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Development of Design and Manufacturing Support Tool for Optimization of Ultrasonic Machining (USM) and Rotary USM

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Abstract

Ultrasonic machining (USM) is a mechanical material removal process used to erode holes and cavities in hard or brittle work pieces by using shaped tools, high-frequency and an abrasive slurry. This paper addresses the concept and development of an expert system (ES) for hard and brittle material, such as glass, quartz, diamond, carbides, semi conducting materials, ceramic and graphite which can be manufactured with ultrasonic machine or rotary ultrasonic machining. The expert system is developed based on object oriented technique. The system links with a feature based CAD system in order to extract design data. The expert system is linked with databases. The machining cycle time, cost, penetration rate and productivity, of each selected design feature are estimated. The system provides useful information such as machining cycle time and cost, penetration rate and efficiency of machining of the selected design feature for product designers and manufacturing engineers to select optimum machining parameters. Also the expert system compares ultrasonic machining (USM) and rotary ultrasonic machining (RUSM) for the same design feature in concurrent engineering environment.

Keyword

Expert system, Ultrasonic machining, Rotary Ultrasonic

1. Introduction

The limitation of conventional and some of the unconventional machining such as electrochemical machining (ECM), electro-discharge machining (EDM), and so on have led to the development of ultrasonic machining for hard and brittle materials [1]. The history of USM traced back to Lewis Balamuth, who invented the process about forty three years ago [2]. The benefits of discovery of USM to industry were quickly realized, and in 1950 the production of USM-tools began [3]. A wide range of material especially hard materials (e.g. tungsten and titanium carbides die and tool steels etc.) and brittle materials (e.g. germanium, silicon, ferrites, ceramics, glass, quartz etc.) could be effectively machined by this method [4, 5]. The principle of ultrasonic machining was recognized in 1927.The first useful description of the USM technique wasn’t given in industry literature until about 1940. Since then, ultrasonic machining has attracted a great deal of attention and has found its way into industry on a relatively wide scale. By 1953-1954, the first ultrasonic machine tools, mostly based on drilling and milling machines, had been built. By about 1960, ultrasonic machine tools of various types and sizes for a variety of purposes had been seen, and some models had begun to come into regular production. USM provides a number of advantages compared to conventional machining techniques. Both conductive and nonconductive materials can be machined, and complex three-dimensional contours can be machined as quickly as simple shapes. Additionally, the process does not produce a heat-affected zone or cause any chemical/electrical alterations on the workpiece surface, and a shallow, compressive residual stress generated on the workpiece surface can increase the high-cycle fatigue strength of the machined part. However, in USM, the slurry has to be fed to and removed from the gap between the tool and the workpiece. As a result, the material removal rate slows considerably and even stops as the penetration depth increases. The slurry can also wear the wall of the machined hole as it passes back toward the surface, which limits accuracy, particularly for small holes. Additionally, the abrasive slurry “machines” the tool itself, which causes considerable tool wear and, in turn, makes it very difficult to hold close tolerances. Rotary ultrasonic machining was invented by P. Legge in 1964. In the first rotary ultrasonic machining device, the slurry was abandoned, and a vibrating diamond-impregnated tool was used against a rotating workpiece. However, because the workpieces were held in a rotating four-jaw chuck, only circular holes could be machined, and only comparatively small workpieces could be drilled with this device. Improvements led to the development of a machine comprising a rotating ultrasonic transducer. The rotating transducer head made it possible to precisely machine stationary workpieces to close tolerances. With different shaped tools, the range of operations could be extended to end milling, tee slotting, dovetail cutting, screw threading, and internal and external grinding. The attraction of USM is unlike ECM and EDM and the material removal rate is affected by brittleness and hardness of materials. USM is used in wide range of industry including aerospace, electronics, optics, and automobile industries [6]. The rapid progress in this field can be seen from the number of published papers. It is reported that about 350 papers had been published until 1960s. Ultrasonic machining (USM) is a mechanical unconventional machining process by which material is removed through direct hammering of the abrasive particles on the work piece by the vibration of tool and flow of the abrasive particle. The mechanisms involved in material removing by USM have been described in previous studies [3, 7, 8]. The history of USM began with a paper by R.W. Wood and A.L. Loomis in 1927 [9, 10] and the first patent was granted to American engineer Lewis Balamuth in 1945 [11, 12]. USM has been variously termed ultrasonic drilling; ultrasonic abrasive machining ultrasonic cutting; ultrasonic dimensional machining and slurry drilling [13]. However, from early 1950s it was commonly known either as ultrasonic impact grinding or USM [11, 14, 15]. Since its invention, USM has developed into a process that is relied upon to solve some of the manufacturing community's toughest problems [1]. The USM process begins with the conversion of low-frequency electrical energy to a high-frequency electrical signal, which is then fed to a transducer [13, 14, 15, 16, 17, 18]. The transducer converts high-frequency electrical energy into mechanical vibrations, which are then transmitted through an energy-focusing device, i.e. horn/tool assembly [19, 20, 21]. This causes the tool to vibrate along its longitudinal axis at high frequency (usually ≥20 kHz) [1, 13]. The tool vibrates with a total excursion of only a few hundredths of a millimeter in a direction parallel to the axis of tool feed [20, 21]. For efficient material removal to take place, the tool and tool holder must be designed with consideration given to mass and shape so that resonance can be achieved within frequency range capability of the USM machine [14]. Typical power ratings range from 50 to 3000 W and can reach 4 kW in some machines [22, 13]. A controlled static load is applied to the tool and abrasive slurry (composing a mixture of abrasive material; e.g. silicon carbide, boron carbide, alumina, etc. suspended in oil or water) is pumped around the cutting zone [13]. The vibration of the tool causes the abrasive particles held in slurry between the tool and the work piece, to impact the work piece surface causing material removal by micro chipping [23]. The elements of USM process include of a transducer, abrasive slurry that flows between the work piece and tool vibration and work piece. The process which is widely recognized as the technological characteristics of USM, depends on several operational and physical parameters. Much research is conducted on the mechanism of process and parameter interactions. Many of the parameters are interrelated and affect other. Even though, it is not possible to summarize the previous results of the parameters. Here we briefly summarize some of the important factors which directly influence on MRR and machining productivity. As mentioned before, the material removal rate (MRR) is influenced by abrasive type, size, concentration and the temperature of the abrasive liquid. The abrasive grid size should be about equal to the vibration amplitude and the temperature of abrasive between 2 to 5^o C. As Abrasive concentration in water or oil increases, the material removal rate and the rate of penetration increase until they reach a maximum. Penetration does not increase after the maximum penetration is achieved, because there is a jamming effect at the interface of tool and work piece [24]. As the abrasive grain diameter increases, the rate of MRR increases to a maximum and then decreases. It is more difficult for larger grains to get to the work area as penetration increases, therefore penetration rate drops. Boron carbide is most widely used in USM. The frequency used in most USM operations is set at 10 to 40 kHz. The most common frequency is 20 kHz. The amplitude of vibration is between 0.013 to 0.10 mm. Tool tip forces are usually less than 44.5 N, but force as high as 445 N is possible. In this type of process, parameters such as depth of cut, static load and area of cut are also very important. Typical accuracy of +/- 0.025 mm and surface roughness of 0.51 to 0.76 μm can be achieved [10, 25]. The size of abrasive grid affects surface roughness. Smaller size makes finer finishes, but it reduces the material removal rate. The surface created by USM typically shows a shallow depth of compressive residual stress. Holes can be produced as small as 0.078 mm diameter and as large as 90 mm diameter with depth of up to 64 mm. The main parts of an USM are shown in Fig.4. It consists of the following elements, (i) Electronic oscillator with amplifier and means for adjusting the required frequency, (ii) the