

INVESTIGATION OF VIBRATION IN MICRO MILLING
WITH MINIMUM QUANTITY LUBRICATION

BY

MUHAMMAD SHAFFIQ BIN HUSSIN

A thesis submitted in fulfilment of the requirement for the
degree of Master of Science (Manufacturing Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

JANUARY 2020

ABSTRACT

Micro milling with minimum quantity lubrication (MQL) have the ability in reducing cutting temperature and prolongs the tool life. However, uncontrolled vibration, known as chatter remains as a critical issue in micro milling process especially with the presence of MQL. Thus, the main aim of this research is to analyse the vibrational signal produced by the various combination of micro milling and MQL parameters during machining in target to control and reduce the undesired chatter. High-precision CNC machine tool was used to machine the microchannels onto a copper workpiece with a 500 μm micro end mill tool which is lubricated using an MQL system. This research consists of two parts which are the preliminary investigation (1st part) and vibration investigation (2nd part). Preliminary experiment (1st part) determines and isolates the significant parameters towards the vibrational signal. During this part, spindle speed, depth of cut, feed rate, nozzle air pressure, and nozzle distance were used as the controlled parameters. The vibrational signal; spindle speed frequency (SSF) amplitudes, and overall amplitudes; were measured using an accelerometer and a data acquisition system. It was found that, the parameters which influence the vibrational signals were the spindle speed (20000 – 50000 rpm), depth of cut (20 – 50 μm), oil flow rate (3.75 – 11.25 ml/hr), nozzle air pressure (0.200 – 0.275 MPa), and nozzle direction (90 - 270°). These parameters were used as the controlled parameters in the vibration investigation (2nd part). In this 2nd part, Taguchi L₁₆ was used to design the experimental run. The accelerometer and the data acquisition system were used to measure the SSF amplitudes and chatter amplitudes. Based on the amplitudes, chatter ratio were calculated and analyzed using signal-to-noise (S/N) ratio and analysis of variance (ANOVA). It was found that the nozzle direction and depth of cut has the highest influence on the chatter ratio followed by nozzle air pressure, spindle speed and oil flow rate. The optimum parameters for minimum chatter ratio (0.0104) were found to be 3.78 ml/hr oil flow rate, 0.275 MPa nozzle air pressure, 270° nozzle direction, 49.89 μm depth of cut, and 49959 rpm spindle speed. The developed model is found to be adequate since the percentage error is relatively small ($\approx 7\%$). As a conclusion, chatter ratio is the best indicator compared to other amplitudes in determining the presence of chatter produced during micro milling process with MQL.

