Ultrasonic machining and micro-machining-An Industrial perspective

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Abstract
Ultrasonic machining finds suitability in machining of non-conductive, brittle material such as glass, ceramics etc. Amongst the non-traditional machining processes such as laser beam machining (LBM), electric discharge machining (EDM), plasma arc machining etc. which causes thermal damage to the material and shows great improvement in residual stresses. Therefore, UMS is advantageous over other non-conventional machining processes. Ultrasonic machining is mechanical process in which material removal takes place by brittle fracture and with control machining parameters, it is most promising methodology to machine brittle material. In this study, we present the principle of ultrasonic machining and how various parameters are involved in effective and efficient machining.
Keywords: Ultrasonic machining, micro machining, Deburring process

History of USM Process

The history of ultrasonic machining (USM) began with a paper by Wood and Loomi in 1927 in which the scope of using high frequency (about 70 kHz) sound waves were proposed[1].The first useful description of the technique of ultrasonic machining is contained in a British patent granted to Balamuth in 1945.[2].While investigating the ultrasonic grinding of abrasive materials, Balamuth observed the disintegration of abrasives when the tip of an ultrasonically vibrating transducer was placed close to it. Piezoelectric vibrators with concentrators consisting of conical glass tubing filled with water were used in the first laboratory tests. Because of the rapid developments in science and engineering, the ultrasonic4 method has been considerably improved and has been used in the industry. Information concerning the industrial use of ultrasonic for machining hard brittle materials was published in the technical press in 1951[3]. It has been named in variously termed as 'slurry drilling' [4], ultrasonic drilling' [5], 'ultrasonic dimensional machining' [6], 'ultrasonic abrasive machining' [7], and 'ultrasonic cutting'[8]. However, from the early 1950s it is commonly known either as 'ultrasonic impact grinding (UIG)' or 'ultrasonic machining (USM).

Introduction

Ultrasonic machining (USM) is non-conventional machining process employed to machine hard and brittle material both conductive as well as non-conductive. Recently, the need for semiconductor devices, extremely compact electrical circuits, and integrated circuit packages that contain devices having micro dimensions have led to introduction of micromachining. The circuit board must have micro hole if relay and switches are essentially required to be assembled in micro sized part. Fuel injection nozzle for automobile have become smaller in size and more accurate to solve many environmental problems. In area of biotechnology that include biological cell and genes, the tool required to handle them must have micro effector. Miniaturisation of medical tool for inspection and surgery in another candidate for micromachining process [9].

Micro in micromachining indicate machining in microlevel and represent the range of 1-999um.However, micro likewise means very small. In the field of machining by material removal, micro indicates part that are very small to be easily machined. In fact, the range of micro varies according to era, person, machining method, and type of material for product. In micromachining there are two guidelines, specially, the reduction of unit removal rate and improvement of equipment precisely. The unit removal rate (UR) is the part of workpiese that removed during one cycle of removal action. Unit removal rate can express in length, cross section area or volume. For micromachining UR is smaller because object is smaller than 500um.

BASIC PRINCIPLE OF USM

"Tool is vibrated at ultrasonic frequency greater than 20 KHz which strikes the abrasive particle, this impact from tool propel the the grain across the gap between tool and work piece. These particles attain the kinetic energy which is sufficient to remove the material from work piece by cavitation erosion".

1. Tool is hammering the abrasive particles.

2. The impact of the abrasive particles which move freely
3. Cavitations Erosion of abrasive slurry

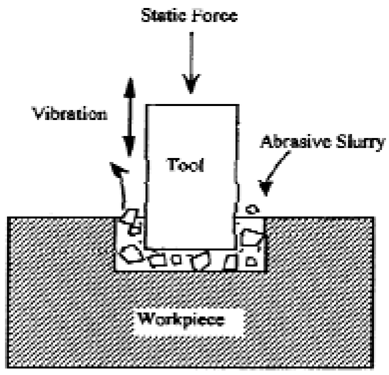

Fig 1: Basic principle of UMS

Selection of material for work piece, tool & abrasive grain

1. **Work piece material**

The USM process can machined any material, but more suitable for hard and brittle material, the material divided as

- First is material is machined very easily because of porosity and fragility e.g. Glass, germanium, and silicon, for that material removal rate is high and tool wear is <1%
- Some materials are difficult to machined because of less porosity e.g. Ceramic, oxide, carbide, precision stone but tool wear varies from 2 to 10% for machining such material titanium, tungsten carbide or diamond is preferred
- Material very hard (ceramic) or very ductile (metal alloy) poor material removal rate observed as few mm3/min and tool wear is 30 to 100%.

