Chapter 2
Recent Advancement on Ultrasonic Micro Machining (USMM) Process

S. Das, B. Doloi and B. Bhattacharyya

Abstract There are a lot of developments in the micro manufacturing methods for the production of the three-dimensional miniaturized products made up of different advanced materials. Ultrasonic micro machining is an essential technique for the fabrication of micro parts on the hard, brittle and non-conductive materials like glass, ceramics and silicon with high aspect ratio. Ultrasonic micro machining is the mechanical type non conventional micro machining process. Material removal mechanism of USMM is similar to macro ultrasonic machining process. Adequate surface finish with stiff tolerances and dimensions can be achieved by ultrasonic micro machining (USMM) on hard and brittle materials. During the last decades, a number of researchers have explored experimentally and theoretically this ultrasonic micro machining (USMM) process technique with different materials. Recent development on ultrasonic micro machining (USMM) process has been highlighted and discussed in details with different types of ultrasonic micro machining (USMM) set up and material removal mechanism. Design and developments of micro-tools for USMM process have also been discussed. Influences of different process parameters on various responses of USMM have been discussed here.

S. Das (✉) · B. Doloi · B. Bhattacharyya
Production Engineering Department, Jadavpur University, Kolkata 700032, India
e-mail: somnath96@gmail.com

B. Doloi
e-mail: bdoloionline@rediffmail.com

B. Bhattacharyya
e-mail: bb13@rediffmail.com

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2.1 Introduction

Fabrication of the miniaturized products with multi functions are the urgent need of manufacturing industry. Micro-parts are required to meet the increasing demands in various areas like electronics, aerospace, automotive, medical devices, etc. The main advantage of those miniaturized products are small space requirement, less energy and material consumption, easiness in delivery and less price of the product.

Now the products with the extraordinary characteristic of materials such as high hardness, strength, corrosion resistant and heat resistant etc. are machined at the micron range of dimensions. Production of complex 3D miniature components such as fabrication of micro holes in thousand numbers on filters for processing food and textile industries, which are not possible by any conventional machining methods. Such features on those components can get only through the non-conventional micro machining process.

The generation of micro machining features on ceramics, glass, carbides and metallic alloys, etc. by traditional machining method is tremendously difficult and it also takes more time. Adequate surface finish with stiff tolerances and dimensions can be achieved by ultrasonic micro machining (USMM) on hard and brittle materials. Other Non Traditional machining process like μEDM, μECM, and LBM etc. can't machine those materials in proper shape and size [1]. Using other non-traditional machining process it is difficult to machine square, irregular and complex shaped holes and surface impressions. Ultrasonic micro machining (USMM) can be used for those purposes. Any hard and fragile material can be machined using USMM. The main advantage of ultrasonic micro machining process is that it can machine any electrical conductive and non-conductive materials [2]. Micro tool development and fixing on the USMM system is the very much problematic area. This problem can be eliminated by micro tool development with the help of wire electro-discharged grinding (WEDG) method and the same tool can be utilized to make micro-holes 5–20 μm in diameter on a silicon plate [3, 4].

A number of research works have been reported in micro-USM processes. Recent advancement on ultrasonic micro machining (USMM) process has been highlighted and discussed in details with different types of ultrasonic micro machining (USMM) set up and material removal mechanism. Design and developments of micro-tools for USMM process have also been discussed. Influences of different process parameters on various responses of USMM have been discussed in this chapter.

2.2 Fundamentals of Ultrasonic Machining (USM) Process

Ultrasonic Machining (USM) is a mechanical type non-conventional machining method used for machining both electrically conductive and non conductive materials, which have low ductility and a high hardness above 40 HRC such as ceramics, inorganic glasses, and quartz etc. The ultrasonic frequency of the tool is above 20 kHz with amplitude of 8–30 µm. Water based abrasive particles are supplied through the machining zone by a recirculation pump. The tool is pressed on the workpiece with fixed static load and the workpiece material is nonstop hammered by numerous abrasive particles with high kinetic energy imparted by the vibrated tool. Flushing of abrasive slurry refreshes the machining area and also removes the debris from the machining zone.

2.2.1 Background of USM

In 1927, R.W. Wood and A.L Loomis observed the drilling and cutting action with the help of ultrasonic vibration. After a long interval L. Balamuth proposed ultrasonic machining in 1942, while he was investigated the dispersion of solid in liquid by means of a magnetostrictively vibrating nickel tube. Several types of ultrasonic machine tool have been developed in recent year. The first communication on equipment and techniques for ultrasonic cutting appeared in 1953–54 [5]. Originally USM used to be a finishing operation for the component processed by the electro spark machines. However, this use becomes less important because of the development in electric discharge machining. But then with the boom in solid state electronics, the machining of electrically non-conducting, semi conductive, and brittle material become more and more important. For this reason, ultrasonic machining again gained importance and prominence. Through research and development on ultrasonic machining technology, different types of ultrasonic machining systems have been developed.

2.2.2 Process Development of USM

The material removal mechanism of ultrasonic machining process is purely mechanical. Figure 2.1 shows the various process equipments of ultrasonic machining process. In this process water based abrasive particles are presented to the machining zone.

Workpiece material does not depend on electrically conductive or chemically reactive in this machining process. Cutting, drilling and engraving is easily done by this machining method. The range of vibration of the tool is of 18–40 kHz and amplitude of 10–50 µm. Water based abrasive slurry is continuously supplied into the gap between the bottom area of the tool and the top surface of stationary workpiece. The tool is pressed with a static pressure depending on the size of the tool tip. The abrasive particles are hammered by the tool into the top surface of the workpiece, and as a result the particles abrade the workpiece material into a

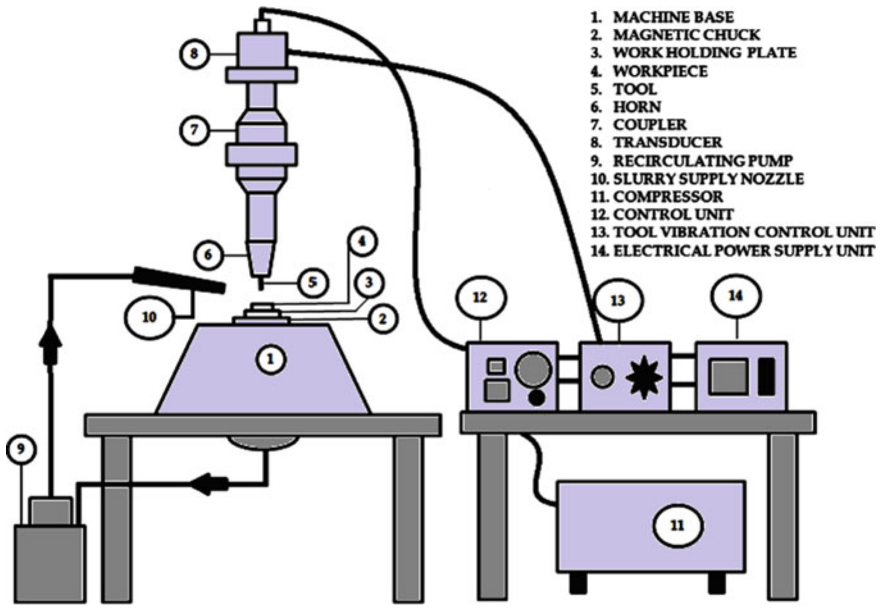

Fig. 2.1 Schematic diagram of ultrasonic machining set-up with process equipments

conjugate image of the tool form. Due to the fact USM is not restricted to the manufacture of circular holes. The tool can be prepared to the required shape, and therefore extremely complex shapes can be created on hard and brittle materials. Any damaging or thermal effects on the metallic structure of the workpiece does not found in this machining process.

