EXPERIMENTAL STUDY OF BIOMEDICAL STAINLESS STEEL 316L VIBRATION ASSISTED MILLING USING RETROFITTABLE 1D UVAM WORKTABLE

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DEDICATION

MY BELOVED PARENTS,

Abdul Latif bin Shaari and Roshida binti Hasan

For their love and support throughout my whole life

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Dr. Mohd Rasidi Bin Ibrahim

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ABSTRACT

Nowadays, the demand in industry for hard and brittle materials including alloys and glasses components has been increasing. Thus, it is important to ensure machining for these parts are done in a high precision manner. Ultrasonic vibration assisted milling (UVAM) is a well-known precision machining equipment. It improves the machining performance and could perform machining on extremely delicate components. UVAM is an advance machining process which consists of the combination of conventional milling with ultrasonic vibration assistance. This research investigates the effect of imposing ultrasonic vibration assisted milling with feed and cross-feed vibration on conventional milling (CM). The desired vibration is proposed from the workpiece by a specialised one-dimensional UVAM worktable. A series of end-mill experiment in dry cutting conditions were conducted on stainless steel 316L. A commercially available cutting tool manufactured by HPMT with a diameter of 6 mm and featured with differential pitch was used in this research. The ultrasonic vibration generator excites the workpiece with a frequency in the range of 9~18 kHz and an amplitude of 0.5~3 µm. The values of the cutting parameter were chosen with regards to the recommendation by the manufacturers. Several parameters including cutting force, cutting temperature, surface roughness, chip formation and tool wear progression were compared between CM and UVAM. The results showed that a considerable improvement was identified in UVAM. It was found that end milling with ultrasonic vibration in the feed vibration of 18 kHz with an amplitude of 3 µm was able to reduce 13%(F_x) and 18%(F_y) of cutting force, reduce 18.4% of cutting temperature and improve the surface roughness up to 60% as compared to CM. Apart from that, it also decreased the tool wear progression as compared to conventional milling, In addition, the chip formation has shown a positive trend where larger amplitude and higher frequency would produce smaller chips as compared to conventional milling.

ABSTRAK

Pada masa kini, permintaan bahan keras dan lembut di industri sangat tinggi seperti aloi keluli dan komponen kaca. Proses pemesinan perlulah dilakukan secara tepat dan jitu. Pemesinan Berbantukan Frekuensi Getaran Mesin Kisar (PBFGMK) dikenali sebagai pemesinan yang jitu dan tepat. PBFGMK mampu meningkatkan prestasi pemesinan dan dapat melakukan pemesinan komponen yang sangat kecil. Proses pemesinan ini yang menggabungkan mesin kisar konvensional dengan getaran sistem berbantu ke dalam proses pemotongan tunggal. Kajian ini akan mengkaji kesan ultrasonik berbantukan getaran dengan arah suapan dan merentas getaran pada mesin kisar konvensional. Getaran dihasilkan daripada satu dimensi PBFGMK mesin. Satu siri eksperimen mesin kisar dalam keadaan pemotongan kering telah dijalankan pada keluli tahan karat 316L. Alat memotong didapati secara komersial yang dihasilkan oleh HPMT dengan diameter 6 mm dan mempunyai sudut mata alat yang berbeza telah digunakan. Penjana getaran ultrasonik menghantar isyarat frekuensi 9 ~ 18 kHz dan amplitud 0.5 ~ 3 µm. Parameter pemesinan dipilih seperti yang disyorkan oleh pengeluar mata alat. Daya pemotongan, potongan suhu, kekasaran permukaan, pembentukan serpihan dan kadar mata alat haus telah dibandingkan antara mesin kisar konvensional dan PBFGMK. Keputusan menunjukkan bahawa peningkatan yang besar dalam PBFGMK, dengan getaran ultrasonik dalam getaran suapan pada 18 kHz dengan amplitud 3 µm dilihat dapat mengurangkan 13% (Fx) dan 18% (Fy) daya pemotongan, mengurangkan 18.4 % daripada suhu pemesinan dan penambahbaikan kekasaran permukaan sehingga 60% berbanding dengan pemesinan konvensional. Selain itu, ia juga dapat mengurangkan kadar mata alat haus jika dibandingkan dengan permesinan konvensional dan pembentukan serpihan juga menunjukkan corak yang positif di mana amplitud yang lebih besar dan frekuensi yang tinggi akan menghasilkan tatal lebih kecil berbanding dengan permesinan konvensional.