2. **Abrasive materials**

Abrasive material plays important role in material removal; the hardness of abrasive particle has to be higher than that of work piece material.e.g. diamond, silicon nitride, silicon carbide etc. diamond is the only abrasive that able to machine hard material like diamond

3. **Tool materials**

Tool generally used made up of ductile material like stainless steel, brass etc but in some cases diamond also used as a tool material. it will resist wear very well it can be machined by wire EDM or EDM.

$$\text{TOOL WEAR} = \frac{\text{material removal rate on w/p}}{\text{Material removed on tool}}$$

Effect of process variable on removal rate

1. **Abrasive particle**

In general, by increasing the diameter d of the impinging particle leads to rise in the amount of material removal. Material removal proportional to d4. as particle size increases material removal also increases attain optimum value and then decreases.

In micromachining the grain size is very small, in order to move and not to block

They should be at least 10 times smaller than the smallest passage. In micromachining particle of 2um or less diameter is used. They remove the small amount material, in recent study 0.2um particle have been used to drill hole of 9um in glass or silicon, by use of 5um size tool

Grain concentration also effect on removal rate grain concentration lead to increase the removal rate; too high concentration has an adverse effect the concentration kept between 20 to 30%.

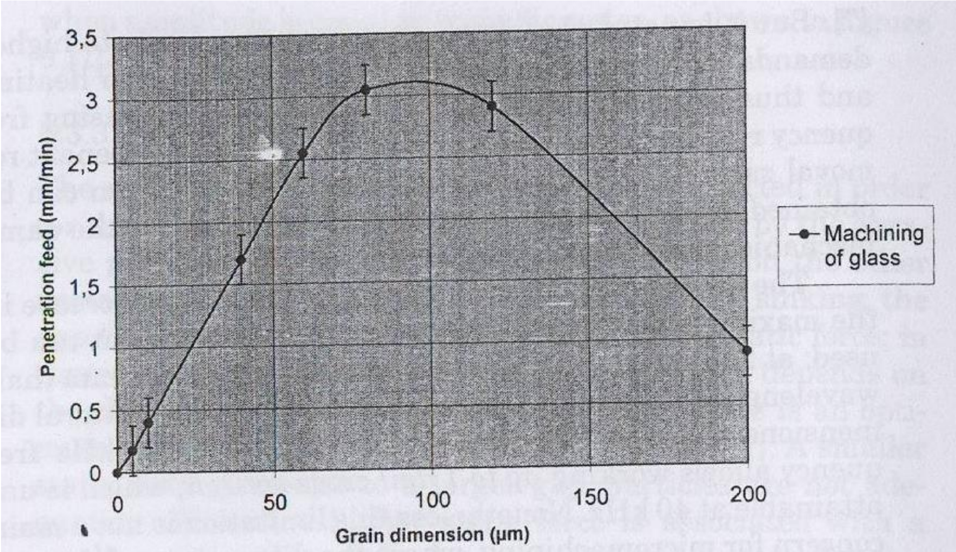

Fig 2: Material removal rate variation with grains dimensions

2. Process variables

Amplitude and frequency are the variable, removal rate increases with frequency, increasing frequency is a decrease in the maximum dimension of acoustic properties that can be used at 20 KHz, the tool length is around 125mm and at 40KHz it is 62.5mm.the lateral dimension also depends upon frequency. A 20 KHz frequency allow working up to 1dm^2 cross section, which is unattainable at 40 KHz frequency. in micromachining higher frequency thus used.

Amplitude is key of the process, the relation observed between removal rate and velocity of particle is $Q=V^{\wedge n}$ where n depends upon material, angle of contact, grain shape, & their dimension (n=2 to 3 for ductile material, 5 to 6 for brittle material), as velocity proportional to amplitude ,increasing amplitude leads to increases material removal rate , maximum removal rate is obtain when amplitude equal to grain diameter.

The machining condition has to carefully select in order for the working gap to provide effective action by abrasive particle. These conditions in turn depend upon the other variable and on the material to be machined. In sinking the gap between tool and part is adjusted by static force; in countering there is no adjustment of gap which depends upon choice of the variable used.

