An Intelligent Concurrent Advisory and Manufacturability Evaluation System for Ultrasonic Machining

Morteza Sadegh Amalnik[a], Mohsen Sadegh Amalnik[b] *
a Department of Manufacturing Engineering, Tabriz University, Tabriz, Iran
b Department of Industrial Engineering, Tehran University,Tehran,Iran

Abstract

This paper addresses the concept and development of an Intelligent knowledge-based-system (IKBS) for advisory and manufacturability evaluation system in concurrent engineering environment for unconventional process such as Ultrasonic machining (USM) based on object oriented technique. A feature based approach for acquiring design specification is used. Description of different classes of design features such as circular holes, square holes, pockets, slots and so on are interactively acquired. Attributes of 6 different type of metal for workpiece, two different type of material for tools, three different type, size and concentration of abrasive and liquid for carrier fluid and parameters of USM process are stored in databases. The knowledge base is linked with databases. The machining cycle time, cost, penetration rate, efficiency and effectiveness, of each selected design feature are estimated. The system provides useful information such as machining cycle time and cost, penetration rate, efficiency and effectiveness of machining of the selected design feature for product designers at the conceptual stages of design process and also advises manufacturing engineers to select optimum machining parameters.

Keywords: Design feature; USM; CE; IKBS; Advisory system; Manufacturability Evaluation, Machining time & cost; Penetration rate

1. Introduction

The limitation of conventional and some of the unconventional machining such as electrochemical machining (ECM), electrodischarge 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 specially 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 attraction of USM is unlike ECM and EDM the material removal rate is affected by brittleness and hardness of materials. USM is used in wide range of industry including aerospace, electronic, optics, and automobile industries [6]. The rapid progress in this field can be seen from the number of published papers. It is reported that up to 1960s about 350 papers had been published. Ultrasonic machining (USM) is a mechanical unconventional machining process by which material is removed through direct hammering of the abrasive particles on the workpiece 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]. USM includes the flowing three activities, (i) direct hammering of the abrasive grains between tool and workpiece, (ii) microchipping by impact of the flow of the abrasive particles, (iii) Erosion of workpiece for some metals such as graphite by cavitation in the slurry stream. It has been reported that the fist two are the most essential factors for material removal, While the third process is applied only for some of the material such as graphite [5, 9, 10]. Influence of different parameters on material removal rate is reported by [10-14]. These parameters can be classified into the following categories: (i) frequency and amplitude of vibration and tool pressure, are the major importance in USM, (ii) type and grit size and slurry concentration and volume of the abrasive slurry, (iii) material type (iv) geometric shape and description of feature for tool and workpiece, (v) machining time, productivity and penetration rate.

The resonance transducer or vibrator converting the electrical power received from the oscillator into mechanical vibration. This is the main source of mechanical oscillation. The output of transducer is inadequate for USM operation. It should be amplified so that the output and the amplitude are sufficiently large for USM operation. To overcome this problem a device so called horn is used. The horn or tool holder is a waveguide or concentrators which is fitted from one side to the end of transducer and from the other side is stick to the tool head. Its cross sectional area is decreases from the transducer to the out put tool. The tool shape is complementary to the design feature and attached to the end of the horn. The abrasive slurry is fed between tool and workpiece. A special mechanism is used to maintain the static pressure between tool and workpiece. For effective USM operation, the machine tool must provide vibration of the tool at maximum amplitude at a given frequency [2].

The effects of process parameters such as static pressure, ultrasonic vibration amplitude and frequency, abrasive size etc. on the process performances such as material removal rate, tool wear, etc. have been also investigated experimentally by various researchers, the conclusions are summarized in [15]. Static pressure has a great effect on tool wear and material removal rate (MRR). As static pressure increases tool wear increase and MRR increase to the maximum level and then decreases. Vibration amplitude has also effect on MRR. As the vibration amplitude increases up to some point, MRR increase, but further increasing of the vibration amplitude above this point results in a reduction in MRR.

Other process parameters including parameters such as amplitude and frequency of tool vibration, abrasive slurry characteristics (type, size, concentration), magnitude of the applied force and material specification of the workpiece. Holes as small as 0.076 mm up to 89-mm diameter with maximum 64-mm depth can be produce with USM [10].

