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Micro Ultrasonic Machining

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***Abstract:* -- With increasing demands for miniaturized products there are a lot of developments in the micro manufacturing methods for the fabrication of the threedimensional micro shapes made up of different materials. Micro ultrasonic machining is a promising technique for the fabrication of micro shapes on the hard, brittle and nonconductive materials like glass, ceramics and silicon with high aspect ratio. Due to its non- thermal ,non-electrical and non-chemical nature this process does not changes much the physical, chemical or the metallurgical properties of the materials .But the main concern in this process is the difficulty in handling the micro tool due to dynamic nature of the system and hence the accuracy of the set up. This paper discusses the potentialities and limitations as well various developments in micro ultrasonic machining method.**

***Index Terms*— Micromachining, Micro ultrasonic machining, Brittle materials.**

I. INTRODUCTION

With the emergence of micro electromechanical, micro biomedical, micro chemical systems the attention has been focused on developing efficient micro machining techniques .Micro machining primarily involves the use of a variety of technologies to form microstructures and micromechanical parts for use in micro sensors, micro actuators and micro instruments. Miniaturization is proceeding in various types of industrial products.[11]The greater interest is focused on the achievement of 3D sculptured surfaces and high aspect ratio.[8] Most micromachining methods like Photolithography, Etching, LIGA (LithographieGalvanoformungAbformung) use silicon as the substrate material. But these processes are not capable of making true 3D structures e.g. free form surfaces. Their applications are also limited in range of materials.[7] Some non-traditional machining techniques are being developed in the microscopic scale like laser micromachining, micro electro discharge machining and micro ultrasonic machining to make real 3D sculptured complex components.[4]

Micro-ultrasonic machining (MUSM) is a promising micromachining technique to generate micro features with high aspect ratio in hard and brittle materials like glass, ceramics, composites , quartz and graphite[1][2]where the other known methods are not successful. Micro USM has been used to drill micro holes of diameter 5µm in silicon [3] These holes will meet the requirement of the Integrated circuit packages which are required to contain devices having micro dimensions.The circuit board also must have micro holes.The micro holes are also required for various parts including fluidic filters, grids, biomedical filters, ink-jet printer nozzles, fuel injection nozzles, optical apertures, high-pressure orifices, micropipettes. pneumatic sensors and manipulators. Some of the applications of hard and brittle materials at micro scale are shown in table1[14]

This paper gives a brief review of developments in Micro Ultrasonic machining

II. PRINCIPLE OF MICROULTRASONIC MACHINING

MUSM is a method derived from the conventional ultrasonic machining (USM) process. A typical MUSM (Fig. 1)depends on the projection of very hard abrasive particles on the part to be machined by the use of a tool called sonotrode vibrating at a very high frequency generally in the ultrasonic frequency domain of 20kHz or more .The ultrasonic oscillator produces the ultrasonic vibrations which are transmitted to the tool. The vibrating tool is pushed on to the work and the material removal takes place by the mechanical action of the abrasive particles on the surface of the work piece.

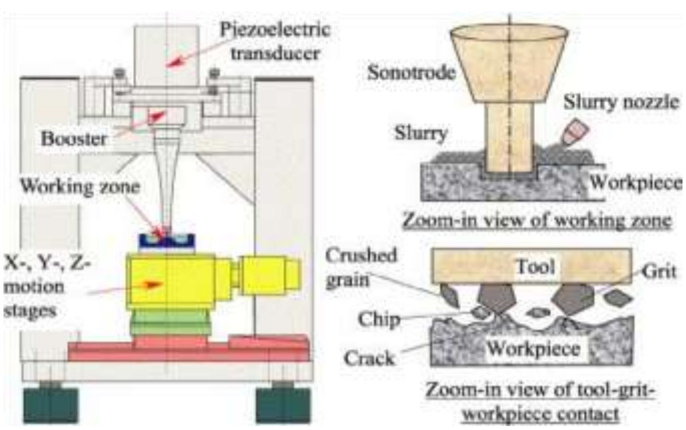

TABLE I. APPLICATIONS OF HARD AND BRITTLE MATERIALS[14]

Material	Applications
Glass	Micro-fluidic systems,accelerometers,monolithic grid structure, lab-onchip,micro device for blood analysis,membrane in fuel cell
Quartz Crystal	Accelerometers,opticalchopper,pressuresensor,acoustic wave esonator,filter and sensor
Lead ZirconateTitanate (PZT)	Actuators and transducers,Medical imaging transducers
Silicon Carbide	High temperature pressure sensor,vibrationsensor,micro gas turbine engine, micro motors operating up to 500^{o}C.
Silicon Nitride	Biaxial pointing mirrors, solid immersion lens
Alumina	Micro gimbal, bilayer lipid membrane sensor, vacuum windows

Figure 1.Principle Of Micro Ultrasonic Machining[6]

