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A Review on Ultrasonic Micromachining (USMM) and Research Considerations

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ABSTRACT: Conventional Machining processes have long been preferred over other newer processes mainly because of their superior Material Removal Rate (MRR). However, with the increasing trend of miniaturization of components, the drawbacks of conventional methods of machining parts (having dimensions of the order of microns) have been realized and given rise to the need for better alternatives. Ultrasonic machining (USM) transfers the energy of a tool vibrating at ultrasonic frequency to abrasive particles which in turn removes materials from the workpiece. Ultrasonic Micromachining (USMM), is a variant of USM which is used to micro-machine hard, brittle and inert insulating materials like ceramics, glass and silicon and is a non-thermal, non-chemical and non-electrical process. The biggest research issue lies in designing the tool for the USMM process and fixing it to the machine. This paper reviews the process of USMM, associated parameters, identifies the challenges and solutions proposed by various research teams and organizations.

KEYWORDS: Material Removal Rate, Miniaturization, Ultrasonic Machining, Ultrasonic Micromachining.

I. INTRODUCTION

With the increasing demand of micro components with complex features coupled with dimensional accuracy and surface characteristics, newer machining techniques are being adopted for material removal in micro scale. Unique advantages associated with micro components are that they consume less material and energy, and occupy less space. Hence demand for these components in various fields such as optics, medical, biotechnology, automotive, communication and avionics is currently rising [9]. One such machining technique which can be used to machine these micro components is Ultrasonic Micromachining (USMM) or micro-USM in which ultrasonic vibrations are introduced to free abrasive particles, which removes material from the workpiece.

USM takes advantage of indirect contact between tool and work piece which takes place through the abrasive particles within a fluid, also called as abrasive slurry [1]. The downscaling of conventional Ultrasonic Machining for serving the purpose of generating micro features is USMM. The work piece is vibrated at ultrasonic frequency instead of the tools to obtain precise tool rotation [4]. In USMM process the work piece placed on the work table vibrates at ultrasonic frequency (40 kHz) followed by which the abrasive slurry is introduced at the top of the workpiece. Abrasive particles hit the rotating tool which in turn hits the work piece and chips away the material from the work piece [7]. The tools are designed to possess certain angles in order to reduce the force required to move the tool over the work piece. The tool angle along with cutting force, relative speed between the tool and work piece, the presence of fluids for lubrication and cooling are the main factors affecting the dimensional accuracy and surface finish of the micro components [6].

The vibrations given to the work piece ensure that fresh abrasive particles are in contact with the work piece at all times and they also help in removing the debris from the work piece and tool gap. The abrasive slurry has multiple roles during the process, to act as the lubricating agent and the other to act as coolant. During the cooling action the abrasive slurry reduces the frictional heat produced due the movement of the abrasive particles on the work piece and

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heat generated by the vibrations produced by the transducer. The slurry also collects the debris from the machined area. In general, micro USM is carried out using water as the medium because water has excellent cooling properties and it also ensures easy removal of the debris from the machining zone due to low viscosity and it is easily available at low cost. In many other conventional machining processes such as grinding, milling and broaching, oil has been used as the cutting fluid. These oils can either be used as straight oils or emulsifiers. Straight oils are used in the processes which work under low speeds, low clearance and which require high surface finish. These oils have a slight edge over water in terms of lubricating properties causing less tool wear. Hence it would be more suitable if oil-based slurry is used in the micro USM [8]. Although USM is capable of machining hard and brittle materials, there are some difficulties in its application in micromachining such as handling of the micro tools. In such cases fabrication of the micro tool can be done to achieve dimensional accuracy and appropriate surface finish [3]. Fig. 1 shows the basic principle of micro USM.

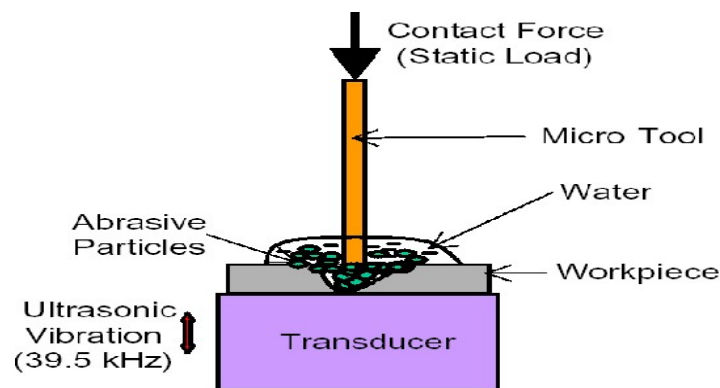


Fig.1. Principle of USM [7].