Surface finishes for the USM range from 0.2 to 1.5 ìm R_a with no chemical, thermal or electrical alterations of the surface. Accuracies of 0.013 mm are typical, tolerances of 0.005mm can be achieved for specialized applications, with good machining condition, machining depth of 64 mm can be obtained [16] the sonotrode tool is made by using electrodischarge machining (EDM). Grin size yields essential effect on surface roughness, where changing from 600 to 280 mesh increases the surface roughness more than twice (Ra from 1 to 2.5 ìm) [14]. In case of ceramic, it has been reported that any increase in the amount of work/energy imparted onto the ceramics in terms of the amplitude of the conic wave, the static weight applied and the size of the abrasive, will result in (i) increase in material removal rate, (ii) a roughening of machined surface [17].

The process can be controlled by varying the gap between tool and workpiece. During the machining the actual distance between tool and workpiece should be kept constant [18].

USM has many benefits as discussed before, but it has some drawbacks such as material removal rate reduce as the penetration depth increase, the slurry may wear the wall of the machined hole as it passes back toward the surface which limits the accuracy specially for small hole, the action of slurry causing considerable tool wear which in turn makes it very difficult to hold close tolerances. In order to overcome the USM problems, rotary ultrasonic machining (RUM) is introduced in 1964 by Percy Legge, a technical officer at United Kingdom Atomic Energy Authority (UKAEA) [15].

Ultrasonic polishing has been developed by the GrafEx Division of Extrude Hone Corporation for variety of polishing applications. In this type of process, t he extend of polishing determined by the initial surface roughness of the workpath finishing requirement after polishing. surface improvement range from 5:1 to 10:1; finishes as low as 4 ìinch (0.1ìm) R_a can be obtained [19].

Advanced ceramics are increasingly used in industry for their superior properties such as high strength, resistance to chemical degradation, wear resistance and low density, but the only problem is high cost of machining with current technology. For instance the cost of machining of a part with a high accuracy can be as high as 90 % of the total cost. Among the various processes, rotary ultrasonic machining has the potential for high material removal rate with low machining pressure resulting in less surface damage [20]. Ceramic materials have a wide range of application from insulation to very complex applications such as artificial teeth, bones, joints, internal combustion engines, thermal barrier coatings, tougher metal cutting tools etc. [21], USM techniques can be used to machine a wide variety of ceramic components, some of the USM applications are shown in [22].

RUS is a hybrid machining process that combines the material removal mechanisms of diamond grinding and USM. Experimental results have shown that the machining rate of RUM is nearly 6-10 times higher than from a conventional grinding process under similar conditions, and 10 times faster than USM [15]. Other worker reported the machining time of RUM is half to one third of USM [23]. In RSM slurry is replaced with abrasives bounded to the tool. The efficiency of RUS (ultrasonic diamond) milling and drilling of deep holes depends on the mechanical properties of the workpiece material, the design of the diamond tool and the machining conditions. With increasing specific load, removal rate increases significantly [24]. RUM including a rotary tool metal bonded diamond abrasives vibrates while the workpiece is fed towards the tool at a constant pressure. The coolant pumped through the internal hole of the drilling tool, washes away the swarf, reduce the tool temperature and prevents jamming [20], [25]. Experimental investigations have been conducted on the productivity and surface quality and tolerances in ultrasonic machining of ceramics [26].

The tool is shaped based on design feature specification. A constant flow of slurry which is automatically cooled and recirculated between tool and workpiece to carry away the chips from the workpiece. As a result of that material is removed and workpiece crushing. This is shown in Fig.1. The components of USM is also shown which including elements such as Oscillator; the resonance transducer; the horn, tool holder; tool; clamping system; abrasive slurry; and static pressure system.

Recent advances in rotary ultrasonic machining (RUM) has the potential for high material removal rates while maintaining low cutting pressures. As a result of that little surface damage and little strength reduction (Pei et al, 1995). In RUM process, a rotating core drill with metal bounded diamond abrasives is vibrated by a transducer while the workpiece is fed towards the tool at a constant pressure. The tool is ultrasonically vibrated by the means of transducer.

