Expert System Approach for Optimization of Design and Manufacturing Process for Rotary Ultrasonic Machining

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Abstract: An expert system for evaluating rotary ultrasonic machining, in concurrent engineering environment and based on object oriented techniques, is developed. The design specification is obtained through a feature based approach. Different classes of design features are interactively acquired. The attributes of different hard and brittle materials like glass, composite, stone and ceramic as work piece materials are stored in database. The system is also linked with tool material and machine databases. For each design feature, information is needed in manufacturing, such as machining cycle time, and cost, penetration rate, and efficiency are estimated by the expert system. Software system such as expert system based on object oriented technique is used to develop the expert system. The system links with a feature based CAD system in order to extract design data. The expert system provides useful information such as machining cycle time and cost, penetration rate, efficiency of machining of the selected design feature for product designers and advises of manufacturing engineers to select optimum machining parameters. In order to test the validity of the system, results of expert system is compared with the results of experimental rotary ultrasonic machining.

Keywords: Expert system, Machining time & cost, Penetration rate, Rotary ultrasonic

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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]. Rotary Ultrasonic Machining is a nontraditional manufacturing technique for machining hard and brittle materials such as titanium alloys [4] and ceramics [5]. These materials are hard to machine by conventional techniques such as drilling, milling, turning and expensive to machine by other non conventional techniques such as laser and EDM.

RUM offers a convenient and inexpensive way of machining these hard and brittle materials. The RUM process involves material removal by hybrid action of ultrasonic machining (USM) and conventional grinding. The setup for RUM consists of an ultrasonic spindle kit, feeding device and a coolant system. A rotating and ultrasonically vibrating abrasive bonded tool is fed towards the workpiece. The tool removes material from the workpiece because of the ultrasonic impacts and the grinding action of the abrasives. RUM has been used to machine materials such as alumina [5], [6], beryllium oxide [7], canasite [8], composites [8], [9], ferrite [10], glass [11], polycrystalline diamond compact [12], silicon carbide [13], silicon nitride [14], zirconia [15, 16], titanium alloys [4], and stainless steel [17]. RUSM was developed as an improvement over ultrasonic machining (USM). USM uses abrasive slurry (essentially a mixture of abrasive and coolant) which is fed between an ultrasonically vibrating tool and the workpiece during machining.

In RUSM, the loose abrasives are abandoned and are bonded to the tool itself. As a result, some of the disadvantages of the ultrasonic machining were overcome in RUSM. For example, in the presence of the abrasive slurry, the escaping debris and the suspended abrasive particles tend to erode the walls of the machined hole during flushing thus making it hard to hold close tolerances. The use of diamond impregnated tool was reported to improve the hole accuracy and it was easier to drill deeper holes. It is not always desirable to expose the workpiece to the abrasive slurry; consequently, with the abandoning of the abrasive slurry, RUSM could be extended to a wider range of applications. RUSM was reported to be capable of machining ten times faster than USM under similar conditions. A superior surface finish and a low tool pressure could be achieved compared to USM [18]. Rotary Ultrasonic Machining (RUSM), by definition, is a hybrid machining process where the ultrasonic machining and conventional grinding occur simultaneously to remove material from the workpiece by micro chipping and grinding action of the abrasives. The setup for RUSM consists of a rotating and ultrasonically vibrating diamond abrasive studded tool which is fed towards the workpiece such that a constant pressure or a constant federate is maintained during machining. A coolant injected between the tool and the workpiece through a hollow tool flushes away the debris. RUSM has also been referred to as Ultrasonic Impact Drilling [19] and Ultrasonic Vibration Assisted Grinding [20]. A workpiece for RUSM is usually characterized by properties of high hardness and brittleness. Thus, machinability of a material is independent of its other material properties such as electrical conductivity and chemical reactivity.

RUSM is a non- thermal, non-chemical and non-electrical process. As a result, the metallurgical, chemical or physical properties of the workpiece do not change post machining [21]. Virtually a stress free surface is generated after machining, thus, the fatigue strength of the machined material does not deteriorate. RUSM has been used for drilling and coring [22]. It has also been extended to milling [14], [23], disk grinding [24] and contour machining [25]. Literature reports that RUSM was developed as an improvement over ultrasonic machining (USM) [18]. Unlike USM, instead of using the loose abrasive slurry, the diamond abrasives were impregnated into the rotating tool. Typically, RSUM was used for drilling holes through hard and brittle materials. The development of RUSM as a successor of ultrasonic machining (USM) is discussed in this section.