transducer or vibrators which acts as a transformer is magnetized with direct current. It transforms electrical power received from the electronic oscillator to mechanical vibrations, but the amplitude of this vibration is not adequate. The power supply for USM is more accurately characterized as a high power sine-wave generator that offers the user control over both the frequency and power of the generated signal. It converts low-frequency (60 Hz) electrical power to high-frequency (approximately 20 kHz). This electrical signal is supplied to the transducer for conversion in to mechanical motion [1, 13, 26]. USM is combined with electrical discharge machining (EDM) and abrasive flow machining (AFM) [17, 19, 21, 27, 28, 29]. Nowadays ultrasonic vibrations are used successfully to enhance machining capability of micro-EDM to handle titanium alloys [30]. It has been found in micro-hole machining of titanium plate that micro-ultrasonic vibration lapping enhances the precision of micro-holes drilled by micro electro-discharge machining [31]. Ultrasonic assisted conventional/non-conventional machining. USM assisted turning is claimed to reduce machining time, work piece residual stresses and strain hardening, and improved work piece surface quality and tool life compared to conventional turning [8, 29, 32, 33]. There are also non- machining ultrasonic applications such as cleaning, plastic/metal welding, chemical processing, coating and metal forming [13]. The tool is made by silver brazing shaped conversely to the desired hole or cavity and positioned near, but not touching, the surface of the work piece [34, 35]. Many USM applications are involved in drilling where a tool of either simple or complex cross-section penetrates axially in to the work piece to produce either a through or blind hole of the required dimensions [13]. For three-dimensional cavity, a process analogous to die sinking is generally employed, [10, 36, 37, 38, 39]. Although USM volumetric material removal rates are relatively low, the process remains economically competitive because of its ability, with a single pass of the tool, to generate complex cavities or multiple holes in work piece materials that are too hard or fragile to machine by alternate processes. Using this technique graphite electrode for EDM has been shaped in 30 min instead of the 20 hours required by copy milling [40, 41, 42, 43]. The problem with using tools of complex form, however, is that they are not subject to same machining rate over the whole of their working surface and experience differential wear rate, both of which affect the product shape [13, 44]. In addition, there are also greater problems in tuning a complex tool to achieve maximum performance compared to more basic tool [13]. An alternative approach is using a simple "Pencil" tool and contour machine with the complex shape and a CNC program. Hypodermic needle was used to ultrasonically drill small holes through a silicon nitride (Si_3N_4) work piece [45]. For the stationary USM, an approach to model MRR has been proposed and applied for titanium and its alloys. In this MRR model for stationary USM, macro-modeling concept has been used. In macro-model, the need to write a mathematical equation for developing relationships is bypassed. The model developed is mechanistic in the sense that these parameters can be observed experimentally from a few experiments for a particular material and then used in the prediction of MRR over a wide range of process parameters. This has been demonstrated for titanium and its alloys, where very good predictions have been obtained using an estimate of multi parameters. On the basis of this model, Singh and Khamba studied the relationship between the MRR and the controlling machining parameters. These relationships agree well with the trends observed by experimental observations made by them [46, 47, 48, 49, 50, 51, 52, 53, 54, 55]. This model has been applied for predicting the MRR for pure titanium, (ASTM Gr.2) and titanium alloy, (ASTM Gr.5). In this study the effect of six controllable parameters (tool material, slurry type, slurry concentration, grit size, slurry temperature, and power density) were revealed with titanium work piece as noise factor. In the case of USM transducer, electrical energy is converted in to mechanical motion [13, 56, 57]. With a conventional generator system, the tool and horn are set up and mechanically tuned by adjusting their dimensions to achieve resonance [13]. Recently however, resonance following generators has become available which automatically adjust the output high frequency to match the exact resonance of the horn/tool assembly. They can also accommodate any small error in set up and tool wear and give minimum acoustic energy loss and very small heat generation [20]. The power supply depends on the size of transducer [22, 58]. Two types of transducers used for USM are based on two different principle of operation, piezoelectric and magnetostrictive [1, 59]. Piezoelectric transducers are used for USM generate mechanical motion through the piezoelectric effect by which certain materials, such as quartz or lead zirconatetitanate [60, 61, 62, 63]. Piezoelectric transducers, by nature, exhibit extremely high electromechanical conversion efficiency (up to 96%), which eliminates the need for the water-cooling of the transducer. These transducers are available with power capabilities up to 900 W [13, 32, 59, 60, 63, 64]. The function of tool holder is to attach and hold the tool to the transducer. Additionally, the tool holder also transmits the sonic energy to the tool, and in some applications, also amplifies the length of the stroke at the tool. Half hard copper washers are used between the transducer and tool holder to dampen and cushion the interface, which further reduces the chances of unwanted ultrasonic welding. The horn is variously referred to as an acoustic coupler, velocity/mechanical transformer, tool holder, concentrator, and stub or sonotrode. The oscillation amplitude at the face of the transducer is too small (0.001–0.1 μm) [63, 65, 66], in order to achieve any reasonable cutting rate; therefore, the horn is used as an amplification device [9, 67, 68]. Different horn is designed with and without additional tool heads [67]. Tool holders are available in two configurations: non-amplifying and amplifying. Non-amplifying tool holders are cylindrical and result in the same stroke amplitude at the output end as at the input end. Amplifying tool holders have a modified cross-section and are designed to increase the amplitude of the tool stroke as much as 600% [58]. The material used should have high wear resistance, good elastic and fatigue strength properties, and have optimum values of toughness and hardness for the application [10, 63, 69]. Tungsten carbide, silver steel, and monel are commonly used tool materials [13]. Polycrystalline diamond (PCD) has recently been detailed for the machining of very hard work piece material such as hot iso-statically pressed silicon nitride [70]. Tool can be attached to the horn by either soldering or brazing, screw/taper fitting [13, 35]. Also, the actual tool configuration can be machined on to the end of the horn [10, 13, 22, 41, 71, 72, 73]. Threaded joints are conventionally used because of quick and easy tool changing, however problems can occur such as self-loosening, loss of acoustic power, fatigue failure, etc.[74]. The machines for USM range from small, tabletop-sized units to large-capacity machine tools. In addition to the part-size capacity of a USM machine, suitability for a particular application is also determined by the power rating [1]. The material removal rate is directly related to power capability of the USM machine. All USM machines share common subsystems regardless of the physical size or power [1]. The most important of these subsystems are the power supply, transducer, tool holder, tool and abrasives [1, 13]. To minimize tool wear, tools should be constructed from relatively ductile materials such as stainless steel, brass and mild steel [1, 13]. Depending upon the abrasive used, the work piece material, work piece/tool wear ratio can range from 1:1 to 100:1 [11, 56, 57]. The tool is normally held against the work piece by a static load exerted via a counter weight/static weight, spring, pneumatic/hydraulic or solenoid feed system [10, 25, 66, 69, 75]. For optimum results, the system should maintain a uniform working force while machining and be sufficiently sensitive to overcome the resistance due to the cutting action [68, 72]. Static load values of about 0.1–30 N are typically used [13]. The force is particularly critical when drilling small holes less than 0.5 mm diameter as bending of the tool can occur under too high a load. The transport medium for the abrasive should possess low viscosity with a density approaching. It is required the abrasive, good wetting properties and preferably, high thermal conductivity and specific heat for efficient cooling and water [9, 11, 68]. The abrasive material is mixed with water to form the slurry. The most common abrasive concentration is 50% by weight [1, 58]; however this can vary from 30–60%. Thinner mixtures are used to promote efficient flow when drilling deep holes or when forming complex cavities [11, 66, 69, 76, 77]. Once abrasive has been selected and mixed with water, it is stored in a reservoir at the USM machine and pumped to the tool–work piece interface by re-circulating pumps at rate up to 26.5 L/min [58]. Extensive work on the mechanism of material removal is reported by Shaw [22], Miller [78] and Cook [79], and others