II. SETUP

Fig. 2 illustrates the experimental setup of a basic USMM process. The process begins with the introduction of ultrasonic vibration with a frequency of 50 kHz and amplitude of 0.8 to 5 micrometres through a power source and ultrasonic transducer. The work piece is held on the face of the ultrasonic horn using a vacuum clamping system. The vibration produced is transmitted to the work piece through the booster and horn. The vacuum clamping system consists of a vacuum pump, liquid separator and flexible tubes. The slurry delivery system consists of a magnetic stirrer, flexible tubing and peristaltic pump. The flexible tubing helps to supply fresh abrasive particles to the machining zone. Before feeding the slurry into the system agitation is done by means of a magnetic stirrer. The magnetic stirrer prevents the particles from settling down and thereby provides a homogeneous suspension of the particles in water. A peristaltic pump with flexible tubing helps deliver the slurry into the machining zone with a controlled flow rate. A micro tooling system employs a precision mandrel on which micro tools with diameter of 75 to 300µm can be mounted and can be rotated with controllable speed up to 6000 rpm and a run out of less than 0.3µm. The length of micro tool out of mandrel is maintained within 2mm. The machining force is measured using a precision load cell as a force sensor with a high frequency of 1 KHz. The average of the measured force is considered as the applied static load in the process. The machining gap is controlled by using a piezometer with driver and it receives the commands from the computer for tool positioning in z axis with steps of 30 nm and feedback from the precision force sensor and control interface [1].

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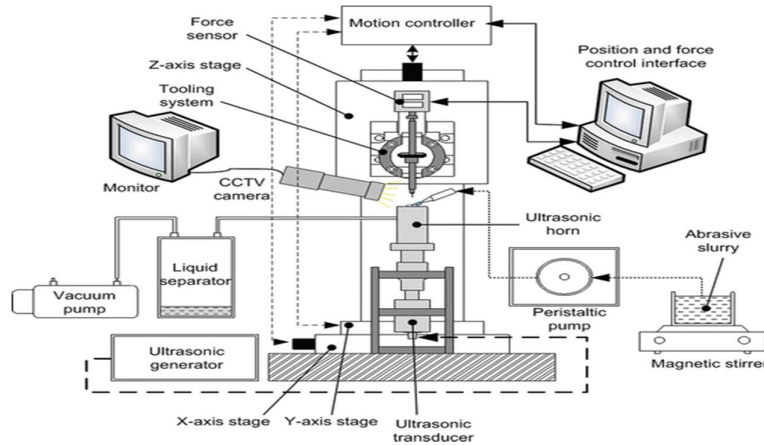


Fig. 2. Setup of USMM process [1]

III. TYPES OF ULTRASONIC MICROMACHINING

The USMM process can be categorized in mainly three ways depending on the nature of interaction between the tool and the workpiece:

1. Stationary USMM

This type of micro-USM process uses a tool which does not rotate and uses only a linear vibrating motion having frequency in the ultrasonic range. The vibration may be imparted either to the tool or the workpiece depending on various considerations. It is seen that ultrasonic machining majorly suffers from tool wear which in-turn causes the length of the tool to decrease continuously. This greatly hinders the ability of the system to maintain a near constant amplitude of vibration at the tip of the tool [8]. The amplitude of vibration varies at different positions along the length of the tool axis and the shortening of tool length due to wear causes a continuous shift in the position of the tool tip which is what makes it difficult to maintain a constant amplitude. For this reason, applying ultrasonic vibrations to the workpiece has been found to be more useful as there is no influence of tool wear on the tip of the tool. The added advantage is that the slurry containing abrasives gets stirred due to the vibrating workpiece, thus increasing the machining action of the abrasive particles [3].