USM was patented in 1927 and has been used in the industry since 1940 for machining materials with high hardness and brittleness. This process uses abrasive slurry (essentially a mixture of diamond abrasives and a cooling fluid) which is fed between an ultrasonically vibrating tool and the workpiece during machining. P. Legge developed RUSM for the first time in 1964. There are Advantages of RUSM over USM in the literature. Some of the disadvantages of the ultrasonic machining were overcome in RUSM. In the presence of the abrasive slurry, the escaping debris and the suspended abrasive particles tend to erode the walls of the machined hole during flushing thus making it hard to hold close tolerances. The use of diamond impregnated tool was reported to improve the hole accuracy and it was easier to drill deeper holes. It is not always desirable to expose the workpiece to the abrasive slurry. Consequently, on abandoning of the abrasive slurry, RUSM could be extended to a wider range of applications. RUSM was reported to be capable of machining ten times faster than USM under similar conditions. A superior surface finish and a low tool pressure could be achieved compared to USM [18], [26]. RUSM has many applications. Applications of hard and brittle materials is used in both USM and RUSM, applications of hard and brittle materials like glass, quartz crystal, lead zirconate, titanate (PZT), silicon carbide, silicon nitride, alumina and etc.

2 MECHANISM OF MATERIAL REMOVAL IN RUSM

The mechanism of material removal has been investigated by studying the surface topography of the machined surface and mechanisms involved in the single grit scratching experiments [27], [28]. Dominant mode of material removal was due to brittle fracture. The impact, grinding and erosion generated by tool rotation and vibration were responsible for the brittle fracture [28], [11]. The impact was found to be a major factor for material removal towards the tool tip, while grinding was dominant near the walls of the hole. The debris produced due to impact and grinding mixed with the pressurized coolant were responsible for erosion at the hole walls during machining. Ductile mode of material removal also contributed towards machining [16].

In recent studies, the advantages of ductile regime machining of brittle materials were emphasized [30]. Minimal subsurface damage and better surface finish are the results of ductile regime machining. Ductile machining is based on the fact that all materials deform plastically if the degree of deformation is small enough. There exists a critical depth of indentation for the abrasive grits involved. If the applied force on the abrasive grain exceeds this critical value, cracks are developed in the workpiece. However, if this depth of indentation is below the critical depth, material is removed by plastic flow [30]. During ultra precision diamond turning, as the tool traversed across the workpiece, zones of machining were formed as the tool traverses across the workpiece: (i) a ductile zone where continuous chips are formed and the surface defects such as micro-cracks and craters are absent (ii) a ductile-brittle-transition zone where the surface is semi-brittle fractured and (iii) a brittle fractured surface where holes, cracks and severe surface damage can be observed [31]. Figure 2.4 illustrates the three zones of machining. Experiments with single point diamond tool reveal that the use of ultrasonic vibrations increased the critical depth of cut to a higher value allowing ductile (plastic flow) machining to occur up to a higher value. The reduction in the cutting forces and frictional forces as a result of using the ultrasonic vibrations was proposed to be a reason for this increased value of the critical depth of indentation [32]. This phenomenon has also been observed for ultrasonic assisted grinding of Nano ZrO2 ceramics [33]. The critical chip thickness has been defined as a function of material properties. The process parameters and tool geometry are also important factors in ductile-regime machining [31].

3 SYMBOLS, AND ABBREVIATIONS

USM	Ultrasonic machining
RUSM	Rotary ultrasonic machining
Mach.	Machining
Diam.	Diamond
Dia.	Diameter
St.	Steel

4 MACHINING PARAMETERS AND PERFORMANCE

The machinability of materials such as titanium alloy [4, 34], advanced ceramics [5], [18], [26], ceramic matrix composites [9], silicon carbide [13], stainless steel [17], dental ceramics [35], potassium dihydrogen phosphate [36], glass [11] is investigated under different machining conditions in the recent years. A summary of literature regarding the effect of different machining parameters on material removal rate (MRR), average surface roughness, tool wear and edge chipping is presented in the following sections.

Material removal rate (MRR): MRR was found to increase with an increase in the machining pressure [18], increase in the feed rate, at a higher spindle speed [18], [4] and with increase in ultrasonic frequency [19]. Vibration amplitude was found to have a significant effect on the MRR [18]. With increase in abrasive grit size and abrasive concentration, MRR was found to increase up to a certain optimal value and then a decreasing trend was observed [18], [37]. During RUM of ceramics, MRR reduced as the strength of the bond increased [18]. The type of coolant (oil or water) did not affect the MRR [38].

Cutting force: The cutting force was observed to reduce as the spindle speed was increased [4], [5], [13], [17], 18] and federate was decreased [5], [9], [13], [18] during RUM of different materials. Ultrasonic vibration power had significant effect on the cutting force [4], [17]. Lower cutting forces were produced when a larger abrasive grit size, a higher abrasive concentration [34] and water-based coolants were used compared with synthetic coolants or tap water. [39].