2.2.3 Types of Machining Operation

Depending on the machining condition different types of ultrasonic machining is shown. The different types of machining configuration are discussed here.

i. **Stationary ultrasonic machining (USM)** is a non traditional machining process that removes material from the workpiece surface through high frequency with low amplitude vibrations of a tool against the material surface in the presence of water based abrasive particles. The low-frequency electrical signal is applied to the transducer for converting the electrical energy into high-frequency (above 20 kHz) mechanical vibration. This mechanical vibration is transmitted to the horn and tool assembly. The tool movements are vertically or orthogonal to the top of the workpiece surface. The abrasive grains are mixed with water is distributed across the tip of the tool. The abrasive particles are mixed with water and are hammered by the tool into the workpiece surface. Then the material is removed from the workpiece and the conjugate images of the tool form are produced [6].

ii. **Rotary ultrasonic machining (RUM)** is a hybrid machining process that combines the rotating diamond grinding tool with ultrasonic machining (USM). Higher material removal rates (MRR) are found using rotary ultrasonic machining. In this machine set up, a rotary core drill with metal bonded diamond abrasives tool is ultrasonically vibrated in the axial direction and the tool is fed toward the workpiece at a constant pressure. Coolant is pumped through the machining zone to prevent jamming of the tool and keeps it cool. RUM provides a fast, high-quality material removal process for a variety of glass and ceramic applications using abrasives bonded tools with combining rotation and vibration [7].

iii. USM combined with electric discharge machining [8].

iv. Ultrasonic supported cutting or grinding. Ultrasonic assisted turning is the most familiar process and is claimed to reduce machining time, residual stresses of the working zone and improve surface quality and tool life compared to conventional turning [9, 10].

2.3 Fundamentals of Ultrasonic Micro Machining (USMM) Process

The ultrasonic micro machining (USMM) process is copied from macro ultrasonic machining (USM) for micro machining on any hard and fragile materials. The tool frequency of USMM is above 20 kHz and lower amplitude of 0.5–5 μm. The abrasive particles size of USMM is few microns of 0.5–15 μm. The material removal mechanism is same as conventional USM.

2.3.1 Background of USMM

Masuzawa of Tokyo University in the mid 1990s was first attempted of downsizing macro-USM for micromachining [11]. The ultrasonic micro machining is used for producing micro feature on any hard and brittle materials such as any bio ceramic materials, glass and silicon etc. [12]. Ultrasonic micro machining has similar process parameters as macro-USM. However, the micromachining process requires a micro-sized tool with smaller amplitude, and micro-sized abrasive particles [13].

Table 2.1 Comparison of ultrasonic micro machining (USMM) and macro USM

Parameters	Ultrasonic micro machining (USMM)	MACRO-USM
Vibration frequency, kHz	Usually >20	Usually >20
Vibrated component	Tool or workpiece	Tool
Amplitude, μm	0.5–5 μm	8–30 μm
Abrasive particle size, μm	0.5–15 μm	50–300 μm
Static load	Gram force	Kilogram force
Tool diameter	<500 μm	>500 μm
Thickness of workpiece	maximum 3 mm	Maximum 50 mm
Tool material	Tungsten carbide (preferred)	Stainless steel (preferred)

2.3.2 Process Development of USMM

Ultrasonic micro machining (USMM) is a very essential micromachining method to generate micro features with high aspect ratio. Due to technological development, lot of improvements were done in the macro USM. Then the macro USM is converted into micro USM. A comparison of the Ultrasonic micro machining (USMM) and macro USM parameters are presented in Table 2.1.

2.3.3 Types of Ultrasonic Micro Machining Operation

Ultrasonic Vibration can be provided either in tool or in workpiece. There are three types of machining setup.

i. **μ-USM setup with Tool vibration**: Sun et al. developed μ-USM setup with provision of tool making using Electric Discharge Machining (EDM) and Wire electro Discharge Grinding (WEDG). In this μ-USM setup the tool is vibrated with ultrasonic vibration. The WEDG unit is permanently fixed on the machine body for grinding fine electrodes. Four axes X, Y, Z and C are numerically controlled by the machine. The μ-USM unit consists of a high frequency oscillation generator, transducer and horn-tool combination. Computer control system is used to control the operation of μ-USM setup [14]. Figure 2.2 shows the μ-USM setup with tool vibration.
ii. **μ-USM setup with Workpiece vibration**: The μ-USM setup with Workpiece vibration as shown in Fig. 2.3. In this setup a micro tool is holed properly and also rotated by a DC motor to move in X, Y and Z directions. Micro tools are prepared by wire electrical discharge grinding (WEDG). Due to sensitiveness, bending, vibration, and breakage of the micro tool, the controlled and limited

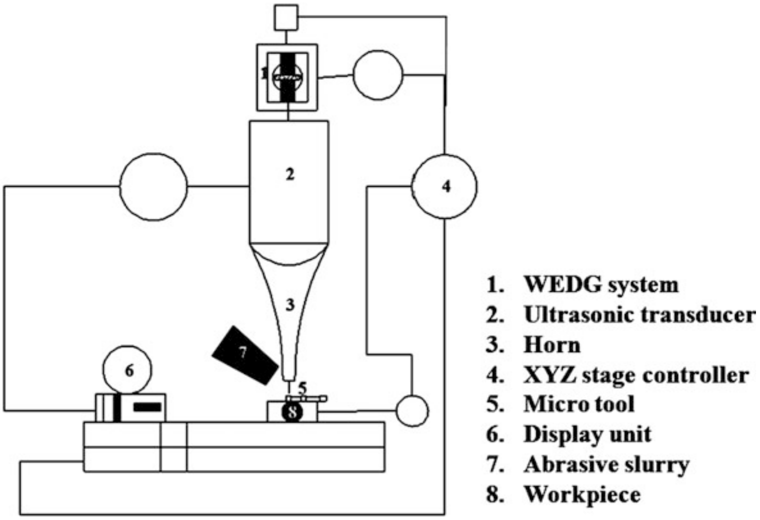

Fig. 2.2 Schematic diagram of μ-USM setup with tool vibration

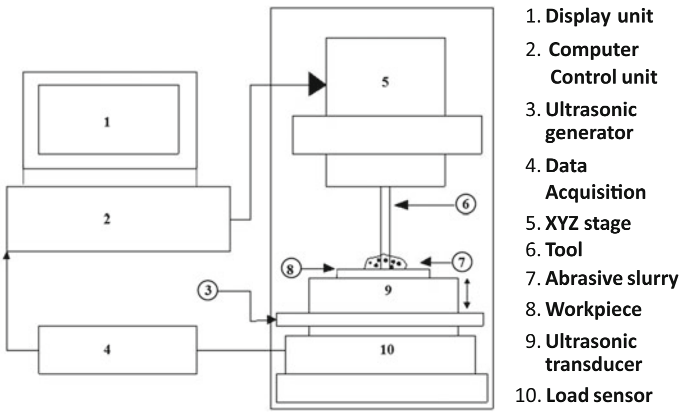

Fig. 2.3 Schematic diagram of μ-USM setup with workpiece vibration

contact force between tool and workpiece is required during machining. A close-loop control system with force feedback from an electronic balance is implemented in this machining set up, which is positioned near the vibrator. The contact force between the tool and workpiece is regulated by this system [15].

iii. **μ-RUSM setup with Workpiece vibration**: Micro rotary ultrasonic machining (MRUM) experimental set up is discussed here. Figure 2.4 exhibits the schematic diagram of micro rotary ultrasonic machining.

