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A review on ultrasonic machining

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Abstract

Ultrasonic machining is a contemporary manufacturing method usually employed for processing materials with higher hardness/brittleness such as quartz, semiconductor materials, ceramics etc. The machined surface produced by ultrasonic machining is found to be free from any surface defects (heat affected zone, cracks, recast layer, etc.) in contrast to the thermal based machining processes like; electric discharge machining, laser beam machining etc. In this article, a review has been reported on the fundamental principle of ultrasonic machining, effect of operating parameters on material removal rate, tool wear rate, and surface roughness.

Keywords: ultrasonic machining; material removal rate; tool wear rate; surface roughness.

1. Introduction

In the today's era of advancement, several industries such as; nuclear reactors, aerospace, aircraft and automobile have been observed to encounter umpteen issues regarding the efficient processing of advanced engineering materials. The conventional machining solutions are unable to process such materials effectively. Hence, different advanced machining processes including abrasive jet machining, ultrasonic machining, electrochemical machining, electrical discharging machine (EDM), wire-cut EDM, etc. are employed to machine these technically advanced materials. The contemporary machining methods process the material irrespective of its mechanical properties such as strength, hardness, toughness or brittleness. The non-traditional machining processes are classified on the basis of type of energy sources used such as; mechanical, electrical, chemical or thermal etc, which cause the removal of work material through different mechanisms.

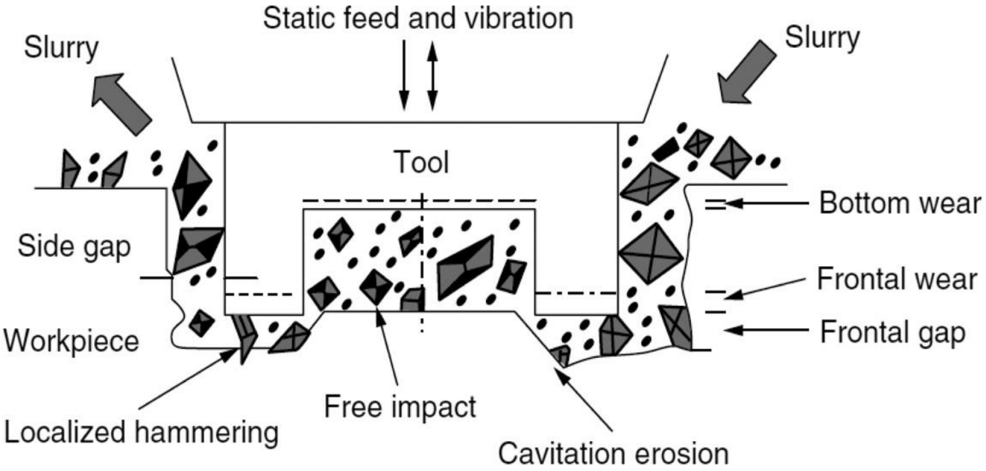

Figure 1: Basic mechanism of material removal in ultrasonic machining (Thoe et al., 1998)

Ultrasonic machining is a modern machining method typically utilized for the purpose of machining materials with higher hardness/brittleness such as; glass, ferrites, ceramics, quartz, germanium materials etc. (Thoe et al., 1998; Singh and Khamba, 2006a; Kumar, 2013; Singh et al., 2015; Kataria et al., 2016). The process came into existence in 1945 when L. Balamuth was granted the first patent for the process. Ultrasonic machining is also termed as ultrasonic grinding, ultrasonic drilling, slurry drilling, ultrasonic cutting, ultrasonic abrasive machining, and ultrasonic dimension machining. Figure 1 shows the basic mechanism of material removal in ultrasonic machining.

In USM, high frequency electrical energy is converted into linear mechanical vibrations via a transducer/booster combination, which are then transmitted to an energy focusing as well as amplifying device, known as horn or sonotrode. This causes the tool to vibrate along its longitudinal axis at high frequency; usually greater than 20 kHz, with an amplitude of 12-50 µm. The power rating ranges from 50 to 3000 W and a controlled static load is applied to the tool for providing feed in the longitudinal direction. Abrasive slurry, which is a mixture of abrasive material (such as; silicon carbide, boron carbide and alumina etc.) suspended in water or some suitable carrier medium is continuously pumped across the gap between the tool and work. The vibration of the tool causes the abrasive particles held in the slurry to impact over the work surface, leading to material removal through micro-chipping.

