" to further analyse the signal where the data have undergone through Fast-Fourier Transform (FFT). From the graph in Figure 6, it can be seen that as the spindle speed increased, the amplitude of SSF also increased. Higher energy also resulted in higher cutting force which can later improve or decrease the performance of the machining process and the tool life.

Furthermore, the harmonics of SSF is also visible in the vibration signal and its amplitude is recorded in Table 5. Harmonics of '1X' is the frequency which is the same as the SSF and it is usually called as fundamental frequency. '2X' harmonics is the multiplication of fundamental frequency by 2 times and '3X' as the multiplication by 3 times, and so on (Taylor, 2003). In summary, spindle speed does show a significant vibration signal in the form of SSF, harmonics, and overall amplitude. Therefore, it can be included as one of the factors in the vibration investigation and the suggested value for spindle speed are 20000, 30000, 40000, and 50000 rpm.

Table 4. Experimental parameters for the preliminary experiment

Controlled Parameters		Experimental Conditions
Micromilling parameters	Spindle speed (rpm)	20000, 30000, 40000, 50000
	Depth of cut (μm)	20, 30, 40, 50
	Feed rate (mm/min)	5, 10, 15, 20
	Tool overhang (mm)	20, 30
	Machining length (mm)	8
MQL parameters	Nozzle air pressure (MPa)	0.20, 0.25, 0.30, 0.35
	Nozzle distance (mm)	20, 30
	Nozzle direction ($^{\circ}$)	90, 135, 225, 270
	Oil flow rate (ml/hr)	3.75, 6.25, 8.75, 11.25

Table 5. Design of experiment for spindle speed dry run experiment

No.	Spindle Speed, N (rpm)	SSF (kHz)	SSF Harmonics Amplitude (m/s^2)			Overall Amplitude (m/s^2)
			1X	2X	3X	
1	20000	0.334	0.023	0.014	0.008	0.218
2	30000	0.499	0.109	0.023	0.006	0.417
3	40000	0.670	0.173	0.085	0.035	0.515
4	50000	0.834	0.460	0.184	0.077	1.275

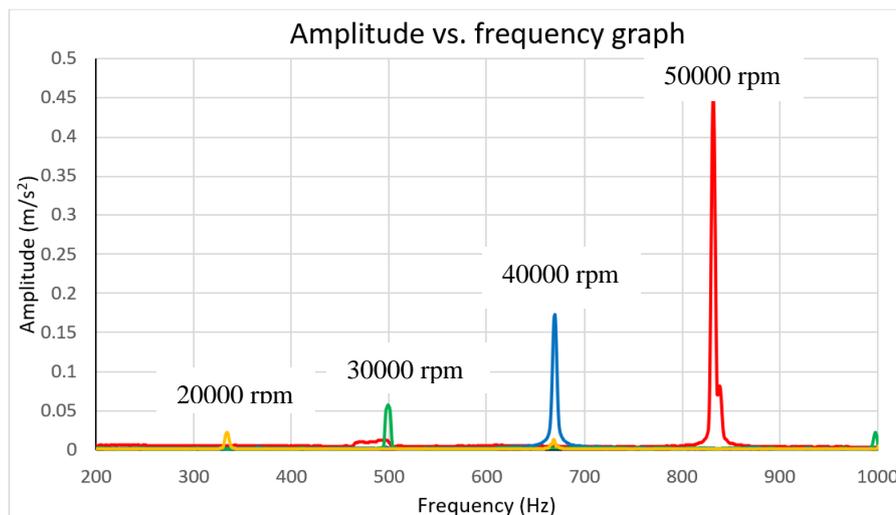


Figure 6. Frequency graph showing the increases in amplitude with increasing spindle speed

4.2 Depth of cut selection

Depth of cut is one of the most influential parameters that affect the micromilling output. In addition, it also affects the cutting force which further affects the cutting tool wear (Sun, To, Zhang and Zhang, 2018). Therefore, to determine the vibration signal produced by the changes in depth of cut, an experimental design with eight runs involving two spindle speed and four depth of cut is varied and tested. The result shows that as the depth of cut increased, the SSF and its amplitude decreases, and this trend is same for both speeds. The decreases in SSF happens because when the cutting tool goes deeper higher resistance and friction interfere the tool rotation.

Compared to the previous preliminary experiment which is done using dry-run method, this experiment involved machining process. The contact between the cutting tool with the workpiece introduces a new vibration frequency which possesses a significantly high amplitude compared to the SSF's amplitude. This new frequency and its amplitude are named as the 'peak frequency' and the 'peak amplitude'.

In summary, depth of cut does shows effects onto vibration signal in the form of SSF's amplitude, harmonics, and overall amplitude. Therefore, based on its significance, it can be included as one of the variables in the vibration investigation. The suggested value for depth of cut is 20 μm , 30 μm , 40 μm , and 50 μm .

4.3 Feed rate selection

To test the significance of feed rate onto the vibration signal, it must be varied in experiment together with the spindle speed. It showed that the SSF value is not changed significantly when the feed rate is changed. This indicates that by increasing the feed rate, the cutting force is not significantly changed thus the spindle speed is not reduced. Therefore, feed rate will be set as the fixed parameter in vibration investigation. The value of feed rate to be used was selected as 15 mm/min to shorten the machining time.