[38, 65, 80, 81]. Most of work is on machining mechanism of hard and brittle material [51, 55, 56]. Material abrasion is effected by direct hammering of the abrasive particles against the work piece surface [6, 21, 22, 23, 32, 36, 43, 66, 72, 78, 82]. Micro chipping is also affected by impact of the free moving abrasive articles [11, 22, 37, 43, 72, 82]. Cavitations' effect is from the abrasive slurry [11, 22, 37, 43]. Researchers considered that cavitation erosion and chemical effects were of secondary significance with the majority of work piece material acting essentially to weaken the work piece surface, assist the circulation of the abrasive and the removal of debris [10, 22]. The individual or combined effect of the above mechanisms results in a work piece material removal by shear by fracture (for hard or work hardened material) and displacement of material at the surface, without removal [29, 72, 77, 83] and by plastic deformation [29] which will occur simultaneously at the transient surface [13]. With porous materials like graphite as opposed to hardened steels and ceramics, cavitation erosion is a significant contributor to material removal [6, 11, 22, 82].

2. Expert system and its component

Expert Systems are computer programs that are derived from Artificial Intelligence (AI). Expert system goal is to understand intelligence by building computer programs that exhibit intelligent behavior. It is concerned with the concepts and methods of symbolic inference, or reasoning, by a computer, and how the knowledge used to make those inferences will be represented inside the machine. The term intelligence covers many cognitive skills, including the ability to solve problems, learn, and understand language. The Expert system links with A feature based CAD system in order to extract design data. The expert system is linked with databases. The machining cycle time, cost, penetration rate, and efficiency of each selected design feature are estimated. The system provides useful information such as machining cycle time and cost, penetration rate, and efficiency of machining of the selected design feature for product designers and also advises manufacturing engineers to select optimum machining parameters. Also the expert system compares ultrasonic machining (USM) and rotary ultrasonic machining (RUSM) for the same design feature in concurrent engineering environment.Figure1 is demonstrated expert system environment. Figure 2 shows flowchart of the expert system.

