Chapter 2
Advancement in Ultrasonic Machining for 3D Profile Cutting

S. Das, S. Kumar, G. Kibria, B. Doloi, and B. Bhattacharyya

Abstract Hard and fragile materials for example ceramics, glass and quartz crystals are getting extra consideration in modern years owing to their higher characteristics for example high strength, high hardness, chemical durability and low density. Ultrasonic machining is an abrasive based advanced machining with non-chemical, non-electrical and non-thermal process that is particularly suitable for those brittle and hard materials. The USM process principle, mechanism of material removal, varieties of USM set up, tool development of USM process, improvement and production of 3d profile by USM process and various research issues are studied and summarized in this chapter. It also highlights the effects of different parameters of USM process on performance and development of USM process.

Keywords Ultrasonic machining · Profile accuracy · Ceramics · Surface roughness · Material removal rate

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2.1 Introduction

From the beginning of the human race, researchers have developed state-of-the-art products with the help of various energy sources and tools to meet the demands of making life easy and enjoyable. Since the last decade, manufacturing industries will face some new challenges. The main driver of industrial innovation is better quality of life and higher work efficiency. Modern improvements in the properties of materials have resulted in high durability, high rigidity and extremely hard and brittle materials to meet the requirements of advanced industry. As a result, engineers and technologists are facing more and more problem to produce complex profiles on these materials. They are tremendously complicated to machine by manual or traditional machining processes. This also requires the improvement of better tooling materials to maintain productivity. Such materials can be machined economically by non-traditional processes based on direct use of various energy sources, such as ultrasonic machining (USM), electro-chemical machining (ECM), electron-beam machining (EBM), electro-discharge machining (EDM) etc. [1, 2]. Ultrasonic machining has great applications for machining hard and brittle materials, specifically ceramics, tungsten, carbides and glass etc. those are eclectically poor conductors. USM can easily machine workpiece harder than 40 HRC [3, 4]. During the ultrasonic processing process tool of preferred shape oscillates at an ultrasonic frequency from 19 to 25 kHz at a working amplitude of 15–50 μm [5, 6]. The desired shape tool is vibrated on the machining zone and the transmitted the kinetic energy to the abrasive particles which act as an indenter. In USM material is removed due to initiation of crack, propagation of this crack and brittle fracture of the material [7–9]. Production of non-circular holes and cavities on ceramics, metal and other components through superior geometric and dimensional accurateness is a difficult task [10–15]. It is shown that the material removal rate increases with increasing tool tip amplitude diameter of abrasive particles [16]. The purpose of this chapter is to improve the 3D profile and product presentation through the USM process principle, mechanism of material removal, tool development of USM process. The effects of various parameters of USM process on performance of ultrasonic machining and process development of USM process also describe into this section.

2.2 Basics of Ultrasonic Machining Process

The fundamental of USM process involves tool, normally prepared of a ductile and strong material is vibrating by small amplitude and extremely high frequency and nonstop flow of slurry mixed with abrasive between the tiny gap of tool and the workpiece. USM process is non-traditional mechanical process employed for machining conductive as well as non-conductive materials; by preference those by means of small ductility and hardness higher than 40 HRC for example inorganic glasses, ceramics, bio-ceramics and quartz etc. Water mixed with abrasive grains flush into the gap between the tool and workpiece during machining. The desired shape tool is vibrated at ultrasonic frequency of 20 kHz and amplitude of 8–30 μm. The tool is pushed to workpiece with definite static power. The energized abrasive grains which are transmitted by the vibrated tool are directly hammering on the workpiece. In the machining area, wash out of slurry refreshes the abrasive particles. It also takes away the debris and damaged abrasive elements left from the gap.

2.3 Different Types of USM Setup

In 1927, the cutting and drilling action through the assist of ultrasonic vibration was explained by A. L Loomis and R. W. Wood. After a long period, in 1942 L. Balamuth was first proposed ultrasonic machining, while his investigation was stated that the dispersal of solid into liquid by magneto-strictively vibrated nickel tube. The primary announcement of whole apparatus and techniques in ultrasonic machining was published in 1953–54 [5]. All through suitable research work and progress on USM equipment, various types of USM processes have been introduced.

2.3.1 Stationary USM Process

In this process the abrasive slurry is injected into the space between a vibrating tool and stationary workpiece. Material is abraded away until a mirror image of the tool is cut into the workpiece. A hard metalic tool is pressed with high frequency and low amplitude of oscillation perpendicular to workpiece, which convey high velocity to fine particles of abrasive presented between the workpiece and tool. These particles strike the workpiece, chipping away small particles, and the tool is gradually fed into the workpiece. The "chips" are carried away from the workpiece by a constant flow of cooled slurry. The workpiece is abraded into a mirror image of the tool. Figure 2.1 shows the schematic of stationary USM system.

2.3.2 Rotary USM Process

Rotary type USM is an invention of two machining process that merges diamond grinding elements with stationary USM process, increasing higher material removal rate (MRR) than diamond grinding or stationary USM. In rotary USM process a revolving drill bonded with diamond abrasive particles are vibrated ultrasonically on the axial whereas spindle is supplied at a constant pressure in the direction of the workpiece. The coolant is pumped with the drill core, preventing jamming of the drill and keeping it cool. Using directly bonded abrasives tool in RUM process and simultaneously combining rotation and vibration, it provides very fast and high