خلاصة البحث

يُعد الطحن الدقيق مع أدنى كمية من التشحيم (minimum quantity lubrication) ذو قدرة على تقليل درجة حرارة القطع وإطالة عُمر الأداة. ومع ذلك ، فإن الاهتزاز غير المنضبط ، والمعروف باسم chatter ، لا يزال يُمثل مشكلة حرجة في عملية الطحن الدقيق خاصة مع وجود MQL . بالتالي ، فإن الهدف من هذا البحث هو تحليل الإشارة الاهتزازية التي تنتجها مجموعات متنوعة من عوامل الطحن الدقيق و MQL أثناء التشغيل وذلك للتحكم والتقليل من الاهتزاز غير المرغوب فيها . تم استخدام آلة CNC ذات الدقة العالية لصناعة قنوات دقيقة على قطعة نحاسية مع أداة ذات نهاية دقيقة تبلغ 500 ميكرون مشحمة باستخدام نظام MQL . يتكون هذا البحث من جزئين هما التحقيق الأولي (الجزء الأول) والتحقيق في الاهتزاز (الجزء الثاني). الاختبار الأول (الجزء الأول) يحدد ويعزل العوامل الهامة في إشارة الاهتزاز. خلال هذا الجزء ، تم استخدام سرعة الدوران وعمق القَطْع ومُعدل التغذية وضغط هواء الفوهة ومسافة الفوهة كعوامل يتم التحكم بها . تم قياس كُلٍّ من إشارة الاهتزاز، و اتساع تردد سرعة الدوران (spindle speed frequency) والسعة الكلية باستخدام مقياس التسارع ونظام الحصول على البيانات وقد وجدنا أن العوامل التي تؤثر على الإشارات الاهتزازية هي سرعة الدوران (20000 - 50000 دورة في الدقيقة) ، عمق القطع (20 - 50 ميكرون) ، معدل تدفق الزيت (3.75 - 11.25 مليلتر/ ساعة) ، ضغط هواء الفوهة (0.200 - 0.275 ميغا باسكال) واتجاه الفوهة (90 - 270 درجة). تم استخدام هذه العوامل كعوامل مُتحكم بها في فحص الاهتزاز (الجزء الثاني). في الجزء الثاني ، تم استخدام Taguchi L₁₆ لتصميم المدى التجريبي، و تم استخدام مقياس التسارع ونظام الحصول على البيانات لقياس إتساع تردد سرعة الدوران وسعة الاهتزاز. بناءً على نتائج السعات ، تم حساب نسبة الاهتزاز وتحليلها باستخدام نسبة الإشارة إلى الضوضاء و ANOVA . أظهرت النتائج أن اتجاه الفوهة له أكبر تأثير على نسبة الاهتزاز. تم التوصل إلى أن العوامل المثلى لنسبة الحد الأدنى للثرثرة (0.0104) هي 3.78 مليلتر/ ساعة لتدفق الزيت ، و 0.275 ميغا باسكال لضغط هواء فوهة ، و 270 درجة لاتجاه الفوهة ، و 49.89 ميكرون لعمق القطع، و 49959 دورة في الدقيقة لسرعة الدوران. تم التوصل إلى أن النموذج المطور مناسب لأن نسبة الخطأ صغيرة نسبياً (~ 7%). في الختام ، فإن نسبة الاهتزاز تعتبر أفضل مؤشر مقارنة بالسعات الأخرى في تحديد وجود الاهتزاز الناتجة عن عملية الطحن الدقيق باستخدام MQL .

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Manufacturing Engineering)

.....
Mohammad Yeakub Ali
Supervisor

.....
Mohamed Abd. Rahman
Co-Supervisor

.....
Md. Sazzad Hossien Chowdhury
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Manufacturing Engineering)

.....
Tasnim Firdaus Mohamed Ariff
Internal Examiner

.....
Che Hassan Che Haron
External Examiner

This thesis was submitted to the Department of Manufacturing and Materials Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Manufacturing Engineering)

.....
Mohamed Abd. Rahman
Head, Department of Manufacturing
and Materials Engineering

This thesis was submitted to the Kulliyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Manufacturing Engineering)

.....
Ahmad Faris Ismail
Dean, Kulliyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Muhammad Shaffiq Bin Hussin

Signature

Date

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

**DECLARATION OF COPYRIGHT AND AFFIRMATION OF
FAIR USE OF UNPUBLISHED RESEARCH**

**INVESTIGATION OF VIBRATION IN MICRO MILLING WITH
MINIMUM QUANTITY LUBRICATION**

I declare that the copyright holders of this thesis are jointly owned by the student
and IIUM.

Copyright © 2020 Muhammad Shaffiq Bin Hussin and International Islamic University Malaysia.
All rights reserved.

No part of this unpublished research may be reproduced, stored in a retrieval system,
or transmitted, in any form or by any means, electronic, mechanical, photocopying,
recording or otherwise without prior written permission of the copyright holder
except as provided below

1. Any material contained in or derived from this unpublished research
may be used by others in their writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print
or electronic) for institutional and academic purposes.
3. The IIUM library will have the right to make, store in a retrieved system
and supply copies of this unpublished research if requested by other
universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM
Intellectual Property Right and Commercialization policy.