Surface roughness: Surface roughness was found to reduce with decrease in machining pressure, decrease in feed rate [18], decrease in ultrasonic vibration frequency [19] and at a higher spindle speed [4], [9]. A nonlinear dependence of ultrasonic power on the surface roughness was observed while machining ceramics. A reduction in average surface roughness was found with increase in ultrasonic power while machining two metals including stainless steel and titanium alloy [4], [13]. With increase in abrasive grit size the surface roughness increases up to a certain value and then decreases [18], [34]. Natural diamond was observed to reduce the surface roughness compared to the synthetic diamond abrasive [18]. A high abrasive density led to a decreased surface roughness. However, if the abrasive density is very high, the strength of the abrasive layer is reduced, leading to an increased tool wear and thus higher surface roughness [37]. Coolant pressure affected the surface roughness significantly [39].

Tool wear: Accuracy and surface finish of the machined feature are affected as the tool wears out. It is therefore important to understand the mechanism and the influence of machining parameters on tool wear. In RUM, the wear of tool was calculated as specific tool wear which was defined as the ratio of the volume of the material removed to the volume of the tool wear. Specific tool wear provides no information on the mechanism of tool wear [19]. In an investigation of the tool wear mechanism in silicon carbide, attritious tool wear and bond failure, similar to those in grinding, were observed. Tool wear at the end face was more severe than the tool wear at the lateral face. Correlation of the tool wear with cutting forces was proposed to be used for online monitoring of the tool wear [40]. In another study, acoustic emission signals were used to assess the wearing patterns of the tool for monitoring purposes [41]. The influence of different tool variables including grit size, metal bond type, and diamond concentration on the tool wear during machining of titanium alloy were studied [34].

Edge chipping**:** Finite element models were developed to study the edge chipping and cutting forces during machining of ceramics. The results were compared with the experimental data. A higher spindle speed and lower feed rate resulted in a lower chipping thickness because of the reduced cutting forces [42]. Efforts were made to reduce the edge chipping in a further study [43]. It was found that on increasing the support length (the radial length of contact area between workpiece and the fixture) and decreasing the cutting force, the edge chipping thickness decreased [44].

Machining temperature: The grinding temperatures were found to reduce significantly when grinding with the aid of ultrasonic vibrations. In a study of tool wear, it was found that the surface color of the diamond grains changed after machining. This implied that the surface temperature of the diamond grains was high [40]. However, study focusing on the temperature changes during machining has not been conducted yet.

Feed mechanism: Two types of feed mechanisms, either a tool-down feeding or workpiece-up feeding have been used [44], [45]. Either constant feed rate or constant force/pressure control are usually employed for controlling the feed mechanism in the process. A stepback feed mechanism, involving forward-stepping the tool followed by a small back stepping helped in efficient debris removal [46].

Tools: Most of the studies make use of a cylindrical tool with a through hole in its centre for supplying the coolant to the working gap. A slotted diamond tool was used in one of the studies. Surface roughness improved compared to conventional RUM with cylindrical tool. No significant difference in cutting force was observed [45]. Electroplated tools and diamond impregnated tools have been used for RUSM, however, electroplated tools wore out faster even if material removed by them is at a greater rate [37], [44].

Ultrasonic vibrations: A method was developed for designing a horn for transmission of ultrasonic vibrations using the finite element method [47]. The ultrasonic vibrations are applied along the axis of the tool and perpendicular to the plane of the tool rotation so that the abrasive grains bonded to the tool impact the workpiece. The ultrasonic vibrations can be applied either to the tool or the workpiece. While drilling using a diamond impregnated tool, ultrasonic vibrations were applied to the tool and low-frequency vibrations were applied to the workpiece. When vibrations were applied to both, the tool and the workpiece, the cylindricity error and edge chipping were reduced [48]. In another experimental study, a recently developed very high frequency ultrasonic transducer (400 kHz) was used for micro ultrasonic grinding. The spindle rotating the tool was vibrated at the ultrasonic frequency during boring of glass, ferrite and alumina. This transducer provided longitudinal, torsional, and complex (longitudinal and torsional) modes of vibration. Use of complex modes of vibration (longitudinal and torsional) resulted in the best performance due to reduced chipping and stabilized grinding force. The amplitude of vibration was kept constant by a feedback control mechanism so that the depth of cut was maintained constant at a submicron level [46].

Coolant system**:** In an innovative coolant system developed, the effect of coolant flow (continuous or intermittent) was investigated. The intermittent flow removed the debris efficiently resulting in a better performance [49]. Theoretical models were developed for predicting MRR in RUSM based on brittle fracture [6], [50] and ductile flow [16]. A physics based model was developed for predicting the cutting force while machining at a constant federate [20]. In this paper an expert system is developed for rotary ultrasonic machining.