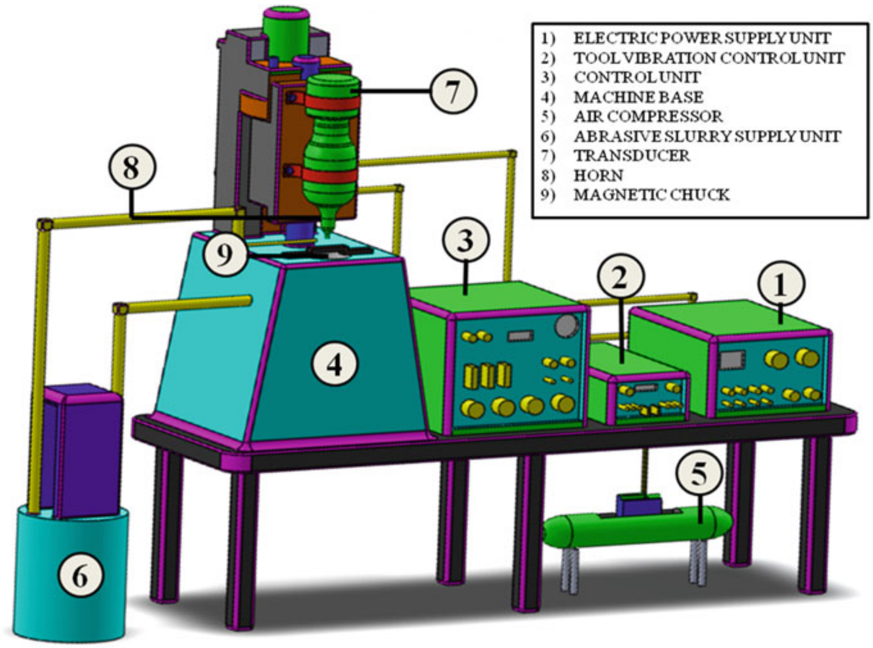


Fig. 2.1 Diagram of USM set up

quality machining technique for various glass and ceramic applications. It is easier to drill deep holes with RUM than USM and improve hole accuracy with higher surface finish. Spindle speeds in rpm are programmable using a CNC controller for controlling the speeds of up to 8000 rpm. Different types of tool shapes are used for RUM process on ceramic and glass machining applications are commonly used in diamond-synthesized tool. Figure 2.2 illustrates the schematic of Rotary Ultrasonic Machining process.

2.4 Detail Description of Mechanism of Material Removal in USM Process

In this process the material of workpiece is removed from the machining zone by the grazing action of liquid based abrasive slurry, which is circulating between the vibrated tool and workpiece. The tool does not contact the workpiece directly, so that the machining pressure is rarely used. For that reason this operation is perfect for machining tremendously brittle and hard materials, for example ceramics and glass with producing no heat.

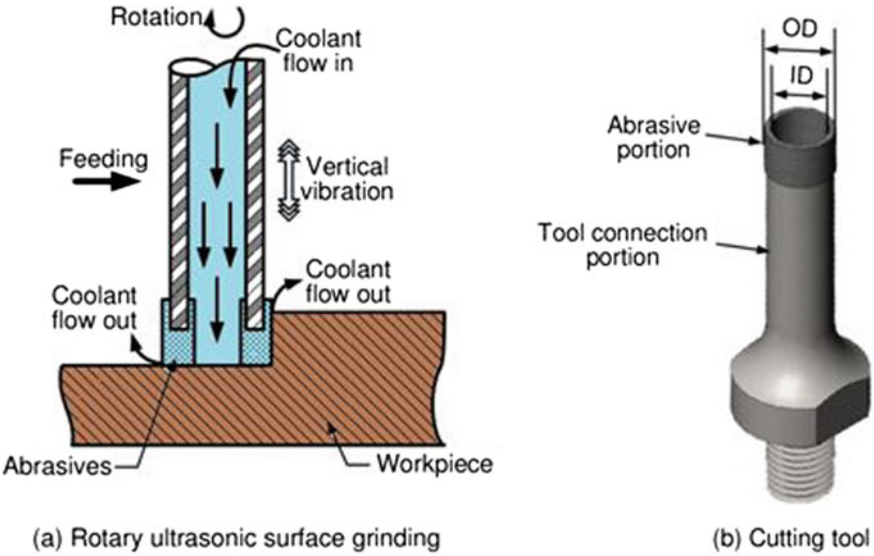


Fig. 2.2 Schematic of Rotary Ultrasonic Machining (RUM) and cutting tool

2.4.1 Material Removal Mechanism

Owing to micro-cracks generation through the fracturing in brittle nature of the workpiece, the material is detached from the machining region of the workpiece during USM process. Mechanism of crack production has been investigated in USM in order to develop machining effectiveness and accuracy. The collision of a particular abrasive grain for the duration of USM process is able to very essential for proper crack production of the workpiece. The most important reasons for taking away the material from the workpiece have been documented as follows:

(i) The main principle is hammering effect. This phenomenon is happened by abrasive particle when the workpiece and tool get in touch with each other.
(ii) The another reason is impact action by abrasive particle with free-moving in the machining zone.
(iii) The cavitations erosion plays a role for removal of materials by abrasive slurry concentration [5, 6].

In general material removal mechanism of USM, cavitations erosion is not significant all time. The schematic diagram of step by step mechanism of material subtraction in USM is shown in Fig. 2.3. The mostly responsible reason is first two mechanisms for material elimination owing to micro cracks. These are produced owing to the quick hammering of all coarse particles. The striking stroke is largely established as a main reason in crack production [7].

The material is taking away from the workpiece in the USM process depends largely on radial cracks start and proliferation of lateral cracks. The beginning of

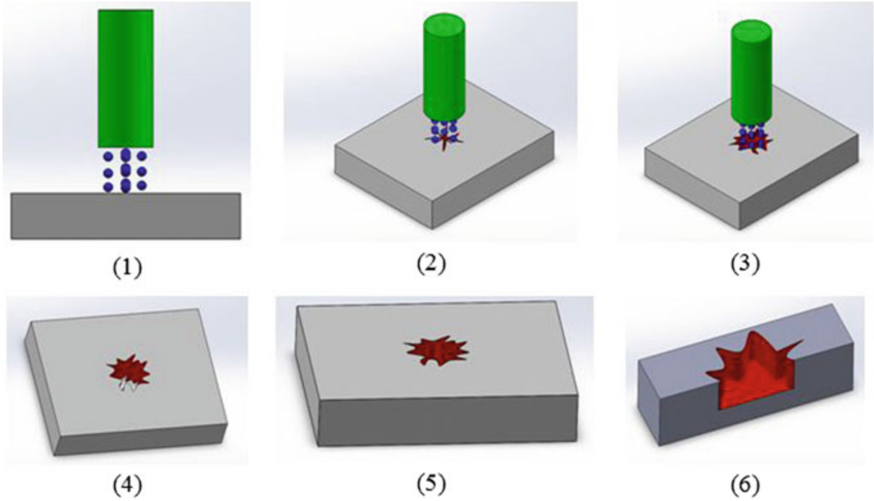


Fig. 2.3 Schematic diagram of step by step mechanism of material subtraction in USM

localized deformation and cracks formation of any hard and brittle workpiece material is shown in Fig. 2.4. Abrasive particles are produced these cracks and perform as an indenter [8, 9]. The fracture begins on the upper surface of the workpiece by striking the abrasive grains in the machining region. Various researchers have been studied in these regions.