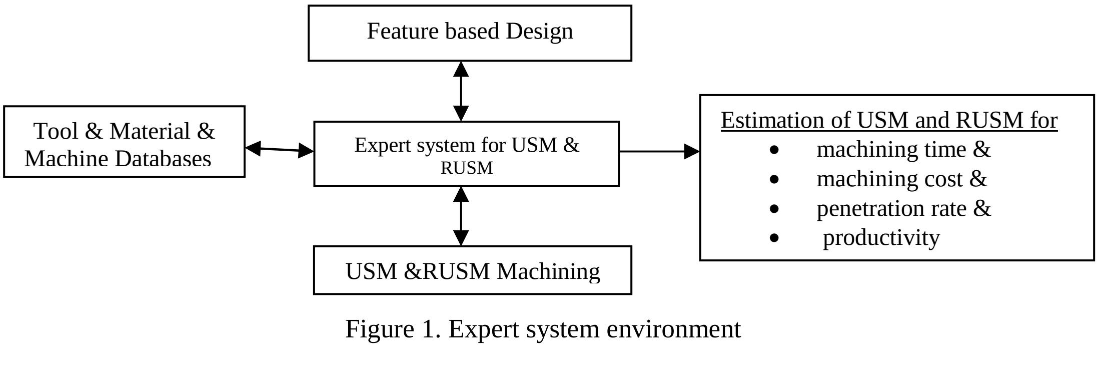

Figure 1. Expert system environment

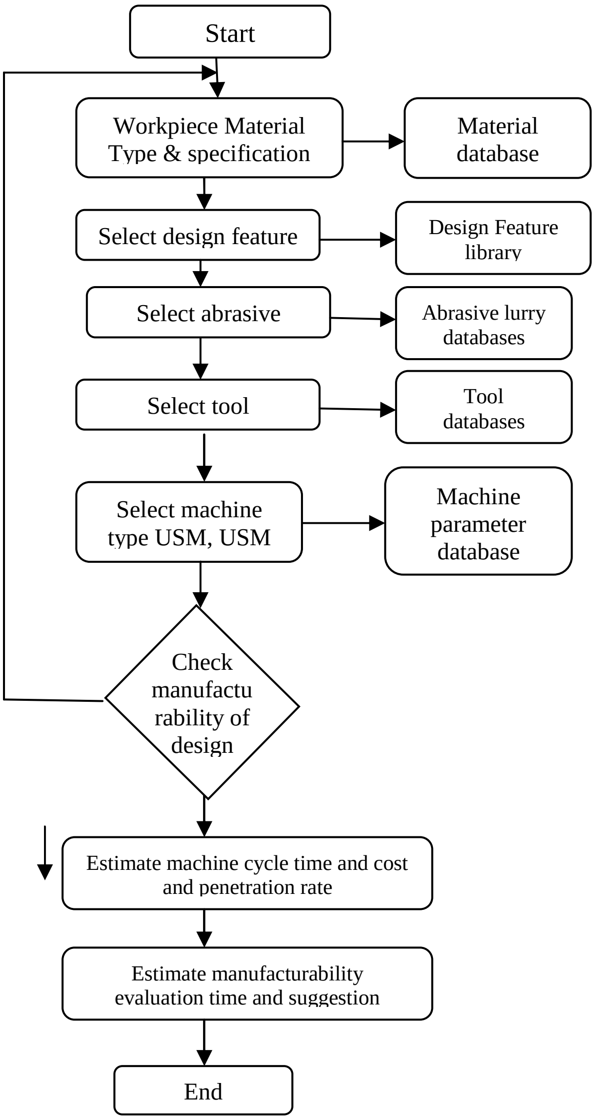

Figure 2. Flowchart of the expert system

3. Experimental verification

In USM spindle is fed toward the work piece at a constant pressure. Figure 3 shows the basic elements of an USM. In rotary ultrasonic machining, a rotating core drill with metal bonded diamond abrasives is ultrasonically vibrated in the axial direction while the spindle is fed toward the workpiece at a constant pressure. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool. By using abrasives bonded directly on the tools and combining simultaneous rotation and vibration, RUM provides a fast, high-quality machining method for a variety of glass and ceramic applications. A variation of USM, known as rotary ultrasonic machining (RUM), involves the use of rotating diamond- plated tools on drilling, milling, and threading operations [1, 13]. The construction of RUM machines is nearly identical to USM machines except for the addition of a 0.37–0.56 kW (1/2–3/4 HP) rotary spindle motor capable of rotating up to 5000 rpm [13, 25]. The ultrasonic power required for the RUM process is considerably less than that used for USM; RUM machines typically are rated at

300 W or less [1]. Machining performance in the rotary mode is found to be much superior to the conventional mode [26]. Recently the feasibility to machine ceramic matrix composites (CMC) using RUM has been investigated, which results into better MRR and hole quality (in terms of chipping dimensions) [27]. Recently, the feasibility of using this technique has become of interest and has been investigated in a number of countries including the UK, France, Switzerland, Japan, etc. [13, 23]. A few CNC controlled path rotary USM systems are available commercially such as the SoneX300 from Extrude Hone Limited (France) and the Erosonic US400/US800 from Erosonic AG (Switzerland) [13]. Figure4 demonstrates arotary USM process.