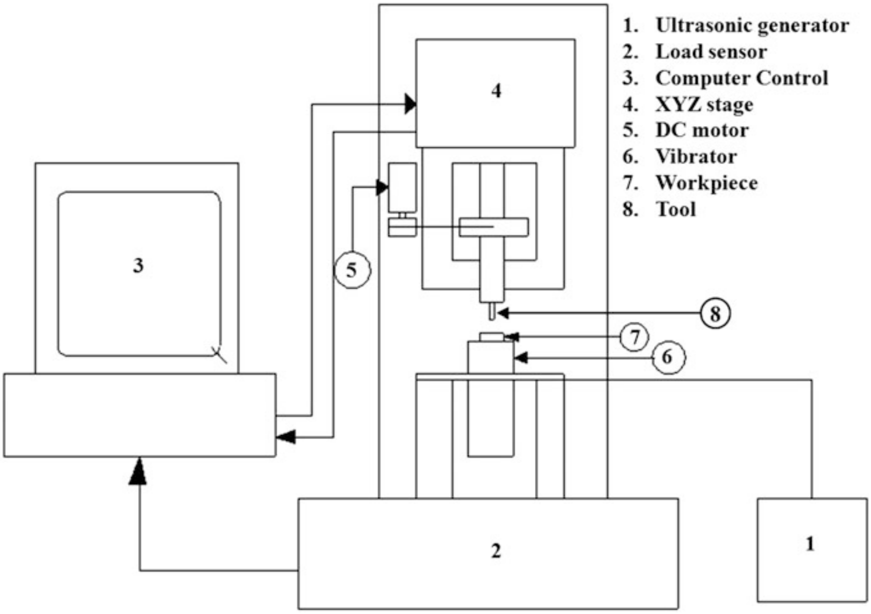

Fig. 2.4 Schematic diagram of micro rotary ultrasonic machining

The basic component of the micro rotary ultrasonic machine system is ultrasonic vibration system (transducer and generator), positioning system (XYZ-stages), cutting force feedback sensor, system controller, machine spindle, tool holder and work piece holder. The system is an assembly of a piezoelectric ultrasonic transducer. A spindle for rotating tool and position of tool is controlled in X, Y and Z axis by a precision motion controller with 25 nm resolution. The work piece is vibrated ultrasonically at 39.5 kHz by mounting it on the free end of the transducer. The abrasive slurry mixed with water is injected into the machining gap between the work piece and tool [16, 17].

2.4 Principle of Material Removal in Ultrasonic Micro Machining (USMM) Process

The mechanism of material removal of ultrasonic micro machining (USMM) process is classified in two parts, one is ductile mode and another is brittle mode. Elastic or plastic deformation in the surface of the workpiece is only responsible for ductile mode. On the other hand, the mode of brittle mechanism is found due to brittle fracture on the workpiece surface. It is extensively recognized that the transition mode from ductile mode to brittle mode absolutely exists in the material removal mechanism of brittle materials, if the depth of the cut is reduced [18].

Zarepour et al. investigated the mechanism of material removal and the relationship between process parameters. They also investigated the analytical mode of material removal mechanism in ultrasonic micro machining (USMM) process on silicon material [19]. Yu et al. [20] studied the debris accumulation and reported an explanation of the influences of abrasive particles on the surface roughness. Guodong Lia et al. investigated the material removal mechanism on quartz crystals. When the roughness value is very less, the machined surface by ultrasonic micro machining (USMM) process is comparatively smooth. This was one of the proofs of the existing of ductile machining [21]. Zarepour et al. [22] presented a new method for the static force measuring and the workpiece clamping for the ultrasonic micro machining (USMM) process. The proposed control system and force measurement provide a compact arrangement and prevent the undesirable effects of vibration of the horn.

In the ultrasonic micro machining (USMM) process, abrasive particles with random shapes and sizes are supplied in the machining gap between the micro tool and the workpiece. At each vibration cycle, each abrasive particle is interacted with the workpiece in one of the following ways [23]:

i. Appling direct impact force on the workpiece surface by the abrasive particles: this is common when the abrasive grain size is larger than the machining gap.
ii. Impact of free-moving abrasive particles on the workpiece surface: this is common when the abrasive grain size is smaller than the machining gap.
iii. Cavitations effect erosion: the high frequency vibration power generates a high frequency mechanical pressure in the slurry medium causing the abrasive particles to impact the workpiece surface.

2.4.1 Mechanism of Material Removal

In USMM, the tool vibrates above 20 kHz, and water based abrasive slurry is pumped to the small gap between the workpiece and the tool [2]. The removal of material from the workpiece by USMM process is caused of micro-cracks by the brittle fracturing of the workpiece. Understand crack generation in USMM in order to improve machining efficiency and precision is investigated. The impact of a single abrasive grain during USMM process can be very useful for understanding crack generation of the workpiece. The main activities for removing material from the workpiece have been described by some researchers as follows:

i. The hammering effect by abrasive particle is shown when the tool and workpiece are in contact.
ii. The impact action is also shown by a free-moving abrasive particle in the working gap.
iii. The cavitations erosion phenomenon is shown by abrasive particle in slurry concentration [24–26].

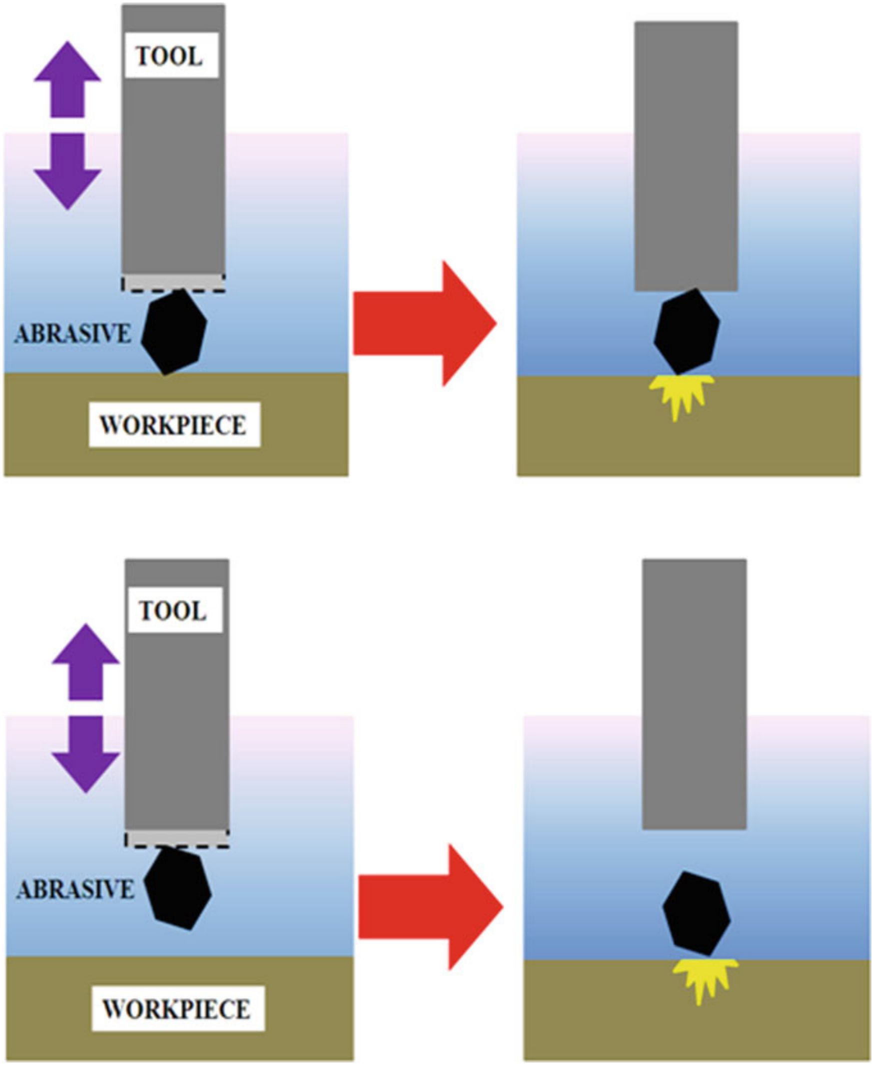

Fig. 2.5 Schematic diagram of material removal in MUSM: **a** Hammering action, **b** Impacting action

Generally, cavitations erosion is not significant for regular material removal mechanism of USMM [27]. The whole mechanisms are schematically shown in Fig. 2.5. The first two mechanisms are mainly responsible for material removal mechanism due to micro cracks, which are generated due to the rapid striking of the abrasive particles. The hammering action is broadly accepted as a major factor in crack generation.

