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A Review on Current Research Trends in Ultrasonic Machining (USM)

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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, amplitude, ultrasonic drilling, tool wear rate, surface roughness.**

1. Introduction

A. *Introduction of USM*

Ultrasonic machining is used in the manufacturing industries to obtain a superlative performance. The main advantage of this machining process is it evolves less heat during the process. Ultrasonic machining processes are cost effective and best in results. Ultrasonic machining is an abrasive process which material in hard and brittle form with the help of its vibrating tool by the indirect passage of abrasive particles towards the work piece. It is a low material removal rate machining process. It is also known as Ultrasonic impact grinding an operation, that involves a vibrating tool fluctuating the ultrasonic frequencies in order to remove the material from the work piece. The process involves an abrasive slurry that runs between the tool and the work piece. Due to this, the tool and the work piece never interact with each other. The process rarely exceeds two pounds.

The use of ultrasonics in machining was first proposed by L. Balamuth in 1945. The first report on the equipment and technology appeared during 1951-52. By 1954, the machine tools, using the ultrasonic principle, had been designed and constructed. Originally, USM used to be a finishing operation for the components processed by the electro spark machines. 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.

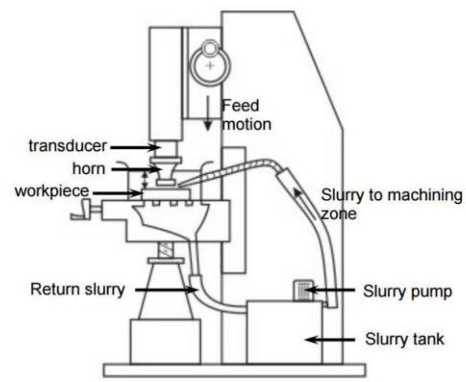

Fig. 1. Schematic Diagram of USM

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

B. *Principle of USM*

Ultrasonic machining (USM) is the removal of material by the abrading action of grit-loaded liquid slurry circulating between the work piece and a tool vibrating perpendicular to the workface at a frequency above the audible range. Ultrasonic machining, also known as ultrasonic impact grinding, is a machining operation in which an abrasive slurry freely flows between the work piece and a vibrating tool. It differs from most other machining operations because very little heat is produced. The tool never contacts the workpiece and as a result the grinding pressure is rarely more, which makes this operation perfect for machining extremely hard and brittle materials, such as glass, sapphire, ruby, diamond, and ceramics.

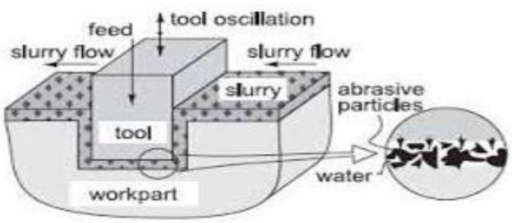

Fig. 2. Ultrasonic machining.

The working process of an ultrasonic machine is performed when its tool interacts with the workpiece or the medium to be treated. The tool is subjected to vibration in a specific direction, frequency and intensity. The vibration is produced by a transducer and is transmitted to the tool using a vibration system, often with a change in direction and amplitude. The construction of the machine is dependent on the process being performed by its tool.

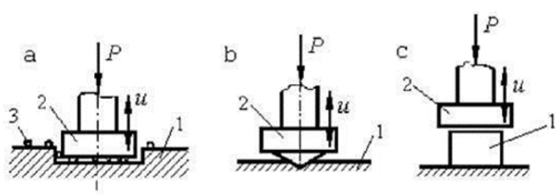

Fig. 3. Ultrasonic erosion process

The above figure shows the ultrasonic erosion process used to machine hard, brittle materials. The workpiece 1 is placed under the face of the tool 2 which is subjected to high frequency vibration perpendicular to the surface being machined. Abrasive slurry is conveyed to the working zone between the face of the tool and the surface being machined. The tool moves towards the workpiece and is subjected to a static driving force P. repetitive impact of the tool on the grains of the abrasive material, falling from the slurry onto the surface to be treated , lead to the fracture of the workpiece material and to the creation of a cavity with the shape mirror formed of the tool. The abrasive particles are propelled or hammered against the workpiece by the trans mitted vibrations of the tool. The particles then microscopically erode or "chip away" at the workpiece.

Generally, the tool oscillates at a high frequency (about 20,000 cps) in an abrasive slurry. The high speed oscillations of the tool drive the abrasive grain across a small gap of about 0.02-0.10mm against the workpiece.