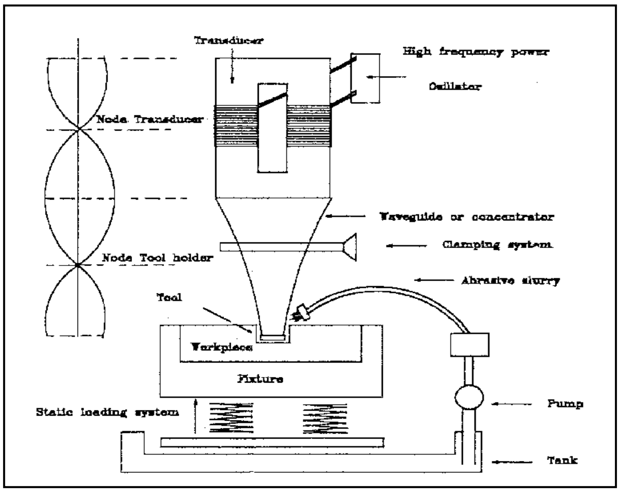

Figure 3. Basic elements of USM

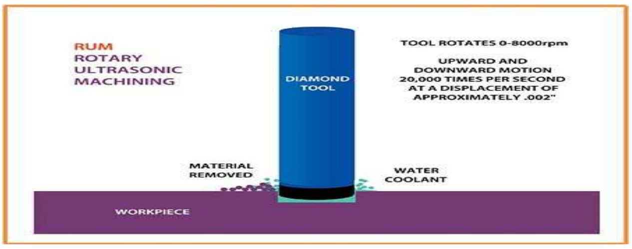

Figure4. Rotary ultrasonic machining process

RUM devices contain a uniquely designed spindle that is coupled to an ultrasonic transducer. The ultrasonic power supply converts conventional line voltage into 20 kHz of electrical energy. This output is fed to the piezoelectric transducer located in the spindle, and the transducer converts electrical input into mechanical vibrations. By changing the setting of the output control of the power supply, the amplitude of the ultrasonic vibration can be adjusted. The spindle speed (measured in revolutions per minute [rpm]) is programmable using the CNC controller for speeds up to 8000 rpm. A variety of tool shapes are used for rotary ultrasonic machining, and ceramic and technical glass machining applications typically use either a diamond-impregnated or electroplated tool. Diamond-impregnated tools are more durable, but electroplated tools are less expensive, so the selection depends on the particular application. One of the major differences between USM and RUM equipment is that USM uses a soft tool, such as stainless steel, brass or mild steel, and a slurry loaded with hard abrasive particles, while in RUM the hard abrasive particles are diamond and are bonded on the tools. Another major difference is that the RUM tool rotates and vibrates simultaneously, while the USM tool only vibrates. These differences enable

RUM to provide both speed and accuracy advantages in ceramic and glass machining operations. In many instances, the rotary ultrasonic machining method yields a competitive edge, and application information is not disclosed to maintain the proprietary nature of this work. However, followings are some generic examples that indicate the type of work being performed. Experimental results of USM and RUSM are presented in table 1. The results of expert system for USM and RUSM for the same design feature (circular hole making) are presented and compared with experimental one and also presented in table 1. The tool diameter is 15 mm and the depth of holes is 1.3, 5.0, 6.8, and 10 mm. In practical USM, estimates of machining time and cost, penetration rate and productivity are time-demanding on experienced personnel. In contrast the knowledge-based system can provide these estimates usually in less than 30 seconds. In Figure 4 machining time, Figure 5 machining cost and Figure 6 penetration rate for USM, RUSM, ESUSM, and ESRUSM is demonstrated. In Figure 8 rotary USM CNC machine is shown.

Data for experimental USM: Frequency 20 kHz, Amplitude 40 μm, Static force 3, Abrasive B_C, Tool steel. Data for expert system: Frequency 20 kHz, Amplitude 38 μm, tool mild steel for USM and mild steel with diamondcoted for RUSM. The tool diameter is 15 mm and depth of holes is 1.3, 5.0, 6.8 and 10 mm.

Table 1: Comparison of experimental USM, Rotary USM and Expert System results

Hole depth	Work piece	Procedure	Machining Time USM	Machining cost USM (US$)	Penetration Rate USM	Machining Time RUSM	Machining Cost RUSM (us$)	Penetration Rate RUSM
1.3	Graphite	Experimental	1.1	0.44	1.18	0.8	0.32	1.62
5.0			3.7	1.48	1.35	2.8	1.78	1.78
6.8			5.0	2.0	1.36	3.75	1.5	1.8
10.0			9.0	3.6	1.11	6.75	2.7	1.48
1.3	Graphite	Expert System	0.99	0.40	1.31	0.75	0.30	1.73
5.0			3.33	1.33	1.50	3.5	1.4	1.42
6.8			4.50	1.8	1.51	4.2	1.68	1.62
10.0			8.10	3.24	1.23	6.22	3.11	1.6

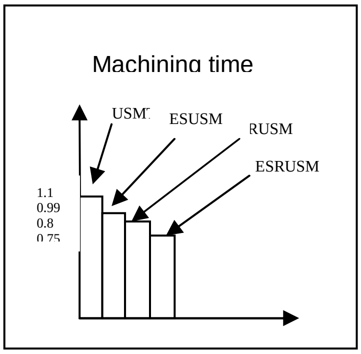

Figure 5 Machining time for USM, RUSM, ESUSM, ESRUSM

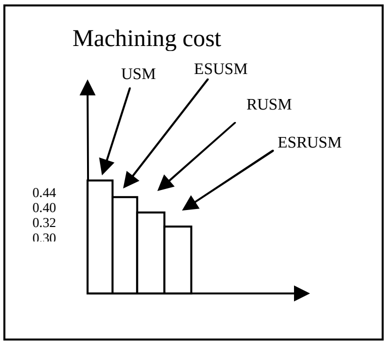

Figure 6 Machining cost for USM, RUSM, ESUSM, ESRUSM

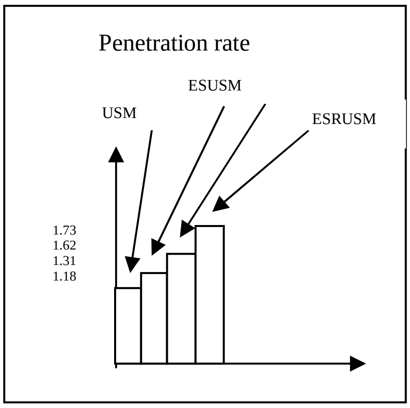

Figure 7. Penetration rate for USM, RUSM, ESUSM, ESRUSM

Figure 8. Rotary USM CNC machine

The expert system result of a circular hole making with different material type for work piece, abrasive and tool for the same design feature specification is presented in table 2.

Designers of manufacturing engineers select work piece material and design feature from the work piece and feature library. Then work piece specification and design description for each selected design feature are obtained interactively by the expert system. The system estimates all necessary parameters such as spindle force, abrasive size, concentration, carrier fluid, frequency, power, machining time and cost, penetration rate and efficiency.