4.4 Nozzle pressure and distance selection

MQL parameters also needs to be experimented as it affects the surface roughness which is directly related to vibration signal (Gupta and Laubscher, 2016). It is known that two main controllable parameters in MQL are the air pressure at the tip of the nozzle (nozzle pressure) and the distance between the nozzle and the workpiece (nozzle distance). Thus, four values of nozzle pressure and two values of nozzle distance were tested. The schematic diagram and machining setup for nozzle pressure and distance experiment are shown in Figure 1 as well as Figure 4(b).

Four values of nozzle pressure tested were 0.20, 0.25, 0.30, and 0.35 MPa, while the two values of nozzle distance tested were 20 and 40 mm. Nozzle pressure of less than 0.200 MPa was excluded from tested value because the pressure was too low for the MQL to function properly. The results showed that both of the parameters do affect the vibration signal which resulted in the increment of the overall amplitude. However, there are no significant changes in overall amplitude for when the nozzle distance is changed. Nonetheless, distance of 20 mm is selected for 0.5 mm nozzle diameter to be suitable as it improves the diffusive capabilities of the lubricant which ensures droplet penetration onto the machining zone (Gupta and Laubscher, 2016).

4.5 Tool overhang, nozzle direction, and oil flow rate

In this research tool overhang, oil flow rate, and nozzle direction were selected based on literature review. Tool overhang which is the length measured between the spindle collet and the end of cutting tool is one of the controllable parameters in micromilling process. Research comparing tool overhang value towards the machining stability shows that tool overhang of 20 mm is the suitable length as it provides the most stability during cutting process (Wang, Wang, Liu, Gao, Loser and Ihlenfeldt, 2018). Next, oil flow rate value was suggested to be 3.75 ml/hr, 6.25 ml/hr, 8.75 ml/hr, and 11.25 ml/hr was selected accordingly. Finally, nozzle direction was selected to be 90° and 270° (Zheng et al., 2013) and 135° and 225° (Lopez, Angulo, Lamikiz and Sanchez, 2006). The angle of nozzle direction illustration is as shown in Figure 7.

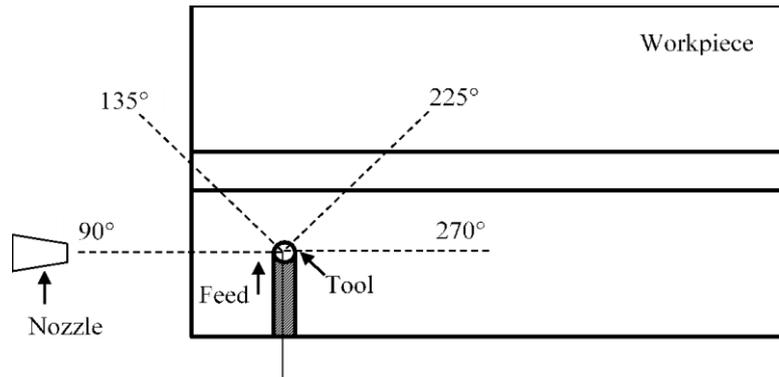


Figure 7. MQL nozzle direction based on the feed of the cutting tool

5. CONCLUSIONS

In this research, the issue of vibration produced during micromilling process with minimum quantity lubrication (MQL) was highlighted. From the experimental results and the literature review suggestion from other research investigations, several significant and non-significant parameters, and their values for micromilling and MQL were identified. The selected parameters listed in Table 8 which could be used for the experimental design such as design of experiment and Taguchi method for further investigation of vibration. The research showed that:

- Vibration signal was found to be significantly influenced by spindle speed, depth of cut, and nozzle air pressure. On the other hand, oil flow rate, feed rate, tool overhang and nozzle distance were also selected as variables based on literature review and benchmarking.
- It is recommended to use two or more accelerometers placed at different points on the air bearing spindle (X-axis, Y-axis and Z-axis) for better and thorough measurement of vibration.

Table 8. Selected parameter and values used in vibration investigation experiment

Controlled Parameters		Experimental Conditions			
		I	II	III	IV
Micromilling parameters	Spindle speed (rpm)	20000	30000	40000	50000
	Depth of cut (μm)	20	30	40	50
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
Fixed parameters					
Micromilling parameters	Feed rate (mm/min)	15			
	Tool overhang (mm)	20			
MQL parameters	Nozzle distance (mm)	20			

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7. REFERENCES

Ali, M.Y., Banu, A. and Bakar, M.A., 2018. Influence of wire electrical discharge machining (WEDM) process parameters on surface roughness. *IOP Conference Series: Materials Science and Engineering*, 290(1), 0–5.

