Fundamental Aspects in Designing Vibration Assisted Machining: A Review

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Abstract. Sustainable development for machining strategies, process, and technologies, is compulsory in the industries. Machining surface quality improvement and the extension of tool life-time are commonly set as goals by many researchers, in the fulfilment of that sustainable development. Unforeseen and uncontrollable vibration or known as passive vibration is an unavoidable effect and a menace in machining. However in contrary, adding active vibration with stable frequency and amplitude, and small depth of cut during machining, give positive impact toward machine performance and surface quality. Vibration Assisted Machining (VAM) generates active vibration on the tool or workpiece. That vibration repeatedly causes tool-workpiece separation for a period of time during machining. The tool-workpiece separation is the main reason of VAM advancements. Adding VAM to conventional machining requires further consideration in term of design and cutting method, which are investigated in this comprehensive literature review. Critical aspect in adding VAM to micro milling machine was also discussed.

Keywords: Micro Milling, Piezo-actuator, Product Design, Vibration Assisted Machining

1. Introduction
Manufacturing process which is synergy with the environment, social, and economic [1, 2], had become the primary concern in current development of machining strategy, process, and technology. Products with macro or Nano size, complex features, hard to machine alloy or brittle material, are the characteristic of the preferred products by industries[3]. That synergy and precise products are highly demanding by the industries such as in aviation, medical, and electronic. Vibration Assisted Machining (VAM) works based on the application of sinusoidal waves, with an external energy additional. VAM is an example of sustainable manufacturing concept. Generally, vibration for machining process is an unavoidable effect and gives negative impact, however in contrary Zhang et al. [4] research showed VAM with its active vibration has the ability to improve surface quality due to passive vibration. Passive vibration happens due to the structure respond of the tool holder, tool tip, spindle, and workpiece toward the applied forces during machining, which has values approach the natural frequency of the overall machine structure. Micro product examples, which are manufactured by using VAM, among that are micro mold for LCD panel[5], barcode[6], dimple pattern[7-9], and to sculpture eyes contact lens [10].

Brehl and Dow[11] had mapped out the research about VAM based on the combination of frequency and amplitude set up for turning, grinding, and drilling process within years 2001-2007, and the results are: mostly VAM is placed at the tool holder; two direction vibration or known as 2D VAM is extensively used with a frequency of 20-40 kHz and an amplitude of 3-20 micron meters. Kumar et al. [12] categorized VAM in to conventional and advance machining. Vibration assisted turning, milling, grinding and drilling are categorized into conventional, whilst vibration assisted micro-electro discharge machining, vibration assisted laser machining, vibration assisted electrochemical micro machining, and vibration assisted abrasive machining are categorized in to advance machining. The categorization also stated that VAM advantages are obtained from: the process of tearing gradually and
repeatedly the natural surface roughness, which resulted thinner and discontinuous chip formation; the separation period between tool-workpiece, caused frictions between tool-workpiece not always the case and temperature decreased during machining, that prolong the tool lifetime especially for hard to machine alloy; the combination of round-nose tool tip application, thrust force and amplitude decrease, and temperature decrease, caused uniform cracking and material removal rate; controllable depth of cut caused brittle material to be cut like ductile material; compressive and bending stress caused suppression of burr formation. VAM advancements in comparison to conventional machining (CM) has been investigated in many aspects, and among those aspects are the influence of machining and vibration control parameter set up against machined surface quality [5-10,13], 2D VAM design to mimicking living organism pore for metal surface in order for the cooling fluid to penetrate evenly [14], and hybrid concept application by combining hot treatment at workpiece and turning process with VAM at the tool holder[15].

Those studies about VAM, showed that: VAM application as an additional had a tendency to be placed at the tool holder; the applied vibration control set up for frequency above 20 kHz and for amplitude is within 1-20 micron meters; VAM always plays a role as an assisted process in order to optimize the existing process; VAM for milling is underdeveloped. However heretofore only few studies investigated or discussed about the importance to add VAM in to an existing machine or the design of VAM itself. Therefore this study presents the critical aspect in designing VAM for the existing machine based on literature review.