Affirmed by Muhammad Shaffiq Bin Hussin

.....
Signature

.....
Date

ACKNOWLEDGEMENTS

“In the Name of Allah, the Most Compassionate, the Most Merciful”

Alhamdulillah, praise to Allah SWT for His blessings and mercy in lending me His vast and unlimited knowledge, ever-powerful and mighty strength, and timeless patience to complete my research work successfully.

Highest of appreciations and gratitudes goes to my supervisor, Prof. Ir. Dr. Mohammad Yeakub Ali, and my co-supervisors, Assoc. Prof. Dr. Mohamed Abd. Rahman and Assoc. Prof. Dr. Md. Sazzad Hossien Chowdhury for their relentless guidance and support.

Deepest of thanks to Sr. Asfana Banu for the continuous teaching, tutoring, and correcting my mistakes throughout this research process, and the staff and technicians of Kulliyyah of Engineering especially Br. Mohammad Noor (Computer Integrated Manufacturing Laboratory) and Br. Ibrahim (Metallography Laboratory) for the continuous help in all the experimental works.

Heartful thanks to my family members especially my parents, Hussin Mat Isa and Hafizah Shahar, my siblings for their prayers, understanding and care to witness my ups and downs during all my postgraduate semesters.

Last but not least, thanks to all my acquaintances and friends, who directly and indirectly offers their morale support and company whenever I need them because without them, it is impossible to me survive the life as a postgraduate student.

TABLE OF CONTENTS

Abstract	ii
Abstract in Arabic	iii
Approval Page.....	iv
Declaration.....	v
Copyright Page.....	vi
Acknowledgements.....	vii
List of Tables	x
List of Figures	xii
List of Abbreviations	xv
List of Symbols.....	xvi
CHAPTER ONE: INTRODUCTION.....	1
1.1 Background of the Study.....	1
1.2 Problem Statement	2
1.3 Research Objectives	3
1.4 Significance of Research.....	4
1.5 Research Methodology.....	4
1.6 Scope of Research	5
1.7 Thesis Organization	5
CHAPTER TWO: LITERATURE REVIEW.....	7
2.1 Milling.....	7
2.1.1 Micro Milling.....	8
2.1.2 Differences Between Micro Milling and Conventional Milling...	10
2.2 Metalworking Fluid (MWF)	12
2.2.1 Flood Lubrication.....	13
2.2.2 Minimum Quantity Lubrication (MQL) in Machining.....	14
2.2.2.1 MQL Lubricant Performance Factors: Type of Oil	15
2.2.2.2 MQL Lubricant Performance Factors: Droplet Distribution ..	16
2.2.2.3 MQL Lubricant Performance Factors: Viscosity	16
2.2.2.4 MQL Lubricant Performance Factors: Wettability	17
2.3 Vibration	17
2.3.1 Vibration in Machining.....	18
2.3.2 Vibration Data Acquisition (DAQ).....	19
2.3.3 Vibration in Micro Milling	21
2.4 Design of Experiment	22
2.4.1 Taguchi Orthogonal Arrays (OA).....	23
2.4.2 Signal-to-Noise (S/N) Ratio.....	25
2.4.3 Analysis of Variance (ANOVA).....	27
2.5 Application: Microchannel Heat Exchanger.....	28
2.6 Summary	29
CHAPTER THREE: METHODOLOGY	30
3.1 Methodology	30