5 WHAT IS EXPERT SYSTEM

Expert Systems are computer programs that are derived from a branch of computer science called Artificial Intelligence (AI). AI's scientific 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, AI addresses all of those. But most progress to date in AI has been made in the area of problem solving - concepts and methods for building programs that reason about problems rather than calculate a solution. AI programs that achieve expert-level competence in solving problems in task areas by bringing to bear a body of knowledge about specific tasks are called knowledge-based or expert systems. Often, the term expert systems are reserved for programs whose knowledge base contains the knowledge used by human experts, in contrast to knowledge gathered from textbooks or non-experts. More often than not, the two terms, expert systems (ES) and knowledge-based systems (KBS), are used synonymously. Building an expert system is known as knowledge engineering and its practitioners are called knowledge engineers. The knowledge engineer must make sure that the computer has all the knowledge needed to solve a problem. The knowledge engineer must choose one or more forms in which to represent the required knowledge as symbol patterns in the memory of the computer that he or she must choose a knowledge representation. He must also ensure that the computer can use the knowledge efficiently by selecting from a handful of reasoning methods. Components of expert system consists of two major components: knowledge base and inference engine.

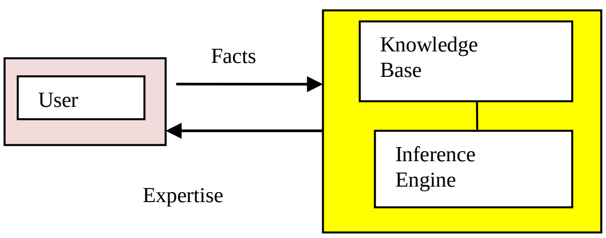

Fig. 1 An expert System environment

Knowledge base contains the domain knowledge which is used by the inference engine to draw conclusions. The inference engine is the generic control mechanism that applies the axiomatic knowledge to the task-specific data to arrive at some conclusion. When a user supplies facts or relevant information of query to the expert system he receives advice or expertise in response. Figure 1 shows an expert system environment.

The Building Blocks of Expert Systems: Every expert system consists of two principal parts: the knowledge base; and the reasoning, or inference, engine. The knowledge base of expert systems contains both factual and heuristic knowledge. Factual knowledge is the knowledge of the task domain that is widely shared, typically found in textbooks or journals, and commonly agreed upon by those knowledgeable in the particular field. Heuristic knowledge is the less rigorous, more experiential, more judgmental knowledge of performance. In contrast to factual knowledge, heuristic knowledge is rarely discussed, and is largely individualistic. It is the knowledge of good practice, good judgment, and plausible reasoning in the field. It is the knowledge that underlies the "art of good guessing."

Knowledge representation: knowledge representation formalizes and organizes the knowledge. One widely used representation is the production rule, or simply rule. A rule consists of an IF part and a THEN part (also called a condition and an action). The IF part lists a set of conditions in some logical combination. The piece of knowledge represented by the production rule is relevant to the line of reasoning being developed if the IF part of the rule is satisfied; consequently, the THEN part can be concluded, or its problem-solving action taken. Expert systems whose knowledge is represented in rule form are called rule-based systems. Another widely used representation, called the unit (also known as frame, schema, or list structure) is based upon a more passive view of knowledge. The unit is an assemblage of associated symbolic knowledge about an entity to be represented.

Typically, a unit consists of a list of properties of the entity and associated values for those properties. The problem-solving model, or paradigm, organizes and controls the steps taken to solve the problem. One common but powerful paradigm involves chaining of IF-THEN rules to form a line of reasoning. If the chaining starts from a set of conditions and moves toward some conclusion, the method is called forward chaining. If the conclusion is known (for example, a goal to be achieved) but the path to that conclusion is not known, then reasoning backwards is called for, and the method is backward chaining. These problem-solving methods are built into program modules called inference engines or inference procedures that manipulate and use knowledge in the knowledge base to form a line of reasoning. The knowledge bases of an expert are what he learned at school, from colleagues, and from years of experience. Presumably the more experience he has, the larger his store of knowledge. Knowledge allows him to interpret the information in his databases to advantage in diagnosis, design, and analysis. Knowledge is almost always incomplete and uncertain. To deal with uncertain knowledge, a rule may have associated with it a confidence factor or a weight.