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SYMBOLS AND ABBREVIATIONS

ρ	-	Density
T_c	-	Cutting temperature
T_2	-	End temperature
T_1	-	Initial temperature
t_2	-	End time
t_1	-	Initial time
$\dot{V}$	-	Volume flow rate
λc	-	Cutoff length
r	-	Diameter of Shank (mm)
S	-	Spindle Speed (rpm)
T	-	Cutting Tool Life (cycles)
t	-	Cutting Time (s)
Wv	-	UVAM Width of Cut (mm)
w	-	Rotational speed
Vb	-	Flank Wear (µm)
x	-	X-axis Displacement
F_c	-	Cutting Force
F_x	-	Cutting Force in X Component
Fy	-	Cutting Force in Y Component
Fz	-	Cutting Force in Z Component
a_p	-	Axial Depth of Cut

a_e	-	Radial Depth of Cut
f	-	Feed per rev
V_C	-	Cutting speed
A	-	Vibration Amplitude (mm)
D	-	Cutting Tool Diameter (µm)
f	-	Frequency (Hz)
fr	-	Feed Rate (mm min^{-1})
k	-	Hinge Spring Constant
N	-	Number of Cutter Teeth
R	-	Radius of Cutting Tool (mm)
R_a	-	Surface Roughness (µm)
HRB	-	Rockwell Hardness
CM	-	Conventional Machining
UVAM	-	Ultrasonic Vibration Assisted Milling
PBFGMK	-	Pemesinan Berbantukan Frekuensi Gegaran Mesin Kisar
DM	-	Dry Machining
PREMACH	-	Precision Machining Research Centre
SEM	-	Scanning Electron Microscope
UTHM	-	Universiti Tun Hussein Onn Malaysia
MRR	-	Material Removal Rate (mm^3 min^{-1})

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In the process of machining, milling is the most appropriate operation to perform metal shaping process. To increase the accuracy, a higher value of cutting parameter such as cutting speed, feed rate and depth of cut are needed. A higher value cutting parameter would increase the generation of heat energy. Thus, the cutting temperature would also increase. A higher cutting temperature will cause deterioration on the surface quality as well as affecting the tool life (Childs *et al.,* 2000). This phenomenon would happen due to the failure of penetration of the conventional cutting fluid to the chip-tool interface during high-speed milling processes.

To overcome this problem, the Ultrasonic Vibration assisted machining (UVAM) was introduced. UVAM is an advance machining process where it is grouped under non-traditional machining process. It is commonly used to machine conductive, non-conductive, hard and brittle work materials. Vibration assisted drilling, vibration assisted turning, vibration assisted milling, vibration assisted abrasive are all categorised under the scope of vibration assisted machining. Vibration assisted machining was introduced during the early 1950's and today, it has become a widely accepted method in precision metal cutting industries (Rasidi, 2010). A hydrostatic bearing with its sub-micrometer rotational accuracy was the first component of precision metal cutting to benefit from the efforts of researches. Along with the refinement of conventional machine component (spindle, metrology, frames, etc.), the development of linear motors in the late 1970s and piezoelectric driven stages in the 1980s allowed tool positioning and control to be on nanometer scale. Besides, researches on material and the development of the monocrystalline diamond tool with Nano metric edge sharpness had ensured the levels for errors to occur and surface roughness to be reduced significantly (Brehl & Dow, 2008). This has attracted many researches to further develop various systems to suit different applications.

Vibration is one of the mechanism that can be used to assist machining processes. Vibration is an oscillation of an object about a static position. There are a few range of vibrations that can be produced to assist machining processes. Ultrasonic vibration has been widely used for industries in Japan, where the machining processes have widely adapted vibration technologies to improve the machining processes in order to obtain a better and fine result for the products.

