12th GLOBAL CONGRESS ON MANUFACTURING AND MANAGEMENT, GCMM 2014

Vibration Assisted Conventional and Advanced Machining: A Review

Maroju Naresh Kumar[a]*, Kanmani Subbu S.[b], Vamsi Krishna P.[c] and Venugopal A.[d]

[a,b,c,d] *Department of Mechanical Engineering, National Institute of Technology Warangal, 506004, Andhra Pradesh, India.*
[a]*maroju.nareshkumar@gmail.com,* [b]*sksubbu@nitw.ac.in,* [c]*vamsikrishna@nitw.ac.in,* [d]*venu@nitw.ac.in.*

Abstract

Increasing demand for precision miniaturised components made of hard and brittle materials can no longer meet the requirements by conventional machining and advanced machining processes. To facilitate high precision machining, vibration is introduced in any of workpiece, tool and working medium, which is called Vibration Assisted Machining (VAM). In this review, the advancements of VAM in conventional machining as well as in advanced machining are presented. In detail, general overview, classifications, basic kinematics of 1-D and 2-D VAM, chip formation and instrumental implementation issues of VAM, are discussed. In addition to this the reasons for improvements in machining process and promising areas to be explored in VAM are summarized.

*Keywords:*Vibration; Precision machining; VAM; Micro machining.

1. Introduction

The need for micro featured components with high precision, made of hard and brittle materials such as glasses, lens, advanced ceramics, high strength alloys, mono crystalline materials etc. are required for industries like aerospace, electronics, bio-medical, power generation and etc. Hence development of high precision machining in recent years has been focused on machining of micro scale parts with high surface finish [1,2,11,14,16,17,18,20,23].

─────────

* Corresponding Author. Tel +91-770-235-4525;
 *E-mail address:*maroju.nareshkumar@gmail.com.

Conventional machining techniques can no longer meet the requirements of machining meso and micro components in precision. Although conventional and advanced ultra-precision machining can generally be used to machine the above said materials with high accuracy and precision are difficult. Generally the unit material removal is less along with critical depth of cut is 1 μm or less which leads to high precision in machining [1,2,22], but results in less surface finish and is more expensive [4,8]. Further, there is a need to eliminate or reduce the use of cutting fluids during machining due to their ecological hazards. To achieve better surface finish, high accuracy and high precision at low cost, the vibration is introduced, in any one of the tool, workpiece and working medium in conventional and advanced machining, hence is called Vibration Assisted Machining (VAM) [1,2,8,9,11,17,28]. It combines machining with small-amplitude vibration to improve the process [1].

This paper provides a comprehensive review of VAM in conventional machining (turning, milling, drilling and grinding) and advanced machining (micro-EDM, laser machining, micro-ECM and abrasive machining). In addition to that advantages derived from using VAM are discussed.

2. Classification of VAM

The systems that work on VAM principle can be divided into two main classes based on the frequency of vibration:
- Resonant system: This system can only operate at discrete frequencies greater than 20 kHz, and produce displacement amplitudes less than 6 μm.
- Non resonant system: This system can operate at the range of operating frequencies (1 kHz – 40 kHz) as well as amplitudes 10 times greater than the resonant system.

Further these systems can be sub classified as two types based on mode of vibration introduced in tool or work piece, as shown in Fig.1.
- 1-Dimensional VAM: This system operates in a plane parallel to the work piece surface which is in line with the cutting force.
- 2-Dimensional VAM: This system produces an elliptical tool motion, where the major axis of the ellipse is in line with the cutting force and the minor axis is in line with the thrust force. The amplitude of vibration in each axis may or may not to be the same and is described as amplitude of vibration along major axis (A) × amplitude of vibration in minor axis (B) which is represented by A μm × B μm [1].
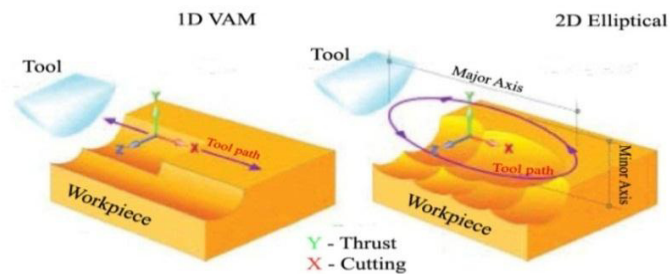

Fig.1. Types of VAM based on modes of vibration (a) 1-Dimensional VAM, (b) 2-Dimensional VAM [33].