Knowledge engineering: Today there are two ways to build an expert system. They can be built from scratch, or built using a piece of development software known as a "tool" or a "shell." Before we discuss these tools, let's briefly discuss what knowledge engineers do. Though different styles and methods of knowledge engineering exist, the basic approach is the same: a knowledge engineer interviews and observes a human expert or a group of experts and learns what the experts know, and how they reason with their knowledge. The engineer then translates the knowledge into a computer-usable language, and designs an inference engine, a reasoning structure, that uses the knowledge appropriately. He also determines how to integrate the use of uncertain knowledge in the reasoning process, and what kinds of explanation would be useful to the end user. Next, the inference engine and facilities for representing knowledge and for explaining are programmed, and the domain knowledge is entered into the program piece by piece. It may be that the inference engine is not just right; the form of knowledge representation is awkward for the kind of knowledge needed for the task; and the expert might decide the pieces of knowledge are wrong. All these are discovered and modified as the expert system gradually gains competence.

Tools, Shells, and Skeletons: Compared to the wide variation in domain knowledge, only a small number of AI methods are known that are useful in expert systems. That is, currently there are only a handful of ways in which to represent knowledge, or to make inferences, or to generate explanations. Thus, systems can be built that contain these useful methods without any domain-specific knowledge. Such systems are known as skeletal systems, shells, or simply AI tools. Building expert systems by using shells offers significant advantages. A system can be built to perform a unique task by entering into a shell all the necessary knowledge about a task domain. The inference engine that applies the knowledge to the task at hand is built into the shell. If the program is not very complicated and if an expert has had some training in the use of a shell, the expert can enter the knowledge himself.

Many commercial shells are available today, ranging in size from shells on PCs, to shells on workstations, to shells on large mainframe computers. They range in price from hundreds to tens of thousands of dollars, and range in complexity from simple, forward-chained, rule-based systems requiring two days of training to those so complex that only highly trained knowledge engineers can use them to advantage. They range from general-purpose shells to shells custom-tailored to a class of tasks, such as financial planning or real-time process control. Although shells simplify programming, in general they do not help with knowledge acquisition. Knowledge acquisition refers to the task of endowing expert systems with knowledge, a task currently performed by knowledge engineers. The choice of reasoning method, or a shell, is important, but it is not as important as the accumulation of high-quality knowledge. The power of an expert system lies in its store of knowledge about the task domain. Advantages of Expert Systems are: 1-Availability: Expert systems are available easily due to mass production software. 2- Cheaper: The cost of providing expertise is not expensive. 3- Reduced danger**:** They can be used in any risky environments where humans cannot work with. 4- Permanence: The knowledge will last long indefinitely. 5- Multiple expertise: It can be designed to have knowledge of many experts. 6- Explanation: They are capable of explaining in detail the reasoning that led to a conclusion. 7- Fast response: They can respond at great speed due to the inherent advantages of computers over humans. 8- Unemotional and response at all times: Unlike humans, they do not get tense, fatigue or panic and work steadily during emergency situations. The set of methods for using uncertain knowledge in combination with uncertain data in the reasoning process is called reasoning with uncertainty. An important subclass of methods for reasoning with uncertainty is called "fuzzy logic," and the systems that use them are known as "fuzzy systems." Most expert systems have the ability to answer questions of the form: "Why is the answer X?" Explanations can be generated by tracing the line of reasoning used by the inference engine. The most important ingredient in any expert system is knowledge. The power of expert systems resides in the specific, high-quality knowledge they contain about task domains.

6 DEVELOPMENT OF EXPERT SYSTEM FOR RUSM

The term expert system in RUSM covers many cognitive skills, including the ability to solve problems. 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, efficiency of each selected design feature are estimated. The system provides useful information such as machining cycle time and cost, penetration rate of the selected design feature for product designers and also advises manufacturing engineers to select optimum machining parameters. Also the expert system in RUSM is compared with experimental one. Input and output of developed expert system environment are demonstrated in figure 2. Figure 3 shows flowchart of the expert system.