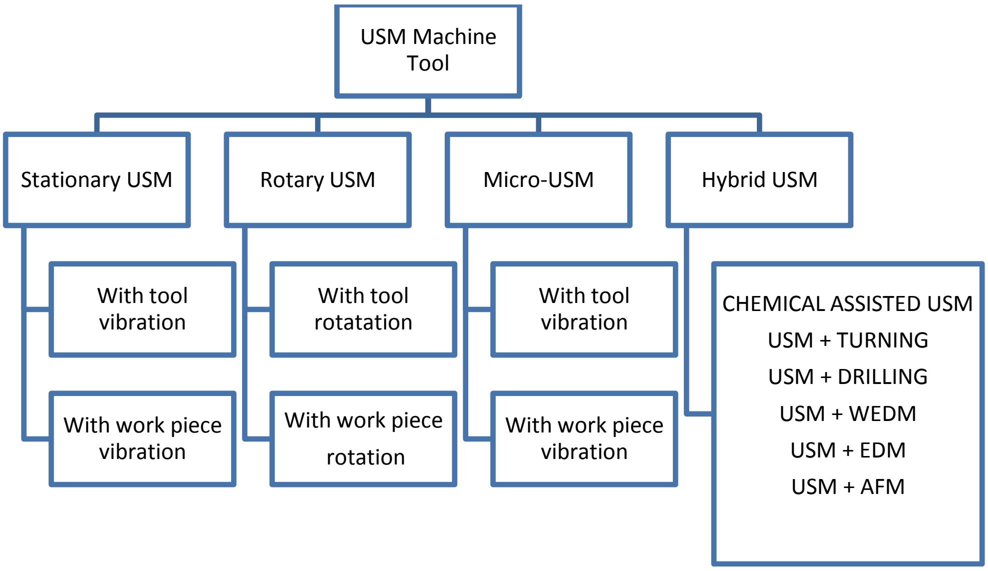

Figure 2: Basic classification of ultrasonic machine tool

USM is generally associated with low material removal rates; however its applications are not limited by the electrical or thermal characteristics of the work material. Because the process is non-thermal and non-chemical, the materials processed are not altered either chemically or metallurgically (Thoe et al., 1998; Singh and Khamba, 2006a; Kumar, 2013). Holes as small as 76μm in diameter can be drilled; however the depth to diameter ratio is limited to 3:1(Kumar, 2013). For efficient machining to take place, the tool and horn must be designed with consideration given to mass and shape so that resonance can be achieved with in frequency range capability of the ultrasonic machine. Figure 2 shows the different types of ultrasonic machining and its hybridization with other processes.

2. Basic components of ultrasonic machine tool

Ultrasonic machine comprises of a number of essential elements, which are necessary for the functioning of the machine. These major components are; ultrasonic power supply, transducer or converter, ultrasonic horn, tool and tool assembly etc. Figure 3 shows the basic element of ultrasonic machining set-up.

In ultrasonic machining, the power supply is characterized as a high power sine wave generator that offers the user control over the frequency and power of the generated signal. It converts low frequency (50-60 Hz) electric power to high frequency (20-25 kHz) electrical signals. This electric signal is applied to transducer which further converts it into linear vibration. The transducer converts the electrical signals into mechanical motion.

In the ultrasonic machine tool, there are two type of transducers based on their principle of operation, piezoelectric and magnetostrictive. In piezoelectric transducer, the mechanical motion is achieved by piezoelectric effect generated from certain materials such as; quartz or lead zirconate titanate. On the other hand, another type of transducer is generally constructed from a laminated stack of nickel or nickel alloy sheets. Magnetostictive type transducer results in high electrical losses and low efficiency (about 55-60%), while piezoelectric transducers possess high efficiency (90-96%). The horn is another essential element of ultrasonic machine tool. The function of the horn is to attach and hold the tool with the transducer, and also to transmit energy towards the tool. Horn (or tool holder) is attached to the transducers by the means of a large, loose-fitting screw. Horns are available in two configurations namely; amplifying and non-amplifying. Generally used materials for making horns are; monel, titanium, stainless steel, aluminium etc. The designing of tool should be done in such a manner that can provide the maximum vibration amplitude at the free end at a given frequency. The tool material should have desired mechanical properties such as; high wear resistance, good elastic and fatigue strength. Commonly applicable materials for tool are; mild steel, tungsten carbide, silver steel, monel etc. The tool can be attached to the horn by several means like; soldering, brazing, screw/taper fitting.