2.1 Servo system of VAM

Resonant 1-D system is the most common type for VAM system used in applications. As shown in Fig.2 (a), an ultrasonic generator uses a piezoelectric or magnetorestrictive actuator to create reciprocating harmonic motion with high frequency and low amplitude. A shaped acoustical wave guide booster and horn (sonotrode) amplifies this ultrasonic motion. A cutting tool is attached at the end of the horn, aligned in such a way that the rake face of cutting tool is normal to the direction of vibratory motion. Typical amplitudes and frequencies are 3–100 μm and 20– 40 kHz, respectively [1].
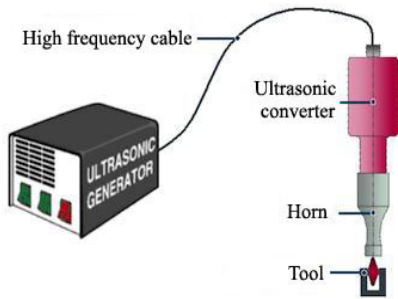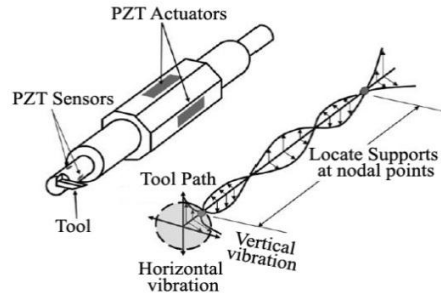
Fig.2 (a) 1-D VAM system.
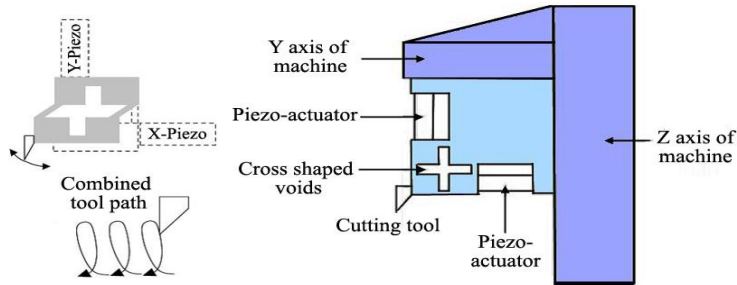
Fig.2 (b) 2-D Resonant system [1].

Fig.2 (c) 2-D Non resonant system [1].

2-D resonant system as shown in Fig.2 (b) induce a circular or elliptical tool motion by producing the supporting structure to vibrate at its resonant frequency in two dimensions. It can be also produced by placing tool away from the centerline of a 1-D VAM system. Typical frequencies are 20–40 kHz with tool path is 3 μm × 3 μm to 8 μm × 4 μm.

In 2-D non-resonant systems as shown in Fig.2 (c) the linear motion of the piezo stacks is converted into elliptical tool motion by a mechanical linkage. The flexure has an internal cross-shaped void to limit crosstalk between the two directions of motion and to eliminate shear stress in one stack by the motion of the other. The tool path generated is a quasi-ellipse. Typical frequencies are less than 1 kHz with tool path as 5 μm × 4 μm [1].

3. Kinematics of VAM

Fig.3 represents kinematics of 1-D VAM, tool is driven harmonically in a linear path, which is superimposed on the upfeed motion of the workpiece. At time t_1, tool rake face has come into contact with the uncut material and is starting to cut. Then at time t_2, the tool is at the extreme limit of the linear vibrating path with velocity equal to zero, and is about to return. In position 3, tool is withdrawn and in position 4, tool is advancing into contact with the workpiece and commences another machining cycle [1].
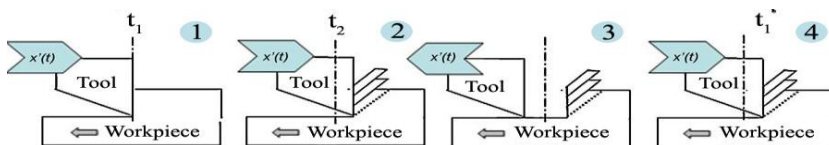
Fig.3. Principle of machining in 1-D vibration assisted machining [1].

3.1. Characterization parameters of 1-D VAM

Critical upfeed velocity (V_{crit}), for a given vibration frequency f, there exists $V_{crit} = 2\pi f A$ where, A= amplitude of vibration, below which the rake face of the tool will periodically break contact with the uncut material. Generally,

interrupted cutting, V < Vcrit, is desirable as most of the benefits are achieved [1]. F_{up}, it is the distance between equivalent points on the vibration path for successive cycles [1]. Duty Cycle, it can be defined as portion of each vibration cycle in which the tool is machining the workpiece. Fig.4 (a) interprets resultant relative motion generated by tool and work which represents the amount of cutting time. Horizontal speed ratio (HSR), it is the ratio between workpiece upfeed velocity and the peak horizontal vibration speed of the tool. Non-interrupted cutting occurs when HSR less than or equal to 1. Fig.4 (b) shows the effect of HSR on duty cycle.
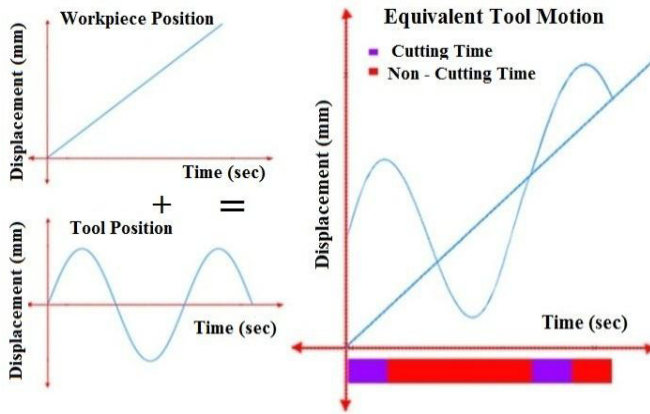