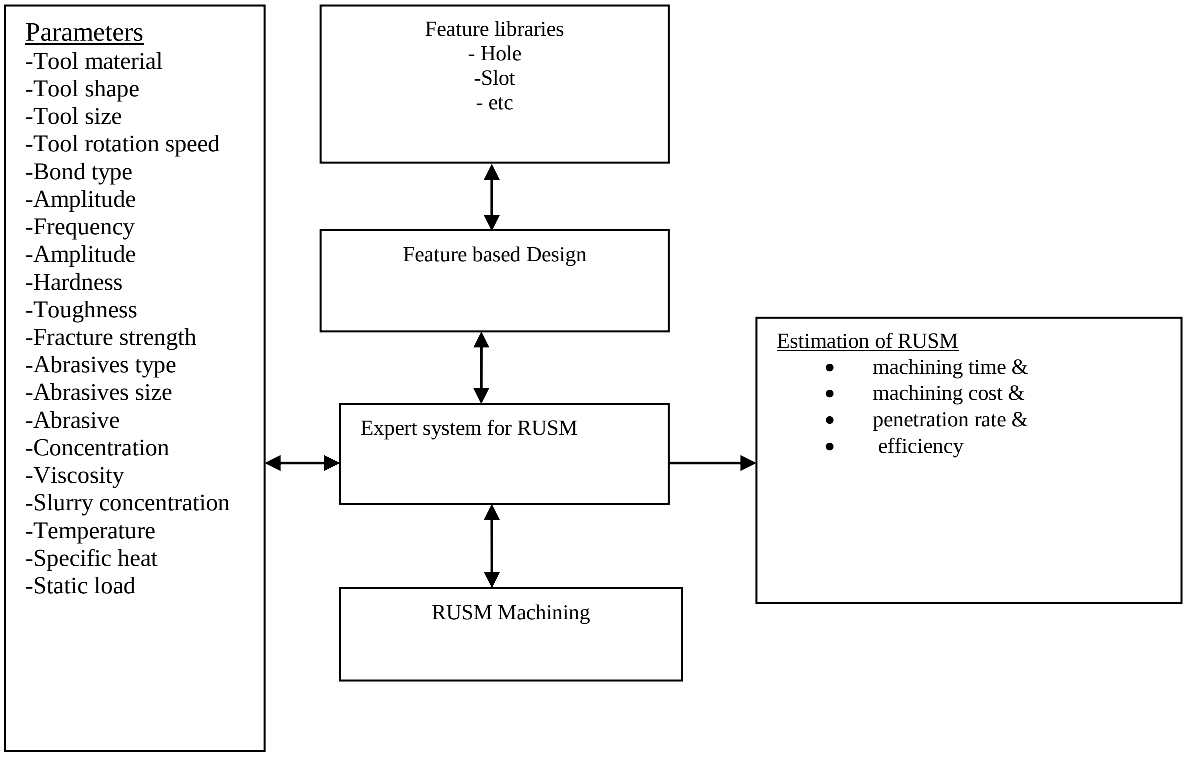

Fig. 2 Input, output of developed expert system environment

Knowledge based system (KBS) for rotary USM

A knowledge based system (KBS) for rotary ultrasonic machining (RUSM) has been developed based on object oriented techniques (OOT). A Hewlett Packard (HP) model 715/80 workstation was used as the hardware for development of the expert systems. A geometric specification of the features of the component was sent for manufacturability evaluation for the various stages of its design. Within the manufacturability procedure, the cost and cycle time and penetration rate of RUSM is estimated. In the design of a part, its features can be described in terms of its geometry, its particular, its volume and the amount of material has to be subsequently removed.

The attributes of different classes of work piece materials, and different type of tool material are stored in database. The expert system can retrieve information from databases and advise the designer on the appropriate choice of material, design feature description and machine type for his decision. The expert system also contains information for manufacturability evaluation, knowledge of design representation in three dimensions in terms of features, rules for good practice, machine and process capabilities and constraints of features that can be manufactured by a particular process. For the present expert system, knowledge has been gathered from experiments on RUSM at Universities and also from technical journals and handbooks. For each design feature undergoing evaluation for manufacturability by RUSM, the cost and time of the machine cycle, and penetration rate and efficiency is a major consideration.

Architecture of expert system for RUSM

The expert system contains RUSM expertise gathered from experiment and from general knowledge about the process that can be provided to designers and manufacturing engineers. A flow chart for the expert system is presented in Fig. 3. The system contains the following modules:

1. Feature library: Feature library contains different classes of design features such as holes, slots, pocket, etc., each of which can be produced by RUSM.

2. Work piece material: Material library contains seven different classes of material for work piece including glass, ceramics, hard metals with hardness of (40 to 60 R_c), composites (e.g. glass epoxy), tungsten carbide, graphite and stone that can be accepted by the system and are stored in the system.

3. Tool material: Tool material library contains diamond impregnated tools that has been used. Three different type of material for RUSM tool is stored in tool data base.

5. Rotary Ultrasonic machines parameters: Information related to the other machining parameters including wear ratio, MRR, frequency, amplitude vibration, power range,

and so on for each type of material for work piece are stored in process data base.

6. Machining cycle time module: The knowledge base provides estimates of cycle time and costs for each selected design feature, based on the selected work piece and tool materials, and process conditions.

7. Manufacturability: The three elementary quantities associated with a design feature are its size, machining time and cost that are used to obtain the penetration rate and efficiency of each design feature or machining operation. The created feature size is depended on tool diameter and path needed to produce the design feature. The size of these features is specific in terms of their volume which is equal to the amount of material removed from work piece.