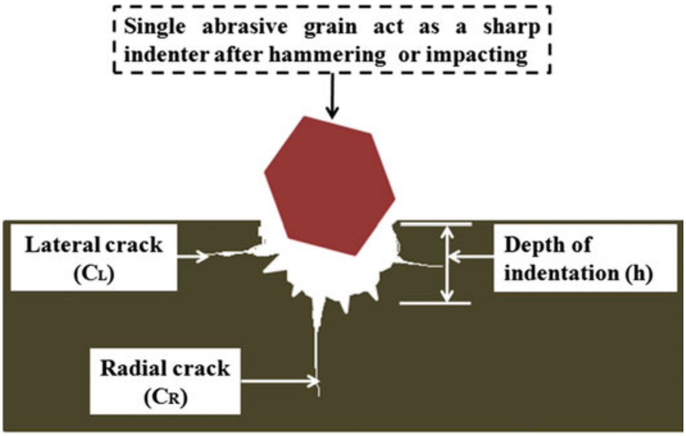

Fig. 2.6 Deformations and fracture of brittle material due to indentation

2.4.1.1 Formation of Cracks in Brittle Materials Due to Indentation

The material removes from the workpiece in the ultrasonic micro machining process is very much depended by Initiation and propagation of median as well as lateral cracks. Figure 2.6 shows that initiation of cracks and localized deformation of a brittle material. This is generated by large or a small abrasive grain, which acts as an indenter [28–30].

The abrasive particles act as indenter on the workpiece surface. The fracture is started on the surface by impression of an indenter in the machining area. Many authors have investigated in this area. It has been found that at first the sharp point of the indenter produces an inelastic deformation zone during machining. Then deformation is induced and suddenly develops into a small crack or median crack. The median crack is increased progressively by increasing the load. The median crack begins to close during unloading and inducing the formation of lateral vents. The lateral vents are carried on their extension toward the workpiece surface upon complete unloading and may lead to chipping. The sequence of crack procedures that occur during the machining has been shown in Fig. 2.7.

+P means increasing load; −P means decreasing load. The sequence of vent crack propagation is summarized as follows:

i. An inelastic deformation zone is produced by the sharp indenter.
ii. After that the deformation flow suddenly develops into a little crack. This is known as median crack.
iii. Next the median cracks are developed gradually with increasing the load.

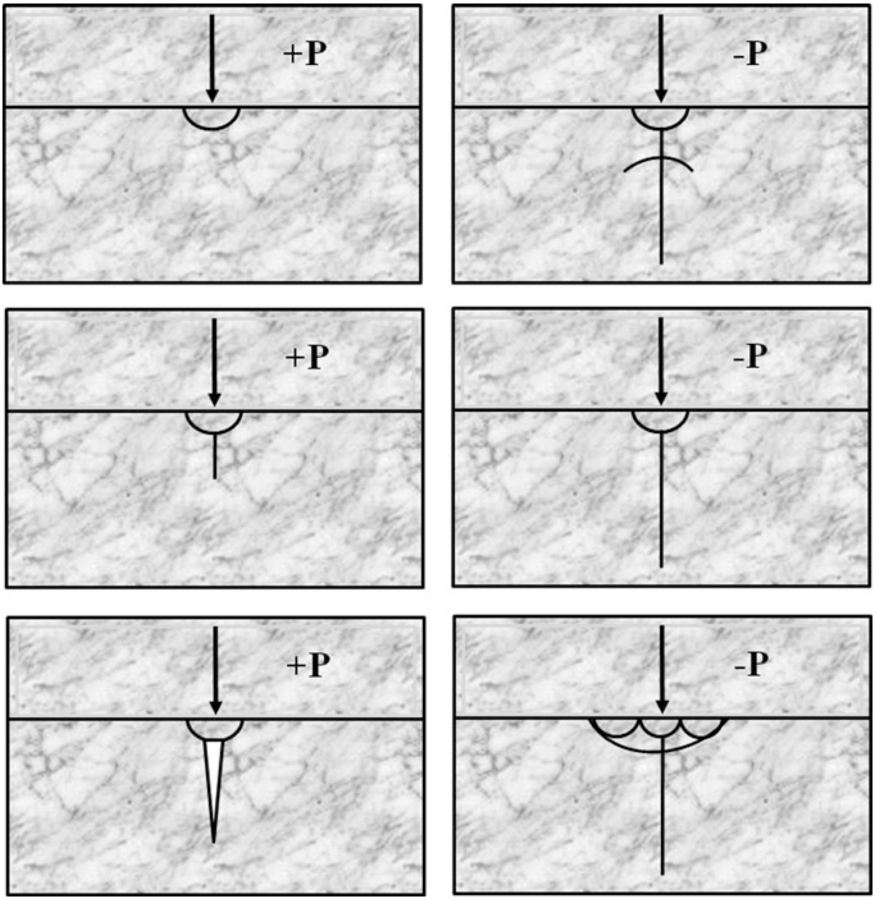

Fig. 2.7 Representation of vent-crack development under point indentation

iv. The median crack begins to close upon unloading.
v. The lateral vents are carried on their extension toward the workpiece surface upon complete unloading and may lead to chipping.
vi. The propagation of these median and lateral cracks lead eventually to chipping of the brittle material.

A critical load P_c for the beginning of a median crack is given by [31]:

$$P_c = \alpha \frac{K^4}{H_v^3} \tag{2.1}$$

where

α is a dimensionless feature which is related to the indenter geometry;
K is the fracture toughness of the workpiece; and
H_V is the vickers diamond hardness of the workpiece.

For the size of the median or radial crack (C_R) and lateral crack (C_L), the following equations have been derived [32]:

$$C_R^m = \xi_1 P \tag{2.2}$$

$$C_L = \xi_2 \left(\frac{P}{K}\right)^{3/4} \tag{2.3}$$

where, m = 1−1.5,

P is the applied load,
ξ_1 and ξ_2 are proportionality constants [33].

The depth of indentation is established by equating the mean static force. This mean force comes from impacting the tool on the grains. Assume the number of abrasive particles in the gap between tool and workpiece are inversely proportional to the square of the diameter of each of the abrasive particles. The following expression for machining depth h is described as follows [34]:

$$h = \left[\frac{8FAd}{\Pi K_1 H_V C(1+q)}\right]^{1/2} \tag{2.4}$$

where

F is the applied static force,
A is the vibration amplitude of the tool,
H_V is the hardness of the workpiece,
q is the hardness ratio of the workpiece to that of the tool,
d is average abrasive grain diameter,
C is the abrasive slurry concentration and
K_1 is proportionality constant.

2.4.2 Models on Material Removal Mechanism

Based on previous research work various models on material removal mechanism along with assumptions taken for developing the models are presented as follows:

Name of investigators	Mechanism of material removal	Assumptions
Shaw [34]	At first direct hammering of abrasive particle. After that impacting by free moving particles.	i. All abrasive grains are the same size, very stiff, and sphere-shaped. Impact forces of all particles are identical. ii. The removal of material is comparative to volume of material is removed for each impact and it also depends on number of particles impacting per cycle and frequency of impacting. iii. Depth of cut for penetrating the material is inversely proportional to hardness and flow stress of work material. iv. A number of active grains are inversely proportional to square off the mean diameter of all grains under the tool face area.
Miller [35]	Material is removed by chipping plastically deformed and work hardened material. MRR also depends upon work hardening while in brittle material on size and rate of chip for ductile material formation.	i. All abrasive particles are same size and cubical form. Plastic deformation is directly proportional to the applied stress. ii. Plastic flow stress equals burger vector times of shear modulus. iii. Cross sectional area of the cut does not vary in the machining time. iv. Viscous effects in water of the abrasive slurry are almost negligible.
Rozenberg et al. [36]	Brittle fracture.	All abrasive particles are irregular shape and incompressible but can be considered as spherical shaped having projections whose radius of curvature are proportional to the average dimensions of particle. From the experimental proof, the numerical distribution of each abrasive grain size d is given by: $\varphi(d) = 1.095\frac{N}{d_m}\left[1 - \left(\frac{d}{d_m} - 1\right)^2\right]^3$ where N is number of active abrasive grains, d_m is the mean diameter of grains.
Cook [37]	Hemispherical indentation fracture.	i. All abrasive grains are uniform and spherical in form. ii. The tool and all abrasive particles are rigid. iii. Viscous effects of the slurry concentration are negligible. iv. A linear relationship between part of active grits and ratio of indentation depth of radius of the each abrasive grit has been assumed.
Kainth et al. [38]	Indentation fracture due to direct hammering action.	i. All abrasive grains are spherical in shape and followed by Rozenberg's size distribution functions to take into account particle size in homogeneity. ii. Motion of tool remains sinusoidal under loaded conditions.
Nair and Ghosh [39]	Brittle fracture.	i. All abrasive grains are rigid and spherical in shape. ii. No consideration for MRR for impacting the abrasive particles, cavitations or chemical action of abrasive slurry. iii. The movement of tool tip is simple harmonic motion.