UVAM is an advanced machining process that combines ultrasonic vibration as a supporting mechanism in milling process. From previous researches, it is found that by adding vibration to milling processes, several improvements were identified such as extended cutting tool life, reduction of cutting force and improvement on the cutting quality especially on surface roughness. In current technologies, the vibration mechanism can be installed on either the cutting tool itself or at the worktable. When a small amplitude of vibration is applied to the tool or to the work piece, it could help the machining process to achieve a better result as compared to conventional machining. There are many types of vibrations that exist in this world. Nevertheless, only a few types of vibrators could produce an efficient vibration at small amplitude. Piezo actuator is one of the devices that could produce a precision vibration amplitude (in micro and nano) at both high and low frequencies. Both the vibration installation method and vibration emitter component have their own capabilities and disadvantages, and these factors could actually deliver different outcomes. In addition, the interaction between high frequency vibrations with the cutting tool motion will enhance the characteristics of the outcome of the milling process. The motions of the vibration exist in different directions including X, Y, and Z or a combination of the axis. However, the frequency rate as well as the amplitude of vibration is usually manageable. These characteristics could usually become the parameter factors that control and distinguish the outcomes from UVAM process and conventional milling process.

Typical ultrasonic vibration assisted milling consist of three main parts which are data output (computer), data acquisition card (DAQ), and the vibration device (piezoelectric actuator). Nevertheless, a typical UVAM would still have a few drawbacks. In recent years, there are various researches which was conducted to improve the current UVAM which is by applying a closed-loop control system. Closed-loop system is a system that utilises feedback where the feedback is used to make decision about any changes to the control signal that is driving the system. In a closed-loop control system, sensors are being used to obtain reading from the output signal (vibration amplitude of cutting tip). Then, the software would react according to the changes of the system by recalculating and readjusting the driven signal (input signal). The system responds to changes by having several samples taken repeatedly, and the cycle continues until the system reaches the desired state. At the desired state, the software will cease making further changes. Previous researchers (Barr, 2002; Moriwaki & Shamoto, 1995; Rasidi, 2010; Shamoto & Moriwaki, 1994; Shamoto, Suzuki, Moriwaki, & Naoi, 2002) have developed a closed-loop control system for ultrasonic vibration in order to stabilise the ultrasonic elliptical vibration. The results of their experiments showed that amplitude of vibration as well as phase difference are kept constant, and the average resonant frequency is successfully organised in the present the control system.

This research would focus on the effect of one-dimensional vibration towards cutting force, cutting temperature, surface roughness, tool wear and chip formation. Cutting force is the force that is required to cut the material to desired dimensions. Cutting force would commonly affect the tool wear. When the cutting force is set to be high, the tool that is being used will have to exert a greater force and this could lead to the rapid wear of the tool. Next, the heat generated in machining operation is an important factor in addressing several metal cutting issues such as dimensional accuracy, surface integrity and tool life. A higher value of cutting temperature will increase the deterioration of surface quality as well as affecting the tool life (Childs *et al*., 2000). Furthermore, this research will also compare the effect of cutting force, cutting temperature, surface roughness, tool wear and chip formation when vibration is being applied or not being apply during the milling process. The UVAM worktable that was used in this experiment is a 1-D UVAM, where it includes two motions either in X-axis or Y-axis. 1-D UVAM has a linear movement where it can only move in one motion. It is notable that in 1-D UVAM, the cutting force and tool wear can be reduced. Apart from that, the 1-D UVAM can extend the tool life significantly as compared to conventional machining.

1.2 Problem Statement

Machining AISI 316L is complicated due to the properties of low thermal conductivity which creates and builds up heat in the cutting zone. Cooling lubricant is commonly recommended to machine this group of alloys. It helps to achieve a better result in terms of tool life, surface finishes and ensure a smooth chip flow. However, in recent years, its usage in industries is nonetheless characterised to have problems during waste disposal. These issues have caused a large number of ecological problems, environmental concerns and had also been identified to be one of the major factors for sickness among the workers. Some researches claimed that, cost related to cutting fluids is enough to represent an enormous amount of expenditure which could overtake the cost of cutting tool. Thus, dry cutting machining is a relevant and beneficial alternative which could fulfill the needs for cost reduction and environmental concerns. Nonetheless, it is notable that dry cutting is not suitable in some applications that require high accuracy of the finished components as well as high surface integrity. In conventional milling machine, high force and friction are produced during the process of machining. As a result, it will induce rapid tool wear and could alter the surface integrity of the machining product. Furthermore, a higher force could reduce the quality of the products. The tool could also easily wear out during the processes. This could increase the maintenance cost and decrease the quality of surface integrity.