Water is used as the slurry medium due to its good property for transferring ultrasonic wave.The unit removal (UR) which is defined as the part of a work piece removed during one cycle of removal action, can be realized in MUSM when the submicron particles are available for use as abrasive. In order to fabricate micro shapes,microtools are needed . Although these micro tools can be fabricated using the processes like EDM they are difficult to be mounted on to the USM machine. This is because using the precise mechanical chuck will lead to its loosening due to ultrasonic vibrations and also matching the natural frequency of the chuck to the oscillator would be difficult .So, soldering is used for tool mounting but then there comes the problem of accuracy as concentricity cannot be maintained. Also, the machining load for a tiny tool will become too small to set .In addition ,slurry supply to the small machining zone between tool top-point and workpiece also becomes difficult due to the capillary effect. Hence ,the major problems in MUSM are the accuracy of the setup and the dynamic behaviour of the equipment.[1]Ultrasonic vibration of the machining head makes accurate tool holding difficult with precise force monitoring and robust work piece clamping.[6]These problems have however being overcome by the recent developments.[2][3]

III. DEVELOPMENTS IN MICROULTRASONIC MACHINING

In order to overcome problems with the USM at the micro level, significant developments have been made. They include(a) rotated tool[6](b)on machine tool preparation[2] (c) work-piece vibration.[3](d)Multipole Machining method[13]

A. Rotated tool method

Rotated Ultrasonic Machining was developed as an improvement over ultrasonic machining (USM).[13]Rotary ultrasonic machining (RUM) is a method in which the material is removed by the combination of the conventional grinding and ultrasonic machining. In this method the tool will rotate as well when it vibrates. As this method uses the abrasive bonded tool(fig. 2) it prevents the erosion of the walls of the machined holes which takes place in Ultrasonic machining (USM) during flushing due to the presence of abrasive slurry there. Downscaling of RUM for micro scale machining is essential to generate miniature features or parts from hard and brittle materials and requires the micro-sized abrasive bonded tool and a machining system capable of applying very small load on the micro tool with necessary feedback and control mechanisms. The use of diamond impregnated tool was reported to improve the hole [13].Also theout-of – roundness of the machined hole is reported to be improved [6] ,however the machined hole tends to increase in its diameter. (fig 3)

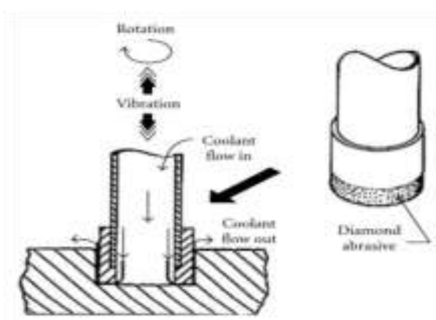

Figure2. Rotary Ultrasonic Machining Process[13]

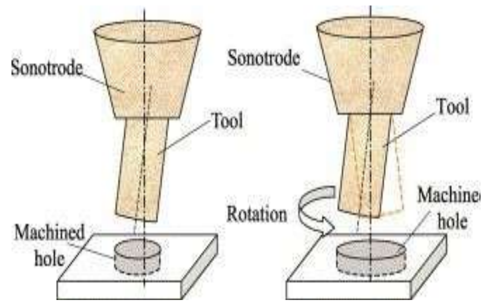

Figure3. Misalignment of tool with sonotrode[6]

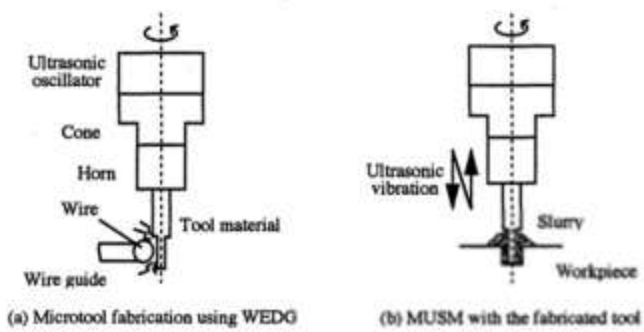

Figure4 Set up of MUSM by on-Machine tool preparation[2]

B. On machine tool preparation method

One of the major difficulties with the conventional method was to obtain the accuracy in the machining .This happened because the tool was subjected to ultrasonic vibrations and hence the problems of its loosening lead to the difficulty in its accurate holding .The on- machine tool preparation method could overcome this problem. In this approach, the tool was soldered to the machine head before its preparation. The tool is machined by wire electro discharge grinding (WEDG) to the desired dimensions and the subsequent machining of workpiece takes place on the same machine tool(fig. 4) As the tool material is soldered before it is fabricated into a microtool the tool setting is free from the low accuracy problems. However as the tool is prepared on the machine itself ,this method prevents measurement of the size and the shape of the fabricated tool. The holes of 20µm diameter have been produced in silicon by this method of on-the-.machine fabrication of the tool.

C .Workpiece Vibration Method

In this method the set up is such that the ultrasonic vibrator does not vibrate the tool but it vibrates the workpiece instead. The work piece is directly attached to the tip of the oscillator and because in MUSM the vibration amplitude required is less than 5µm, there is no need of horn to amplify the vibrations and hence this set up is simple and compact as it does not include a massive horn and cone. Fig 5 shows the entire machining procedure. The micro tool is first prepared in the micro-EDM machine and then mounted on the MUSM set-up .This method eliminates the main drawback of tool wear. Micro holes with diameter as small as 5µm is obtained on silicon and quartz glass using this set up [3].