In USM, abrasive materials are utilized for the preparation of abrasive slurry. There have been different types of abrasives materials used for slurry such as; boron carbide, aluminium oxide, silicon carbide etc. While, in precision processing of very hard workpieces, cubic boron nitride and diamond powder are also used as abrasive materials. Low viscosity, good wetting properties, high thermal conductivity, high specific heat etc. are the different desired properties of an ideal transport medium used for slurry preparation. However, water is the commonly used medium for forming the slurry.

3. Model for material removal mechanisms

There have been different models proposed by various investigators on the mechanisms of material removal in USM (Kennedy and Grieve, 1975; Thoe et al., 1998; Kumar 2013). These developed models have well described the material removal as a function of different process parameters such as; vibration amplitude, grit size, power rating, frequency etc. As per the literature, four different mechanisms have been observed which cause the removal of material from the work surface. These mechanisms are as follows:

- Material abrasions by direct hammering of the abrasive particles against the work piece surface.
- Micro-chipping by impact of the free moving particles.
- Cavitation effect caused due to abrasive slurry.
- Chemical action associated with fluid employed.

Table 1 is illustrates the different models proposed by various investigators to describe the materials removal mechanisms in USM.

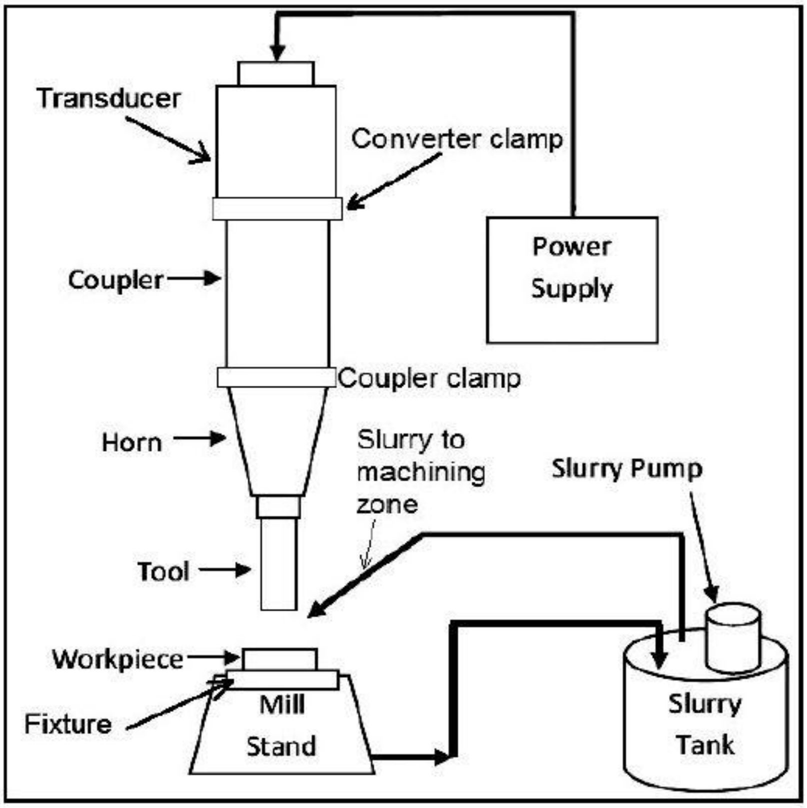

Figure 3: Schematic representation of USM set-up

Table 1: Models reported for ultrasonic machining

Name of Investigator	**Mechanism of material removal**	**Assumptions**	**Limitations**
M.C.Shaw (1956)	Direct hammering of abrasive particle (primary) Impacting by free moving particles (secondary)	All abrasive particles are identical rigid spherical in shape. Material removal is proportional to volume of material removed per cycle and frequency of impacting. Penetration depth is inversely proportional to flow stress of work material. For a given area of tool face, number of active grains is inversely proportional to square of the mean diameter of grains.	Analysis does not agree with experimental results qualitatively. Does not predict the effect of variation in amplitude, feed force or frequency correctly. Predicts infinite increase in machining rate with static force while an optimum value exists due to grain crushing. No allowance for grain size variation and for crushed grains.