Table 2. Comparison of USMES and RUSMES results for different material and features

Procedure	Design feature Type	Abrasive	Tool material type	Work piece material type	Penetration rate (mm/min)	Machining time (min)	Machining cost ($US)
Expert system for USM	Circular hole with diameter 10 depth 10 mm for USM	Boron carbide (B_C)	Steel	Glass	6.25	1.6	0.60
				Composite	3.34	3	1.12
				Stone	31.25	0.32	0.12
				Ceramic	0.83	12	4.5
Expert system for RUSM	Circular hole with diameter 10 depth 10 mm for RUSM	Boron carbide (B_C)	Steel Diamond coated	Glass	9.0	1.16	0.44
				Composite	5.0	2.18	0.81
				Stone	43.0	0.23	0.087
				Ceramic	1.14	8.72	3.27

4. Validation Results of the Expert System

As a result, table 1 shows that estimation of expert system for machining time and cost for USM hole making is 10 percent less and better than experimental USM. Also shows that estimation of expert system for machining time and cost for RUSM hole making is 10 percent less and better than experimental RUSM, because in expert system, optimum parameters are selected. As a result, table 1 and figure 3 show that machining time and cost for hole making for graphite material for experimental RUSM is 37.5 percent less and better than experimental USM. Table 1 and fig 4 show that machining time and cost for hole making for graphite material for experimental RUSM is 37.5 percent less than experimental USM; But penetration rate of hole making for graphite material for experimental RUSM is increased with 37.5 percent. Estimation of expert system for machining time and cost for USM hole making is 10 percent less than experimental USM. Estimation of expert system for machining time and cost for hole making for RUSM is 10 percent less than experimental RUSM. Table 1, table2 and fig 5 showthat penetration rate and productivity for hole making for USM is 37.5 percent less than RUSM. Also show that estimation of expert system for penetration rate and productivity for RUSM hole making is 10 percent more than USM. Table 2 shows estimation of expert system for machining time and cost, glass, composite, stone and ceramic material for RUSM is 37.5 percent less than estimation of expert system for USM for the same material. Also estimation of expert system for penetration rate and productivity glass, composite, stone and ceramic material for RUSM is 37.5 percent more than estimation of expert system for USM for the same material. Table 2 shows estimation of expert system for machining time and cost, glass, composite, stone and ceramic material for RUSM is approximately 37.5 percent less than estimation of expert system for USM for the same material. Table 2 also shows estimation of expert system for penetration rate and productivity for composite material for RUSM is 37.5 percent more than estimation of expert system for USM for the same material.

5. Conclusions and summery

1. USM and RUSM are non-thermal process, which does not rely on a conductive work piece and is preferable for machining work pieces with low ductility and hardness above 40 HRC.
2. Expert system is developed to estimate machining time and cost, penetration rate and productivity for different design hole on different materials such as glass, composite, stone, graphite and ceramic for USM and RUSM with less than 30 seconds.
3. Estimation of expert system for machining time and cost for USM hole making is 10 percent less than experimental USM, because in expert system, optimum parameters are selected.
4. Estimation of expert system for machining time and cost for RUSM hole making is 10 percent less than experimental RUSM, because in expert system, optimum parameters are selected.
5. Machining time and cost for hole making for graphite material for experimental RUSM is 37.5 percent less than experimental USM.
6. Ultrasonic drilling caused no deformation of the work piece microstructure.
7. low temperature (10°C) machining is performed better surface finish attained than at room temperature (27°C) and at high temperature (60°C), at all Power Rating values.
8. The design of tool and horn play an important role in providing a resonance state in USM and MRR.

9. For complex design feature, machining a simple USM tool followed by CNC programming is preferred rather than die sinking using complex form tools.
10. The optimum static load for maximum machining rate has been found to be dependent on the tool configuration (e.g. cross-sectional area and shape), the amplitude and mean grit size.
11. The hardness of slurry material should be more than the work piece. In general, larger abrasive grit sizes and higher slurry concentrations results in to higher MRR.
12. During machining in USM slurry is splashed out from tank because of high vibrations of tool, proper care should be made for fixing the slurry concentration and slurry flow rate as it will have a serious effect on tool life.

6. References

[1] Kremer, D., Saleh, S. M., Ghabrial, S. R. and Moisan, A. 1981. State of the Art of Ultrasonic Machining., Annals of the CIRP, 30(1), 107-110.

[2] Seah, K. H. W., Wong Y. S. and Lee, L. C. 1993. Design of tool holders for ultrasonic machining using FEM, Materials Proc. Tech., 37, 801-816.

[3] McGeough, J. A. 1988, Advanced methods of manufacturing, Chapman & Hall.

[4] Kainth, G. S., Nandy, A. and Singh, K. 1979, On the mechanics of material removal in ultrasonic machining, Int. J. Mach. Tool. Des. Res., 19, 33-41.

[5] Soundararajan, V. and Radhakrishnan, V. 1986, An Experimental investigation on the basic mechanisms involved in ultrasonic machining, Int. J. Mach. Tool Des. 26(3), 307-321.

[6] Kamoun, H., Houbt, M., Kremer D., Lecoco, B. and Coffignal, G. 1993, Modelling the material removal in stationary mode for ultrasonic contour machining, Manufacturing Science and Engineering, ASME, 64, 759-770.

[7] Milton C. S. 1956. Ultrasonic grinding, Microtecnic, 10(6), 257-265.

[8] Markov, A. I. 1966. Ultrasonic machining of intractable materials. London ILIFFE Books.

[9] Nishimura, G.U. 1954. Altrasonic machining Part I, J. Fac. Eng. Tokyo Univ., 24(3), 65–100.

[10] Neppiras, E. A. 1956, Report on ultrasonic machining Metalwork. Prod. 100, 1283–1288.

[11] Weller, E. J. 1984. Non-traditional Machining Processes (2nd ed.), Society of Manufacturing Engineers,15–71.

[12] Fairer, J. O. 1948, English Patent No. 602801, USM.