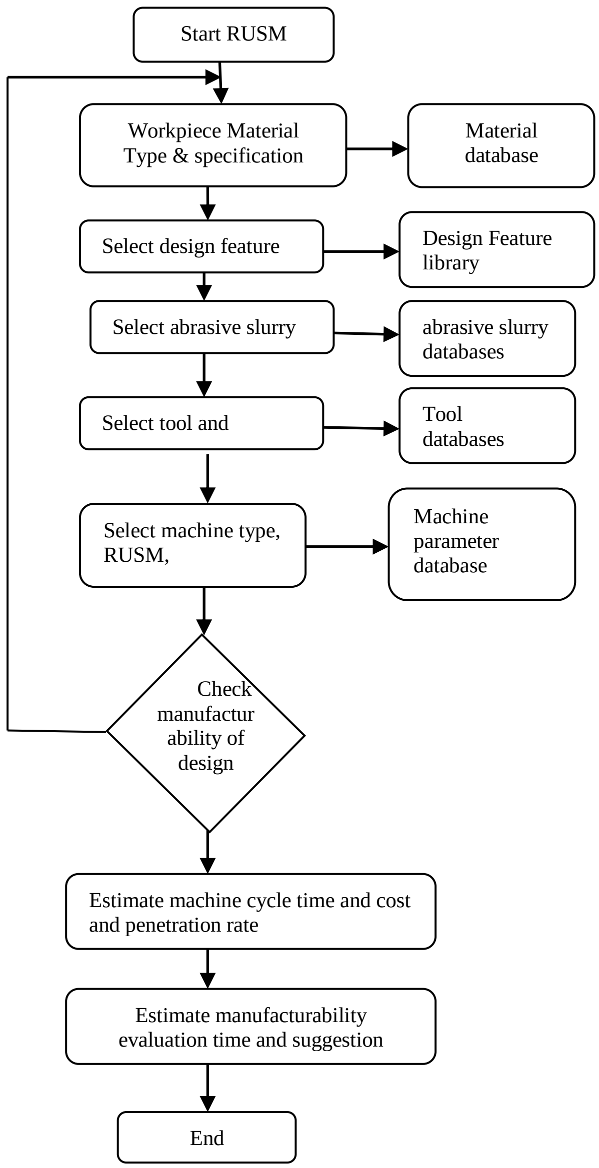

Fig. 3 Flowchart of the RUSM expert system

7 EXPERIMENTAL VERIFICATION

In RUSM spindle is fed toward the work piece at a constant pressure. Figure 3 shows the basic elements of a RUSM. 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 is known as rotary ultrasonic machining (RUM). In figure 4. CNC RUSM machine is demonstrated.

Fig. 4 CNC RUSM machine

RUSM 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. In Fig. 5 a rotary ultrasonic tool for drilling process is demonstrated.

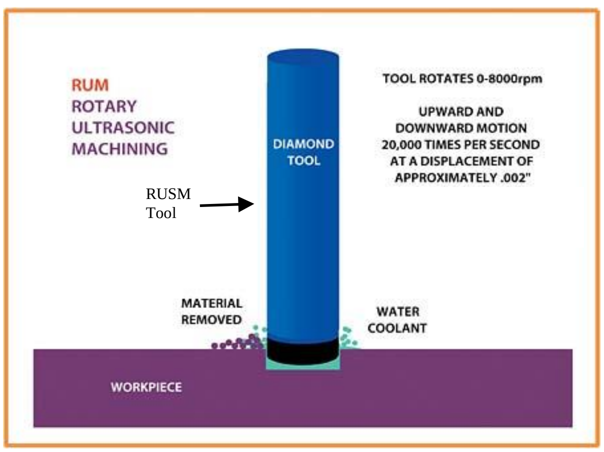

Fig. 5 Rotary ultrasonic tool for drilling process

In Fig. 6, a rotary ultrasonic machining process is shown.

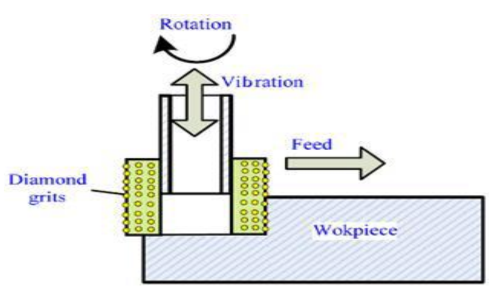

Fig. 6 Rotary ultrasonic machining process

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 RUSM 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 RUSM tool rotates and vibrates simultaneously, while the USM tool only vibrates.

These differences enable RUSM 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, following are some generic examples that indicate the type of work being performed. Experimental results of RUSM are compared with the results of expert system for the same design feature (circular hole making) and is 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 experimental and practical rotary ultrasonic machining, and estimating of machining time and cost, the feasibility to machine ceramic matrix composites (CMC) using RUSM 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] and [23].