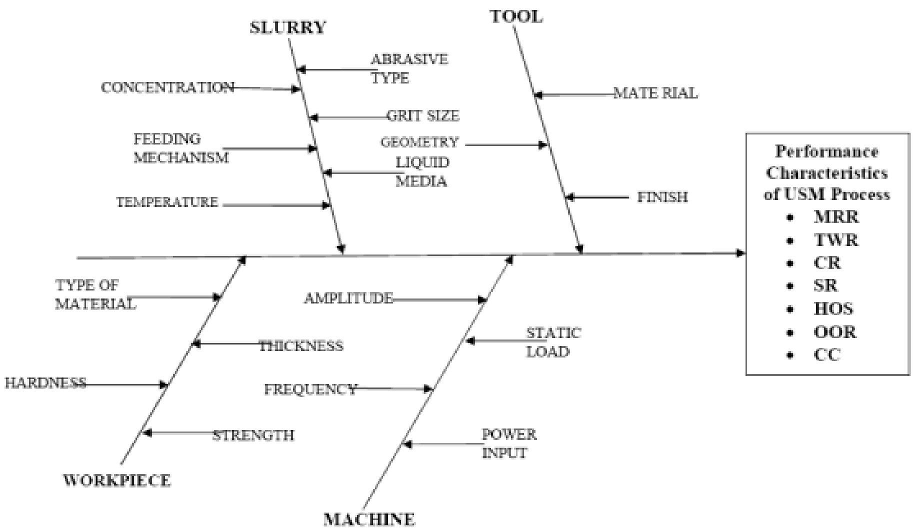

Fig 3: cause and effect diagram

Accuracy and tolerance in USM

Relation between quality and abrasive characteristics

Grain diameter has great effect on quality. Smaller the grain ,lighter the impact and better the quality , the relation is found in between grain diameter and crater dimensions; crater diameter is about d/3;creter depth is approximately d/10(9), for better quality fine grain is used.Roughining is performed with large grain (20 to 120 um) to give sufficient material removal rate; finishing is achieved with fine grain (0.2 to 10um), tool wear is also one of the important factor for accuracy. So that in micromachining diamond as abrasive gives 1% maximum wear ratio. where as carbide can lead to 75% ratio when machining hard ceramics.

1. **Accuracy**

In sinking, the lateral gap between tool and part is found one and two times more than the abrasive main diameter. The frontal gap is larger due to amplitude of vibration. In general, when drilling; use of roughing (40um) and finishing(5um) can provide +/-10um accuracy. When fine grain about 1um or less accuracy can be obtained +/-5um. In countering accuracy can even be better, since tool imperfection can be compensated by 3D movement.

2. **surface roughness**

Ultrasonic gives stress free surface, it depends on particle size. Also depended on work piece material being treated. Very brittle material will propagate micro cracks readily than less brittle material. Resulting in larger crater and poor surface roughness.

Reduction in surface always required finer grain. in a recent study on small drill hole a roughness of 0.3um Ra has been obtained on glass when 0.2um particle has been used. Ultrasonic machining can also be used for polishing purpose, in this case energy given to the particle decreases so that they only affect surface peak without removing much material from the part. sinking and countering can be used, better result obtained in case of countering in which injection of particle into the gap through the tool is used; these procedures impart lateral motion to these particles during their passage along the work piece surface. This method applied to fragile or ductile material.

There are two main methods that can be used, sinking and countering

1. sinking – is a reproduction process using form tool which its shape in negative into the work piece; machining is done on one axis only, parallel to the longitudinal axis of the tool, and its obtained either by static force or pressure.
2. countering- is a generating process using a simple shape tool working gap; machining motion is 3D NC axes.

In sinking the stand-off distance between tool and work piece is maintained by static force which is main parameter. Smaller static load gives larger gap and particle is not efficient enough

And vice versa. In countering no adjustment of gap, which depends on parameter choice parameter will depth of cut, lateral feed speed. increasing these two parameters gives more material removal rate per unit time and thus decreases the working gap. Here also an optimum has to be found for selecting all parameter, which are interdependent.

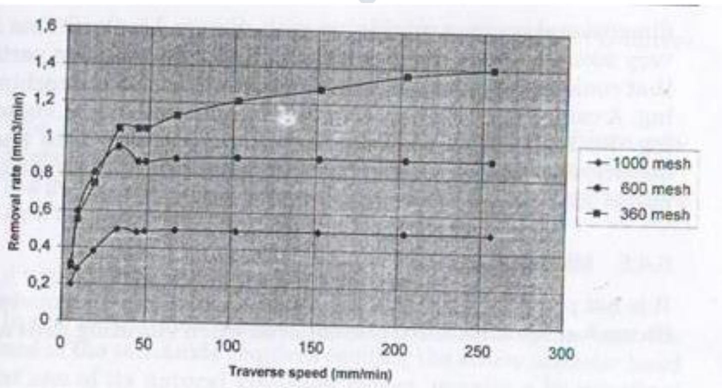

Fig 4: Material removal rate as a function of transverse speed.