(continued)

(continued)

Name of investigators	Mechanism of material removal	Assumptions
Rajurkar et al. [40]	Combined effect of impact indentation and fracture phenomenon.	i. Work-piece is considered as a semi-infinite solid. ii. The movement of abrasive grit is perpendicular to the free surface during machining. iii. Speed of abrasive is same as that of vibrating tool.
Lee and Chan [41]	Brittle fracture.	i. Pre-existing defect is considered in the workpiece material for the initiation of median or lateral cracks. ii. Median or lateral crack size is related to pseudo pressure between tool and work-piece.
Wiercigroch et al. [42]	Micro-cracking due to impacts of grains.	i. MRR depends on the magnitude of impact force and its frequency. ii. Diamond grain is equally distributed over the working part of the tool with a uniform grain size. iii. Ultrasonic amplitude of vibration, frequency and tool geometry remain constant.
Nath et al. [43]	The hole entrance chipping, lateral gap.	i. The effects of material removal phenomena from the workpiece on the hole integrity such as entrance chipping, wall roughness and subsurface damage are considered. ii. Material removal mechanism takes place in the gap between the outer periphery of tool and the hole wall (called 'lateral gap'). iii. The radial and the lateral cracks are founded due to adjacent abrasives, which are under the tool face. It extends towards radial direction of the hole resulting in entrance chipping. iv. The angle penetration and the rolling actions of the each abrasive particle, which are at the edge of the cutting tool. It contributes the entrance chipping. After that the lateral gap of the sliding and the rolling mechanisms by the larger abrasive particles take part of the material removal. v. Unfavourably micro-cracks in the radial direction are produced and cause subsurface damages, which are ultimately responsible for rough surface. vi. The size of micro-cracks in brittle materials is depended by abrasive grain size. vii. It is realized that such nature of the hole integrity during USM can only be minimized by using smaller abrasive grain size, but cannot fully be reduced.
Ichida et al. [44]	liquid cavitations, cavitations erosion.	i. Non-contact ultrasonic abrasive machining (NUAM) method is introduced. ii. Abrasive particles are excited by ultrasonic energy. iii. Material is removed by the erosion due to liquid cavitations collapse pressure or impact force. iv. Material removal based on colliding or sliding of the abrasive grains, which are accelerated by the impact force due to cavitations collapse on the workpiece surface.

2.5 Basic Element of Ultrasonic Micro Machining Set up

The essential part of ultrasonic micro machining set up consists of ultrasonic power supply, oscillating system, horn, coupler, the mechanism of tool feeding, and the abrasive slurry supply system unit. Figure 2.8 shows the schematic diagram of ultrasonic micro machining set up.

2.5.1 The Ultrasonic Power Supply

The power supply for an ultrasonic machine tool is characterized as a sine wave generator that supplies the frequency and power of the generated signal. The output power supply with internal or external power control is variable. Low frequency (50 Hz) electrical power is converted high frequency (greater than 20 kHz) by this. The power supply is capable of automatic frequency control and automatic load compensation at optimum efficiency. It also provides constant output amplitude at required setting during the operating cycle for meeting the different energy requirement. One overload monitor system is incorporated to the power supply for defending the system from any failure conditions. If any overload condition takes place, the overload indicator lamp is indicated on monitor and the ultrasonic frequency is closed for balancing the cycle. After that the monitor is automatically come to the reset position itself for stopping the operation until the fault condition is

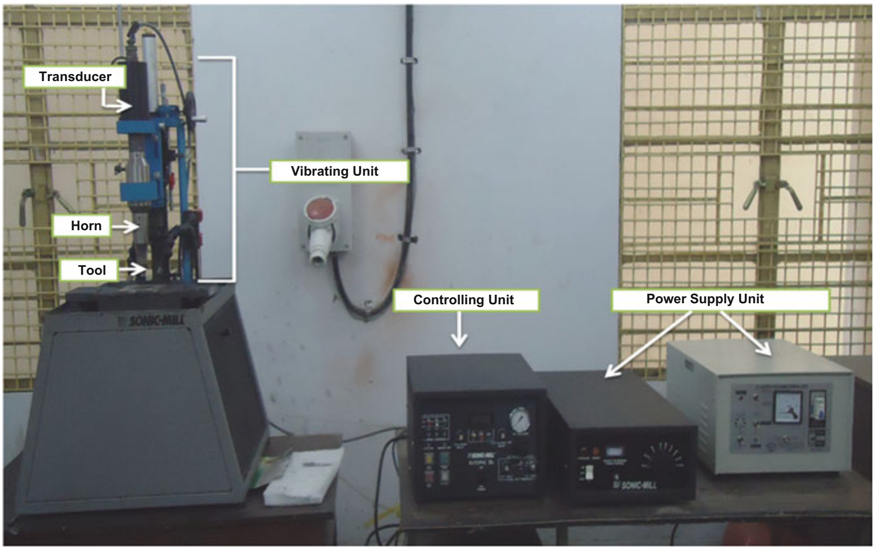

Fig. 2.8 Ultrasonic micro machining setup

eliminated. The monitor is reactivated on every operating cycle for avoiding the damage to the transducer.

2.5.2 Oscillating System

Ultrasonic transducer is the main part of this machining setup. It generates the ultrasonic frequency of vibration above 20 kHz and range of the amplitude of 0.8–5 μm for USMM. The electrical supply voltage provides 50 Hz electrical energy, which is also applied to the transducer element. The converter transforms the high frequency electrical vibrations into high frequency mechanical vibrations. Lead zirconate is the heart of the converter. This is actually titanate electrostrictive element. When alternating voltage is applied, it expands and contracts at the frequency of the voltage. This electrostrictive converter is highly efficient for saving energy.

i. **Magnetostrictive Transducer**
   Joule was first discovered the magnetostriction effect in 1874. According to this effect, ferromagnetic metals and alloys is changed in their length in the presence of an applied magnetic field. The ferromagnetic material is only responsible for positive or negative deformation. One coil is wrapped around a stack made of magnetostrive material (iron–nickel alloy) and electric signal of ultrasonic frequency is fed into this coil. This stack is fully laminated for minimizing eddy current and hysteresis losses; moreover, it must be cooled to dissipate the generated heat. The stack expands and contracts at the same frequency with the help of the alternating magnetic field produced by the AC generator. The maximum magnetostriction effect is achieved using the high frequency AC current, which must be superimposed on appropriate DC pre-magnetizing current. That must be exactly adjusted for getting optimum or working point. When this point is accurately adjusted, the maximum magnetostriction effect (maximum oscillating amplitude) is provided and it also prevents the frequency doubling phenomenon.
   If the frequency of the ac signal in the magnetic field is tuned by same value of the natural frequency of the transducer and the whole oscillating system, so it acts at mechanical resonance. This time oscillation amplitude becomes moderately large and the exciting power reaches its smallest value.
ii. **Piezoelectric Transducer**
   Piezoelectric transducer works with piezoelectric effect. When an electric current is passed through the piezoelectric material, then it expands. But when the current is removed the piezoelectric material reaches its original size. This phenomenon actually is called piezoelectric effect. The voltage measuring instrument shows the electric voltage produced by piezoelectric transducer, which can be used to measure forces. The main drawback of magnetostrictive transducers is the high power loss (η = 55%). The power loss is converted into

heat. For this reason piezoelectric transducers are used and the efficiency is greater than 90%, even at higher frequencies (f = 25–40 kHz). Piezoelectric transducers use crystals like quartz that undergoes the dimensional changing proportional to the applied voltage.