[13] Thoe, T. B., Aspinwall, D. K. and Wise, M. L. H. 1998. Review on ultrasonic machining, Int. J. Mach. Tools Manuf. 38(4), 239–255.

[14] Scab, K. H. W. 1990. Parametric studies of ultrasonic Machining SME Tech. Paper MR90-294,11.

[15] Neppiras, E. A. 1972, Macroson. Ind. Ultrasonics, 10, 9–13

[16] Perkins, J. 1972, An outline of power ultrasonics, Technical Report. Kerry Ultrasonics, 7.

[17] Farago, F.T. 1980, Abrasive Methods Engineering, Industrial Press, 2, 480–481.

[18] Balamuth, L. 1964, Ultrasonic vibrations assist cutting tools, Metalwork. Prod. 108(24), 75–77.

[19] Kennedy D.C. and Grieve, R.J. 1975, Ultrasonic machining, Prod. Eng. 54(9), 481–486.

[20] Kremer, D. 1991, New developments on ultrasonic machining SME. Technical Paper, 91, 13.

[21] Clifton, D., Imal, Y. and Mc-Geough, J. A. 1993. Some ultrasonic effects on machining materials encountered in the offshore industries, Proceedings of the 30th International MATADOR Conference, 119–123.

[22] Shaw, M. C. 1956. Ultrasonic grinding, Microtechnic, 10(6), 257–265.

[23] Moreland M. A. 1991. Ultrasonic machining Book Chapter: Ceramics and Glasses, Engineering Material Handbook, ASM International, 4, 359–362.

[24] Metcut, 1980. Machining Data Handbook 3th Edition, Machining data handbook, Vol. 2.

[25] Komaraiah, M., Manan, M. A., Narasimha Reddy P. and Victor,S. 1988. Investigation of surface roughness and accuracy in ultrasonic machining Precis. Eng. 10(2), 59–65.

[26] Mc-Geough, J. A. 1988. Advanced Methods of Machining Chapman & Hall, 170–198.

[27] Kennedy D.C. and Grieve, R.J. 1975, Ultrasonic machining a review, Prod. Eng., 54, 481–486.

[28] Adithan, M. 1976. Production accuracy of holes in ultrasonic drilling, Wear 40(3), 309–318.

[29] Neppiras, E.A. and Foskett, R.D. 1957. Ultrasonic machining II Operating conditions and performance of ultrasonic drills, Philips Tech. Rev., 18(12), 368–379.

[30] Wojchiechowski, M. P. *et al.*, 1972, Ultrasonic machining Past, present and future, SME Paper MR72-188, 12.

[31] Instruction manual for stationary SONIC-MILL 500 W Model 2002 (U.S.A).

[32] Kazantsev, V. F. 1966, Improving the output and accuracy of ultrasonic machining Mach. Tooling 3**7**(4), 33–39.

[33] Pentland E. W. and Ektermanis, J. A. 1965, Improving ultrasonic machining rates some feasibility studies. J. Eng. Ind., Trans. ASME, Ser. B 87, 39–46.

[34] Miller, G. E. 1957, Special theory of ultrasonic machining. J. Appl. Phys. 28(2), 149–156.

[35] Cook, N. H. 1966. Manufacturing Analysis, Addison-Wesley, New York, 133–138.

[36] Graff, K. F. 1975. Macrosonics in industry. Ultrasonic machining, Ultrasonics13, 103–109.

[37] Kremer D. 1981. The state of the art of ultrasonic machining Ann. CIRP, 30(1), 107–110.

[38] Kainth, G. S., Nandy, A. and Singh, K. 1979, On the mechanics of material removal in ultrasonic machining. Int. J. MTDR 19, 33–41.

[39] Neppiras E. A. and Foskett, R. D. 1957, Ultrasonic machining I. Technique and equipment. Philips Tech. Rev. 18(11), 325–334.

[40] Singh R. and Khamba, J. S. 2003. Proceedings of 13th National Conference of Indian Society of Mechanical Engineers (ISME-2003) IIT Roorkee, (Uttranchal) India, December 30–31, 59.

[41] Singh, R. and Khamba, J. S. 2003. Silicon carbide slurry effect in ultrasonic assisted drilling of titanium alloy (TITAN15). Journal of Manufacturing Technology Today, 2(7), 08–11.

[42] Singh R. and Khamba, J. S. 2004. Machining characteristics comparison of titanium alloys in ultrasonic assisted drilling. Proceedings of the International Conference on Recent Advances in Composite Materials (ICRACM2004) Institute of Technology, B. H. U., India, December 17–19, 438–442.

[43] Komaraiah M. and Narasimha Reddy P. 1993. A study on the influence of workpiece properties in ultrasonic machining. *Int. J. Mach. Tools Manuf.*, 33(3), 495–505.

[44] Li, Z. C., Jiao,Y., Deines T. W., Pei Z. J. and Treadwell, C. 2005. Rotary ultrasonic

machining of ceramic matrix omposites: feasibility study and designed experiments, Int. J. Mach. Tools Manuf., 45(12–13), 1402–1411.

[45] Seah, K. H. W., Wong Y. S. and Lee, L. C. 1993. Design of tool holders for ultrasonic machining using FEM. J. Mater. Process. Technol. 37(1–4), 801–816.

[46] Neppiras, E. A. 1964. Ultrasonic machining and forming, Ultrasonics, 2, 167–173.

[47] Wang, A. C., Yan, B. H., Li X. T. and Huang, F. Y. 2002. Use of micro ultrasonic vibration lapping to enhance the precision of microholes drilled by micro electro-discharge machining. Int. J. Mach. Tools Manuf. 42(8), 915–923.

[48] Li, Z. C., Jiao,Y., Deines, T. W., Pei Z. J. and Treadwell, C. 2005. Rotary ultrasonic machining of ceramic matrix composites: feasibility study and designed experiments, Int. J. Mach.Tools Manuf. 45 (12–13), 1402–1411.