3D ULTRASONIC MICROMACHINING

Microproducts and minimisation technology rapidly increasing in industries due to need of efficient use of space and saving in energy. The pursuit of product miniaturization has led to the development of microelectromechanical system (MEMS) device which has capability of sensing and actuating. Many microfabrication technologies have been developed to fabricate micro-electromechanical (MEMS) component and device. silicon is most material used in MEMS, also other material such as glass and quarts crystals used in industries. Glass is used in fabricating the optical component or reaction chamber in biological science and quartz is used for manufacturing micro actuator element. Ceramic also used in industries

Micromachining technology such as lithography and etching also used in micro manufacturing industries to fabricate IC. But has limitation that is this process not suitable to generate 3D feature.and the corresponding generated structure has low aspect ratio. it very difficult to curb the size and shape in Z direction. Mechanical manufacturing process such as milling and turning has ability to machine 3D shape in many metallic and non-metallic materials. Usually tool material is diamond and the machined work piece is convex shape. however, the mechanical contact induced deformation, heat generation and distortion result in poor accuracy. also, EDM and ECM have been used to generate 3D complex shape in only electrically conductive material.

Micro USM has ability to drill micro hole up to diameter of 5um. However, the design of tool, its fabrication and adverse effect of tool wear on the accuracy of machined component continued to posed challenge in achieving full potential of micro USM.For generating 3D micro shape using simple shaped tool (such as cylindrical shape) with capability of self-compensation of tool wear [10].

Table 1: Machining environment for micro hole drilling

Amplitude of vibration	5 μ m
Work piece material	Silicon
Tool material	Tungsten
Tool size	50 μ m, 100 μ m and 150 μ m
Abrasive grain type	polycrystalline (PCD) powder
Abrasive grains size	1–3 mm
overall tool feed	515 mm

Micro ultrasonic using multitool

For machining number of holes at a time, multitool has been fabricated and use with USM so as to get array of holes, machining with single tool is very time-consuming process, so as to minimise thee time of the process the researchers introduce the concept of multitool.the multitool fabrication process include.

1. Shaping small diameter tungsten electrode by WEDG.
2. drilling array of micro holes in cu foil by EDM
3. Fabricating the multi tool by EDM using foil as electrode with an assistance of ultrasonic oscillation.

Micro deburring technology using ultrasonic vibration with abrasive

It is very difficult task to deburr the edge of work piece which are created due to plasticity during mechanical manufacturing process. Generally, burr removed by method of physics or chemistry. apart from these ultrasonic is also one of the process for deburring the burr created at edges of the work piece, these burrs lower the precision of components and cause many problems imparts assembly. Especially, burrs drastically reduce the performance of microelectronic parts. Thus, the removal of burrs becomes an important feature for automated production lines.

Study of micro burr deal with burr removal and control for which a number of methods include mechanical burr removing using abrasive, barrelling and brushing and chemical deburring such as etching.

Advantages

1. It is applicable for generating 3D micro shape.
2. Micro USM used to remove the burr present on work piece surface
3. With use of multi tool in USM, no of holes can be drill with minimum possible time, and reduces the production time.
4. Very hard material can be machined eg ceramic, glass etc.
5. It is reliable process

Disadvantages

1 In multi tool, the alignment problem arises

2 Tool wear is associated with USM

Application

MEMS (microelectrode mechanical system) the emergeous of MEMS has strongly enhanced the use of harder work material and their micromachining technology, for achieving such requirement ultrasonic micromachining play very important role for producing microstructure with high aspect ratio

Discussion and conclusion

USM is a mechanical non-traditional machining process which does not rely on conductive workpiece and is applicable for machining workpieces with low ductility and hardness above 40 HRC. Ultrasonic machining is burr free and stress-free process extensively used in the industries. The selection of tool material and design of horn is important material removal rate is governed by horn and appropriate selection of tool material. There are various controlling factors involved in UMS which govern the process such as frequency of vibration, amplitude, slurry concentration, abrasive size, stand-off distance etc.

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