UVAM is an effective method to counter this problem and could be utilised in machining operations. Besides, UVAM processes have a lot of advantages as compared to conventional milling processes. However, it is still uncommonly used in the industry. This phenomenon is due to various major drawback factors that still could not be fully understood in depth by current researchers. Vibration amplitude, vibration frequency and voltage supply are several key factors in determining the performance for surface integrity, cutting force and cutting temperature. In previous studies conducted (Rasidi, 2010), it has been shown that an increase in the vibration amplitude could lead to the reduction in cutting force, lower cutting temperature, improvement in surface integrity and enhancing tool life. In this study, both performance between X-axis and Y-axis ultrasonic vibration assistance are investigated in order to further comprehend the mechanism of 1-D UVAM. The amount of vibration amplitude that can be obtained during machining process is mainly depended on the types of piezoelectric actuators being used. Different types of piezoelectric actuators have different capabilities of vibration amplitude and resonance frequency. Thus, a number of experiments have been done to determine the optimum vibration amplitude and frequency that can be produced by the selected piezoelectric actuator.

Cutting force and temperature is an importance factor in metal cutting process and it is linked to many issues in cutting process such as product accuracy, surface roughness and tool life. Theoretically, cutting force and temperature in ultrasonic vibration assisted milling should be much lower than conventional milling since there are intermittent gap being produced during the cutting process. The intermittent gap produced is mainly depended on the vibration amplitude and vibration frequency. A higher amplitude of vibration could result in a larger intermittent gap being produced and a higher vibration frequency would cause the frequency of the intermittent gap to increase. The increase in both vibration amplitude and vibration frequency would decrease the cutting force and its temperature. However, there is a lack of scientific evidence or research study to understand and explain this theory.

1.3 Objective

i. To design a UVAM worktable
ii. To investigate the experimental and simulation of compliance mechanism
iii. To study the performance of Ultrasonic Vibration Assisted Milling (UVAM) with feed and cross-feed vibration against dry machining in terms of
    1. Cutting force

2. Cutting temperature
3. Surface roughness
4. Tool wear
5. Chip formation

1.4 Scope of Study

In order to achieve the objectives, this study has been carried out with some limitations and assumptions. This research would include finite element analysis, experiments, visual observations and measurements. The works were done under the following scope.

i. Machining parameter:

a) Spindle speed, n : 2387 (min^{-1})
b) Feed, V_f : 191 mm/min
c) Depth of cut a_p : 0.1 mm
d) Condition : Dry cutting
e) Workpiece : Stainless steel 316L
f) Cutting tool : Nitico 30
: 6 mm diameter
: 4 flute end mill
: Differential pitch
: Uncoated
g) Type of cutting : Slot milling (Up and Down milling)

ii. UVAM parameter

Signal Pattern	Sine Wave			
Amplitude, μm	0.5	1.0	2.0	3.0
Frequency, kHz	9	13	15	18

iii. UVAM work table:

a) Vibration motion : 1D motion (Linear X or Y axis)

b) Vibration emitter : Thorlab discrete piezo stack PK4FQP2

iv. Material

a) Stainless Steel 316L

1.5 Significance of Study

This study focused on the machining of 316L stainless steel with a higher creep, stress to rupture and tensile strength at elevated temperatures as the technology for machining process of this particular material is still developing. Through this study, the development of the machining process for stainless steel 316L was enhanced by using UVAM.

This study is also an effort to build the market value for UVAM machining in industry as it has a wide usage and bright future development. Although UVAM had already been used by advance technology in global market, the knowledge regarding the process is still incomplete. This study could fulfill the missing knowledge of the UVAM especially on effect of the cutting force, cutting temperature, surface roughness, tool wear and chip formation.