3.1.1 Preliminary Investigation: Parameter Selection (1 st Part).....	32
3.1.2 Vibration Investigation: Mathematical Model (2 nd Part).....	35
3.1.3 Validation of Mathematical Model.....	35
3.2 Equipment and Materials Selection	36
3.2.1 Micro End Milling Tool.....	36
3.2.2 Workpiece Material	37
3.2.3 Micro Milling Machine.....	38
3.2.4 High-Speed Micro Milling Air Bearing Spindle	39
3.2.5 MQL System.....	40
3.2.6 Accelerometer	41
3.2.7 Data Acquisition (DAQ) System	42
3.3 Summary	43
CHAPTER FOUR: PRELIMINARY INVESTIGATION	44
4.1 Spindle Speed Selection.....	44
4.2 Depth of Cut Selection.....	48
4.3 Feed Rate Selection.....	51
4.4 Nozzle Pressure and Distance Selection	52
4.5 Tool Overhang, Nozzle Direction, and Oil Flow Rate.....	55
4.6 Summary	56
CHAPTER FIVE: VIBRATION INVESTIGATION	57
5.1 Design of Experiments (DOE).....	57
5.2 Experimental Procedures	59
5.3 Vibration Analysis	61
5.3.1 Vibration Signal Recording and Processing	61
5.3.2 Vibration Signal Analysis	62
5.4 Machined Surface Analysis	64
5.5 Analysis and Modelling	64
5.6 Summary	65
CHAPTER SIX: RESULTS AND DISCUSSIONS	66
6.1 Results.....	66
6.2 S/N Ratio of the Chatter.....	72
6.2.1 Effects of Oil Flow Rate on Chatter	74
6.2.2 Effects of Nozzle Air Pressure on Chatter.....	75
6.2.3 Effects of Nozzle Direction on Chatter.....	76
6.2.4 Effects of Depth of Cut on Chatter	77
6.2.5 Effects of Spindle Speed on Chatter	78
6.2.6 Ranking of S/N Ratio for the Chatter	79
6.3 Anova Results on Chatter	80
6.5 Summary	84
CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS	86
7.1 Conclusions.....	86
7.2 Recommendations	88
REFERENCES.....	89

LIST OF TABLES

Table 3.1: Experimental parameters for the preliminary experiment	33
Table 3.2: Specifications of the selected micro end milling tool	36
Table 3.3: Specifications of copper workpiece	37
Table 3.4: Selected specification of Mikrottools DT-110	39
Table 3.5: Specification of Nakanishi ABS-400 Air Bearing Spindle	40
Table 3.6: Bluebe FK model specifications	41
Table 3.7: Dytran 0397a2 accelerometer specifications	42
Table 3.8: Graphtec GL7000 DAQ system specifications	43
Table 4.1: Design of experiment for spindle speed preliminary experiment	45
Table 4.2: Design of experiment for depth of cut preliminaries experiment	49
Table 4.3: Peak frequency and peak amplitude	50
Table 4.4: Design of experiment for feed rate preliminary experiment	52
Table 4.5: Design of experiment for nozzle pressure and distance preliminary experiment	54
Table 4.6: Selected parameter and values to be used in vibration investigation experiment	56
Table 5.1: Experimental parameters	58
Table 5.2: Taguchi L ₁₆ design of experiment	58
Table 5.3: Graphtec GL7000 settings	63
Table 6.1: Experimental parameters and measured responses results	70
Table 6.2: Calculated ratio of chatter and SSF amplitude	71
Table 6.3: Calculated S/N ratio from the ratio of SSF chatter amplitude and SSF amplitude	72
Table 6.4: Calculated S/N ratio mean for oil flow rate factor	74
Table 6.5: Calculated S/N ratio mean for nozzle air pressure factor	75

Table 6.6: Calculated S/N ratio mean for nozzle direction factor	76
Table 6.7: Calculated S/N ratio mean for depth of cut factor	77
Table 6.8: Calculated S/N ratio mean for spindle speed factor	78
Table 6.9: Ranking of S/N ratio mean	79
Table 6.10: ANOVA for main and interaction effects of micro milling and MQL factors towards chatter	80
Table 6.11: ANOVA modelling statistics results	82
Table 6.12: Optimized parameter value and response with desirability	84
Table 6.13: Optimized and actual chatter ratio value with percentage error	84