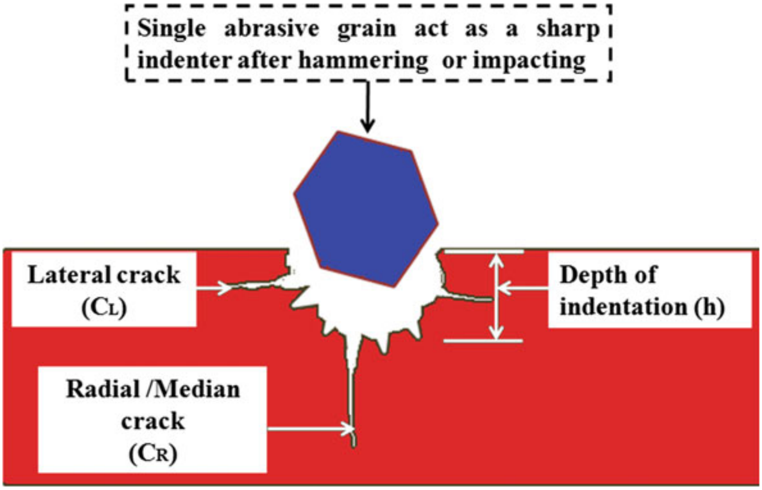


Fig. 2.4 Fractural deformation of brittle material

2.4.2 Review Work of MRR Model

Various investigations have been done in the region of material removal mechanism. Following section includes the details of research work carried out by various researchers in the mechanism of material removal in USM.

M. C. Shaw explored the material removal mechanism in USM process. Material was removed primarily the nonstop hammering by abrasive grains and secondarily striking by free exciting particles. Every abrasive particle was assumed as rigid, identical and round in shape. Every single one impacts were considered as identical. Depth of penetration was also considered as inversely proportional to work material flow stress. For the tool face given area, the numbers of active grains were inversely proportional to the square of the average grain diameter [16]. G. E. Miller proposed a model of the material removal mechanism in ultrasonic machining. Primary physical principles and equation of machining rate were derived from this model. In this case circular solid tools were used with puddle slurry. A relationship of the calculations of the theory was made with the experimental data that the theory gave a right correlation between the machining speed and the variables involved in the machining process [17]. L. D. Rozenberg et al. proposed that the material was removed from the workpiece by brittle fracture. All abrasive grains were incompressible and unequal contour but could be considered as spherical shape [18]. Based on the investigational confirmation, the statistical calculation of abrasive grain diameter size d was given by:

$$\varnothing(d) = 1.095\frac{N}{d_m}\left[1 - \left(\frac{d}{d_m} - 1\right)^2\right]^3 \tag{2.1}$$

where, N is number of active abrasive grains and d_m is the mean dia. of grains.

N. H. Cook proposed the material removal mechanism in USM. As per discussion the workpiece material was removed due to indentation fracture by the hemispherical shape abrasive. All abrasive grains were assumed as spheres of uniform radius. Viscosity effects of slurry concentration were considered insignificant. According the MRR model, material removal rate was considered as proportional to square root of grain radius [19]. G.S. Kainth analyzed the mechanism of material removal in ultrasonic machining. According to proposal the direct impact on the workpiece by abrasive grains was main reason for removing material from the workpiece. The investigation had been applied to compute material removal during machining on glass materials using abrasive of 400 mesh size. In that experimentation the mild steel tool with different static force and amplitude of tool oscillation was used [20]. E. V. Nair et al. performed one hypothetical study into the mechanics of USM. The periodic hammering by the cutting tool on the workpiece material through rigid spherical abrasive particles is responsible for material removal. The dislodging of material from the workpiece during USM process was owing to brittle fracture. The cavitations erosion was negligible for removal of the material. Finally, the differences of machining rates were depended by mean diameter of abrasive grains, amplitude and frequency of vibration [21]. K. P. Rajurkar et al. suggested that USM process was an efficient advance machining process for ceramic materials. This research presented the experimental model of the MRR mechanism during machining of alumina ceramic [22]. T.C. Lee et al. explained the basic mechanism of the USM of ceramic composites. The effects of the MRR and the surface roughness were measured and discussed with changing the static load applied, the amplitude of the tool tip and the size of the abrasive. It was concluded that if the static load applied, amplitude of the tool tip and the grit size of the abrasive was increased, the material removal rate also increased and it was roughening of the workpiece machined surface [23]. M. Wiercigroch et al. suggested that the improvement of material removal rate (MRR) in USM was very much associated with high amplitudes forces produced by develop tool on the workpiece and it also developed micro-cracking in the cutting zone. Mechanism of material removal was observed as micro-cracking produced on the workpiece due to impact of grains [24]. C. Nath et al. suggested that due to quick mechanical indentations the micro-chipping via micro-cracks is generated by abrasive grits. The basic material removal mechanism during USM of hard–brittle materials like glass and ceramics was observed [25].

2.5 Tool Development of USM Process

The final form and dimension of the developed products depends on the tool during ultrasonic machining (USM). The production of micro tool is in actuality immense challenge. Holding the micro tool appropriately with good accuracy is not an easy task of the job owing the purpose of vibrations at the tool ending. New technique was launched to conquer this difficulty. This tool is prepared on the machining time in other technique. In the beginning the macro tool was set to head of the tool. Wire electro discharge grinding (WEDG) technique was utilized to manufacture micro tool. Then this tool was utilized for machining [26]. Using this method micro tool of less than 20 μm can be attained [3]. Figure 2.5 shows micro tool used in micro USM process.