G.E. Miller (1957)	By chipping plastically deformed and work hardened material. In ductile material, MRR depends work hardening while in brittle material on size and rate of chip formation.	Abrasive particles are of cubical size. Plastic deformation is directly proportional to the stress. Plastic flow stress equals Burger vector times shear modulus. Cross sectional area of the cut does not change during machining. Viscosity effects in water slurry are almost negligible.	Applicable to ductile materials only as MRR is assumed to depend on plastical deformation. Some non-realistic assumptions such as cubical shape of grains and participation of all grains in cutting action (under the tool tip) have been made. No allowances for grain size variation. Number of active grains derived assuming slurry is drawn when tool recedes.
Rozenberg Kazantsev (1964)	Brittle fracture	Abrasive particles are incompressible and are of irregular shape but can be considered as spheres having projections whose radii of curvature are proportional to the mean dimensions of particle. Based on the experimental evidence, the statistical distribution of abrasive particle size is given by: $\Phi (d) = 1.095\frac{N}{d_m}[1- (\frac{d}{d_m} - 1)^2]^3$ Where N is number of active abrasive grain, dm is the mean diameter of grains.	Involves tedious computation and its solution requires numerous integration.
N.H.Cook (1966)	Hemispherical indentation fracture	Abrasive grains are spheres of uniform radius. Tool and abrasives are rigid. Viscosity effects are negligible. A linear relationship between fraction of active grits and ratios of indentation depth to grit-radius has been assumed.	Model predicts linear relationship between static stress and MRR, while MRR drops after a certain value of feed force. It predicts that MRR is proportional to square root of grain radius, while practically an optimum value exists.
G.S. Kainth Et al. (1979)	Indentation fracture due to direct hammering action	Abrasive grains are spherical in shape and follow Rzenberg's size distribution functions to take into account particle size inhomogeneitly. Motion of fool remains sinusoidal under loaded conditions.	Computationally intensive. Predicts linears relationship between MRR and static force F that is practically not true. Predicts linear increase in MRR with grain size, while and optimum value exists. Theoretical machining rate is higher than practical values.
Nair and Ghosh (1985)	Brittle fracture	Abrasive particles are rigid spheres. No consideration for MRR due to particle impacting, cavitation or chemical action of slurry. Tool tip motion is SHM and abrasive particle rests on a brittle half-space and receives only a single impact in this position.	Derivation of the model is computationally intensive. The volume fractured by a single abrasive grain is to be calculated using fracture profile.

Wang and Rajurkar (1995)	Combination effect of impact indentation and fracture phenomenon	Work-piece is assumed to be semi-infinite solid. Axis of moving grit is perpendicular to the free surface during machining. Speed of abrasive is same as that of vibrating tool.	Can be used for perfectly brittle material only like amorphous glass. Results are not true for material which exhibits some plastic behavior like carbide.
Lee and chan (1997)	Brittle facture	Pre-existing flaws are assumed in the material for the initiation of median or lateral cracks. Size of median or lateral crack is related to pseudo pressure between tool and work-piece. Cutting tool is assumed to be a slender column.	Applicable to brittle material only.
Wiercigroch et al., (1999)	Micro-cracking due to impacts of grains	MRR is a function of the magnitude of impact force and its frequency. Diamond is uniformly distributed over the working part of tool with a uniform grit size. Ultrasonic vibration, amplitude, frequency and tool geometry remain unchanged.	Applicable to hard and brittle material only. Tool geometry changed with progress in machining as the wear on the surface of tool is not uniform.

4. Effect of process parameters on MRR

Deng and Lee (2002) studied the effect of properties of work material on the material removal rate in ultrasonic machining of alumina-based ceramic composites. MRR was reported to be low while machining composites of higher fracture toughness. Guzzo et al. (2004) studied the ultrasonic machining of different hard and brittle materials (alumina, zirconia, LiF, quartz, soda-lime glass and ferrite). Results reported that material removal rate and surface roughness are dependent upon intrinsic stiffness, hardness and fracture toughness of the work materials. Majeed et al. (2008) carried out the ultrasonic machining of $Al_2O_3/LaPO_4$ composites. Results showed that an increase in the hardness of the composite improves the material removal rate up to a critical limit, after which it stabilizes. The use of Hollow tool gives more MRR as compare to solid tool. Reported results show that tool material plays a significant role for material removal rate in the ultrasonic machining. Komaraiah and Reddy (1993b) studied the influence of tool material properties on material removal rate in ultrasonic machining of glass. Results reported that the MRR increases with an increase in the hardness of the tool material. The order of decreasing overall performance of the tool materials is as follows: nimonic-80A > thoriated tungsten > silver steel > maraging steel > stainless steel > titanium > mild steel. Kumar and Khamba (2010a) reported tungsten carbide as the better tool material while performing ultrasonic machining of titanium alloy. It was also reported that the tool with higher hardness gives better outcome in terms of MRR. Kumar et al. (2008) examined the tool material performance in terms of MRR and found that high carbon steel tool gives better MRR than titanium alloy tool. Different types of tool materials (tungsten carbide, brass, mild steel, silver steel, stainless steel, and copper) have been investigated by Neppiars (1957) in order to observe their influence on MRR. The performance of several tools as reported from this study in decreasing order is; tungsten carbide> brass> mild steel> silver steel> stainless steel> copper.