LIST OF FIGURES

Figure 2.1: Micro milling machining process	8
Figure 2.2: Mechanism of material removal in micro milling	9
Figure 2.3: Types of milling burrs	10
Figure 2.4: Two-flutes micro end milling cutting tool with the diameter of 200 μm	11
Figure 2.5: MQL setup	14
Figure 2.6: Droplet distributions using 30 mm distance at 4, 8 and 12 psi	16
Figure 2.7: A body of mass producing vibrations	17
Figure 2.8: Primary frequency and its harmonics	19
Figure 2.9: Frequency domain graph compared to time domain graph	20
Figure 2.10: Regenerative chatter in milling	22
Figure 2.11: General model of process/system in DOE	23
Figure 2.12: Sample of Taguchi OA for 12 experiments	24
Figure 2.13: Taguchi OA sample rules	25
Figure 2.14: Microchannel heat exchangers (a) top view and (b) cross-section isometric view	28
Figure 2.15: Microchannel produced on acrylic plates using milling	29
Figure 3.1: Flow chart of the research	31
Figure 3.2: Schematic diagram of micro milling process with MQL	34
Figure 3.3: HPMT (NiTiCo 30) micro end mill tool	37
Figure 3.4: Copper workpiece with dimensions, (a) before machining and (b) after micro milling machining	37
Figure 3.5: Thermal conductivity values of possible heat exchanger materials	38
Figure 3.6: Mikrotools DT-110 multi-process CNC machine tool	39
Figure 3.7: Nakanishi ABS-400 high speed air bearing spindle	40
Figure 3.8: Bluebe FK model MQL system	41

Figure 3.9: Dytran 0397a2 accelerometer	42
Figure 3.10: Graphtec GL7000 DAQ system	43
Figure 4.1: Schematic diagram for spindle speed selection preliminary experiment	44
Figure 4.2: Machining setup for spindle speed preliminary experiment	45
Figure 4.3: Frequency graph showing the increased in amplitude as spindle speed increased	46
Figure 4.4: Amplitude vs. frequency graph for 50000 rpm indicating the harmonics	47
Figure 4.5: Schematic diagram for depth of cut and feed rate preliminary experiment	48
Figure 4.6: Machining setup for depth of cut and feed rate preliminary experiment	49
Figure 4.7: Schematic diagram for nozzle pressure and nozzle distance preliminary experiment	53
Figure 4.8: Machining setup for (a) nozzle pressure and (b) nozzle distance preliminary experiment	53
Figure 4.9: MQL nozzle direction based on the feed of the cutting tool	56
Figure 5.1: Vibration investigation schematic diagram	59
Figure 5.2: Vibration investigation machining setup	59
Figure 5.3: Accelerometer sensor attached onto the high-speed spindle attachment	60
Figure 5.4: Time domain (a) and frequency domain (a) graph differences	62
Figure 5.5: Differences of frequency spikes and noises in frequency domain	63
Figure 5.6: Machined workpiece (a) examined under optical microscope and (b) microchannels images which shows chatter marks	64
Figure 6.1: Example of SSF, 2X harmonic, and chatter frequency occurs in frequency domain graph	67
Figure 6.2: Example of no chatter occurs in frequency domain graph	67
Figure 6.3: Optical image of machined surface (a) without chatter marks and (b) with chatter marks	68
Figure 6.4: Vibration signal when (a) chatters occur at both SSF and 2X harmonic frequency and (b) optical image of the 'S'-shaped chatter marks on the surface	69
Figure 6.5: S/N ratio mean for oil flow rate	74

Figure 6.6: S/N ratio mean for nozzle air pressure	75
Figure 6.7: S/N ratio mean for nozzle direction	76
Figure 6.8: S/N ratio mean for depth of cut	77
Figure 6.9: S/N ratio mean for spindle	78
Figure 6.10: Chatter ratio contour graph for the interaction of nozzle air pressure and nozzle direction with oil flow rate, depth of cut and spindle speed set to 4.40 ml/hr, 50 μ m and 50000 rpm	83