The main problem is to design and build up the tool for ultrasonic machine for producing any shape. A cylindrical rod of stainless steel of grade 304 has been selected for fabricating the tool. After that the stainless steel tool has been fabricated with the help of lathe as per design of CAD model. Figure 2.6 shows the CAD model of stepped tool steps having both in circular cross section. Figure 2.7 shows the CAD model of stepped tool having one step of square cross section and another step of circular cross section. Figure 2.8 shows the CAD model of hemispherical tool. Next the tool holding hexagonal bolt and the bottom face of the developed tool has been properly cleaned. Then this tool holding bolt and tool have been joined by silver brazing. Silver brazing is a joining process whereby a non-ferrous filler metal, alloy is heated to melting temperature above 800 °C. Silver brazing can employ by flame heat sources. The copper filler metal is used in silver brazing. Flux is necessary for brazing to remove and prevent reformulation of surface oxides on the base metals.

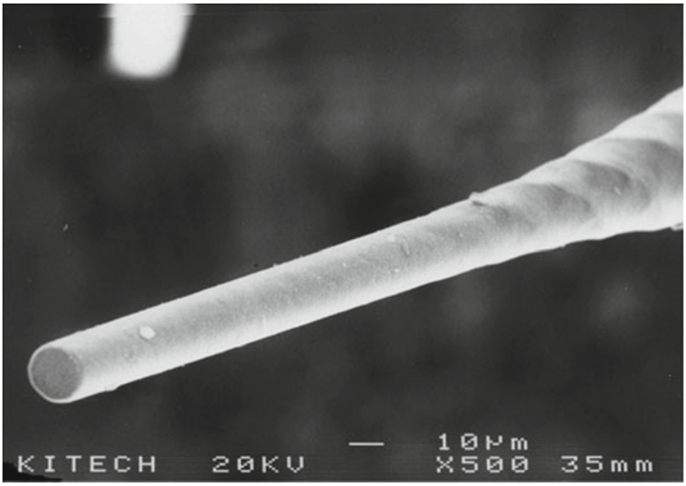
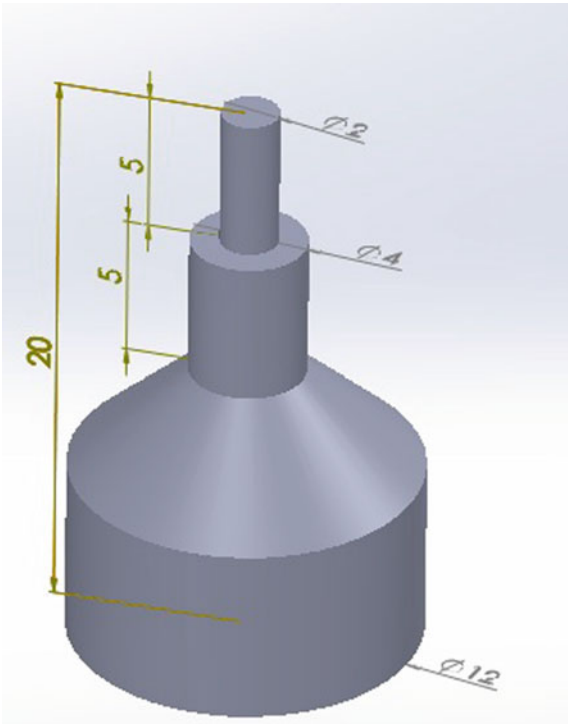


Fig. 2.5 Micro tool prepared for Micro USM [27]

Fig. 2.6 CAD model of stepped tool of circular cross-section



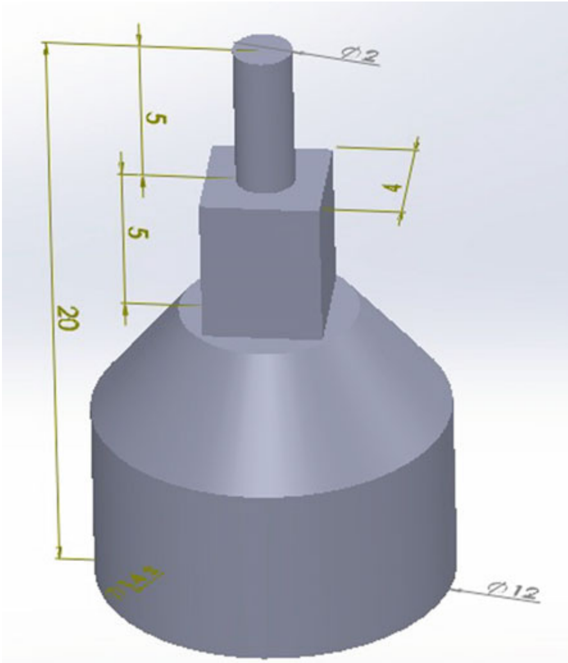


Fig. 2.7 CAD model of stepped tool having both square and circular cross-section

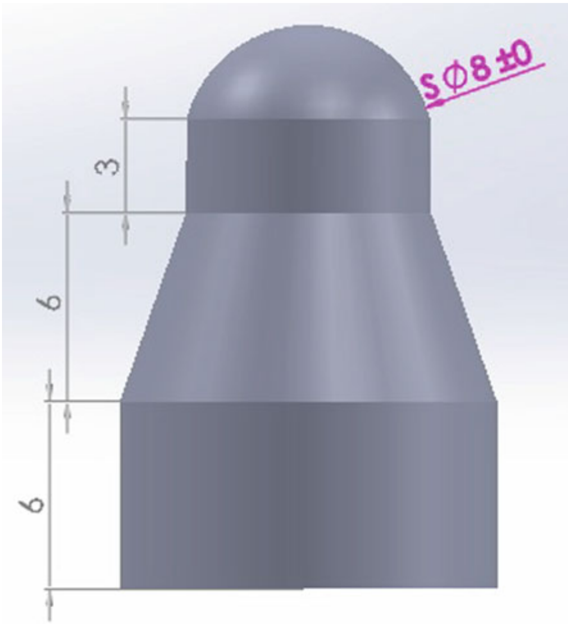


Fig. 2.8 CAD model of hemispherical tool

Fig. 2.9 Photographic view of stepped tool of circular cross-section for USM

Proper brazing is very much essential for good joint design. The photographic views of the developed tools are shown in Figs. 2.9, 2.10 and 2.11.

