Chip Geometry Modelling of 2-Dimension Ultrasonic Vibration Assisted Machining (2D UVAM) on Micromilling Machine With End Mill

Gandjar Kiswanto¹, Y R Johan¹, Poly¹ and T. J. Ko²
¹Department of Mechanical Engineering, Universitas Indonesia, Depok 16424, Indonesia
²School of Mechanical Engineering, Yeungnam University, Republic of Korea

gandjar_kiswanto@eng.ui.ac.id

Abstract. The needs of miniaturized products have increased a lot in this ever-changing world. This makes the micromanufacturing technologies develop fast in order to keep up with this higher needs and to meet the required quality of a product. One of the developed technologies is ultrasonic vibration assisted machining (UVAM). UVAM is different than conventional machining because of the way the cutting tool move relative to the workpiece. This different cutting phenomenon produces a different chip geometry than the conventional machining. The purpose of this paper is to give an understanding through chip geometry models about how UVAM can be a better cutting method rather than conventional milling. MATLAB is used in order to do the modelling of theoretical chip geometry. The approach used in this study is by calculating where the cutting tool edge is in a given unit of time before and after the ultrasonic vibration is induced to the workpiece in X-Y dimension. A characteristic in the cutting edge called the bottom cutting edge angle is also considered. By comparing the two chip geometries, some benefits that UVAM gives are explained.

1. Introduction
The escalating use of portable electronic devices makes manufacturing micro parts with high precision essential. Not only electronic industry, many industries that require hard and brittle materials makes the the development of manufacturing technologies needed to satisfy those demands increases. A manufacturing technology needeed basically require these following statements:
- The technology needs to produce better quality products.
- The technology must cheap enough to suppress manufacturing cost.

In 1979, the new technology for machining was developed. It is reported that a steel can be machined with diamond tool by applying ultrasonic vibration. The result was not achieved to ultra-precision level but then, in 1991 Moriwaki and Shamoto [1] developed ultrasonic vibration tool for ultra-precision diamond turning with a fulfilling result.

Ultrasonic vibration assisted machining is a method used in cutting where vibration with an ultrasonic frequency (higher than 20 kHz) and certain amplitudes are applied either to cutting tool or to the workpiece. Because there is vibration, the relative motion between cutting tool and the workpiece is different compared to the conventional machining.

The advantages of UVAM compared to conventional machining have been studied experimentally [2, 3, 4] and through simulations [5,6]. Rasidi et al [6] have presented the advantages of UVAM by comparing the chip thickness. There is also a study about the cutter-workpiece engagement [7]. However, there are still little study about the cutter-workpiece engage-disengagement and the chip geometries for UVAM. Understanding more about these can analyze further about what the advantages of UVAM are. Chip geometries are generated by calculating where the cutting edge is.
This paper takes into account some characteristics of the cutting tool such as bottom cutting edge to show deeper understanding about the advantages of UVAM.

2. Calculating the cutting edge position

There are several mathematical model used in order to generate the chip geometry. Before looking into them, there are several given parameters used in order to create this modelling simulation. There are cutting parameters, e.g., spindle speed, feed rate, feed per tooth, and depth of cut. Another one is, vibration parameters, e.g., ultrasonic frequency, amplitude (less than 6 $\mu$m [8]). Also, since this is a micro-scale machining, the presence of the tool edge radius, which is comparable in size to the uncut chip thickness itself, introduces a minimum uncut chip thickness (MUCT) [9,10].

2.1. Conventional machining

Chip geometry is generated because there is angular displacement caused by spindle speed and also linear displacement caused by feed rate as seen from figure 1 and figure 2.

![Figure 1. Angular displacement of the cutting edge.](image)

![Figure 2. Feed motion linearly.](image)

For calculating the feed per tooth, equation (1) below is used.

$$fz = \frac{v}{N \times n}$$  (1)

Where $v$ is feed rate (mm/min), $N$ is spindle speed (RPM), and $n$ is number of flute. While the cutting tool edge position can be calculated as equation (2) and (3) below.

$$X = R \sin \Delta \psi$$  (2)

$$Y = R \cos \Delta \psi$$  (3)

Where $X$ is cutting tool edge position on X axis with reference to tool center coordinate system (mm), $Y$ cutting tool edge position on Y axis with reference to tool center coordinate system (mm), $R$ is the cutting tool radius (mm), $\Delta \psi =$ cutting tool edge rotation angle around Z axis ($^\circ$).

According to Kouravand and Imani’s work [11], tool center coordinate system is a coordinate system defined to express the center position of the cutting tool on the center of the channel. The origin of the coordinate system is located under the tool axis. In this study, feed direction is along the X axis.