Thus, by conducting this research, a new UVAM worktable that is industry friendly can be designed. However, it can only be done by enhancing the characteristics and reducing the limitations of current UVAM technology. UVAM can assist machining in many ways that are still yet to be discovered. Hopefully this study will be one of the stepping stone that could increase the technology usage of UVAM in Malaysia as UVAM technology is currently being developed by advance countries.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Milling Process

Milling operation is considered one of the most common machining operations in industry. It can be used for face finishing, edge finishing as well as material removal. Milling machine is one of the widely used machine in removing excess material to achieve a desired part. One of the machines that was used in this research was CNC milling (MAZAK Nexus 400A-II CNC). Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges. The axis of rotation of the cutting tool is perpendicular to the direction of feed. This orientation between the tool axis and the feed direction is one of the features that distinguishes milling from drilling. In drilling, the cutting tool is fed in a direction which is parallel to its axis of rotation. The cutting tool in milling is called a milling cutter and the cutting edges are called teeth.

The geometric form created by milling is a plane surface. Other work geometries can be created either by means of the cutter path or the cutter shape. Due to the variety of shapes and its high production rates, milling is considered as one of the most versatile and widely used machining operations. It is an interrupted cutting operation where the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation. Thus, the tool material and cutter geometry must be designed to withstand these conditions.

In milling operation, there are many types of cutting including slot cutting. In slot cutting, the direction of cutter rotation can be distinguished into two forms of milling: up milling and down milling which are as illustrated in Figure 2.1. In up milling which is also called conventional milling, the direction of motion of the cutter teeth is opposite to the feed direction. It is milling “against the feed.” In down milling which is also known as climb milling, the direction of cutter motion is the same as the feed direction. It is milling “with the feed.” The relative geometries of these two forms of milling would result in different cutting actions. In up milling, the chip formed by each cutter tooth would start out very thin and would increase in thickness during the sweep of the cutter. In down milling, each chip would start out thick and would reduce in thickness throughout the cut. The length of the chip in down milling is lesser as compared with up milling. This means that the cutter is engaged with less time per volume of material cut. Thus, this would increase the tool life in down milling (Groover, 2013). The cutting force direction is tangential to the periphery of the cutter for the teeth that are engaged in the work. In up milling, there is a tendency to lift the work part as the cutter teeth exits the material. In down milling, this cutter force direction is downward which is tending to hold the work against the milling machine table.

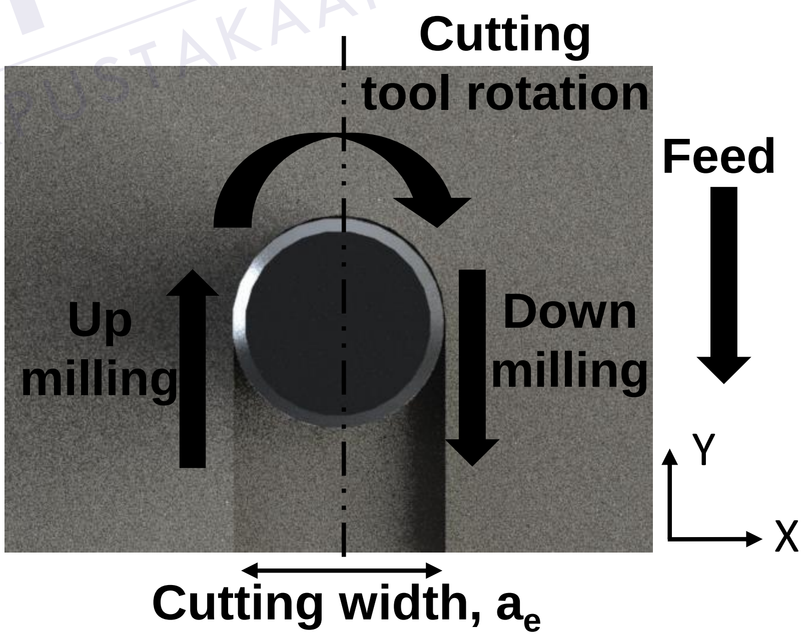

Figure 2.1: Top view of slot cutting

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