2.6 Influences of USM Process Parameters on Responses During Machining

The performance of USM process depends upon process parameters, which is shown in Fig. 2.12. The amplitude of vibration, frequency of vibration, power rating and static load are the process parameters related to energy input during USM. One of the most effective process parameter is abrasive particle. The types of material, hardness, strength of the workpiece, abrasive grain size, abrasive slurry concentration and abrasive slurry flow rate are the process parameters related to effectiveness of abrasive slurry during USM. The tool material, tool geometry and property are tool related process parameters in USM. The controllable process parameters are selected during this present research work i.e. power rating, abrasive grain size, slurry concentration and tool feed rate.

Fig. 2.10 Photographic view of stepped tool having both square and circular cross-section for USM

So many abrasive materials are available in different grain diameters for USM process. The selecting criteria for a particular machining condition depend on hardness, useable life, cost and particle size of the abrasive. Boron carbide, silicon carbide and aluminum oxide are the commonly used abrasive for ultrasonic machining process. Boron carbide abrasive is very costly and it has high hardness and useable life. Abrasive grain sizes are in the range from 240 to 800. In this present research work boron carbide abrasive with different grain sizes are used.

Abrasive slurry concentration is one of the process parameters of USM. The abrasive grains are mixed with water to form the slurry. The concentrations of abrasive slurry are varied from 30 to 60%.

Power rating is another important controllable process parameter of USM. High power is required for drilling very hard material and more penetration.

Tool feed rate is one another process parameter of USM. Tool feed rate is the velocity at which the tool is fed, that is, advanced against the workpiece. It is expressed in units of distance per minute.

The influences of ultrasonic machining process parameters on various responses have been investigated and explained using various graphs.

Fig. 2.11 Photographic view of hemispherical tool for USM

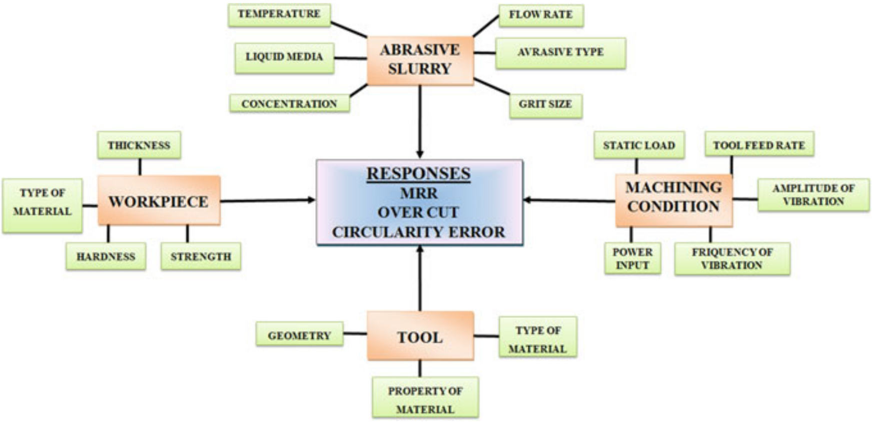


Fig. 2.12 Process parameters of USM

2.6.1 Influences of USM Process Parameters on MRR

The significant parameters in the USM process are abrasive grain diameter. The experiments have been carried out with varying abrasive grain diameter. Figure 2.13 illustrates the outcome of abrasive grain diameter on MRR. From this graph, it is found that small abrasive grain i.e. 14 μm grain diameter provides the less MRR however coarser abrasive i.e. 64 μm grain diameter offers high MRR. Coarser abrasive have spiky corner in every side of grain particle, therefore more MRR is found. This active abrasive grains are taken an influencing part in material removal process whose diameters are large.

Figure 2.14 presents the outcome of concentration of abrasive slurry on MRR of production of square stepped type hole on zirconia bio-ceramics. Hence, the material removal rate depends only how much effective particles of abrasive grains are present in the machining region. When the slurry concentration is more, the density of the slurry is high. So the extra effectual abrasive grains move toward to the effective gap. As a result the more MRR is achieved using high percentage of abrasive slurry concentration.

Figure 2.15 exhibits the outcome of power rating on MRR. In the graph, it is evidently exposed that with enhance in power MRR increases. At that time extra power is used, subsequently the abrasive particles hit on the workpiece surface through high value of force. The active grains are striking through more momentum and rapid crack of the workpiece surface is found owing to quicker transmission of cracks. Therefore the workpiece material takes away from the workpiece at quicker rate as a result improving MRR.

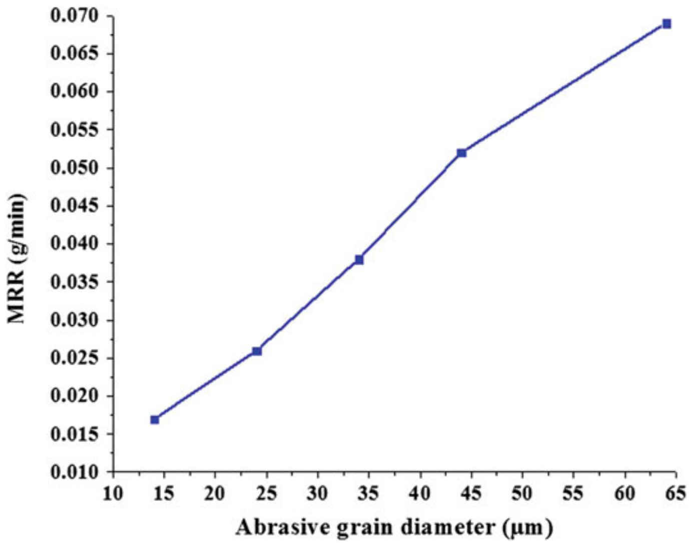


Fig. 2.13 Result of abrasive grain diameter on MRR for square stepped hole generation