2.2. UVAM

On UVAM system, the cutting tool moves towards the workpiece then makes a contact with it until the given positive amplitude (engage), then the cutting tool will move away from the workpiece until it fully loses contact with the workpiece (disengage). Cerniway [12] said that the displacement of cutting tool caused by vibration in a given time domain can be calculated with equation (4) and (5).

$$Dx(t) = A \cos(\omega t) + fz$$  (4)

$$Dy(t) = A \sin(\omega t)$$  (5)

Where $A$ is amplitude (mm), $f$ is frequency (Hz), $t$ is time and $\omega = 2 \times \pi \times f$. 

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This text is a natural language representation of the given image and raw textual content.
From figure 3 above, it shows how the relationship between amplitude and frequency of UVAM system. The illustration only shows 1D vibration cutting for the purpose of simplification and to give clearer look. However in figure 4, it shows when the amplitudes are produced on each axis. In this study, the phase different, or the time difference when voltage is generated to each axis’ actuator, is 0. This makes the cutting tool moves linearly in a diagonal way instead of elliptical motion.

2.3. *Bottom cutting edge feature*

Kouravand and Imani [11] introduces bottom cutting edge angle in their machined surface roughness modelling.

When there is a presence of bottom cutting edge angle, as illustrated on figure 5, the axial depth of cut will vary. In this paper, by analytical approach, the varying can be calculated with equation (6) and equation (7).

\[
Z_i = D_{oc} \\
Z_{i+1} = D_{oc} - \tan(a_p \times f_z)
\]  

3. *Chip geometries*

The chip geometries that are generated can be seen in figure 6 and figure 7 below. The cutting parameters used are axial depth of cut 10 μm, feed per tooth 0.012 mm and spindle speed 50000 RPM. The vibration parameters are amplitude 1 μm and frequency of 24 kHz. Cutting tool used is 2 flute end-mill DIXI 7242 with diameter of 1 mm, and bottom cutting edge angle 3.4393°.

In figure 6, the presence of bottom cutting edge angle creates height difference of the material removed or the chip. For example, in figure 6(a), the red line has shorter height than the blue line. This means the machined surface will have a natural roughness caused by this cutting edge feature.
When removing a material in conventional machining, the right combination of cutting parameters needs to be applied to create better surface quality. Many studies have suggest that lower feed rate can produce better surface quality. This lower feed rates creates less height different in the chip. However, making the feed rate smaller does not always guarantee the good surface quality, even with the right range of spindle speed. This is because there is a minimum chip thickness value that needs to be satisfied in order for chip to be developed. Even when this smaller feed rate is big enough to meet the minimum chip thickness value, the machining time would take longer and creates inefficiency.

In figure 7, the engage and disengage phenomenon can be looked better. When the amplitude is maximum, the cutting edge will have an offset position when compared to the conventional milling. This offset position can act as an additional feed per tooth, making the natural roughness caused by bottom cutting edge angle being cutted or machined, without the needs to reconsider smaller feed per tooth and longer machining time.

![Isometric view of chip geometry](image)

**Figure 6.** Isometric view of chip geometry

Chips can have many shapes [13]. The desired chip is usually moderate, not too long and also not discontinuous. Longer chip can cause built-up edge (BUE) on the rake tool face. BUE will create a rake wear [14]. Hence, thinner chip is preferred. UVAM creates thinner chip so it gives higher tool life compared to conventional milling.

In figure 7(c), interestingly, although the simulation only used 1D VAM, the elliptical motion is generated. This makes sense, because cutting tool is also rotating while the exited vibration is only through the X axis, along the feed direction. On other hand the 2D VAM with no phase difference creates the resultant motion linearly in diagonal way. It can be possible that 1D VAM along the feed direction can gives better overall machining qualities compared to the non elliptical 2D VAM.
In the given amount of time, both conventional and UVAM remove the same amount of material. However, in UVAM, there is a moment where disengage between cutting tool and the workpiece happen which makes the occurrence of removing this amount of material to be divided by several parts [12]. This is why the cutting force could be reduced using UVAM.

4. Conclusion and suggestion
This paper gives an understanding about why UVAM can give some advantages rather than conventional machining using the model of each chip geometry. The reasons are as follows:
The desired chip shape in machining is moderate, not too long and not discontinuous. UVAM makes the removal of material more efficient by making the chip shape thinner than conventional machining.

The engage and disengage cutting tool and the workpiece by UVAM causes the cutting force needed is going to be smaller compared to the conventional machining.

The extra feed per tooth caused by the positive amplitude in vibration creates a greater displacement of the cutting tool to the workpiece, hence making the natural roughness of the workpiece getting machined and generating better surface quality.

Thinner chips are produced instead of thick chip means rake wear caused by built-up edge will not happened as quickly as conventional machining so it increases tool life.

The elliptical motion in 2D UVAM is usually more commonly used. Understanding more about the phase different to create the chip geometry needs to be studied in depth.

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