Figure5. Set Up of MUSM by work-piece vibration[3]

D. Multitool Machining

When it is required to machine a lot of micro holes, multitools are fabricated by Egashira et all [12] and then used on MUSM set upto machine multiholes.Figure 6 shows the multitool fabrication process.First a microtool is fabricated by WEDG(Wire Electro discharge Grinding) using a tungsten electrode.Then, by the process of EDM(Electro discharge Machining) arrays of microholes are obtained using this electrode on the copper foil.The copper foil is used as a electrode and with the help of ultrasonic vibrations a multitool is machined using EDM. Finally ,thismultitool is used on MUSM set up to obtain multi holes on hard and brittle materials.Micro holes 20µm in diameter are obtained in soda lime glass.

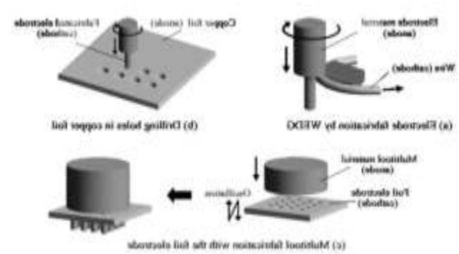

Figure 6.MultitoolMachining[12]

IV. MACHIINING PERFORMANCE MEASURES

The various machining performance measures in MUSM such as metal removal rate, tool wear and surface quality depends upon many parameters such as frequency and amplitude of ultrasonic vibration, static load, rotation of tool, type and size of abrasive particles and concentration of slurry.

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A. Effect of Operating Parameters on metal Removal Rate.

Egashira et al[5].reported the effect of abrasive particle on the machining rate. The machining rate increases with the size of abrasives. Also, the various experimental results show that the machining speed, first increases with the average static load however the speed decreases after the static load increases beyond a certain value .(figure7) To explain this phenomenon ,the debris accumulation in working area which cannot be removed quickly is proposed as the main reason by Z. Yu et al [10].They explained that a part of the static load is used in impacting the debris instead of abrasives.

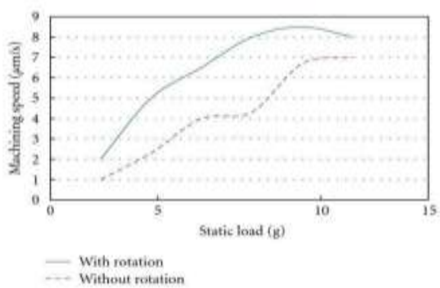

Figure7. Machining speed as a function of average Static load [10]

B. Effect of Operating Parameters on Tool Wear

Tools in MUSM have a short life due to the fast tool wear as the abrasive grains hit the top of the micro tool and tend to erode it.

It has been noticed byAmey V. Patwardhan[9] that abrasive slurry has a significant effect in tool surface and tool wear .Tool wear increases when harder and coarser abrasive grains are used [10]Also, tool wear increases remarkably with a decrease in tool diameter [10].

C. Effect of Operating Parameters on surface Finish

Surface finish of the micro hole after machining is a important performance measure in micro-machining. It is found that abrasive particle size plays an important role in surface finish. Theoretically, when the small abrasive particles are used ,the crater generated is small and sothe surface roughness is also small .However,Z.Yu et all[10] concluded the surface roughness generated by small abrasive particles can be larger than that of big particles because of debris accumulation.When the smaller abrasive particle are used, they may get embedded in the workpiece or in the tool under the static load and may stay in their original craters without moving to other locations during several cycles of vibration and as the thickness of accumulated debris in the working area reaches the exposed height of abrasive particles , it results to a change in the abrasive particle distribution and movement, which may increase the surface roughness. When large abrasive particles are used, more debris is removed from working area and the abrasive particles easily move to new locations by the vibration because of the large number of impacts .The influence of other parameters like static load , amplitude of vibrations and tool rotation is not very significant in determining the surface finish.

V. CONCLUSIONS

(i) MUSM is a non thermal process and is used for machining hard and brittle materials.
(ii) MUSM involves micro-chipping and mechanical abrasion of the work-piece by the abrasive particles.
(iii) The hardness of the abrasive particles should be more than the work-piece material.
(iv) A micro hole of 20μm diameter is obtained on silicon using of MUSM by On-Machine tool preparation method.
(v) Further to obtain a micro hole of much smaller diameter MUSM with work-piece vibration is developed. Micro holes with diameter as small as 5μm is obtained on silicon and quartz glass.
(vi) Debris accumulation in the working area is held responsible for the decrease in machining speed beyond a certain static load.
(v) Larger abrasive sizes increases the MRR.
(vi) As contrary to the general understanding that the finer abrasive particles will result in a better surface finish they cause the damage to the surface as they may get pushed into the eroded cavities and do not get flushed out easily.

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