INVESTIGATION OF VIBRATION IN MICRO MILLING WITH MINIMUM QUANTITY LUBRICATION

BY

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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 L_{16} 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 (≈ 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 بإسم 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 القَطع ومُعدل التغذية وضغط هواء الفوهة ومسافة الفوهة كعوامل يتم التحكم بها .تم قياس كُلٍ 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) ، عُمق القطع (20 – 50 ميكرون) ، معدل تدفق الزيت (3.75 – 11.25 مليلتر/ ساعة) ، ضغط هواء الفوهة (0.200 – 0.275 ميجا باسكال) واتجاه الفوهة (90 – 270 درجة). تم استخدام هذه العوامل كعوامل مُتحكم بها في فحص الاهتزاز (الجزء الثاني). في الجزء الثاني ، تم استخدام Taguchi L_{16} 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 وANOVA . 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 ، و0.275 ميجا باسكال لضغط هواء فوهة ، و 270 درجة لاتجاه الفوهة ، و 49.89 ميكرون لعمق القطع، و49959 دورة في الدقيقة لسرعة الدوران. تم التوصل إلى أن النموذج المطور مناسب لأن نسبة الخطأ صغيرة نسبيًا (≈ 7٪). في الختام ، فإن نسبة الاهتزاز تعتبر أفضل مؤشر مقارنة بالسعات الأخرى في تحديد وجود الاهتزاز الناتجة عن عملية الطحن الدقيق باستخدامMQL .

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)

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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.

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

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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

Ø	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, Karpat, Davim and Perveen, 2016; Oliaei, and Karpat 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).

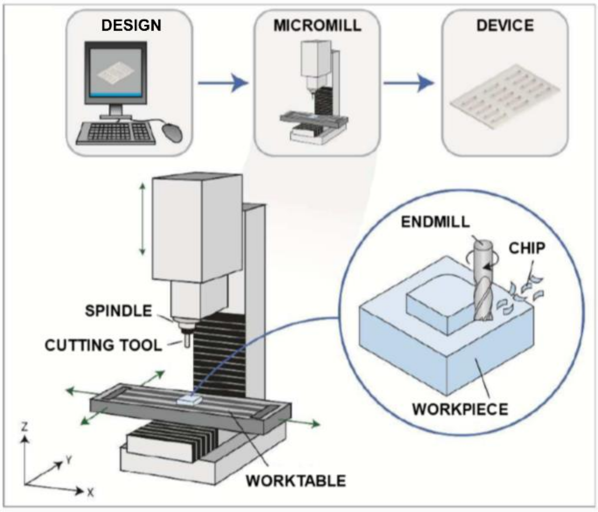

Figure 2.1: Micro milling machining process (Guckenberger et al., 2015)

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