2.5.3 Horn

The horn is also called mechanical amplifiers or concentrators. The functions of the horn describes as follows:

i. The mechanical energy is transmitted to the tool by the horn.
ii. The horn amplifies the amplitudes of vibration.
iii. The horn concentrates the all power on the small machining zone.

The main acoustic horn head is supplied by the company as an essential part with the machine. The required tool is fixed by silver brazing to the free end of the by threading. The difference of amplitude of vibration between the primary horn and secondary acoustic horn is small enough.

2.5.4 Coupler

The coupler attaches between the converter or transducer and horn. This allows for clamping of the converter, coupler, and horn assembly and provides amplitude choices for various applications.

2.5.5 The Mechanism of Tool Feeding

The mechanism of tool feeding should describe as follows:

i. The tool slowly comes to the workpiece.
ii. Sufficient static pressure is provided during machining.
iii. The pressure is decreased before the end of cut to remove fractures of the lower part of the workpiece.
iv. Overrun a little distance for ensuring the desired hole size at the end surface of the workpiece.
v. The tool is took out upward very quickly after machining.

The static pressure is zero, when the tool and the workpiece are not contact each other. When the tool is first making contact with the workpiece during machining, the spring of the machine spindle is expanded for giving the static pressure. The dial gauge indicates the static force. The tool displacement is indicated by the dial gauge.

2.5.6 The Abrasive Slurry Supply System Unit

Several abrasives are available in various sizes for ultrasonic machining. The criteria for selection of an abrasive for a particular application include hardness, size of the abrasive particle, cost of the particle and working life. In order of hardness, aluminium oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C) are the most commonly used abrasives. The abrasive particles are mixed with water with proper ratio to from the slurry. Average particle size of 3–10 μm is selected and the abrasive slurry is supplied by a recirculating pump into the machining zone. The abrasive used for an application should be harder than the material being machined otherwise the usable life time of the abrasive will be substantially shortened. Boron carbide is selected when machining the hardest work piece materials or when the highest material removal rates are desired. Although the cost is five to ten times greater than the next hardest abrasive, silicon carbide, the usable life of boron carbide is 200 machine operating hours before cutting effectiveness is lost and disposal is necessary. This compares with a usable life time of approximately 60 h for silicon carbide. The combination of high removal rates and extended life time justify the higher cost of boron carbide. The abrasive particles size influences the material removal rate and surface finish. Abrasive for USM are generally available in grit sizes ranging from 240 to 800 while the coarser grit exhibit the highest removal rates, they also result in the roughest surface finish and are therefore, used only for roughing operation, conversely, 800 grit abrasives will result in fine surface finishes but at a drastic reduction in metal removal rate. The most popular general purpose abrasive is used, based on the above considerations is 320 grit of boron carbide. The common abrasive slurry concentration is 50% by weight; however, the concentration can vary from 30 to 60%. The thinner mixtures are used to promote efficient flow when drilling deep holes or when forming complex cavities. The abrasive particles are stored in a reservoir at the USM machine and pumped to the tool work piece interface by recirculation pumps at rates up to 26.5 lit/min. higher power ultrasonic machine require the addition of a light-duty cooling system to remove waste heat from the abrasive slurry.

2.6 Design and Developments of Microtools for USMM

In ultrasonic micro machining (USMM), the shape and dimension of the final products depends on the developed tool. The fabrication of micro tool is a really big challenge. It is extremely not easy to hold the micro tool properly with good accuracy of the job due the application of vibrations at the tool end. One method was introduced to overcome this problem. The tool is prepared on the machining time in this method. At first the macro size tool was fixed to the tool head. Wire electro discharge grinding (WEDG) method was applied to fabricate micro tool and machining was done on the same machine tool. Using wire electro discharge grinding (WEDG) method micro tool of less than 20 μm can be achieved [3]. Another method was introduced in 1999, in which workpiece was vibrated ultrasonically. In this method, the better tool holding is possible and high precision can be achieved [4]. Figure 2.9 exhibits the micro tool developed by WEDG method.

Tool wear also occurs during USMM process. To reduce tool wear in USMM, micro tool should be fabricated from stainless steel, brass and mild steel etc.

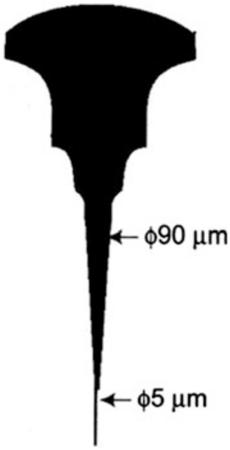

Fig. 2.9 Micro tool developed by WEDG method [4]

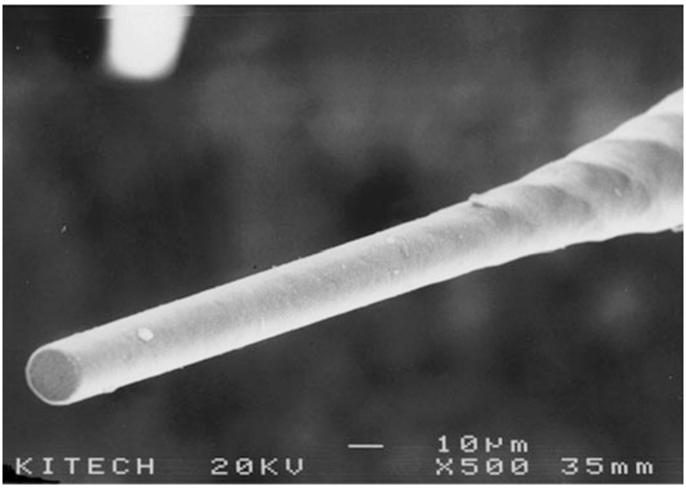

Fig. 2.10 Image of micro tool [47]

More tool wear was found using very hard tool material due to material removal from tool by abrasive particle in the machining zone [45]. The tool material should have superior elastic strength, high wear resistance most favorable values of hardness and toughness, high fatigue strength properties for the application of any hard and brittle material [46]. Tungsten carbide (WC) and sintered diamond (SD) alloy tools were introduced and up to 5 µm micro hole was produced by this tool with good accuracy. With the help of SD tool, micro tool of 21 µm diameter and 150 µm depth on soda glass was generated and the aspect ratio of 7 could be achieved [4, 19]. Figure 2.10 shows micro tool for USMM.

2.7 Parametric Influences of Various Responses of Ultrasonic Micro Machining (USMM)

Very few research works have focussed on the various responses of ultrasonic micro machining such as material removal rate (MRR), tool wear rate, geometrical accuracy and quality of the machined surface etc. The main objective of ultrasonic micro machining (USMM) is to fabricate a micro feature with desired quality of the surface, negligible surface damage, good geometrical accuracy, and satisfactory material removal rate very economically. The possible process parameters in ultrasonic micro machining (USMM) is illustrated by cause effect diagram as shown in Fig. 2.11.