2. Vibration Assisted Machining for Micro Milling

Toolpath design flexibility and high achievement accuracy are some advancements of micro milling process in comparison to turning, grinding, and drilling, which become many researchers consideration in applying the process, to make micro product with complex feature from hard to machine alloy and brittle material. The difference of surface generation as a result from Conventional Machining (CM) and from VAM, are shown at Figure 1[16]. The surface profile with its peak and valley composition as seen in Figure 1(a) is a result from CM, due to tool or workpiece deflection, vibration or tool run out. Whilst Figure 1(b) showed, VAM capability to machining the same surface roughness area from the previous cycle, with the purpose to eliminate the remaining peak and valley profile. Subsequently VAM with high frequency set up might result in a smoother surface.

![Figure 1 Surface profile (a) without and (b) with VAM at the tool][16]

VAM based on its vibration mode is classified in to two groups, which are 1-Dimensional VAM and 2-Dimensional VAM[11, 12]. The vibration direction of 1-Dimensional VAM (1D VAM) is generally in feed or cross-feed direction. The addition of one degree vibration to 1D VAM caused 2-Dimensional VAM (2D VAM) to vibrate in an elliptical motion. The difference between 1D and 2D VAM can be seen from the duty cycle definition. The duty cycle for 1D VAM is based on cutting time, while the duty cycle for 2D VAM is based on the length of the elliptical toolpath when in contact with workpiece [11].

Figure 2 showed the difference kinematic schemes between 2D VAM micro milling which is placed at the tool and at the workpiece. Ding et al. [17] investigated the kinematics for workpiece thru dynamic surface simulation and modelling(as shown in Figure 2(a)), and Chen et al. [16, 18] also investigated the same kinematic thru tool-workpiece separation model which is based on tool path relative to workpiece(as shown in Figure 2(b)). Both Figure 2(a) and 2(c) showed relative motion between tools with the workpiece, is as a result of VAM application, when the duty cycle had non-
cutting time greater than cutting time. The combination of tool and workpiece displacement caused the tool tip to move relative to the displacement of the workpiece. The similarity indicates that both adding VAM to the tool or workpiece has the same role to improve the machine performance and machined surface quality.

![Kinematics of 2D VAM at the workpiece](image1)

![Locus scheme formation at 2D VAM-workpiece](image2)

![Kinematics of 2D VAM at the tool holder](image3)

Figure 2 Kinematics scheme for 2D VAM at workpiece and tool holder

The investigation on how to improve machined surface by using VAM on micro milling, had been carried out by many researchers, based on surface roughness value uniformity, surface roughness improvement, decreasing machining forces, decreasing flank wear, thin and segmented chip formation, are summarized in Table 1.

| Vibration mode                  | Researchers         | Frequency (kHz) | Amplitude (m) | Achievement                                                                 |
|---------------------------------|---------------------|-----------------|---------------|-----------------------------------------------------------------------------|
| 1D VAM at workpiece             | Shen et al.[19-21]  | 19.58           | 2.8           | Surface roughness uniformity, force reduction during machining, thinner and discontinuous chip formation |
| 1D VAM at tool holder           | Denkena et al.[6]   | 2:4             | 30            | Ability to make barcode but not all surface is readable by the scanner       |
|                                 | Ding et al.[17]     | 1               | 2             | Surface roughness reduction                                                 |
| 2D VAM at workpiece             | Ding et al.[22]     | 0.5-3           | 0.5-3         | Flank wear reduction ranging between 5-20%                                   |
|                                 | Jin & Xie[23]       | 5-11            | 1-4           | Surface roughness reduction ranging between 38-40%                          |
| 2D VAM at worktable of workpiece| Chern & Chang[24]   | 0.6             | 10            | Surface roughness reduction and increase the dimension accuracy of the product|
| 2D VAM at tool holder           | Hui Ding et al.[25] | 1:3             | 2.5;7.5       | Thinner and discontinuous chip formation                                     |
|                                 | Kim & Loh[5]        | 18              | 0.5-2.2       | Force reduction up to 50%                                                   |
3. Cutting Method

Toolpath relatively to workpiece can differentiate types of cutting method in VAM as shown in Figure 3, which summarized types of VAM based on the vibration direction and placement. VAM placement either on the tool or workpiece gives impact toward the tool path relative to the workpiece as investigated by Chen et al. [16, 18] where VAM at the workpiece and Brehl & Dow[11] where VAM at the tool. The tool-workpiece interaction influences machining forces.