C. Tool holder

The tool holder transfers the vibrations and, therefore, it must have adequate fatigue strength. With a good tool design, an amplitude gain of 6 over the stack can be obtained. Generally, the shape of tool holder is cylindrical, or a modified cone with the centre of mass of the tool on the centre line of the tool holder. It should be free from nicks, scratches and tool marks to reduce fatigue failures caused by the reversal of stresses.

D. Tool materials and Tool size

The tool material employed in USM should be tough and ductile. However, metals like aluminum, give very short life. Low-carbon steel and stainless steels give superior performance. The qualitative relationship between the material removal rate and lambda i.e. workpiece/tool hardness. Long tool causes overstressing of the tool. Most of the USM tools are less than 25 mm long. In practice the slenderness ratio of the tool should not exceed 20. The under sizing of the tool depends coupon the grain size of the abrasive. It is sufficient if the tool size is equal to the hole size minus twice the size of the abrasives.

E. Transducers

The ultrasonic vibrations are produced by the transducer. The transducer is driven by suitable signal generator followed by power amplifier. The transducer for US M works on the following principle:

- Piezoelectric effect
- Magnetostrictive effect
- Electrostrictive effect

F. Parameters of Ultrasonic Machining

The ultrasonic vibration machining method is an efficient cutting technique for difficult-to- machine materials. It is

Table 1
Tool material used

Material	Chemical Composition	Crystalline Structure	Density (g/cm^3)	*E* (GPa)	*H* (GPa)	*KIc* ($MPam^{1/2}$)
Alumina	Al_2O_3	FCC/polycristalline	4.0	210 - 380	14– 20	3 - 5
Ferrite	-	- / polycristalline	-	~180	6.8	1
LiF	LiF	FCC/single-crystal	2.43	54.6	0.92± 0.03	1.5
Quartz	SiO_2	Trigonal/single-crystal	2.65	78.3	15.0 ± 1.0	0.53± 0.01
Soda-lime glass	SiO_2+Na_2O+CaO	Amorphous	2.5	69	5.8± 0.5	0.48 ± 0.05
Zirconia	ZrO_2	Tetragonal/polycristalline	5.8	140 - 210	10– 12	8 - 10

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found that the USM mechanism is influenced by these important parameters.

- Amplitude of tool oscillation
- Frequency of tool oscillation
- Tool material
- Type of abrasive
- Grain size or grit size of the abrasives
- Feed force
- Contact area of the tool
- Volume concentration of abrasive in water slurry
- Ratio of workpiece hardness to tool hardness; $ʆ=\sigma w/\sigma t$.

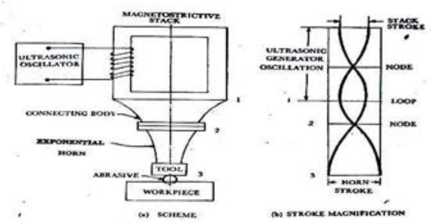

Fig. 4. Ultrasonic machining

2. Literature review

Table 2
Literature survey

S. No.	Name of author	Years	Methods	Methodology used / Parameter analysis	Results and discussion
1	Wang et al.	2012	Investigated	discussed fundamental principles of ultrasonic machining, the material removal mechanism and important factors are calculated.	They also concluded that Decrease in the cutting speed of the work piece and increase in the vibration frequency will result in better surface quality.
2	Basem M. A. Abdo et. al.	2015	Investigated	difficult-to-machine materials such as Ti-6Al-4V are very hard, tough, and possessed high impact resistance, their machinability is low and sometimes impossible with traditional machining processes.	The results of this work identify that the cutting forces increase significantly with increase in coolant pressure, vibration amplitude, depth of cut and feed rate while decrease with increase in spindle speed.
3	Zarepour and Yeo	2012	Modeling	Developed a model to predict material removal modes in ductile and brittle material when the brittle material is impacted by single sharp abrasive particle in micro ultrasonic machining process. They predicted the material removal modes for silicon <100> and fused quartz.	They studied morphology of the crater formed and observed three modes of material removal namely pure ductile, partially ductile (transition mode) and pure brittle.
4	Kang et al.	2006	Investigated	the material removal rate and surface quality of the alumina (Al_2O_3) which was ultrasonically machined using SiC abrasive under various machining conditions. They investigated that material removal rate increases as the static pressure and slurry concentration increases.	They resulted an improved surface roughness of about 0.76 µm when machining was done by using abrasive of mesh number 600.
5	Tamilselvan, Raguraj	2014	Optimization	Process Parameters of Drilling in Ti-Tib Composites using Taguchi Technique. Results showed that The Taguchi's experimental design and Analysis of Variance (ANOVA) techniques have been implemented to understand the effects, contribution, significance and optimal machine settings of process parameters, namely, spindle speed, feed rate, process, and drilling material.	Conclusions were made -Thrust force decreased with the increase in spindle speed, increase in spindle speed plays a predominate role in the drastic reduction of overcut.
6	Muhammad et al.	2012	Investigated	the effect of vibration on cutting forces and temperature levels in a cutting region for various cutting conditions.	They concluded that the cutting force increases with the increase in depth of cut. They also concluded an increase of Temperature in the cutting region increases due to increase in the depth of cut and cutting speed, both in CT and UAT.
7	Yasuhiro Kakinuma et al.	2015	investigated	Ultrafast Feed Drilling of Carbon Fiber-Reinforced Thermoplastics. Demand for through-hole drilling of CFRTPs is increasing.	The results showed that delamination at the outlet surface can be significantly suppressed during high rotational drilling when the feed rate is set to more than 3000 mm/min. By providing appropriate drilling conditions to prevent polymers in CFRTPs from softening, ultra-fast drilling of CFRTPs was successfully achieved under dryconditions.