LIST OF ABBREVIATIONS

2DOF	2-Degree-of-Freedom
3D	3-Dimensional
ANOVA	Analysis of Variance
CAD	Computer-Aided Design
Cu	Copper
DAQ	Data Acquisition
DOE	Design of Experiment
DPs	Design Parameters
EDM	Electrical Discharge Machining
FFT	Fast-Fourier Transform
IEPE	Integrated Electronics Piezo Electric
LIGA	Lithography, Molding, and Electroplating
MQL	Minimum Quantity Lubrication
MWF	Metal Working Fluid
OA	Orthogonal Arrays
OVAT	One-Variable-At-a-Time
S/N	Signal-to-Noise
SSF	Spindle Speed Frequency
TPF	Tooth Passing Frequency

LIST OF SYMBOLS

\varnothing	Diameter
h	Uncut chip thickness
h_m	Minimum chip thickness
R_e	Edge radius
n	Number of iteration
y	Experimental results
s	Variance
n	Spindle speed

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

As the technology in manufacturing keep advancing forward, the requirement for the machining accuracy and dimension also keep getting higher. Thus, the fabrication of the micro products greatly relies on the microfabrication technologies. Microfabrication is the collection of techniques that used to fabricate products in micrometer range (Boswell, Islam, Davies, Ginting and Ong, 2017; Boswell, Islam and Davies, 2017; Chavoshi and Luo, 2015; Franssilla, 2010). These micro-sized products commonly are used in the field of microelectronics, biomedical, and also aerospace (Pratap and Patra, 2014).

Following this, micro milling is recognized as the most flexible microfabrication process that has the capability to generate a wide variety of micro components and microstructures (Chen, Teng, Zheng, Xie and Huo, 2018). In addition, one of the many reasons why micro milling is the suitable choice for microfabrication is because of their ability to fabricate parts directly from a three-dimensional (3D) computer-aided design (CAD) model and making prototypes from designs much easier and faster (Guckenberger, De Groot, Wan, Beebe and Young, 2015).

However, high-speed micro milling process produces high friction between the micro milling tool and the workpiece. This ultimately resulted in high temperature machining and greatly reduces the lifespan of the cutting tool (Koklu and Basmaci, 2017). Hence, the most common way to overcome these problems is by using lubricant during the machining operation where the generated heat is able to dissipate and prolongs the tool life (Vasquez, Gomar, Ciurana and Rodriguez, 2015).

Normally in industries, large amount of continuous flowing cutting fluids also known as flood lubrication or flood cooling are used to lubricate workpiece, remove the generated heat from the machining zone, and protect the cutting tool edge. However, the usage of flood lubrication in micro milling 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). Thus, minimum quantity lubrication (MQL) is selected as the preferred alternative to flood cooling due to its efficiency in lubricating the workpiece and reduces production cost (Sharma, Singh and Sorby, 2015; Sharma, Tiwari and Dixit, 2016).

Although, the application of MQL is considered as a solution for the tool life problem, it does not help in eliminating fundamental machining issues such as vibrations which hugely affects the dimensional accuracy of the machined product. It is known that MQL parameter, when interacting with machining parameters, does influence the vibration during machining process. Interestingly, this fundamental issue of vibration can be controlled by adjusting the parameters involved during machining process (Carou, Rubio, Abrao and Davim, 2016; Guo, Dong, Wang and Ke, 2016). Therefore, by controlling the vibration produced by MQL and micro milling parameters, this ensures the output quality of the workpiece.

1.2 PROBLEM STATEMENT

Micro milling is one of the highly demanding micro processing technologies that offered various advantages such as the ability to machine a wide range of workpiece materials, 3D surface machining, low energy, and high efficiency machining process (Lu, Jia, Wang, Si and Wang, 2016).