Simulation and experimental is conducted to prove or find the significance level between the tool-workpiece interaction and machining force based on the types of material properties, such as 1D VAM application on Titanium[27] and on Carbon Fibre Reinforced Polymers(CFRP) [28], and also 2D VAM application on Al6061[17]. Tao et al. [27] presented force prediction model by varying feed per tooth and amplitude as time function against axial, radial and tangential force. Amin et al.[28] presented practical machining forces model based on the correlation between cutter angles (entry and exit) and chip thickness against axial and feed force. The practical model had limitation on the allowable maximum cutting angle which is 90°. Dedicated dynamic force model for 2D Vibration Assisted Micro End Milling (VAMEM) is presented by Ding et al.[17]. The presented machining force models above indicate the models are specifically made for certain material properties, product, and tool-workpiece interaction conditions.

4. VAM Design Development

Frequency influences the VAM specification selection, which will be applied as a vibration generator at the conventional machining[18]. VAM based on the applied frequency values is classified in to resonant and non-resonant types. Resonant uses frequency above 20 kHz with fix set up, amplitude 1-10 micron meters, and using horn or booster. While Non-resonant uses frequency within 1-40 kHz with adjustable set up, amplitude able to reach hundred micron meters, but the vibration effect hard to handle [11,12, 29]. Piezoelectric actuator is one of the favorable actuators by most researchers to be used as a vibration generator component. The actuator produces vibration by converting electrical signal in to mechanical energy in the form of repeatable displacement[3].

High precision machining such as adding VAM to multi axis micro machine demands durable machine with high static stiffness, low thermal distortion, low motion error, and high damping or dynamic stiffness[22, 30]. Figure 4 and 5 summarized the selected VAM development for milling process. The chorus of current VAM development are industrial demands fulfilment, investigation of optimal machining and vibration control parameter based on workpiece material properties, and improvement of the existing machine performance.

VAM application to make barcode from hard to machine alloy, with 1D VAM resonant (as shown in Figure 4(c)) [6], and 2D VAM application to make pattern for Light Incident Plane (LIP) from brittle material (as shown in Figure 5(b)) [31], had been conducted experimentally by varying machining parameter (cutting speed, width of cut, depth of cut, feed per tooth) and vibration control parameter (frequency and amplitude). Figure 4(c) showed piezo actuator is consists of actuator ring, flexure, tool holder, and disc spring. Figure 5(b) showed the component of VAM, which consists of servo motor, two parallel lead-screws, timing belt, linear motion guide, air dampers, base, and tool plate.

The investigation of VAM application to improve machined surface based on the material properties had been carried out for soft metal and alloy, hard to machine alloy, hard to machine steel, and brittle. Shen et al. [19, 20] and Ko et al. [32] investigated 1D VAM non-resonant application on soft metal and alloy, whilst Chern&Chang [24] investigated 2D VAM effect. Figure 4(d) showed 1D VAM resonant with transducer and horn with the ability to reduce machining force along with the increment of amplitude. Figure 4(e) showed 1D VAM resonant with stack up piezo actuator with the ability to decrease surface roughness, and the shearing process became easier due to the combination of effective rake angle, spindle speed, and depth of cut. Figure 5(g) showed 2D VAM resonant at the workpiece table is consists of workpiece holding block, linear grid way, piezoelectric actuator,
adapting plate, and spring base back. The combination between frequency, amplitude, spindle speed, and feed influenced the slot accuracy made by that 2D VAM resonant.