8	V. Baghlani et al.	2013	investigated	investigated Ultrasonic assisted deep drilling of Inconel 738LC super alloy. Super alloys have a poor machinability and are often drilled using (EDM) methods. However, EDM is a time-consuming process and has low surface integrity. Ultrasonic Assisted Drilling (UAD) technology is a modern method of drilling such materials. The effect of ultrasonic vibration amplitude, spindle speed and number of steps to drill each hole on machining force and surface roughness were investigated.	The results show that increasing material removal rate makes drilling more difficult and increases forces and surface roughness. An average thrust force of 417N and surface roughness of 1.610μm was obtained.
9	H. Hocheng et al.	1999	experiments	carried out experiments on Zirconia ceramic for finding metal removal rate, hole clearance, surface roughness, tool wear rate of the work piece.	The result found that the MRR increases with the increase of amplitude of the ultrasonic machine. At constant amplitude, the clearance decreases with applied load. Better surface roughness can be obtained by the 50% range of amplitude. An increase in applied load leads to decrease in hole clearance. And the larger the static load is favorable for a finer surface.
10	Komaraiah and Reddy	1993	investigated	the influence of work material properties such as fracture toughness and hardness on material removal rate in ultrasonic machining of hard and brittle materials.	The work-piece materials machined in this investigation were glass, ferrite, porcelain, alumina and tungsten carbide. MRR was reported to decrease with an increase in work material hardness and fracture toughness in almost linear fashion under controlled experimental conditions.
11	M. Wiercigroch et al.	2005	experiment	conducted an experiment and showed that an introduction of high-frequency axial vibration significantly enhances drilling rates compared to the traditional rotary type method.	It has been found out that the material removal rate (MRR) as a function of static load has at least one maximum. It is postulated that the main mechanism of the MRR enhancement is associated with high amplitudes of forces generated by impacts. Novel procedures for calculating MRR are proposed, explaining an experimentally observed fall of MRR at higher static loads.
12	Jatinder Kumar et. al.	2008	experiment	conducted experiments to assess the effect of three factors tool material, grit size of the abrasive slurry and power rating of ultrasonic machine on machining characteristics of titanium using full factorial approach for design and analysis of experiments.	It has been concluded that titanium is fairly machinable with USM process. Moreover, the surface finish obtained is better than many of the other non-traditional processes. Surface roughness of the machined surface has been found to depend on grit size of the slurry used. Tool material and power rating have negligible effect on surface roughness. Optimum values for surface roughness were obtained with grit size 500 for alumina.
13	Shrikrushna B. Bhosale et al.	2014	investigation	reported through experimental investigation and analysis of material removal rate, tool wear rate, and surface roughness in ultrasonic machining of alumina-zirconia ceramic composite (Al_2O_3 + ZrO_2). The experiments were conducted using full factorial DOE method with an orthogonal array.	Analysis of results indicates that the amplitude has significant effect on the MRR and surface roughness. An increase in amplitude causes higher MRR and surface roughness. Pure SiC abrasives gave better surface finish, whereas the mixed abrasives produced higher tool wear and MRR.

3. Conclusion

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.

4. Future scope

- Unique cutting in manufacturing industries.
- The scope of Ultrasonic micro machining of micro channels in ceramics, in glass and in the area of fabrication of micro heat exchanger and sensors and in the area of fluid mechanics.

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