Micro milling is a process where it is commonly done in a dry condition. Nevertheless, it possesses a critical problem where high friction causes high cutting temperature during the machining operation. High temperature during machining directly and indirectly affects the surface quality, dimensional accuracy, and tool lifespan of the machining process. Therefore, in order to overcome these problems, lubrication is needed during the machining process since it helps to lubricate and reduce the friction between the workpiece and the tool.

Commonly, lubricant is applied in traditional milling by flooding the workpiece. Nonetheless, flood lubrication is not suitable to be used in micro milling because of its inefficiency in costing, adverse health effects, and environmental problem. Thus, MQL is introduced as the alternative for flood lubrication. MQL which is a near-dry lubrication method is considered as an effective solution due to its advantage in reducing the friction together with the cutting temperature while maintaining less cutting fluid volume usage.

However, vibration in micro milling using MQL is still not fully investigated due to the complex behaviour of MQL mechanism and its combination with micro milling parameters. Furthermore, a mathematical model that can predicts appropriate machining parameters and its values for controlling vibration are still undeveloped. Hence, the vibration issues in micro milling with the presence of MQL are found to be unsolved and it remains as a critical issue.

1.3 RESEARCH OBJECTIVES

The main aim of this research is to investigate and control the vibration produced in micro milling with the presence of MQL. The specific objectives are as follows:

1. To determine the machining parameters that influence the vibration in micro milling with MQL.
2. To analyse the vibration signal and formulate a mathematical model in relation to the machining parameters to control the vibration during micro milling with MQL.
3. To validate the formulated mathematical model and determine the optimum parameters of the vibration produced in micro milling with MQL.

1.4 SIGNIFICANCE OF RESEARCH

The main purpose of this research is to analyse and control the vibration produced during micro milling process with the presence of MQL. The breakthrough of this research is the successful control of vibration during micro milling process with MQL and the identification of the most significant process parameter affecting the vibration. Furthermore, the ability to control the vibration also opens the possibility to reduce the chatter which greatly affects the machining of the workpiece. Finally, the developed mathematical model can be used for the contribution in the field of vibrational studies, especially in micro milling process with MQL.

1.5 RESEARCH METHODOLOGY

The research starts with the literature review in order to identify the possible problem and the objectives that are to be achieved with this investigation. The research continues with the selection of micro milling and MQL parameters that significantly affects the vibration by running several preliminaries experiment. Then, vibration investigation in which the selected micro milling and MQL parameters are combined and experimented using Taguchi orthogonal arrays (OA). Henceforth, the results from this vibration

investigation experimental runs are analysed using signal-to-noise (S/N) ratio and analysis of variance (ANOVA). Finally, a mathematical model is developed to control the vibration produced by the parameters combination and to achieve the best output on the machined workpiece.

1.6 SCOPE OF RESEARCH

The research focuses on the vibration issues in the micro milling process with the presence of MQL. The detailed scopes of the research are as follow:

1. Use of an accelerometer as the sensor and placed at the air bearing spindle for the measurement of vibration during machining process.
2. Use of unmodified vegetable biodegradable based oil without additives as the MQL lubricant.
3. Use of suggested tool overhang and nozzle directions angle as one of the process parameters.
4. Use of two-flutes tungsten carbide end mill with the diameter of 500 μm as the cutting tool and C1100 copper as the workpiece material.
5. Analysis of the chatter to SSF amplitudes ratio onto the chatter marks on the machined microchannel.
6. Use of Taguchi design of experiment with signal-to-noise (S/N) ratio and analysis of variance (ANOVA) as the analysis tools.