5. Effect of process parameters on TWR

In USM, MRR and hole accuracy have been reported to be highly related with the tool wear (Adithan, 1981; Goetze, 1956; Laroiya and Adithan, 1993; Smith, 1973; Venkatesh, 1983; and Weller, 1984). Basically, there are two types of tool wear reported in USM; longitudinal wear (Smith, 1973) and lateral wear (Adithan and Venkatesh, 1978), as shown in Figure 4. However, some other types of tool wear have also been reported to be occurred, as a result of suction or cavitation (Venkatesh, 1983). Different process variables in USM have also been found to be influential for tool wear, due to its complex nature. These factors are work material, thickness of work, tool material and profile, power rating, static load, abrasive material (hardness, grain size) etc.

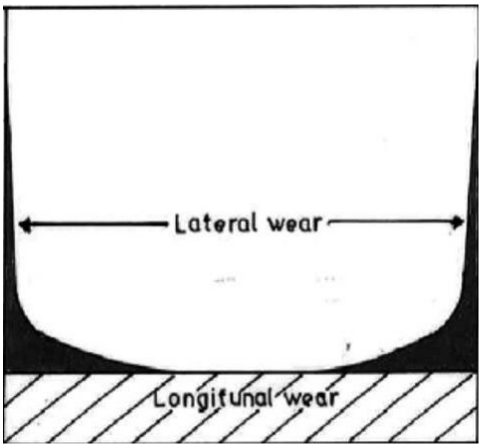

Figure 4: Tool wear patterns (Adithan, 1974)

Kumar and Kumar (2011) evaluated the tool wear rate in ultrasonic machining of titanium using designed of experiments. Tool Material was observed to be most significant factor for tool wear rate. The tool materials can be ranked in order of increasing tool wear rate as Ti alloy<titanium<HSS<HCS<cemented carbide. Kumar et al. (2009) investigated the tool wear rate in ultrasonic machining of titanium at different input parameters settings; tool material (HCS, HSS, titanium, Ti alloy, cemented carbide), abrasive grit (alumina, SiC, boron carbide), grit size (220, 320, 500), and power rating (100, 250, 400) using Taguchi method. The results showed that tool material and power rating affects the rate of wear of the tool very significantly. The optimized parameters setting for tool wear rate is reported as; tool material- Ti alloy, abrasive-alumina, grit size- 500, power rating- 100W. Adithan (1974) studied the tool wear rate in ultrasonic drilling of glass and porcelain. The results showed that tool wear is affected by a number of factors such as; work material, tool material, work material thickness, tool size and cross sectional area, heat treatment of the tool, static load, cutting time and type of abrasives used. Singh and Khamba (2009) developed the mathematical model for tool wear rate by considering significant process parameters (tool material, abrasive, abrasive grit size, slurry concentration, power rating, slurry temperature), to facilitate the optimization of ultrasonic machining of titanium. The optimum tool wear rate was achieved by using stainless steel as tool material, power rating- 450 W, and grit size- 500. Adithan et al. (1981) studied the tool wear characteristics in ultrasonic machining of tungsten carbide and glass. The results showed that stainless steel tools exhibit lower tool wear as compared to tungsten carbide and mild steel. When hard materials such as tungsten carbide are machined, both longitudinal and lateral wear occur.

6. Effect of process parameters on surface roughness

Kumar (2014) investigated the surface roughness and micro-hardness of machined surface in ultrasonic machining of titanium. Reported results show that surface quality of the machined surface is mainly affected with rate of input energy (grit size and power rating). Dvivedi and Kumar (2007) investigated the effects of five controllable factors (work material, grit size, slurry concentration, power rating, and tool) on the surface roughness in ultrasonic drilling of titanium and its alloys using Taguchi method. The results showed that the slurry concentration and grit size have more significant effects on SR than the other process parameters. Lalchhuanvela et al. (2012) investigated the effect of different USM process parameters (abrasive grit size, slurry concentration, power rating, tool feed rate and slurry flow rate) and developed empirical RSM model for surface roughness while machining alumina ceramic. The results reported that the surface roughness decreases with decrease in grit size and power rating. Slurry concentration, tool feed rate, and slurry flow rate have less effect on surface roughness.

