An investigation of cutting mechanics in 2 dimensional ultrasonic vibration assisted milling toward chip thickness and chip formation

I. Rasidi I[1], N.H. Rafai[1], E.A. Rahim[1], S. A. Kamaruddin[1] H. Ding[2] and K. Cheng

[1]Faculty of Mechanical & Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia.
[2]School of Mechatronics Engineering, Harbin Institute of Technology,
Harbin 150001, China
[3]Advance Manufacturing Engineering Enterprise, School of Engineering and Design,
Brunel University, West London UB8 3PH, United Kingdom

*Email: rasidi@uthm.edu.my

Abstract. The purpose of this paper is to investigate the effects of 2 dimensional Ultrasonic Vibration Assisted Milling (UVAM) cutting mechanics, considering tool path trajectory and the effect on the chip thickness. The theoretical modelling of cutting mechanics is focused by considering the trajectory of the tool locus into the workpiece during the machining. The studies found the major advantages of VAM are come from the intermittent tool tip interaction phenomena between cutting tool and workpiece. The reduction of thinning chip thickness formations can be identifying advantages from vibration assisted milling in 2 dimensional. The finding will be discussing the comparison between conventional machining the potential of the advantages toward the chip thickness and chip formation in conclusion.

Keywords: cutting mechanics, milling trajectory, tool trajectory, chip thickness, intermittent cutting.

1. Introduction

A modern industry nowadays is looking forward to miniaturize a precision component to support a high demand of micro and precise product such as electronic part, holographic optical element, micro-mechanical component etc. A high quality and precise machine and tool component is needed to produce the desire product. In order to manufacture in the shop floor machine factory, it significant to find the best solution with taking into account the tool condition, tool failure, thermal softening and surface finish etc. The solution for finding a best method of machining must be emphasize to overcome the demand of product without losing the profit margin, where the cost of tools or production is higher than the product selling.

A lot of efforts have put through over the last few decades and vibration assistance machining has been seen is the most relevant machining method to achieve the desire quality. Vibration assisted machining (VAM) is an addition of small amplitude and frequency into cutting tool. The purpose of the amplitude and frequency is for giving an extra displacement with higher reciprocating in circular or ellipse tool motion. However, there is a no significant comparative published between conventional

cutting and 2D UVAM in term of mechanism and kinematics. Figure 1 shows a machine setup for the 2D UVAM preliminary cutting trial in the lab.
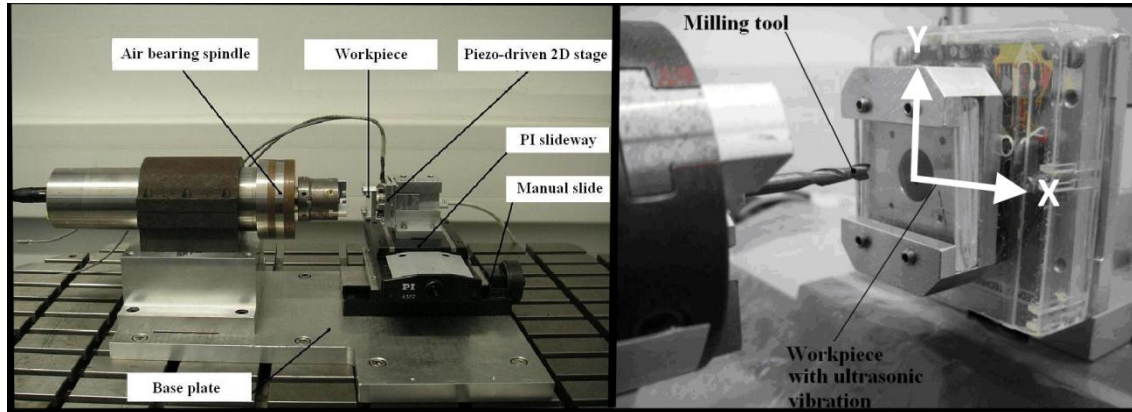

Figure 1. Ultrasonic Vibration Assisted Machining setup

There are many researchers and company design and developed their own VAM for their application and product. Adachi and Arai designed an ultrasonic vibration cutting, low frequency vibration cutting has been found to prolong tool life and help reduce burr sizes in drilling [1]. They developed and electro-hydraulic servo system to generate vibration of 1,000 Hz in the spindle on conventional NC machine. Wang and Zhou proved by their experimental to cut hard and brittle material in high critical depth of cut. By applying at 2 μm amplitude ultrasonic in diamond tool tip a surface roughness of 100 nm has achieved [2]. The material has been cut was a fuse silica with cutting condition vibration amplitude 3 μm, vibration frequency 40 kHz, spindle speed 9,000 rpm, feedrate 5 μm/rev. Ding and Rasidi has modelled the 2 dimensional vibration assisted micro-milling based on the trajectory of tool path. It compose the vibration in X and Y directions relative to the workpiece when the X axis consist a feedrate as a feed direction and Y axis acting perpendicular to the normal motion of workpiece. Through their experimental studies about burr, the height of top burr decreases firstly in ploughing/rubbing--predominate stage and then increases in chip removal process with the increment of feed per tooth [3].