![Figure 3 Cutting method for VAM][12, 13, 16-18, 26]

Many researchers had conducted studies about 1D VAM and 2D VAM application on hard to machine alloy, by varying cutting speed, feed per tooth, width of cut, and amplitude set up against cutting forces, tool wear, and fatigue which occurred during machining. Most experimental studies for that hard to machine alloy used 5 axis milling machine but only 3 axes from the machine are being activated during machining. Suarez et al. [33] investigated 1D VAM application for Ni-Alloy 718, with 1D VAM design as shown in Figure 4(a). The 1D VAM is consists of piezoelectric-actuator, concentrating horn (booster), and tool holder. 2D VAM resonant application to ward hard to machine alloy had been conducted by Niu et al. [35] and Kim & Loh[5]. Figure 5(c) showed 2D VAM resonant which consist of an ultrasonic generator, a wireless transmission tool holder, a helical groove horn, and a tool. Figure 5(d) showed 2D VAM resonant with the preload screw, which had the ability to increase V-groove accuracy and the formation of the thin and curly chip.

The application of 2D VAM non-resonant, on BK-7 optical glass is conducted by Jin & Xie[23] as shown in Figure 5(e) thru experimental. The experimental results are surface roughness improvement happened along with the frequency increment, and steady tool-workpiece separation occurred. 1D VAM resonant application to cut bones (composite looks alike material) has been carried out by Alam et al. [34] as shown in Figure 4(b). The VAM component for bone is consists of a transducer, concentrator, and tool holder. The Experimental results showed cutting forces decreased along with depth of cut decreased, and frequency and cutting speed didn’t give significant effect toward cutting force. Ding et al. [22] investigated the 2D VAM application on hard to machine steel (HRC 55 and HRC 58), by using 2D VAM non resonant, as shown in Figure 5(f) and the investigation results are machined surface quality lower than CM, and flank wear 5-20% below CM. Ammouri et al. [36] introduced 2D VAM design with spoon feeding-like movements, to create groove and in order to improve machine performance. The spoon feeding-like design is as shown in Figures 5(a), which consists of two stacked ceramic multilayer actuator rings and a fixture.

Those previous design development showed that: VAM can improve the machined surface for various material; different machining and vibration control parameter set up produce different machined surface quality; tool-workpiece interaction determines machining forces, which require kinematic model for each type of VAM application; non-resonant VAM gains more attention due to its compact feature, controllable frequency, and uniform displacement and resolution; VAM application to an existing machines requires an evaluation of the machine construction capability to absorb vibration and assembly aspect between VAM and machine.
5. Crucial Aspects in Adding AM to Micro Machining

Review paper is conducted to elaborate the important aspects to install VAM to an existing machine, in order to increase machine performance or improve the quality of machined surface.

5.1. Machine construction and system

The capability of machine construction to absorb vibration determines the stability of the machining process, which is represented by the natural frequency and voltage due to mass and damping load during machining. The natural frequency of existing machine must be known before VAM added, because that frequency cannot be equaled by other additional system, in order to avoid chatter. Tool-workpiece interaction influences machining forces, the most, therefore kinematic evaluation of tool path relative to workpiece during VAM application is a must. The kinematic evaluation can be conducted by many ways and among those are simulation surface generation [17], natural frequency simulation [35], and force simulation and experimental [37]. VAM development from an existing micro machining must consider machine scale, cutting force, the effect of dimension, burr formation and tool size. Consequently, the evaluation of rigidity, mass, and damping of the machining system must be done thru kinematics model and experimental. The evaluation results determine the frequency range that will be used in selecting actuator.