Kumar and Khamba (2008) reported that surface roughness of machined surface is directly proportional with abrasive slurry concentration and grit size. Singh (2010) investigated the surface roughness in ultrasonic machining of titanium alloy. Results reported that the slurry temperature is the most significant factor among all the considered input parameters i.e. tool material, abrasive, slurry concentration, grit size, power rating, slurry temperature. Lee and Chan (1997) developed an analytical model to predict the effects of amplitude of tool tip, static load, and size of the abrasive on surface roughness. They concluded that increase in amplitude of tool vibration, static load, and grit size of the abrasive would result in to an increase in the roughness of the machined surfaces. Bhosale et al. (2014) reported that amplitude has significant effect on the surface roughness in ultrasonic machining of alumina-zirconia ceramic.

7. Optimization of process parameters

Lalchhuanvela et al. (2012) investigated the effect of different USM process parameters (abrasive grit size, slurry concentration, power rating, tool feed rate, and slurry flow rate) and developed empirical RSM model for material removal rate (MRR) and surface roughness (SR) while machining alumina ceramic. The results reported that the higher level of every input parameter gives higher MRR on the workpiece. SR decreases with decrease in grit size and power rating. Slurry concentration, tool feed rate, and slurry flow rate have less effect on SR. The optimal parameter setting is; grit diameter of 55 µm, slurry concentration of 50%, power rating of 40%, tool feed rate of 1.01mm/min, and slurry flow rate of 10 lit/min. Kumar and Khamba (2010a) investigated the effect of different input parameters (tool, abrasive, grit size and power rating) on MRR in the ultrasonic machining of titanium and also developed the micro-model for prediction of MRR using the dimensional analysis. The results showed that power rating is most significant factor with a percent contribution of 42%, followed by abrasive type (21.3%) and slurry grit size (17.2%). Tool material factor can be termed as the least significant for MRR. The optimized parametric setting for MRR is; tool material of cemented carbide, boron carbide as abrasive material, grit size of 220, and power rating of 400 W (80%). Kumar and Khamba (2009) carried out the multi-response optimization of ultrasonic machining of Co-based super alloy using Taguchi’s multi-objective approach. The effect of tool material, abrasive material, slurry concentration, grit size, and power rating were investigated on material removal rate, and tool wear rate. For the optimization of multiple performance characteristics, the percentage contribution of factors in descending order is; power rating: 30.33%, abrasive grit size: 28.67%, tool material: 22.06%, abrasive slurry: 15.41% and slurry concentration: 3.51%, respectively. The optimized parametric setting for MRR and TWR is; tool material - titanium, abrasive - boron carbide, slurry concentration - 30%, grit size - 220, and power rating - 125 W (25%).

Jadoun et al. (2006b) optimized material removal rate in ultrasonic drilling by employing Taguchi robust design methodology in machining of Al based ceramics. The optimal setting of input parameters was validated by conducting confirmation experiments. Dam et al. (1995) carried out the ultrasonic drilling operations in different ceramics (glass, Al_2O_3, TiB_2, SiC, HPSN, TZ12, TZ_3TB). Results reported that tough materials would give a low production rate, high tool wear and low surface roughness. For brittle materials, the relationships would be reversed. Singh and Khamba (2007a) applied the Taguchi method to study the effect of different process parameters (tool material, power, slurry type, grit size, slurry concentration, and slurry temperature) on MRR in ultrasonic machining of titanium and its alloys. They found that ultrasonic power rating significantly improved the MRR with a contribution of 28%, and type of tool had contribution of 24.6%. Third significant factor had been slurry type with contribution of 13.3%, and remaining parameters were observed as in-significant.

8. Conclusions:

Ultrasonic machining is widely used non-traditional processes; especially for hard, brittle and fragile materials. There is ample scope for application of USM for establishing cost effective machining solutions for hard and brittle materials, such as; glass, tungsten carbide, cubic boron nitride, etc. Performance measures in USM process are dependent on the work material properties, tool properties (hardness, impact strength and finish), abrasive properties and process settings (power input, static load, and amplitude). The material removal in USM has been found to occur by propagation and intersection of median and lateral cracks that are induced due to repeated impacts of abrasive grains.

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