2. Rotary USMM

Rotary USMM is the most cost-effective and environmental friendly ultrasonic machining process, which utilizes the effect of mechanical grinding as well as ultrasonic machining, for drilling of holes. This results in higher material removal rate (MRR) than those processes utilizing one of the two stated above [4]. Fig.3 shows a schematic setup of Rotary Ultrasonic Machining (RUM) in which the tool selected is hollow and is made to rotate as well as vibrate. The rotation of the tool causes the contact between the abrasive grains and workpiece to be of both rolling as well as sliding nature which leads to the higher MRR to which the impact of abrasive particles on the workpiece at ultrasonic frequency also contributes [2]. However, the application of RUM to micromachining requires the tool to be micro-sized and also abrasive with the system being capable of applying the necessary load controlled with feedback and control mechanisms [8].

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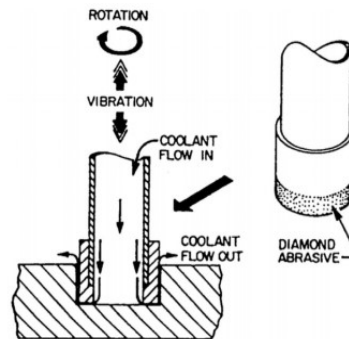


Fig.3 Rotary USMM [4]

3. Hybrid USMM

This type of USMM uses ultrasonic vibrations to assist processes like Electrochemical Machining (ECM), Electric Discharge Machining (EDM), Abrasive Flow Machining (AFM) which overcomes the disadvantages of the above processes. In the case of machining titanium alloys which is generally carried out by micro-EDM process, it has been observed that when ultrasonically assisted, the material removal capacity increases. The micro-ultrasonic vibrations introduced in the EDM cause lapping which greatly improves the precision of the micro-sized structures created by unassisted EDM process. There is also higher surface quality, reduction of machining time, higher tool life observed in ultrasonic assisted micro-EDM compared to its unassisted counterpart [10].

USMM can also be classified based on the type of tool used which are majorly of 2 types [8] :

1. **Solid or Hollow cylindrical tool** as illustrated in Fig.4
2. **Pattern Tool**, where the micro-sized structure desired to be obtained is created at the bottom of the tool. The tool containing the pattern is used to place the impression of the required structure on the workpiece material using a sinking operation by making the tool travel in a vertical linear manner with respect to the workpiece. Fig.5 shows a 3D micro gear and Fig.6 shows a gang drill produced using pattern tools.

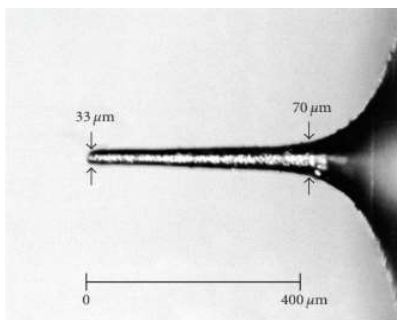


Fig.4. Microtool for USMM [8].

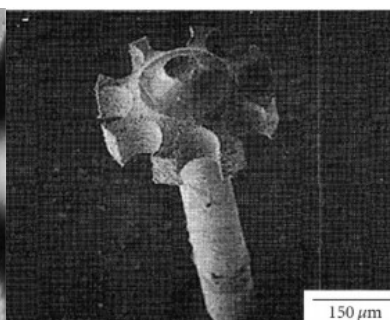


Fig.5. 3D Microgear [8].

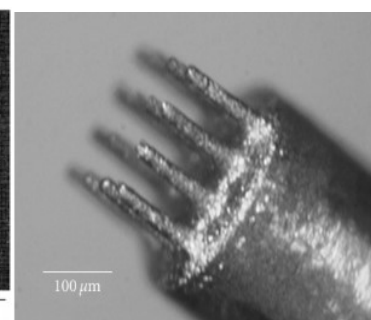


Fig.6. Gang drill [8].

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IV. MECHANISM OF MATERIAL REMOVAL IN USMM

Micro-USM is the downscaled version of conventional USM process requiring smaller abrasive particles in the order of micro meters and even nano meters, micro sized tool small vibration amplitudes and static load for machining of micro features usually in hard, brittle materials; but even ductile materials can be machined. Material removal by various mechanisms occurs due to shear (i.e. by cutting and ploughing) in ductile materials and by fracture and crack propagation in brittle materials. Therefore, the study on the effect of process parameters on material removal mechanisms could result in better control over the characteristics of machined surface in micro-USM [1].