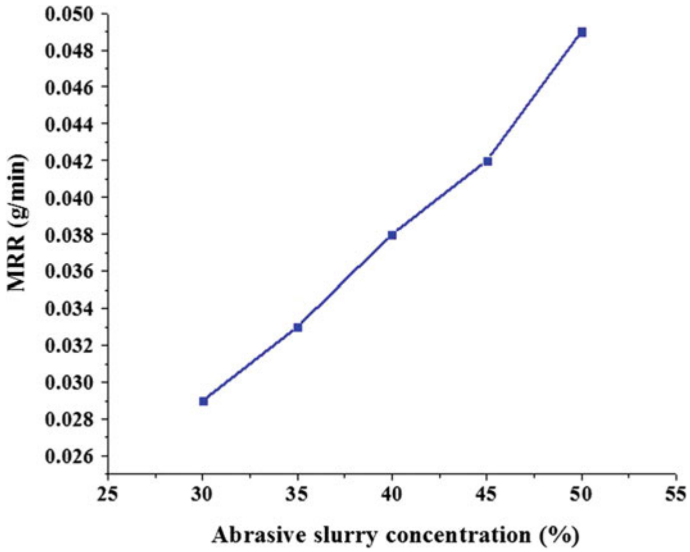


Fig. 2.14 Result of abrasive slurry concentration on MRR for square stepped hole generation

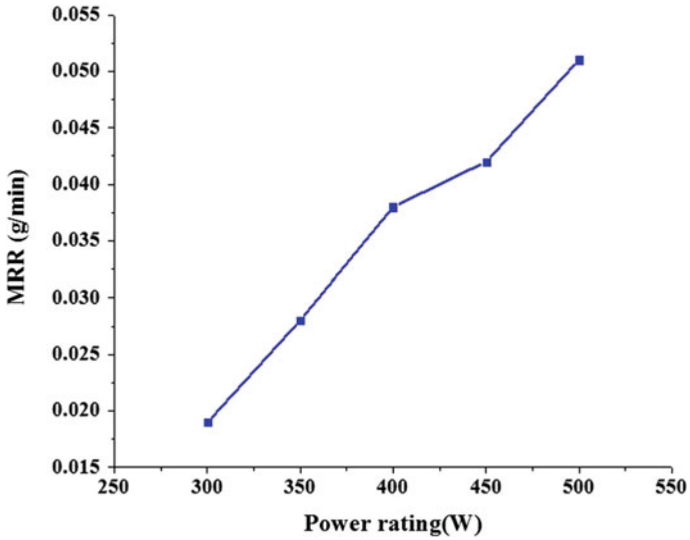


Fig. 2.15 Result of power rating on MRR for square stepped hole generation

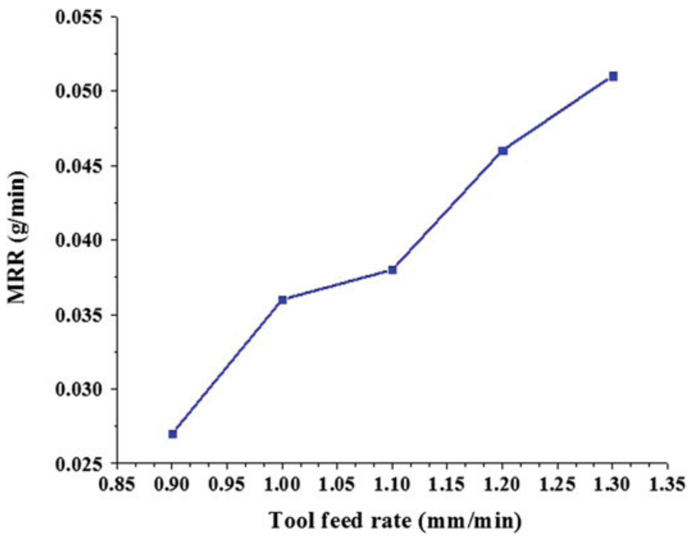


Fig. 2.16 Result of tool feed rate on MRR for square stepped hole generation

It is observed from Fig. 2.16 that material removal rate is influenced by tool feed rate during the square stepped type hole generation by USM. The crack transmission rate on the workpiece is efficiently more when the tool is stirred down at superior tool feed rate. Very quickly material is detached from the workpiece. Therefore high tool feed rate gives highest MRR.

2.6.2 *Influences of USM Process Parameters on FFOC, CCOC and DOC of Square Stepped Hole*

Figure 2.17 illustrates the result of grain diameter of abrasive particles on corner to corner overcut (CCOC), flat to flat overcut (FFOC) and diametrical overcut (DOC) of square type stepped hole on zirconia bio-ceramics. It is observed from the graph, that very small abrasive particles create hole through less overcut and also found least amount flat to flat overcut (FFOC) as well as corner to corner overcut (CCOC) of square hole during USM process. Normally bigger abrasive grain diameter is 64 micron and regular lesser abrasive grain diameter is 16 micron. So that the cutting region of average bigger grain diameter is high compare to the average lesser grain diameter. The smaller abrasive grain diameter has less contact surface area in the machining zone. So that small overcut i.e. DOC, corner to corner overcut (CCOC) and flat to flat overcut (FFOC) of this square hole are achieved by low value of abrasive grain diameter.

Figure 2.18 shows the result of abrasive slurry concentration on corner to corner

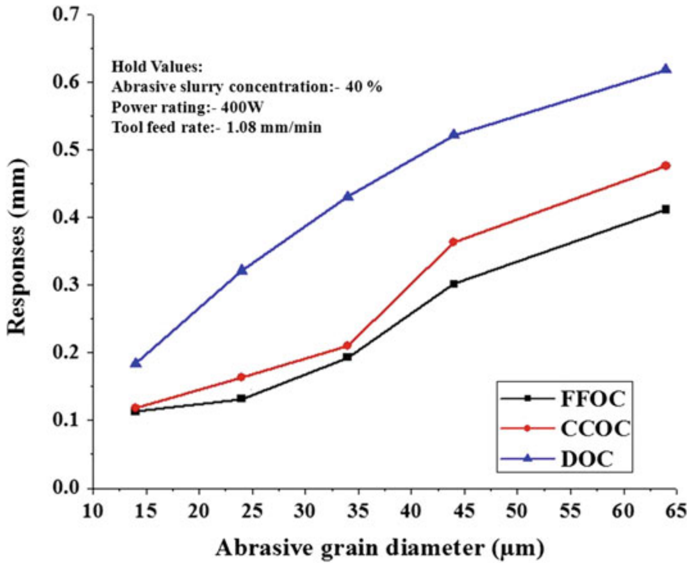


Fig. 2.17 Result of abrasive grain diameter on FFOC, CCOC and DOC for square stepped hole generation