This paper intend explained the advantages of 2D UVAM in chip thickness and formation even there are many researchers proved they can get a good result but they did not emphasized the mechanisms to bring the benefit to this kind of phenomena.

2. Cutting mechanics in 2 dimensional VAM

2.1. Tool path trajectory
In conventional milling, the trajectory of the tool path depends on the spindle speed and feedrate relative to the workpiece. The spindle speed is the important part as it carries the tool tip edge to the round shape, but it is different and shape changing when the feedrate starts to move.

A preliminary concept of motion of 2D UVAM explained with the vibration amplitude in X and Y is the same displacement/amplitude, the vertical vibration (Y axis) increased faster than the circular one. The mathematical equation of these two models can be described,

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{1}$$

Defining the X and Y axis amplitude of the tool in equation (1). Combining for the 2 Dimensional cutting on both axes can be expressed as,

$$
\begin{aligned}
x &= A\cos(2\pi ft) \\
y &= b\sin(2\pi ft)
\end{aligned}
\tag{2}
$$

The centre of the endmill tool bar must be described in order to know the behaviour of the tool tip motion later. The reason because the boundary of the tool bar is taken as a reference to drive the tool tip motion [2]. It can be expressed as:

$$
\begin{cases}
x2 = ft + A\sin(2\pi f_x t + \phi_x) \\
y2 = B\sin(2\pi f_y t + \phi_y)
\end{cases}
\tag{3}
$$

Bao and Tansel have modelled the tool tip trajectory and tried to investigate the chip thickness and difference from the Tlusty and Macneil model using Equation (4) [4, 5].

$$
\begin{cases}
x = \dfrac{ft}{60} + r\sin\left(\omega t - \dfrac{2\pi z}{Z}\right) \\
y = r\cos\left(\omega t - \dfrac{2\pi z}{Z}\right)
\end{cases}
\tag{4}
$$

Liu and Cheng modelled a conventional of the tool path is simply traces by the spindle rotation angular velocity, tool cutter helix angle, regenerative cutter displacement and the cutting tool radius [5]. However, in 2D UVAM, the tool tip motion relative to the workpiece is complex and cannot be considered a helix shape as the vibration acts on the X and Y axes simultaneously.

So, the component of 2D UVAM can be obtained when the described components in Equation 2, 3 and 4 are combined together, which can be expressed by.

$$
\begin{cases}
x1 = ft + r\sin\left[\omega t - \dfrac{2\pi(z_i - 1)}{Z}\right] + A\sin(2\pi f_x t + \phi_x) \\
y1 = r\cos\left[\omega t - \dfrac{2\pi(z_i - 1)}{Z}\right] + B\sin(2\pi f_y t + \phi_y)
\end{cases}
\tag{5}
$$

The trajectory of the tool locus in 2D UVAM is robust. Depending on the 4 important factors described in Figure 2, it contains:
- o Vibration frequency X and Y axis
- o Vibration amplitude X and Y axis
- o Spindle speed
- o Feedrate

The two dimensional vibrations assisted milling process is shown in Figure 2, where the X axis feed direction and amplitude is in the X axis, the Y axis is the normal direction and the Z axis is the depth of cut in order to determine the locus of the tool simulation relatively in to the workpiece.

2.2. Intermittent cutting and chip thickness

Figure 2, generated by MatLab programming, revealed the cutting mechanics in 2D, with effect of vibration frequency and amplitude, promoted many cycles take places in a specified time interval. It is obviously explained by the fact that the cutting force is reduced when the tool point of the tool is in high force to remove the material in one single cut. In 2D UVAM, the vibration introduced non-contact within the tool and workpiece, helping to cut the material to smaller pieces while opposing the frequency and amplitude.
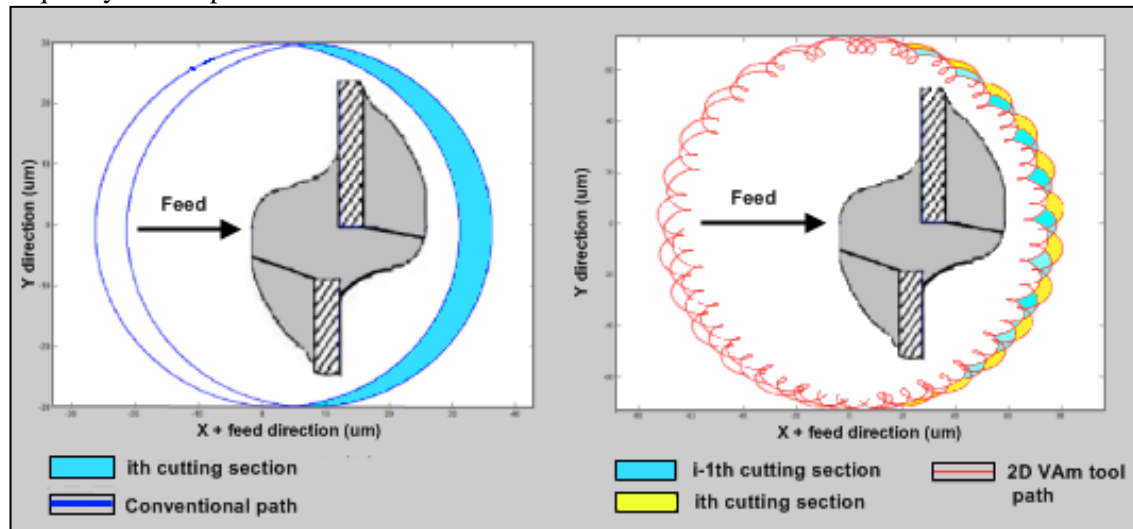
(a) Conventional machining   (b) 2D VAM