Various mechanisms of material removal have been reported in USM process namely, direct hammering, free impact, cavitation erosion and chemical action. Due to varying process parameters one of the above mentioned mechanisms or a combination of them will be the dominating mechanism in the process. It has been reported that direct hammering and free impact are primarily responsible for major material removal except for the case of graphite where cavitation plays an important part in overall material removal [11]. Low kinetic energy impacts of abrasive particles cannot initiate cracks, but tend to deform material gradually and repeatedly, resulting in material removal by ductile mode instead of brittle fracture. The change from brittle fracture-dominated erosion mechanism to ductile fracture-dominated behaviour is called brittle-ductile transition.

As the machining principle of conventional USM is on parallel lines with micro-USM, the fore-mentioned parameters are scaled down in order to minimize the tool-abrasive particle-workpiece interactions, which in turn affect the determining conditions of mechanism of material removal, as in the case of a small tool-workpiece interaction gap which could increase the probability of failure of micro-tool due to the accumulation of used abrasives and particles that have been removed from the machined surface of substrate/workpiece, leading to complex tool-abrasive particle-workpiece interactions and material removal mechanisms.

V. PROCESS PARAMETERS AND THEIR EFFECT ON MACHINING RATE, TOOL WEAR AND SURFACE QUALITY

The important parameters influencing the process of USMM are listed below:

1. Static or Machining load.
2. Vibration or Oscillation amplitude.
3. Abrasive particle size.
4. Slurry concentration.

Effect of process parameters on machining rate:

- Machining rate for a solid tool increases with average static load and beyond a certain value starts to decrease due to the collection of debris (used abrasives and chips from surface of machined substrate) and part of static load being used to impact it instead of removing material from the substrate. For a hollow tool, slightly decreases and then increases with increasing static load.
- Machining rate increases as abrasive particle size increases, whereas when the vibration amplitude increases, the rate of machining decreases [8].

However, tool rotation increases the machining speed and hence the machining rate due to effective debris removal. The relation between machining rate and static load for tool types is shown in Fig. 7.

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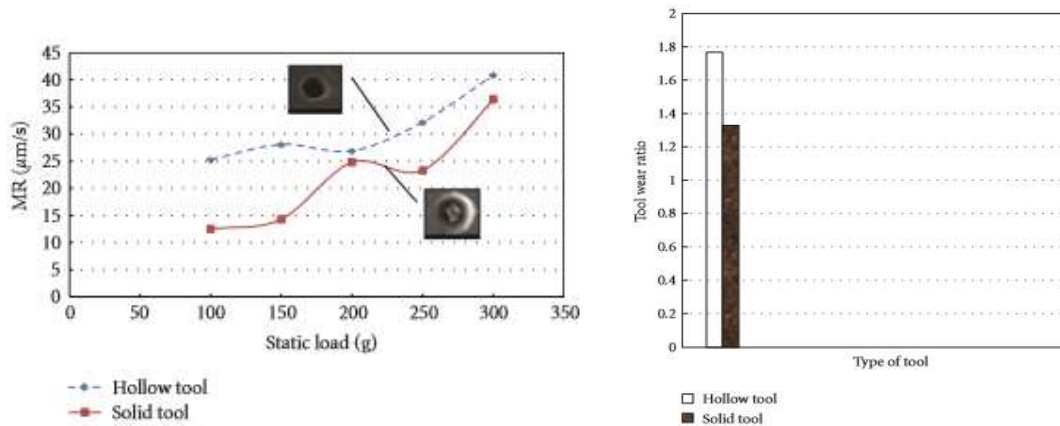


Fig.7. Machining Rate vs Static Load [8]. Fig.8. Tool wear ratio vs Type of Tool [8].

Effect of process parameters on tool wear:

1. The micro tool tends to get eroded in a way similar to the tool in conventional USM process due to the action of abrasives on the tool tip. Therefore, a smaller static load is recommended to avoid breakage of tool. Generally, vibrational amplitudes greater than 2 micro meters or static loads above 5 milli newtons will lead to tool breakage.

Also, tool wear increases when coarser, harder grains of abrasive particles are used [8]. The relation between tool wear ratio and tool type is shown in Fig. 8.