1.7 THESIS ORGANIZATION

This thesis is systematically organized by starting with Chapter One which consist of the background of this research, problem statement, research scope, and research objectives. Next, in Chapter Two, the literature review on the micro milling, the

implementation of MQL, and the relationship between vibration and micro milling process are presented. Taguchi OA as the experimental design while S/N ratio and ANOVA as the analysis method are also discussed in this chapter. Furthermore, in Chapter Three, the methodology of the investigation is explained. This section covers from the flowchart of the research, the material and the equipment used, the experiment designs for preliminaries investigation and vibration investigation, as well as the detailed procedures for both experiments. In addition, Chapter Four discussed on the results of the preliminaries experiments which selects the parameters that significantly affect the vibration and to be used in the vibration experiment design. Then, Chapter Five explained on the design of the vibration investigation which uses the selected parameters from the preliminaries investigation. Chapter Six discussed on the data results and analyses of the vibration investigation using S/N ratio and ANOVA methods. Finally, Chapter Seven concluded the research and provide several recommendations for the upcoming future works.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, a comprehensive literature review of related topics are presented. It includes the introduction to micro milling process, the use of minimum quantity lubrication (MQL) in machining, and the vibration in micro milling.

2.1 MILLING

Milling is a process that removes materials from workpiece by a rotating cutter. It is considered as a secondary process after casting, forging, or rolling is done onto the workpiece material. As the demand of micromachining is increasing to produce miniature devices. Thus, a machining is required, and this introduces micro milling into the industry (Deng, Wan, Huang, Huang and Zhou, 2016; Ali, Khan and Asfana, 2012a; Ali, Mohamed, Asfana, Lutfi and Fahmi, 2012b).

Following this, as the machines and the metrologies keep getting advanced, it critically needs to meet the requirement of part sizes, features, definition, accuracy, and precision (Gao and Huang, 2017). Micromachining refers to the production of high-precision and low-tolerances 3D products. These products consist of features with the sizes that is ranged from tens of micrometer to a few millimeters in a wide variety of materials (Unune and Mali, 2015). As a result, micro milling which is a type of micromachining process is the scale down of its conventional milling process where it has the ability to fabricate a wide range of miniaturize products (Oliaei, Karpas, Davim and Perveen, 2016; Oliaei, and Karpas 2018).

2.1.1 Micro Milling

Micro milling is one of the subtractive manufacturing processes that uses a micro-sized milling cutter with diameter less than or equal to 1 mm. Micro milling have the basic milling system which consist of a worktable, cutting tool, and overhead spindle as shown in Figure 2.1. It is commonly combined with a CNC machine rather than a manual control in order to achieve high accuracy, precision, and automation (Xu, Liu, Wang and Yu, 2017; Guckenberger et al., 2015).

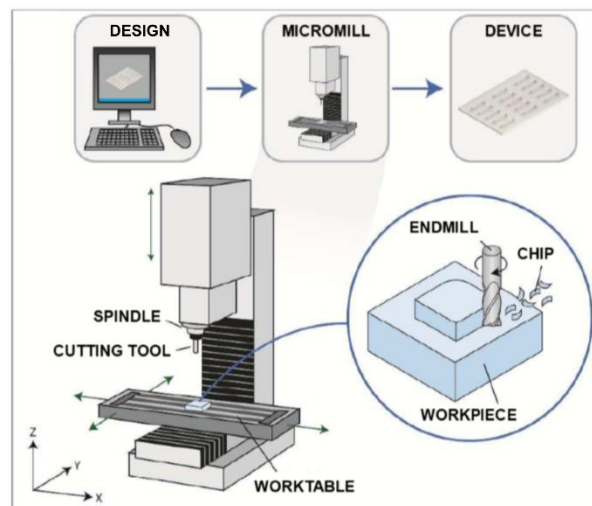


Figure 2.1: Micro milling machining process (Guckenberger et al., 2015)

Micro milling is also considered as a very flexible process because it can be used to machine a wide variety of material such as metals and polymers (Pratap, Patra and Dyanokov, 2015; Pratap and Patra, 2014; Câmara, Rubio, Abrao and Davim, 2012; Dornfeld, Min and Takeuchi, 2006). Normally, in micro milling, the type of the milling process used is the end milling due to the incredibly small diameter of the cutting tool (Guckenberger et al., 2015).

The basic principle of micro milling is quite similar to the conventional milling. The surface of the workpiece is mechanically removed using a cutting tool, in this case