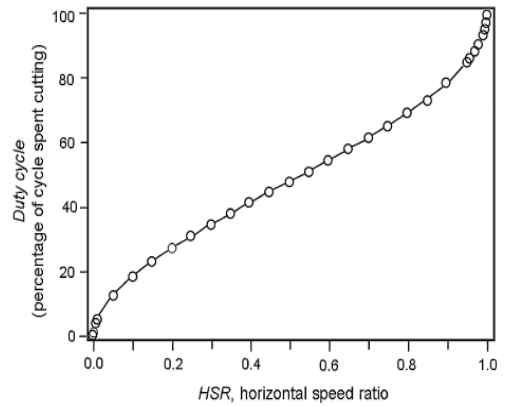Fig.4 (a) Duty cycle (amount of cutting time).   Fig.4 (b) Effect of HSR on duty cycle [1].

Fig.5 shows the kinematics of 2-D VAM, it adds vertical harmonic motion to the horizontal motion of 1D VAM. This causes the tool tip to move in a tiny circle or ellipse, which is superimposed on the upfeed motion.
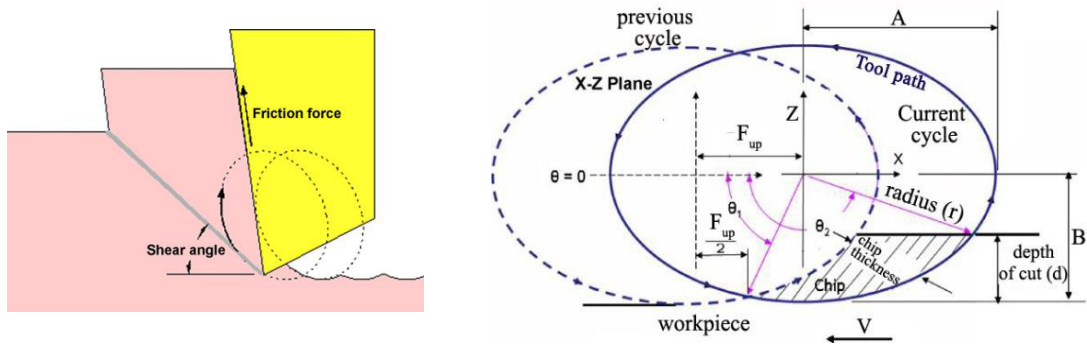

Fig.5. 2D-VAM and its tool path [1].

The characterizing parameters remain the same as that of 1-D VAM. However, duty cycle in 2-D VAM is defined as the length of the elliptical tool path in contact with workpiece, compared to the perimeter of the ellipse. Generally the maximum value for duty cycle in 2-D VAM is 0.5, which occurs when F_{up} is large enough that successive elliptical cycles do not overlap and when the depth of cut is greater than or equal to the ellipse vertical amplitude B [1].

3.2. Chip formation in 2-D VAM

The uncut chip area for each point goes on increasing as the tool progresses upward in its elliptical path, the rake angle becomes progressively more negative. The instantaneous direction of the tool motion relative to the workpiece results in instantaneous chance in rake angle and clearance angle. Parameters should be selected in such a way that

tool flank face should not touch the workpiece. Depth of cut (d) is responsible for determining whether the chip is continuous or segmented. Fig.6. shows the formation of different types of chips, when the depth of cut is smaller than the length of minor axis (B) of the ellipse, that is workpiece surface is below the centerline of the ellipse, a segmented or class B chip is generation. Conversely, when the surface is above the centerline of the ellipse, a continuous chip or class A chip is generated [1,2,5,11,33].
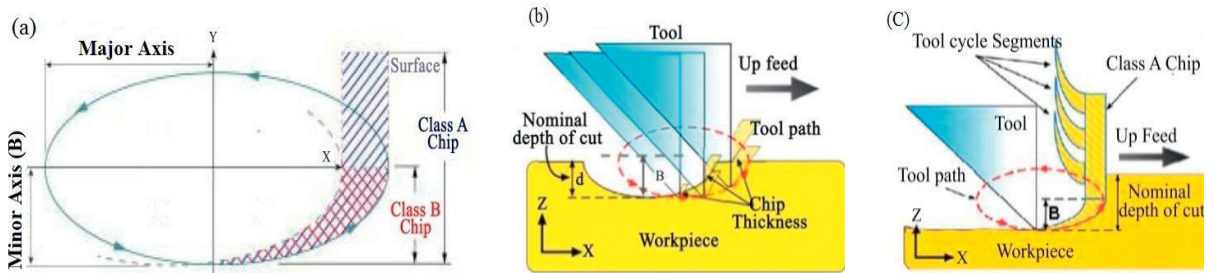