5.2. Actuator

Piezoelectric actuators, especially standing wave or displacement types is widely used as vibration generators in micro machining processes such as for 2D VAM in the turning process [29], 1D VAM in the milling process [6, 19, 32-34], and 2D VAM in the milling process [5, 22-24, 31, 35, 36], because of its superiority [38], which are: large output torque, direct drive, not using a gearbox or brake mechanism,
without bearing, no backlash, not affected by the electric field from the outside, compact design, and low voltage. Piezoelectric actuators selection for VAM which is added to multi axis micro machines, must considers working envelope of the machine, piezoelectric actuator specification and the assembly effect between VAM and machine. The intervention of the working envelop will obstruct the tool path relative to workpiece. Those specifications effect machining stability, frequency selection, and energy sources determination for the actuator.

| VAM Types          | Vibration mode | Tool | Workpiece |
|--------------------|----------------|------|-----------|
| Non-resonant 2D VAM | (a) Bi-directional VAM at tool with stack up actuator[36] | (c) VAM with longitudinal and torsional vibration direction [35] | (e) VAM with flexure[23] |
| Resonant 2D VAM    | (b) Adjustable vibration direction VAM for sheet metal shaping[31] | | (f) VAM at workpiece holder[22] |
|                    | (d) VAM with preload screw[5] | | |

Figure 5 Selected 2D VAM design

The assembly between the VAM and the machine must be considered because the connection will receive loads in the form of mass and damping during machining, so the overall rigidity of VAM system which include machine must evaluated before VAM installment. Therefore VAM requires fasteners with high rigidity and joints with strong bound, to attached VAM to the machine.

5.3. Types of VAM

VAM application to improve machined surface is obtained from the implementation of high frequency and low amplitude, so material removal rate (MRR) increase. Frequency and amplitude set up at VAM
and VAM placement at the machine, will determine VAM types to be used. VAM types affect the tool-workpiece separation pattern especially VAM which is placed at the workpiece [39]. Hence to that VAM additional to multi axis machine requires further kinematic development which based on tool dynamic movement relative to workpiece and workpiece properties.

5.4. Types of material and product complexity

Each material types has different machinability level, whether it is ductile, brittle or composite, so the material characteristics are an important aspect to be considered in the development of VAM [13]. Pattern or texture is successfully proven to be produced by 2D VAM by previous experimental studies. Machining for the pattern or texture requires uniformity in dimensions and surface roughness, and also stability of machining and vibration control parameter set up.

6. VAM Benefit for Micro Machining

6.1. Machining forces

VAM placement on the tool or workpiece decreases machining forces, because both placements make the tool to conduct elliptical path for 2D VAM and leaping path for 1D VAM, which cause separation period between tool and workpiece. So VAM application causes intermittent process during machining, where tool-workpiece separation occurred for period of times. The tool-workpiece separation influences machining and vibration control parameter set up, chip formation, and machined surface quality. The machining forces influences micro machine sensitivity toward vibration and allow tool lifetime extension.

6.2. Machined surface quality

The surface profile resulted from micro machining is in the form of waviness which have sharp peak and valley. Tool geometry causes those waviness and flaw occurrence. The application of VAM makes the tool perform a cutting process resembling grinding process due to the tool cuts off all the surface profile that has been machined beforehand. That tool performance causes the overall waviness cut by the tool and as a result producing smoother surface. Setting machining parameters and vibration control parameters play an important role toward machined surface quality made by VAM. The VAM application is able to improve the machined surface quality in comparison to machining without VAM.

7. Conclusion

Adding VAM to the machining process with the aids of piezoelectric actuators has been successfully developed for more than 1 decade to create patterns and textures. VAM research trend is lead to VAM development for micro milling, because milling superiority to make micro product in comparison to others machining process. VAM application influences the tool-workpiece interaction, machined surface quality, and chip formation. The review showed: The phenomenon that occurs during the machining process with VAM is formed by the relationship between feed rate, depth of cut, frequency and amplitude, against machining forces, surface roughness, and chip types; Adding VAM to micro machining process especially micro milling with multi axis requires evaluation of natural frequency and constrains from the existing machine construction, movement synchronization between machine and VAM, actuator characteristic, and assembly aspects between VAM with existing machine; and The research opportunities to develop VAM is still widely open for 2D VAM Non-resonant at the workpiece.

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