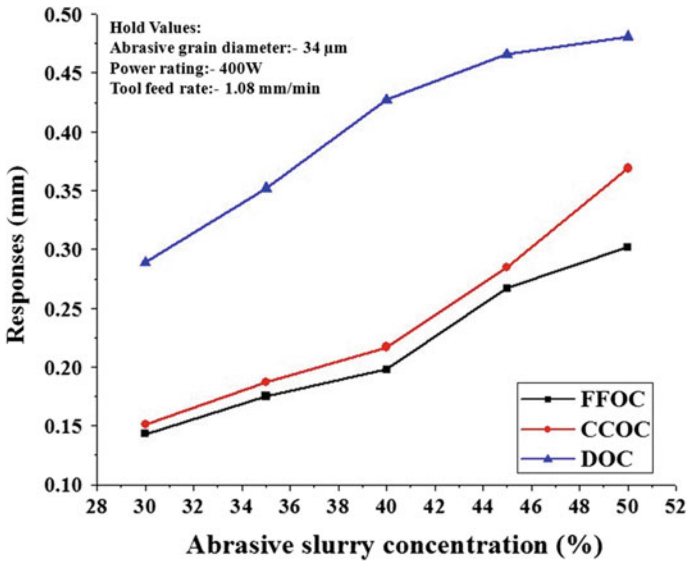


Fig. 2.18 Result of abrasive slurry concentration on FFOC, CCOC and DOC for square stepped hole generation

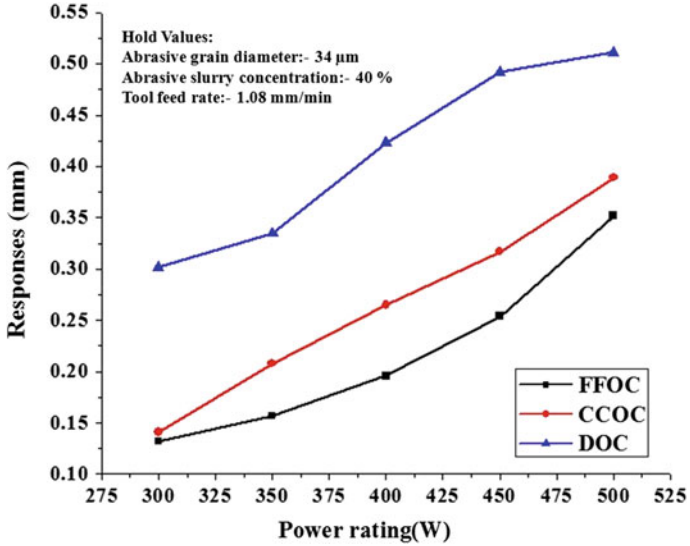


Fig. 2.19 Result of power rating on FFOC, CCOC and DOC for square stepped hole generation

overcut (CCOC), flat to flat overcut (FFOC) and diametrical overcut (DOC) of square form stepped hole on zirconia bio-ceramics respectively. If a lower concentration is used, a high quality precision profile is achieved. When the concentration of the abrasive grain is extremely low, the hitting force is less because the total mass of abrasive in the operating area is small. Therefore, the values of FFOC, CCOC and DOC are less when the small concentration of abrasive slurry is used.

Figure 2.19 demonstrates the outcome of power rating on corner to corner overcut (CCOC), flat to flat overcut (FFOC) and diametrical overcut (DOC) of square shaped stepped hole on zirconia bio-ceramics respectively. In fact, the high applied power means that the tool vibrates with great force and supply high energy to abrasive particles on the surface of the workpiece. Therefore, the material is removed from the workpiece quickly. Therefore, the flat to flat overcut (FFOC), corner-to-corner (CCOC) overcut and diametrical overcut are increased. So to achieve a small FFOC, CCOC and DOC a lesser value of the power is favored.

Figure 2.20 exhibits that the effect on FFOC, CCOC and DOC with varying tool feed rate respectively. With the help of this diagram it is acquired so as to high tool feed rate provides greatest FFOC, CCOC and DOC. With a higher value of the feed rate of the applied tool, additional material is reduced by the abrasive particles just below the tip of the tool. Therefore, the all overcut raise by enhancing the feed rate of the applied tool. Less tool feed rate is chosen to attain lower value of FFOC, CCOC and DOC of square stepped hole.

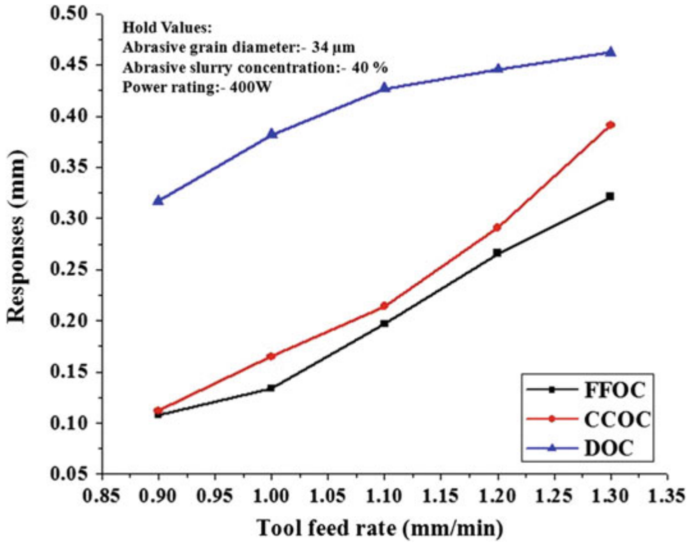


Fig. 2.20 Result of tool feed rate on FFOC, CCOC and DOC for square stepped hole generation

2.7 Improvement and Production of 3D Profile by USM Process

An accurate circular stepped type hole has been created on alumina and zirconia bio-ceramics material during USM process as showing Figs. 2.21 and 2.22. The actual photograph of square stepped hole on the workpiece after machining on shown in Fig. 2.23. The real snap of hemispherical cavity on hydroxyapatite bio-ceramics after machining is shown in Fig. 2.24.