Fig.6. Chip formation (a) 2-D VAM, (b) Discrete thin chips formation when $d/B \leq 1$, (c) continuous thin chips formation when $d/B > 1$ [33,1].

4. Advancements of VAM in conventional machining

4.1 Ultrasonic assisted turning (UAT)

The ultrasonic assisted turning (UAT) has been found to be very effective in machining of high strength alloys such as titanium alloys and nickel alloys [2,3,8], and difficult to machine condition like diamond turning of ferrous and brittle materials [9,10]. Which is to overcome high heat generation and consequent rapid wear of cutting tool edges that occur during conventional turning (CT) [2,5,6,8]. Fig.7 (a) shows the stresses induced at conventional and ultrasonic assisted turning. It is clearly observed that in UAT periodic relaxation reduces effective stresses up to 50 %. Fig.7 (b) shows the level of stresses compared in conventional turning as well as in UAT. There is a 40–45 % reduction in cutting forces, the average cutting force drops to 40 % of the conventional cutting as shown in Fig.7 (c) There is a measurable reduction in normal, thrust forces and cutting temperature hence improving the tool life. During UAT less residual stresses are induced in work and quality of the machined surface is improved [2,3,4,5,6].
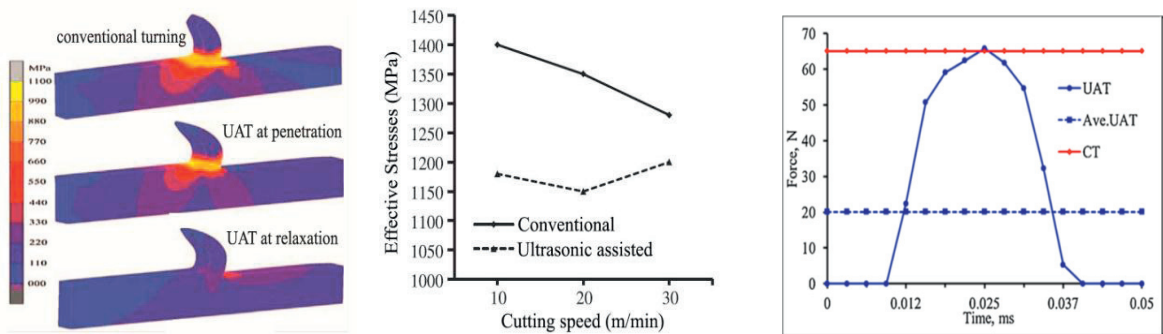

Fig.7 (a) Stress distribution in CT and UAT [2],   Fig.7 (b) Effect of cutting speed on stresses[3],   Fig.7 (c) Comparison of cutting forces [2]

4.2. Vibration assisted milling

Micro-milling of high strength, low thermal conductivity and high work hardening tendency of work materials such as optical glasses, hard materials and composites, VAM techniques have been adopted widely. Fig.8. shows a qualitative comparision of cutting action between vibration assisted and conventional milling. Vibration assisted

milling facilitate consecutive overlapping of toolpaths which results in chips that are thinner than the feed per tooth in conventional milling, leads to reduction in tool forces and heat generated. In addition to that tool life, machining efficiency and material removal rate are enhanced [11,12,13,33].
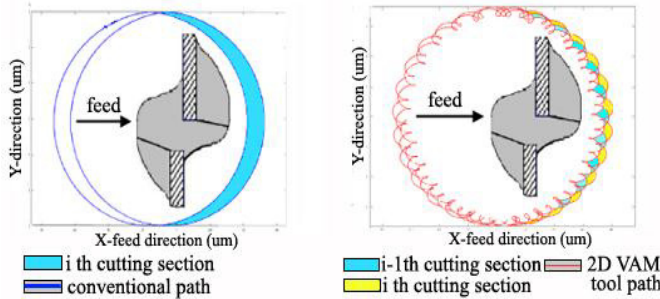

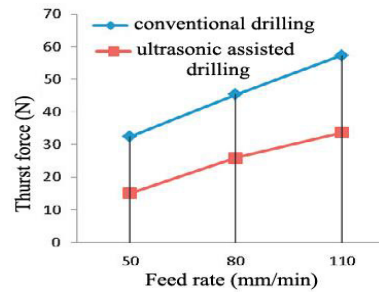Fig.8. Mode of machining in conventional and 2-D VAM milling.