Effect of process parameters on surface finish:

- Surface roughness tends to decrease with increasing static load with values of upto 20 milli newtons beyond which any increase has no appreciable effect. In other words, surface finish increases with increase in static load.
- For static load of 10 milli newtons, surface of machined component had coarser texture with large craters. Due to lateral cracking, localised fracture marks are distributed uniformly on machined surface, representing dominant brittle mechanism of material removal.
- For static load of 40 milli newtons, machined surface has smaller shallow craters and reduced number of fracture marks, representing a combination of brittle and ductile material removal mechanisms with the ductile behaviour being dominant.
- There exists a nearly linear relation between surface roughness and abrasive particle size, with roughness increasing along with size of abrasive particles.
- For vibration amplitudes below 2 micro meters, as amplitude increases surface roughness increases and above the said limit it decreases. For amplitudes of 0.8 micro meters, the kinetic energy available may not be sufficient for initiation of crack, hence a smooth machined surface is generated due to material removal by ductile mode of erosion[1]. The relations are shown in Fig. 9 (a), (b), (c).

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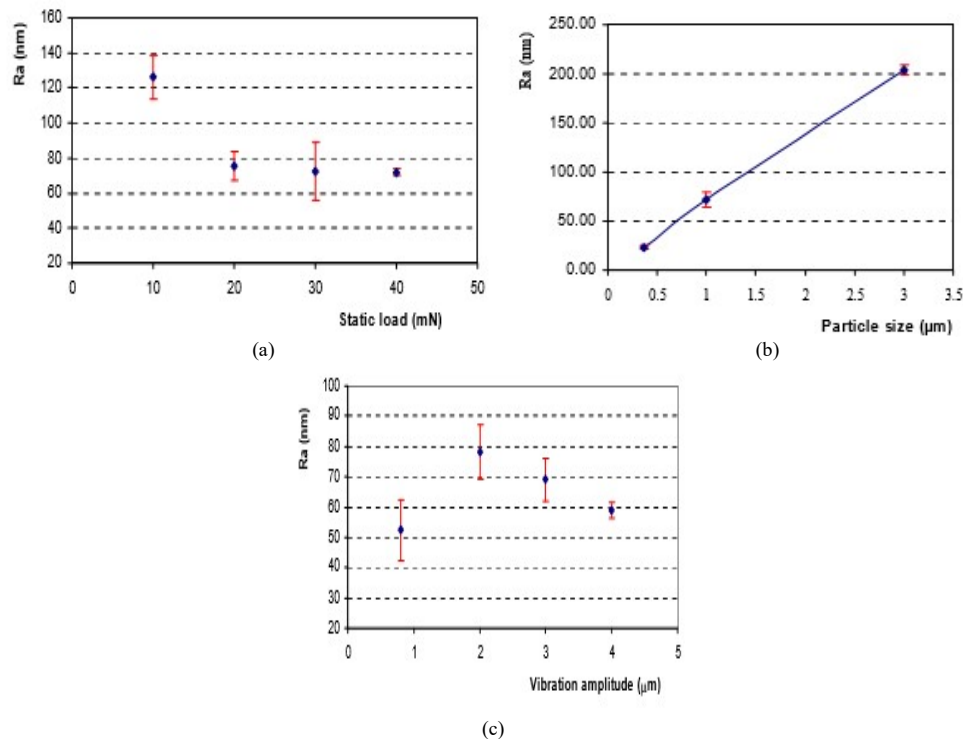


Fig. 9. Relation between Surface Roughness and (a) Static Load (b) Particle Size (c) Vibration Amplitude [1].

Effect of slurry concentration and abrasive particle movement on surface finish

For high slurry concentrations, if static load per particle is taken into consideration, the number of particles in the machining gap increases, therefore load per particle decreases leading to reduced surface roughness due to lesser particle penetration into the workpiece. This contradicts the trend observed by H. Zarepour and S. H. Yeo in [1]. This might be due to the rapid agglomeration of abrasive particles in higher concentrations.

The effect of suspended abrasive particles and their distribution in the slurry intimately relates to the contour of the machined surface in the USMM process. Convex shaped cavities are generated due to the accumulation of machined material in the initial stages of machining, blocking the movement of abrasive particles which move towards the central area in the machining gap, according to a study by W. Pei et.al [5].

Contours in the form of concave cavities are generated easily by increasing the abrasive particle size, using a smaller diameter tool and by increasing the vibration amplitude, under similar conditions.