One new technique was anticipated for ultrasonic micro machining set up. It was producing micro tools through wire electro discharge grinding (WEDG) system. With the help of this technique, micro holes of 20 µm diameter on a silicon plate and quartz of 50 µm in depth could be obtained [3, 4].

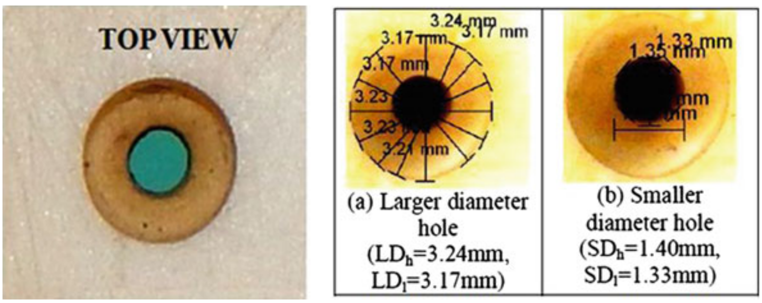


Fig. 2.21 Alumina workpiece after machining

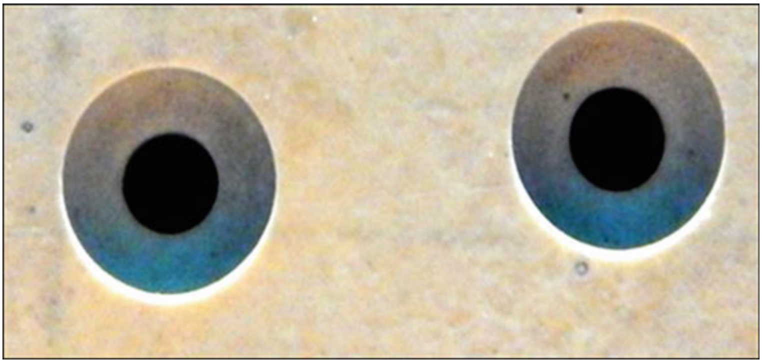


Fig. 2.22 Zirconia workpiece after machining

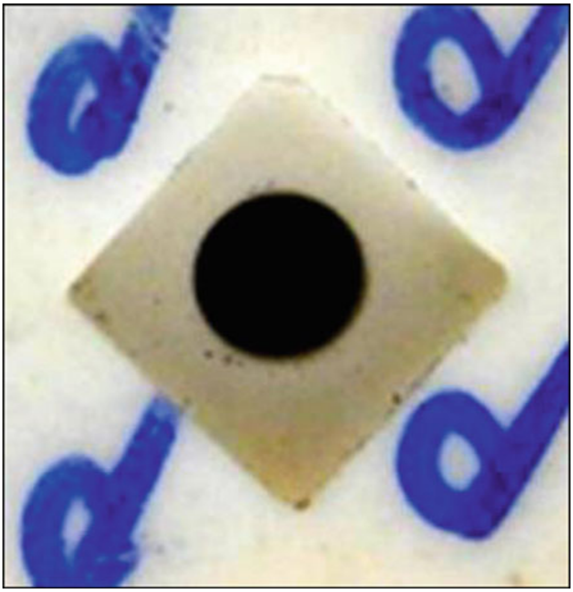


Fig. 2.23 Square stepped hole on zirconia workpiece after machining

Different investigational and hypothetical studies on rotary ultrasonic micromachining (RUSMM) have been conducted for machining different ceramic materials. Sapphire is usually related in the field of electronics, mainly in the production of various circuits and chips which can also be produced by RUM. It has been observed that the highest cutting force of RUM is 34.5% lower than that of conventional diamond side grinding process. 3D micro cavity was successfully made-up on silicon by a micro tungsten tool in cylindrical-shaped. Figure 2.25 shows the 150 μm hole on Soda glass. Figure 2.26 demonstrates the fabrication of 48 holes of 22 μm hole diameter by a single SD tool on Silicon workpiece of 20 μm tool diameter [28].

Fig. 2.24 Photographic view of hemispherical cavity on machined workpiece

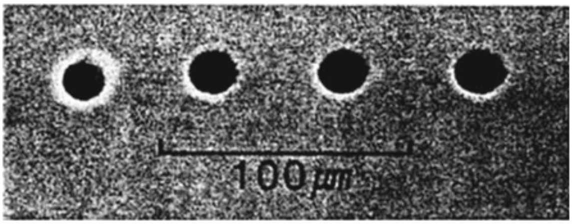


Fig. 2.25 150 μm hole on Soda glass [28]

Fig. 2.26 Fabricated of 48 holes through single SD tool [28]

2.8 Future Scope of Advancement on USM

Process improvement for USM is one of the most essential matters. In USM mainly complicated task is to understand the material removal mechanism. A small number of discussions are existing till nowadays but additional analyse is of the mechanism of material removal is essential for this method. Ecological feature are one of the vital area which barely have been reported. This is one of the main topics of current industrialized process. However the present research work analysis will provide fruitful and technical information to the researchers, scientists and engineers who are working in the area of USM process. It can also provide direction for advancement of USM tool development and complex shaped profile machining of advanced ceramics those are highly demand in biomedical applications.

2.9 Summary

At first this present effort the background of the USM process is introduced. The significance of developing well-organized machining methodology for brittle and hard materials was stated. Through comparing a number of machining procedures, the potentiality of ultrasonic machining process in macro and micro-machining of different brittle and hard materials was pointed out. Within this book chapter the significant matters about various aspects of USM processes have been considered. In addition this section discusses on the working principle of different types of USM and improvement of USM process. Mechanism of material subtraction and influence of ultrasonic machining process parameters have been considered here. Profile accurateness and potentialities of the USM procedure have been discussed here. In USM process abrasive grain with larger sizes and larger abrasive slurry concentrations offer high value of MRR but reduced profile accuracy. In USM process high-quality surface finish can be attained using very smaller size of abrasive grain.

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