Fig.9. Comparison of thrust forces in drilling [18].

4.3. Vibration assisted drilling (VAD)

Drilling of deeper holes in difficult to machine materials such as hard alloys, composites and brittle materials, vibration assisted drilling is found effective. It is observed that there is no compromise in material removal rate during drilling of deeper holes in particle reinforced, polymer reinforced and laminated composites for better accuracy and precision. Fig.9. shows comparison of thrust force in VAD and conventional drilling, it is clearly seen there is reduction of thrust force and tool wear [14,16]. Further, there is reduced burr size and less chance of built-up-edge that results in improved quality of the machined surface, which is due to formation of discrete chips in VAD [16,17]. Fig.10. shows the delamination of laminated composites while drilling of deeper holes in conventional drilling, which can be prevented in case of VAD due to less thrust force [15,18,19].
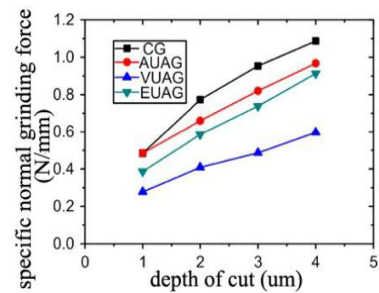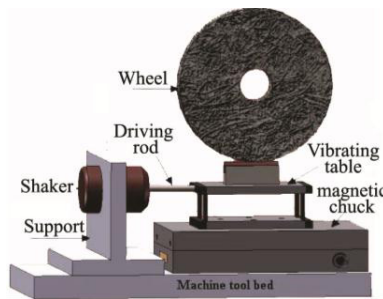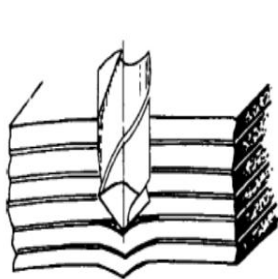

Fig.10. Delamination in conventional drilling   Fig.11. Ultrasonic assisted grinding setup   Fig.12. Comparison of specific grinding forces [20]

4.4. Ultrasonic assisted grinding (UAG)

Conventional grinding (CG) of hard and brittle materials such as glass, ceramic, composites and silicon leads to severe sub-surface damages, cracks, and rapid wear of grinding wheel abrasives, because of the large grinding forces and high grinding temperature. Ultrasonic assisted grinding [1-D axial (AUAG), 1-D vertical (VUAG), 2-D elliptical (EUAG)] is used to overcome the difficulties. Fig.11. shows generalized setup of UAG. Fig.12. shows the reduction of cutting forces in various UAG compared to CG. In UAG improved surface finish is observed due to lapping or polishing effect. Furthermore, enhanced coolant delivery over the entire contact zone helps in heat removal from the grinding zone facilitated by periodic separation [20]. Vibration allows the abrasives to cut with more than one cutting edge and also in self-sharpening process of the grinding wheel that reduces the load per grain, therefore reduces the wear of grinding wheel [20,21].

5. Vibration assisted non-conventional machining

5.1 Vibration assisted micro-electro discharge machining

Micro-EDM is a machining technique primarily used for precision machining of hard metals such as titanium, kovar, inconel and shaping of polycrystalline diamond tools. However during machining due to the improper flushing out the debris, frequent adhesion between tool electrode and workpiece prevents the stability of the machining. To overcome these difficulties, vibration is found helpful in flushing out debris from the gap between the tool electrode and work piece, which helps in extreme reduction of the machining time and improvement in process stability. Fig.13. shows the mechanism of machining of vibration assisted micro EDM. The periodic separation of tool from the work piece facilitates flushing the adhered debris out for each machining cycle inducing proper electric discharge per cycle. Thus resulting in enhanced material removal rate by 11 % and reduced relative tool electrode wear by 21 % [23,24]. Fig.14. shows a quantitative comparison of machining time in vibration assisted and conventional micro EDM with various types of operations, higher frequency and larger amplitude vibrations results in shorter machining times [24].
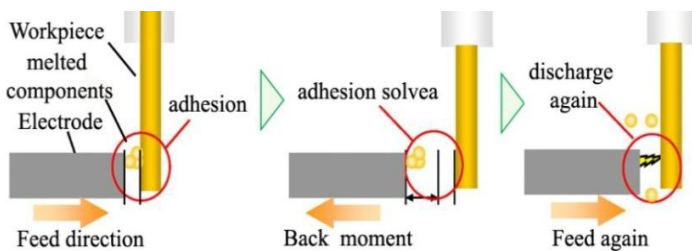

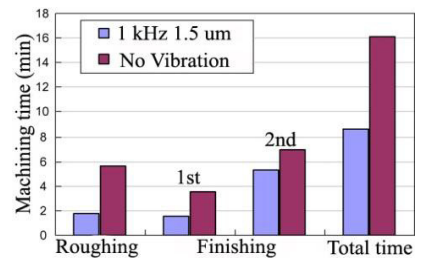Fig.13. Mechanism of micro EDM with VAM [23].