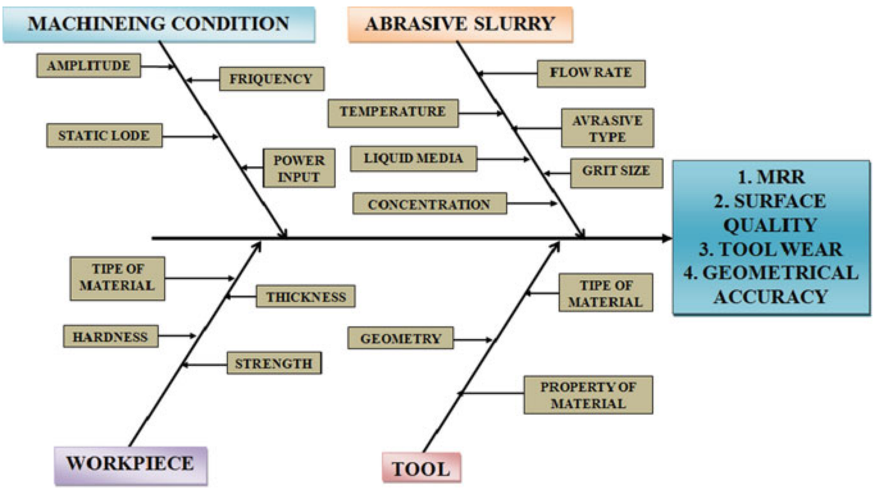

Fig. 2.11 Cause effect diagram for process parameter selection of USMM

2.7.1 Influences of Process Parameters on Material Removal Rate

The material removal rate significantly depends on the type and size of abrasive particle in USMM. More material removal rate is found when the average grain diameter of abrasives particle and hardness of the abrasive particles are increased [3]. Extensively more materials are removed from the workpiece using coarser abrasive particles. So that, material removal rate is increased [47]. The material removal rate also depends on the average applied static load. However, MRR is decreased beyond a certain value with increasing of the average static load. The abrasive particles in the machining region are influenced by the static load. The abrasive particles are striking and removing the more material from the workpiece using high static load. As a result, MRR is increased [6, 48]. The vibration amplitude is one of the major parameter. The material removal rate is increased with increasing the amplitude of vibration [3].

2.7.2 Influences of Process Parameters on Tool Wear

The abrasive particles hit the workpiece and tool also into the machining zone during machining. So that, the tool tendency to erode the materials due to abrasion of those abrasive particles. Tool wear is an significant response of USMM process. The more tool wear is found when coarser abrasive particles are used [3]. Tool wear also depends on the vibration amplitude. Large amplitude of vibration provides more kinetic energy of the abrasives particles under the bottom area of tool tip. At this time the material from the tool tip also is removed and tool wear is shown [49]. Due to extreme tool wear, the stainless steel tool is not suitable in USMM process. More tool wear is found, when the tool diameter is small [16]. The tool wear rate depends on static load, amplitude of vibration also. The tool wear increases with increasing the static load and amplitude of vibration. For achieving low tool wear lower static load and lower amplitude of vibration are used [3].

2.7.3 Influences of Process Parameters on Surface Finish

Surface finish depends on the type and size of abrasive particle, concentration of abrasive slurry. Good surface finished was achieved using fine and small abrasive particles.

Egashira et al. [3] has investigated that most unpleasant surface finish was found using tungsten carbide (WC) tool as compared to titanium carbide (TiC) tool. Less material is removed when fine abrasive particle size of less than 10 µm is used and as a result the smooth surface is generated [6]. The static load and vibration amplitude are the important process parameters. The Ra value of the surface increases with increasing the static load and vibration amplitude due to more material removal from the workpiece [48].

2.8 Development of Micro Feature Using USMM

Ultrasonic micro machining has faced a problem which is proper fixing the micro tools with high precision to the horn in this set up. One method was proposed for USMM set up which was fabricating the micro tools by wire electro discharge grinding (WEDG) procedure. Appling this method, micro holes on a silicon plate and quartz of 20 µm in diameter and 50 µm in depth could be achieved [3, 4]. Figure 2.12 illustrates a micro-hole machining in Al_2O_3 ceramics, with an aspect ratios of 10. Figures 2.13 and 2.14 shows the square, triangular, circular micro holes on silicon and glass. Drilling multiple holes can be made by USMM process. Figure 2.15 shows the array of microholes machined by USMM process.

Figure 2.16 shows micro cavity with 3D view, which was effectively fabricated on silicon with a cylindrical-shaped micro tungsten tool [48]. Figure 2.17 shows that machining of 48 holes with a single SD tool on Silicon, with 22 µm hole diameter, and 20 µm tool diameter and 0.8 µm of amplitude [4].

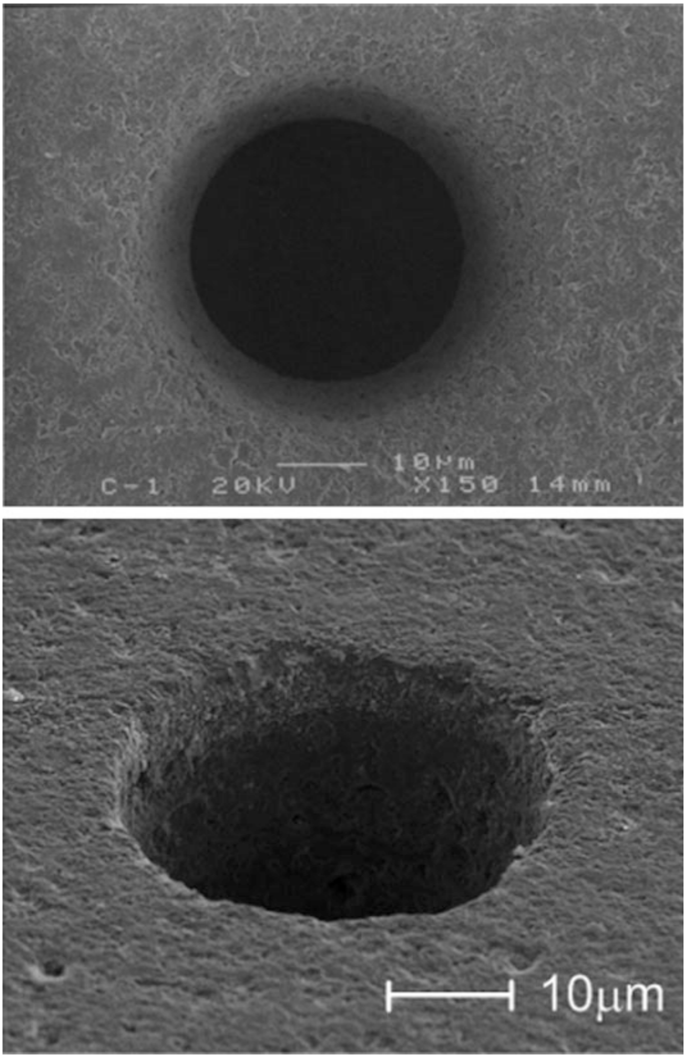

Fig. 2.12 An example of micro-hole machining in Al_2O_3 ceramics, with an aspect ratios of 10 [47]

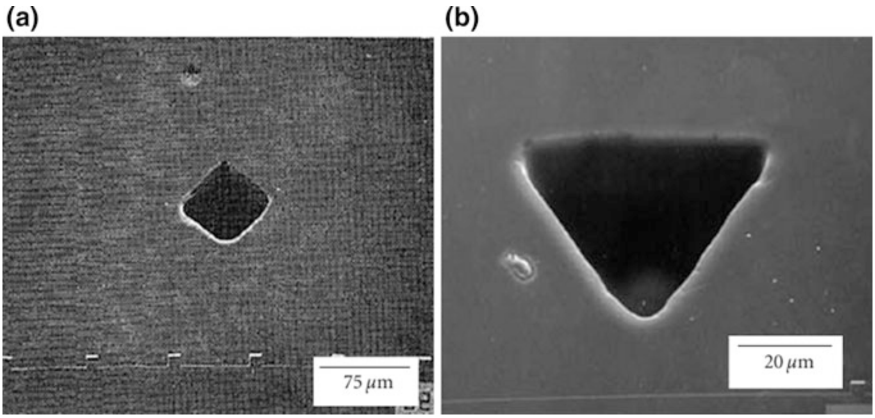

Fig. 2.13 Square and triangular micro hole on silicon [3]