[49] Balamuth, L. A. 1966. Ultrasonic assistance to conventional metal removal. Ultrasonics, 4, 125–130.

[50] Isaev, A. I. 1962. Learning with ultrasonically vibrated reamers. Mach. Tooling 33(6), 27–30.

[51] Singh R. and Khamba J. S. 2003. Silver brazing for tool preparation in USM process. Proceedings of the National Workshop of Welding Technology in India Present Status and Future Trends SLIET Longowal, 61–63.

[52] Singh A. R. and Khamba, J. S. 2004. Tool manufacturing technique in ultrasonic drilling machine, J. Manuf. Technol. Today, 3(1), 5–7.

[53] Machining Data Handbook, 3rd ed., vol. 2, Compiled by the Technical Staff of the Machinability Data Centre, CincinnatiMetcut Research Associates Inc., 1980, pp. 43–63.

[54] Halm, R. and Schulz, P. 1993. Ultrasonic machining of complex ceramic components. Erosion AC Report, 7, 6.

[55] Moreland, M. A. 1988. Ultrasonic advantages revealed in the hole story, Ceram.Appl. Manuf.187, 156–162.

[56] Gilmore, R. 1989, Ultrasonic machining and orbital abrasion techniques, SME Technical Paper (Series) AIR, 89, 1–20.

[57] Moore, D. 1985. Ultrasonic impact grinding, Proceedings of the Non-traditional Machining Conference Cincinnati, 137–139.

[58] Black, P. 1985, An ultrasonic impact grinding technique for electrode-forming and redressing, Proceedings of the Non-traditional Machining Conference Cincinnati, Ohio, ASM, 129–136.

[59] Kremer, D., Bazine, G. and Moison, A. 1983. Ultrasonic machining improves EDM technology. In: J.R. Crookall, Editor, Proceedings of the Seventh International Symposium on Electro Machining Birmingham, 67–76.

[60] Legge, P. 1966. Machining without abrasive slurry, Ultrasonics 4, 157–12.

[61] Rozenberg, L. D. 1973. Physical Principles of Ultrasonic Tech. Vols. 1 and 2, Plenum Press, New York.

[62] Frederick, J. R. 1965, Ultrasonic Engineering, John Wiley and Sons Inc., New York, ISBN 0471277258.

[63] Kaczmarek, Impact Grinding 1976, (Ultrasonic machining—Book Chapter 21: Principles of Machining by Cutting Abrasion and Erosion, Peter Peregrinus Ltd, Stevenage, 448–462, ISBN 0901223662.

[64] Jay, F. 1984. IEEE Standard Dictionary of Electrical and Electronics Terms (3rd ed.), 405–519.

[65] US400—Ultrasonic machining system, Brochure from Erosonic AG, 1994.

[66] Robare M. W. and Richerson, D. W. 1977. Proceedings of the ARPA/NAVSEA-Garrett/Ai Research Ceramic Gas Turbine Engine Demonstration Program Review at Rotor Blade Machining Development Marine Maritime Academy.

[67] Singh R. and Khamba, J. S. 2003. Proceedings of National Conference on Recent Development in Mechanical Engineering (NCME-2003) T.I.E.T., Patiala (Punjab) India, 31 October–1 November, 619–620.

[68] Singh R. and Khamba, J. S. 2003. Proceedings of National Conference on Emerging Technologies (NCMRT-2003) TIET Patiala,(Punjab) India,September 19–20, 75–79.

[69] Singh R. and Khamba, J. S. 2004. Comparison of machining characteristics of titanium alloys: effect of slurry in ultrasonic machining process, Proceedings of the Global Congress on Manufacturing and Management, The International Conference on Manufacturing and Management (GCMM-2004) Vellore Institute of Technology (Tamilnadu) India, December 8–10.

[70] Thoe, T. B., Aspinwall, D. K. and Wise M. L. H. 1995. The effect of operating parameters when ultrasonic contour machining. Proceedings of the 12th Annual Conference of the Irish Manufacturing Committee (IMC-12) Cork, Ireland, September, 305–312.

[71] Prabhakar D. and Haselkorn, M. 1992. An experimental investigation of material removal rates in rotary ultrasonic machining Trans. NAMR1/SME 20, 211–218.

[73] Adithan, M. 1974. Tool wear studies in ultrasonic drilling, Wear 29, 81–93.

[74] Kumehara, H. 1984. Characteristics of threaded joints in ultrasonic vibrating system, Bull. JSME 27(223), 117–123.

[75] Ghabrial, S. R. 1986. Trends towards improving surfaces produced by modem processes, Paper presented at the Third International Conference on Metrol and Prop, of Eng’g Surf Teesside, England, 113–118.

[76] Singh R. and Khamba, J. S. 2005. Proceedings of National Conference on Advances in Condensed Matter Physics (ACMP-05) T.I.E.T., Patiala (Punjab) India, February 11–12, 333–339.

[77] Singh R. and Khamba, J. S. 2004. Proceedings of the 21st AIMTDR conference Vellore Institute of Technology India, December 20–22, 155–160.

[78] Singh R. and Khamba, J. S. 2004. Proceedings of International Conference on Recent Advances in Composite Materials (ICRACM2004) Institute of Technology, B.H.U. (Banaras), India, Dec.17–19, 438–442.

[79] Singh R. and Khamba, J. S. 2004. Proceedings of Global Congress on Manufacturing and Management, The International Conference on Manufacturing and Management (GCMM-2004) Vellore Institute of Technology (Tamilnadu), India, December 8–10, 54–58.

[80] Singh R. and Khamba, J. S. 2004. J. Manuf. Technol. Today, 3(1), 05–07.

[81] Singh R. and Khamba, J. S. 2003. Proceedings of International Conference on Emerging Technologies (ICET) KIIT, (Bhuvneswar) India, December 19–21, 67.
[82] Khairy, A. B. E. 1990, Assessment of some dynamic parameters for the ultrasonic machining process, Wear137, 187–198.
[83] Gilmore, R. 1989. Ultrasonic machining SME Technical Paper EM89-123, 10.