Fig.14. Comparison of machining time with or without vibration in micro EDM [23].

5.2. Vibration assisted laser machining

Laser machining is widely used in various industrial and medical fields because of its high precision, and eco-friendly features compared to conventional machining particularly in micro machining of hard substrates such as ceramic, silicon, diamond, and graphite. Vibration assisted laser machining is an effective method to release the local energy concentration because high frequency repetitive motion distributes spatially concentrated energy uniformly, which further improve surface finish, reduced surface oxidation [26,27] and increased aspect ratio of machined features [25]. Fig.15. shows that a deeper hole with good surface finish can be generated by vibration assisted laser machining with same energy density as that of conventional machining [26].
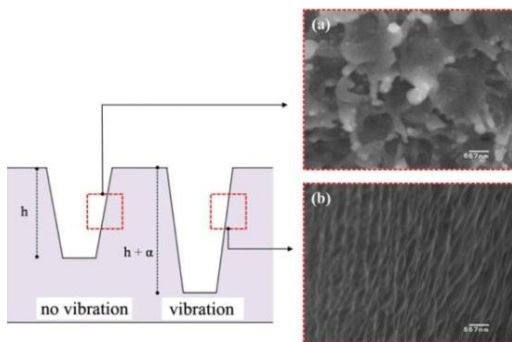

Fig.15. SEM of laser machined hole
(a) With no vibration assistance   (b) vibration assistance [25].
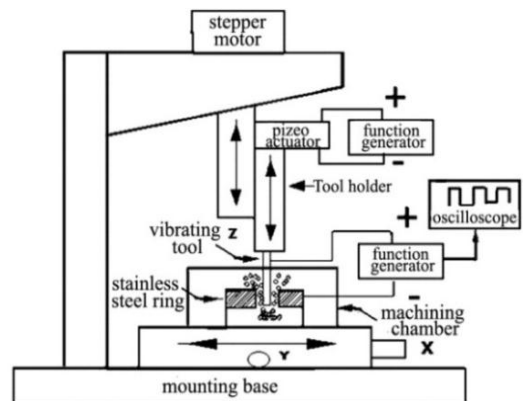

Fig.16. Experimental set up for vibration assisted ECM [28].

5.3. Vibration assisted electrochemical micro machining (VAECMM)

ECMM is an important technology in machining difficult-to-cut materials and to shape free-form surfaces without any residual stress. For ultra-precise micromachining, micro tool is very much essential, good quality micro tools with different shapes can be fabricated by controlling a proper diffusion layer thickness within a very short time by introducing the vibrations [27]. Fig.16. depicts the experimental setup of vibration assisted electrochemical micro machining. The aid of vibration results in improvement of heat generation required for machining and reaction products removal out of machining area [28]. Along with generating the optimal hydrodynamic conditions, increasing coefficient of machinability and decreasing the surface roughness (Ra) in comparison with conventional electrochemical machining [29].

5.4. Vibration assisted abrasive machining (VAAM)

Micro and nano abrasive machining is used for machining a wide range of materials such as ceramics, silica and hardened steels. High-precision and accuracy can be achieved by inducing vibrations (1-D, 2-D and 3-D with less frequency ≤ 1 kHz) on abrasives through tool. Fig.17. shows the excitation of abrasives in between tool and workpiece in VAAM. Fig.18. shows the material removal by abrasives where less unit material removal is achieved with high precision surface finish [30], further the tool wear is significantly reduced [31,32].
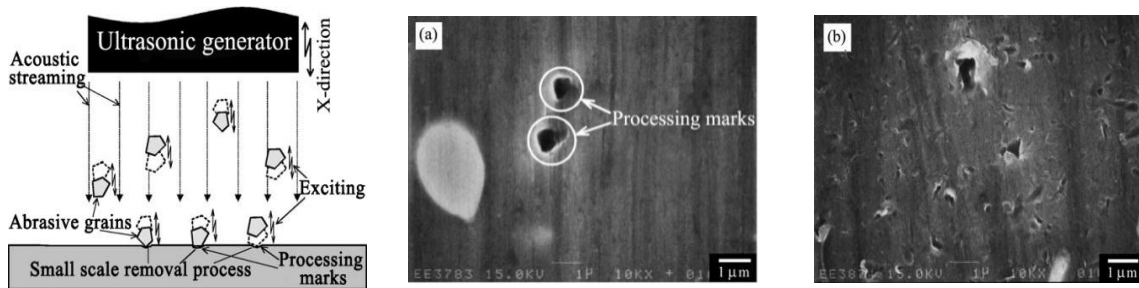

Fig.17. Vibration assisted Abrasive Machining   Fig.18. Processing marks due to abrasives in (a) water, (b) water with 6 wt. % Al_2O_3 grains [30].