Figure 2. Difference of chip thickness affecting cutting force reduction.

Therefore, in 2D UVAM much smaller and shorter chips are produced, instead of a large and continuous chip as in conventional cutting. In addition, the tool motion operates with lower average force for a much larger cumulative distance in repetitive passes, compared to conventional machining in the same amount of time.

Figure 3 shows the chips thickness performs by (a) without vibration and (b) 2D VAM by the test bed in UTHM laboratory. The depth of cut was 500 μm, vibration in X and Y was 3,000 Hz. Figure (a) obviously found the chip thickness is longer, thicker and bigger than (b). It is because the cutting force has been reduced by introducing the 2D VAM affect the discontinuous chip, smaller and thinner. The intermittent motion of tool play important role to get this type of chip. Thus, smaller and discontinuous chip has been preferred by the machinist similar in tool "chip breaker" end-mill type in common industries.

According to the theory of vibration assisted machining higher frequency applied during cutting, the thinner chip will produced but faster cutting process has been achieved. It will promote the higher material removal rate process.
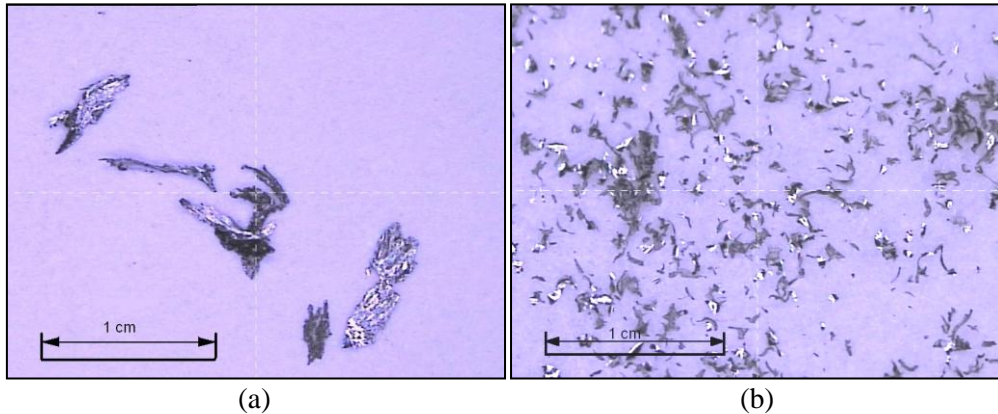
Figure 3. Chip thickness and formation (a) Conventional milling, (b) 2D VAM

In the same volumetric material removal, the work performed by 2D UVAM is therefore much more consistent than with conventional machining. Summary of this paper investigation as shown in Table 1.

Table 1. Comparison investigation between Conventional cutting and UVAM

	Conventional Miling	Ultrasonic Vibration Assisted Machining	Comments
Chip thickness	• Chip always thicker and depending on feedrate and spindle speed only.	• Chip thickness thinner and strongly depending on the amplitude, spindle speed, smaller amplitude, and thinner chip produced. • The consecutive overlapping toolpaths results in chips that are thinner than the depth of cut.	• Conv. machining cut a workpiece in each single rotation in one cycle, but 2D VAM cut the workpiece much smaller cause the frequency and amplitude effect.
Chip formation	• Chip always continuous and depending on feedrate and spindle speed only.	• Discontinuous/shorter chip strongly depending on the frequency, amplitude and spindle speed. Higher frequency, smaller chip produced. • Instantaneous uncut chip thickness at each point in the tool path is less than the depth	• Conv. machining cut a workpiece in each single rotation in one cycle, but 2D VAM cut the workpiece much smaller cause the frequency and amplitude effect.

3. Conclusion

From this paper we can conclude the 2D vibration assisted milling is obviously shown to promote a distinct advantages compared with conventional machining methods over a wide range of precision machining application whether in macro and micro. It is founding the major improvement in reduction cutting force, reduction in temperature, extended tool life, discontinuous, thinning and changes of chip formation and improving the surface roughness came from the effect of engaging and disengages of the tool related to the workpiece. The creating of gap between the rake face and workpiece also play important effect to this major improvement. These mechanics advantages include:

- o   Intermittent gap promote discontinuous, smaller and less chip thickness
- o   Frequency and amplitude helps tool cutting edge to cut in ductile region efficiently.
- o   Alternating cycles motion allows allow cutting force reduction whilst prolong tool wear.

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