A few CNC controlled path rotary ultrasonic systems are available commercially such as the SoneX300 from Extrude Hone Limited (France); and the Erosonic US400/US800 from Erosonic AG (Switzerland) [13]. RUSM 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. In RUSM, the hard abrasive particles are diamond and are bonded on the tools. Another major difference is that the RUSM tool rotates and vibrates simultaneously. RUSM provides 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. However, following are some generic examples that indicate the type of work being performed.

Table 1 Comparison of experimental rotary ultrasonic machining and expert system results for different depth of holes. Data for experimental RUSM: Frequency 20 kHz, Amplitude 40 μm, Static force 3, Tool: steel diamond coated. The tool diameter is 14.90 mm and depth of holes 1.3, 5.0, 6.8, and 10 mm

Procedure	Work piece	Hole depth (mm)	Hole Dia. (mm)	RUSM Mach. Time	RUSM Mach. Cost (us$)	Penetration Rate (mm/min)	RUSM Efficiency
Experimental RUSM	Graphite	1.3	15	0.8	0.32	1.62	0.91
		5.0	15	2.8	1.12	1.78	0.91
		6.8	15	3.75	1.5	1.8	0.91
		10.0	15	6.75	2.7	1.48	0.91
Expert System for RUSM	Graphite	1.3	15	0.73	0.29	1.73	1
		5.0	15	2.55	1.02	1.42	1
		6.8	15	3.4	1.36	1.62	1
		10.0	15	6.2	2.48	1.6	1

Table 2 Comparison of the results of experimental RUSM and results of expert system for different materials Data for experimental RUSM: Frequency 20 kHz, Amplitude 40 μm, Static force 3, Tool steel. Data for expert system: Frequency 20 kHz, Amplitude 38 μm, Tool: steel diamond coated. The tool diameter is 9.94 mm for RUSM and depth of holes is 10 mm for different materials

Procedure	Design feature Type	Tool mat. type & Dia. mm	Material type	Mach. Time (min)	Mach. cost ($US)	Penetration rate (mm/min)	Efficiency mm^3/min
Experimental RUSM	Circular hole dia. 10 mm depth 1 0mm	St. diam. Coated 9.84	Glass	1.22	0.46	8.2	0.91
			Composite	2.2	0.83	4.55	0.91
			Stone	0.26	0.097	39.13	0.91
			Ceramic	9.62	3.61	1.04	0.91
Expert System for RUSM	Circular hole dia. 10 mm depth 10 mm	St. diam. Coated 9.94	Glass	1.11	0.42	9.0	1
			Composite	2.0	0.75	5.0	1
			Stone	0.23	0.086	43.0	1
			Ceramic	8.75	3.28	1.14	1

8 VALIDITY OF THE RESULTS OF EXPERT SYSTEM

As a result, table 1 shows that estimation of expert system for machining time and cost for different depth of hole making with RUSM is about 9 percent less than experimental RUSM. Table 2 shows that estimation of expert system for machining time and cost for hole making by RUSM for different material is about 9 percent better than experimental RUSM, because in expert system, optimum parameters are selected. As a result, table 1 and table 2 show that estimation of machining time and cost for hole making for different material by expert system RUSM is about 9 percent less than and better than experimental results of RUSM. Also penetration rate and efficiency of experimental hole making is 9 percent less than expert system.

9 CONCLUSION

This paper addressed the concept and development of an expert system in computer based concurrent engineering environment for hard and brittle material, such as glass, quartz, diamond, carbides, semi conducting materials, ceramic and graphite which can be manufactured with rotary ultrasonic machine. Expert software based on object oriented technique was used to develop this expert system. The expert system was linked with a feature based CAD system in order to extract design data. The system is linked with tool, material workpiece and machine databases. The machining cycle time, cost, penetration rate, efficiency and effectiveness of each selected design feature were estimated. The system provides useful information such as machining cycle time and cost, penetration rate, efficiency for selected design feature for product designers at the conceptual stages of design process and also advises manufacturing engineers to select optimum machining parameters. Also in this research the following results were obtained:

1. USM and RUSM are non-thermal process, which do not rely on a conductive work piece and are preferable for machining work pieces with low ductility and hardness above 40 HRC.
2. Expert system is developed to estimate machining time and cost, and penetration rate and efficiency 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 RUSM hole making is 9 percent less than experimental USM; Because in the expert system, optimum parameters are selected.
4. Estimation of expert system for penetration rate and efficiency of RUSM for hole making is about 9 percent more 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. Better surface finish is attained in low temperature (10 °C) compared to room temperature (27 °C).
8. The design of tool and horn play an important role in providing a resonance state in RUSM and MRR.
9. 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 type of coated tool.

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