6. Discussion, reasons for improvements in machining process

6.1 Reduced forces and stresses

1-D and 2-D VAM mechanisms modify chip geometry as well as interactions between workpiece and the tool rake face results in thinner and shorter chips, hence required average force to remove the smaller volume is reduced. Further the reduced force induces less stresses and periodic separation helps in relieving the stress in hot condition, resulting in improved lubrication. Also tool velocity exceeding the chip velocity produces a reversed tool-chip friction force there by reducing the thrust force.

6.2 Reduced cutting temperatures

Periodic tool-work separation provide a gap to dissipate heat between tool and workpiece and better lubrication and cooling effects are achieved compared to conventional machining, where no lubrication occurs at high speed. Further the work-tool contact area varies at several points on the 2-D VAM elliptical path reducing the temperature.

6.3 Extended tool life

The reduced forces, stresses and periodic separation help the tool to release stresses which will results in improvement of tool life, especially in case of difficult to machine material. The intermittent contact between tool and work material in VAM reduces, time available for other wear reactions is reduced and allows the tool to cool down considerably.

6.4 Better surface finish and form accuracy

VAM uses tool with round-nose tool while avoiding chatter, lower thrust forces decrease the amplitude of tool vibration relative to the workpiece. Uniform alternating cycles between tool and work provide confined uniform cracking and material removal. Lower friction induces lower temperatures and reduced subsurface cracking and also small discontinuous chips lowers surface roughness.

6.5 Ductile regime machining of brittle materials

When depth of cut is carefully controlled to a small value many brittle materials behave like ductile materials while machining and producing chips by means of plastic flow with minimal subsurface cracking. Smaller tool forces in VAM reduce the depth below the machined surface to which micro fractures propagate and also increase the depth to which ductile regime machining can be achieved.

6.6 Suppression of burr formation

Burr formation is due to the result of instantaneous compressive and bending stresses caused by cutting in the deformation zone at the edges of the cut. These stresses are greatly reduced with the help of VAM and formation of discrete chips which is facilitated by round-nose tool due to less thrust forces.

7. Conclusion and future scope

1-D and 2-D vibration assisted machining (VAM) are described along with their classification, basic kinematics, chip formation, instrumental issues and characterizing parameters of VAM are emphasized. The difficulties involved in conventional machining are addressed in VAM, improvements in machining process and the reasons for these improvements are presented. VAM is found to be effective in advanced machining techniques in improving the process stability and quality of the products. VAM can be applied to almost all the precision machining techniques. Although proper mechanics of the machining process supporting the improvements in machining have to be developed and further reasons for the improvement in processes are yet to be studied in depth.

References

[1] D.E. Brehl, T.A. Dow, Review of vibration-assisted machining, Precis. Eng. 32 (2008) 153–172.

[2] R. Muhammad, N. Ahmed, A. Roya, V.V. Silberschmidta, Numerical modeling of vibration-assisted turning of Ti-15333, Procedia CIRP. 1 (2012) 377–382.

[3] S. Patil, S. Joshi, A. Tewari, S.S. Joshi, Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V, Ultrason. 54 (2014) 694-705.

[4] P. Guo, K.F. Ehmann, An analysis of the surface generation mechanics of the elliptical vibration texturing process, Int. J. Mach. Tools Manuf. 64 (2013) 85-95.

[5] H. Jamshidi, M.J. Nategh, Theoretical and experimental investigation of the frictional behavior of the tool–chip interface in ultrasonic-vibration assisted turning, Int. J. Mach. Tools Manuf. 65 (2013) 1–7.

[6] A.S. Adnan, S. Subbiah, Experimental investigation of transverse vibration-assisted orthogonal cutting of AL-2024, Int. J. Mach. Tools Manuf. 50 (2010) 294–302.

[7] J.L. Overcash, J.F. Cuttino, Design and experimental results of a tunable vibration turning device operating at ultrasonic frequencies, Precis. Eng. 33 (2009) 127–134.

[8] Naseer Ahmed, Ultrasonically assisted Turning: effects on surface roughness, World Appl. Sci. J. 27 (2013) 201-206.

[9] X. Zhang, A.S. Kumar, M. Rahman, C. Nath, K. Liu, Experimental study on ultrasonic elliptical vibration cutting of hardened steel using PCD tools, J. Mater. Process. Technol. 211 (2011) 1701–1709.

[10] J.C. Outeiroa, J.P. Costesa, J.R. Kornmeierb, Cyclic variation of residual stress induced by tool vibration in machining operations, Procedia CIRP. 8 (2013) 493–497.

[11] H. Ding, R. Ibrahim, K. Cheng, S.-J. Chena, Experimental study on machinability improvement of hardened tool steel using two dimensional vibration-assisted micro-end-milling, Int. J. Mach. Tools Manuf. 50 (2010) 1115–1118.