- Aslantas, K. and CiCek, A., 2018. The effects of cooling/lubrication techniques on cutting performance in micro-milling of Inconel 718 superalloy. *Procedia CIRP*, 77, 70–73.
- Boswell, B., Islam, M.N., Davies, I.J., Ginting, Y.R., and Ong, A.K., 2017. A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining. *International Journal of Advanced Manufacturing Technology*, 92(1–4), 321–340.
- Boubekri, N. and Shaikh, V., 2014. Minimum Quantity Lubrication (MQL) in Machining: Benefits and Drawbacks. *Journal of Industrial and Intelligent Information*, 3(3), 205–209.
- Carou, D., Rubio, E.M., Lauro, C.H. and Davim, J.P., 2016. The effect of minimum quantity lubrication in the intermittent turning of magnesium based on vibration signal. *Measurement*, 98, 338–343.
- Chavoshi, S.Z. and Luo, X. (2015). Hybrid micro-machining processes: A review. *Precision Engineering*, 41, 1–23.
- Chen, W., Teng, X., Zheng, L., Xie, W., and Huo, D., 2018. Burr reduction mechanism in vibration-assisted micromilling. *Manufacturing Letters*, 16, 6–9.
- Cheng, K. and Huo, D., 2013. *Micro-cutting Fundamentals and Application*. John Wiley & Sons, Ltd.
- Gao, S. and Huang, H., 2017. Recent advances in micro and nano-machining technologies. *Frontiers of Mechanical Engineering*, 12(1), 18–32.
- Guckenberger, D.J., De Groot, T.E., Wan, A.M.D., Beebe, D.J. and Young, E.W.K., 2015. Micromilling: A method for ultra-rapid prototyping of plastic microfluidic devices. *Lab on a Chip*, 15(11), 2364–2378.
- Gupta, K. and Laubscher, R., 2016. Minimum Quantity Lubrication (MQL) Assisted Machining of Grade-4 Titanium. *Proceedings of International Conference on Competitive Manufacturing (COMA), 27–29 Jan 2016*, 211–217.
- Kim, J. S., Kim, J. W. and Lee, S. W., 2017. Experimental characterization on micro-end milling of titanium alloy using nanofluid minimum quantity lubrication with chilly gas. *International Journal of Advanced Manufacturing Technology*, 91(5–8), 2741–2749.
- Koklu, U. and Basmaci, G., 2017. Evaluation of Tool Path Strategy and Cooling Condition Effects on the Cutting Force and Surface Quality in Micromilling Operations. *Metals*, 7(10), 426.
- Lopez, N., Angulo, C., Lamikiz, A. and Sanchez, J. A., 2006. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *Journal of Materials Processing Technology*, 172(1), 11–15.
- Lu, X., Jia, Z., Wang, H., Si, L. and Wang, X., 2016. Surface roughness prediction model of micro-milling Inconel 718 with consideration of tool wear. *International Journal of Nanomanufacturing*, 12(1), 93.
- Mathonsi, T. N., Laubscher, R. F. and Gupta, K. (2018). On Machinability of Titanium Grade 4 under Minimum Quantity Lubrication Assisted High Speed Machining. *IOP Conference Series: Materials Science and Engineering*, 430(1).
- Rahman, M., Senthil Kumar, A. and Prakash, J. R. S., 2001. Micromilling of pure copper. *Journal of Materials Processing Technology*, 116(1), 39–43.
- Sharma, A. K., Tiwari, A. K. and Dixit, A. R., 2016. Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review. *Journal of Cleaner Production*, 127, 1–18.
- Sharma, V.S., Singh, G. and Sorby, K., 2015. A review on minimum quantity lubrication for machining processes. *Materials and Manufacturing Processes*, 30(8), 935–953.
- Sun, Z., To, S., Zhang, S. and Zhang, G., 2018. Theoretical and experimental investigation into non-uniformity of surface generation in micro-milling. *International Journal of Mechanical Sciences*, 140, 313–324.
- Taylor, J. I. (2003). *The Vibration Analysis Handbook - A practical guide solving rotary Machinery Problems*, 345.
- Vazquez, E., Gomar, J., Ciurana, J. and Rodríguez, C. A., 2015. Analyzing effects of cooling and lubrication conditions in micromilling of Ti6Al4V. *Journal of Cleaner Production*, 87(1), 906–913.
- Wang, D., Wang, X., Liu, Z., Gao, P., Ji, Y., Löser, M. and Ihlenfeldt, S., 2018. Surface location error prediction and stability analysis of micro-milling with variation of tool overhang length. *International Journal of Advanced Manufacturing Technology*, 99(1–4), 919–936.
- Wang, D., Wang, X., Liu, Z., Gao, P., Ji, Y., Löser, M. and Ihlenfeldt, S., 2018. Surface location error prediction and stability analysis of micro-milling with variation of tool overhang length. *International Journal of Advanced Manufacturing Technology*, 99(1–4), 919–936.
- Yang, K., Liang, Y.C., Zheng, K.N., Bai, Q.S. and Chen, W.Q., 2011. Tool edge radius effect on cutting temperature in micro-end-milling process. *International Journal of Advanced Manufacturing Technology*, 52(9–12), 905–912.
- Zheng, X., Liu, Z., Chen, M. and Wang, X., 2013. Experimental study on micro-milling of Ti6Al4V with minimum quantity lubrication. *International Journal of Nanomanufacturing*, 9(5/6), 570.

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