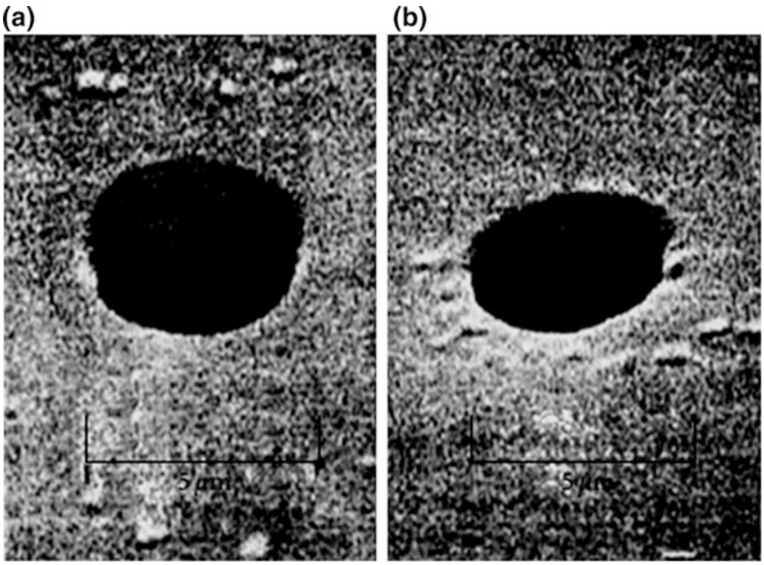

Fig. 2.14 Micro holes on silicon and glass [4]

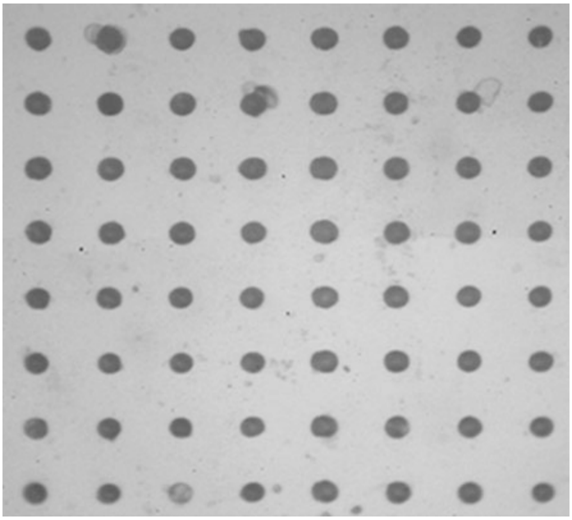

Fig. 2.15 Microholes 20 μm in diameter [50]

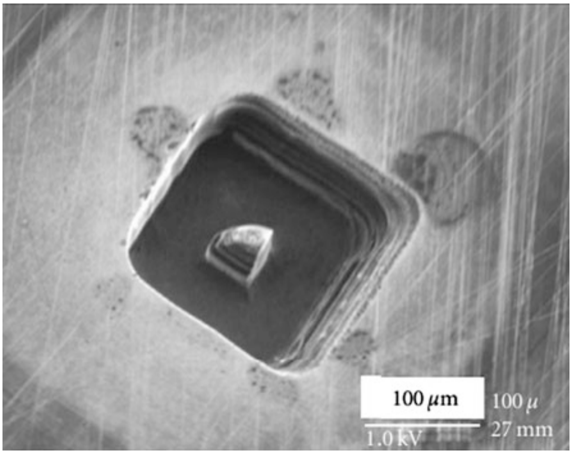

Fig. 2.16 A typical 3D cavity [48]

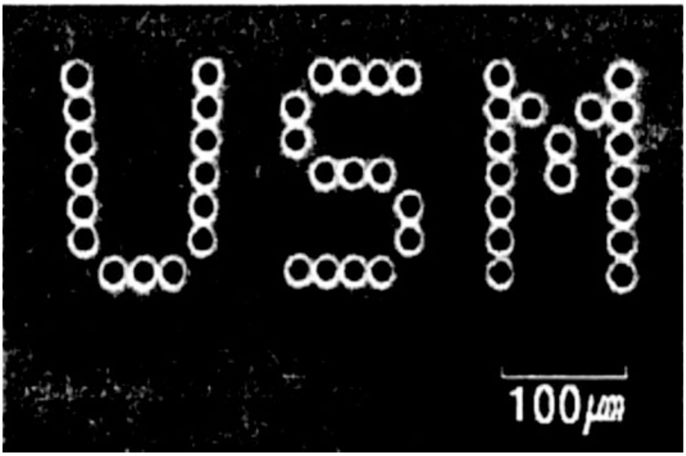

Fig. 2.17 Machining of 48 holes with a single SD tool [4]

2.9 Advantages, Limitations, and Applications of USMM

Advantages of ultrasonic micro machining process are discussed here:

i. The tool and workpiece are not contact together directly and the slurry is used during machining. So that, it is a wet cutting process. No thermal damage is found on the workpiece.
ii. The surfaces produced are free from stress and damages.
iii. It can produce good surface finish and structural integrity.
iv. It can produce burr-less surface.
v. It can machine any hard and brittle material regardless of conductivity.
vi. It does not produce electric, thermal or chemical defects at the surface.
vii. It can drill circular or non-circular holes on very hard and brittle materials, such as glass, silicon, quartz crystal, sapphire, nitride, ferrite and optics.
viii. It produces no thermal stress because of its non-thermal nature.
ix. Micro-holes drilling (hole diameter 5–21 μm) is possible by USMM process.

Limitations of ultrasonic micro machining process:

i. Material removal rate (MRR) is very poor in this machining.
ii. Tool wear is found.
iii. Depth of hole is limited.

Applications of ultrasonic micro machining process:

i. This process is very much applicable on hard and brittle materials like as alloys, glass, fiber material, ceramics, carbides etc.
ii. Engine parts can be machined by this process.
iii. Drilling micro holes in borosilicate glass for the sensors can be possible.

iv. Drilling very fine holes can be possible on shafts and gears which are used in helicopter power transmission.
v. It can be used for producing round, square, irregular shaped holes and surface impressions.
vi. Round through holes with tight-tolerance for processing semiconductor's equipment can be possible.
vii. Micro machining of micro-structured glass wafers is fabricated by USMM process for micro electromechanical systems (MEMS) applications.
viii. High-aspect ratio, 25:1 can be possible in glass and advanced material.
ix. USMM process can be applied in aerospace, tool/mold/machine construction, pump and valve industry, time piece industry/precision mechanics etc.

2.10 Scope of Advanced Research on USMM

Process development for ultrasonic micro machining is one of the most significant issues. In ultrasonic micro machining most difficult task is understanding of the material removal mechanism. Few discussions are available till now but further analysis of the material removal mechanism is necessary for this process. Micro tool fabrication is one another aspect of this process. Preparation of micro tools, handling of micro tools and fixing the micro tools with the tool holder are also the challenging areas of research. The accuracy of micromachining processes depend on these condition of the micro tools. In micromachining, there is reduction in size of tool dimension, abrasive dimension and vibration amplitude etc.

Environmental aspects are one of the essential topics which have hardly been reported. It is one of the important issues of modern manufacturing process.

The fabrication of components for micro fluidic application using USMM process is one of the exploring areas. There is a scope of research in the area of fabrication of micro channels on ceramics, silicon and glass for micro heat exchanger and sensors applications by USMM process.

2.11 Summary

In this book chapter the important issues regarding different aspects of ultrasonic micro machining (USMM) have been discussed. This chapter also focuses on the process development of USMM, working principle and limitations of USMM. Different types of USMM processes, micro tooling for USMM process, material removal mechanism and influences of process parameters have been discussed. Geometrical accuracy and capabilities of the USMM process have been reviewed.

Ultrasonic micromachining (USMM) is well-established process to machine hard and brittle materials (like alumina, zirconia, silicon and glass etc.) The material removal mechanisms in ultrasonic micromachining (USMM) are mechanical abrasion and micro chipping by the abrasive particles against the workpiece surface, cavitations erosion by ultrasonic vibration. In USMM process higher abrasive grain sizes and higher concentrations of abrasive slurry provides higher MRR but poor surface finish. In USMM process good surface finish can be achieved using finer abrasives particles.

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