[12] X.-H. Shen, J.-H. Zhang, H. Li, J.-J. Wang, X.-C. Wang, Ultrasonic vibration-assisted milling of aluminum alloy, Int. J. Adv. Manuf. Technol. 63 (2012) 41–49.

[13] H. Liana, Z. Guoa, Z. Huanga, Y. Tanga, J. Songa, Experimental research of Al-6061 on ultrasonic vibration assisted micro-milling, Procedia CIRP. 6 (2013) 561–564.

[14] S.S.F. Chang, G.M. Bone, Thrust force model for vibration assisted drilling of aluminum 6061-T6, Int. J. Mach. Tools Manuf. 49 (2009) 1070–1076.

[15] V.A. Phadnis, A. Roy, V.V. Silberschmidt, A finite element model of ultrasonically assisted drilling in carbon/epoxy composites, Procedia CIRP. 8 (2013) 141–146.

[16] M.A. Kadivar, J. Akbari, R. Yousefi, A. Rahi, M. Ghahramani Nick, Investigating the effects of vibration method on ultrasonic-assisted drilling of Al/Sicp metal matrix composites, Rob. Comput. Integr. Manuf. 30 (2014) 344–350.

[17] M. Aziza, O. Ohnishib, H. Onikurab, Novel micro deep drilling using micro long flat drill with ultrasonic vibration, Precis. Eng. 36 (2012) 168–174.

[18] P. Mehbudia, V. Baghlania, J. Akbaria, A.R. Bushroab, N.A. Mardib, Applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates, Procedia CIRP. 6 (2013) 577–582.

[19] S. Aoki, S. Hirai, T. Nishimura, Prevention from delamination of composite material during drilling using ultrasonic vibration, Key Eng. Mater. 291– 292 (2005) 465–470.

[20] Z. Liang, Y. Wub, X. Wanga, A new two-dimensional ultrasonic assisted grinding (2D-UAG) method and its fundamental performance in mono crystal silicon machining, Int. J. Mach. Tools Manuf. 50 (2010) 728–736.

[21] J. Liu, D. Zhang, L. Qin, L. Yan, Feasibility study of the rotary ultrasonic elliptical machining of carbon fiber reinforced plastics (CFRP), Int. J. Mach. Tools Manuf. 53 (2012) 141–150.

[23] T. Endo, T. Tsujimoto, K. Mitsui, Study of vibration-assisted micro-EDM–the effect of vibration on machining time and stability of discharge, Precis. Eng. 32 (2008) 269-277.

[24] E. Uhlmann, D.C. Domingos, Investigations on vibration-assisted EDM-machining of seal slots in high-temperature resistant materials for turbine components, Procedia CIRP. 6 (2013) 71–76.

[25] J.-K. Park, J.-W. Yoon, S.-H. Cho, Vibration assisted femtosecond laser machining on metal, Opt. Lasers Eng. 50 (2012) 833–837.

[26] B. Kang, G.W. Kim, M. Yang, S.-H. Cho, J.-K. Park, A study on the effect of ultrasonic vibration in nano second laser machining, Opt. Lasers Eng. 50 (2012) 1817–1822.

[27] W.-J. Kim, F. Lu, S.-H. Cho, J.-K. Park, M.G. Lee, Design and optimization of ultrasonic vibration mechanism using PZT for precision laser machining, Phys. Procedia. 19 (2011) 258–264.

[28] B. Ghoshal, B. Bhattacharyya, Influence of vibration on micro-tool fabrication by electrochemical machining, Int. J. Mach. Tools Manuf. 64 (2013) 49–59.

[27] Sebastian Skoczypiec,   Research on ultrasonically assisted electrochemical machining process, Int. J. Adv. Manuf. Technol. 52 (2011) 565–574.

[29] U.S. Kim, Y.J. Jung, J.W. Park, Vibration electrochemical micromachining based on coulostatic analysis, Int. J. Appl. Phys. Math. 3 (2013) 123-126.

[30] Y. Ichida, R. Sato, Y. Morimoto, K. Kobayashi, Material removal mechanisms in non-contact ultrasonic abrasive machining, Wear. 258 (2005) 107–114.

[31] A. Curodeau, J. Guay , D. Rodrigue, L. Brault, D. Gagne, L.-P. Beaudoin, Ultrasonic abrasive micro-machining with thermoplastic tooling, Int. J. Mach. Tools Manuf. 48 (2008) 1553–1561.

[32] S. James, M.M. Sundaram, A feasibility study of vibration-assisted nano-impact machining by loose abrasives using atomic force microscope, J. Manuf. Sci. Eng. 134 (2012) 061014- (1-11).

[33] MA Cerniway, Elliptical diamond milling: kinematics, force, and tool wear. MS thesis. North Carolina State University, 2001.