VI. GEOMETRICAL ABILITIES

One of the main research issues in the use of micro tool for the USMM process is the fixing of the tool to the system. As the tool is small and ultrasonic vibrations are induced, fixing the tool becomes difficult which in-turn leads to questions of about accuracy of creating micro geometries like slots, 3D cavities, through holes. K. Egashira et al. proposed a technique which uses on-the-tool fabrication by a process called Wire Electro-Discharge Grinding (WEDG) [3]. Fig.10 shows triangular and square hole made on silicon using WEDG.

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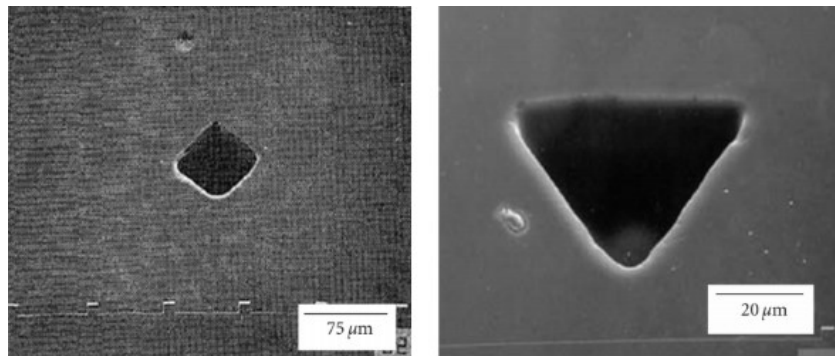


Fig. 10. Triangular and Square Hole made on Silicon using WEDG [3].

A device was developed at FEMTO-ST institute, France that enabled through holes of high quality, blind holes to be created maintaining a depth accuracy within 10μm to create electronic components on piezoelectric quartz crystals [8]. Fig.11 illustrates arrays of pillars of 280μm diameter and 6,000μm depth in Lead ZirconateTitanate (PZT) using a steel disk with honeycomb structure of multiple 300μm diameter holes [12].

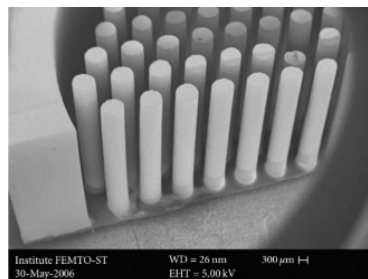


Fig. 11. Structure of micromachined surface [12].

Sun et al. created an array of micro-holes each being 15μm in diameter but 32μm depth using a cement carbide multi tool. 64 holes were created on a soda lime glass workpiece material using a vibration amplitude of 0.8μm and a static load between 0.05 to 0.1N by drilling 4 times [8].

VII. APPLICATIONS

The applications of ultrasonic machining process are as follows [8]:

- Construction of micro holes (less than 100 micro meters in diameter) in silicon and glass wafers, pressure and flow sensors accommodate these micro holes. These micro holes constructed may be circular as well as non-circular in nature.
- Various industrial applications include drilling micro holes in helicopter power transmission shafts and gears, machining of watch bearings and jewels, slicing of semiconductors components.
- With the help of a thermoplastic tool ultrasonic micro machining process can be used to machine and polish tool steel surface.
- Semiconductors being brittle in nature can be machined with ease using the ultrasonic micromachining process hence this process is used in semiconductor industries.

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- With the developments in the fields of microfluidics and heat transfer it is concluded that newer and harder materials are more suitable for experimentation in these fields. With this being said we can surmise that ultrasonic micro machining will have wide range of applications in the fields of microfluidics and heat transfer.
- The electrical and optical industries require cutting of complex and non-uniform shape materials, these cuts can be achieved with the help of USM offering extremely high precision.
- During ultrasonic machining the physical properties of the work material are not altered so it is used in machining highly sensitive materials.

VIII. CONCLUSION

With components having micro-features or micro-components becoming more and necessary in manufacturing, there is a need to combine various forms of micro-machining like micro-USM, micro-EDM, micro-ECM to form hybrid systems. These hybrid systems make up for deficiencies in the individual processes when used separately and thus form the most efficient way of micro machining. Research issues like design and fixing of microtools, mechanisms of machining, effect of various parameters on the quality of the created feature in USMM need to be studied further in order to make USMM more efficient when used independently without any assistance.

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