Ultrasonic machining has been around for more than forty years and many investigators have reported their studies on it. However, these studies have been primarily experimental with little or no attempt to develop an intelligent system. The influences of the ultrasonic vibration amplitude, the applied static pressure, the rotating speed, the diamond type, grit size and bond type and so on the material removal rate (MRR) has been investigated experimentally.

To the authors' best knowledge, no intelligent system have been published for different type of material and to estimates machining time and cost for each USM operation and estimation of penetration rate.

Today there has been better understanding of the USM process as well as deeper and wider spectrum of knowledge is available in the literature. In order to simplify and standardize the application of USM, certain procedures and advises have been recommended. Many factors should be considered when handling a simple operation.

At present, most procedures are based on personal knowledge and judgement. The complexity of the process, and the interrelationship between its process variables mean that designer or even general process planners have limited knowledge of USM. In planning they have to turn to the literature or experts. The information required by the former is often difficult to obtain. Moreover, the training of both process planners and manufacturing operators in USM technology is time-consuming and expensive. Consequently if the knowledge is not available from a reliable source, the USM product development cycle time and cost increases, and both quality and productivity is likely to decrease. Expert system and intelligent knowledge-based system (IKBS) provide a route to overcoming these hurdles to the further advancement of USM, although little has been achieved in these approaches.

IKBS becomes attractive for USM because it could provide a ready, on-line knowledge consultancy system guiding product designers and manufacturing engineers to select appropriate product parameters and process conditions. The more effective design and manufacture of an

USM product by IKBS also needs implementation of a concurrent engineering (CE) approach. At present however, no computer-based systems have yet been reported that apply CE concepts to USM. In the present paper, the implementation of IKBS and CE to design and manufacture for USM is investigated.

2. Concurrent Engineering (CE)

In CE the full range of policies, techniques, practices are used for integration of manufacturing functions and increasing productivity and quality of components, that are developed in shorter times and at lower cost. In design of a product, early consideration of its function and manufacturability need to be made. Two approaches-team and computer-based are used. The former involves a team of from design, manufacturing, marketing and so on, chosen for their knowledge and abilities to contribute to product development. Although this approach has been widely implemented and significant benefits realised [27-33] management of the CE team has been reported to be occasionally ineffective and costly. In consequence, an alternative automated internal logic operation is now being explored. It offers design justification, manufacturability evaluation and optimisation to be assessed for the entire product life-cycle. A computer-based CE approach to USM is the subject of this paper.

3. Computer-based concurrent Engineering for USM

3.1 An IKBS for USM has been developed in a computer based CE environment, the latest version (3) of an expert system shell (NEXPERT), based on object oriented techniques (OOT) is the software used to develop the knowledge-base. 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 sent for manufacturability evaluation for the various stages of its design. Within the manufacturability procedure, the cost and cycle time and penetration rate of USM 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 six different classes of workpiece materials, three type of abrasive and two type of tool material are stored in database. The IKBS 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 IKBS 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 IKBS knowledge has been gathered from experiments on USM at Edinbrough Universities and also from technical handbooks.

For each design feature undergoing evaluation fomanufacturability by USM, the cost and time of the machine cycle, and penetration rate and productivity is a major consideration.

4. Architecture of ECM intelligent advisory system

The intelligent system contains USM expertise gathered from experiment and from general knowledge about the process that can be provided to designers and manufacturing engineers

4.1 Feature library

Feature library, containing different classes of design features such as holes, slots and pocket, each of which can be produced by USM.

4.2 Workpiece material

Material library contains seven different classes of material for workpiece 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 are stored in the system.

4.3 Abrasive solution

Properties of three main USM abrasive including boron carbide (B_4C), silicon carbide (SiC) and aluminium oxide (Al_2O_3) are stored, so that the expert system can deliver information on process conditions such as abrasive type, size, concentration and carrier fluid.

4.4 Tool material

Tool material library contains two different classes of material for USM tool including stainless steel and mild steel.

4.5 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 workpiece are stored in process data base.

4.6 Machining cycle time module

The knowledge base provides estimates of cycle time and costs for each selected design feature, based on the selected workpiece and tool materials, abrasive and process conditions.

4.7 Manufacturability

The three elementary quantities associated with a design feature is its size, machining time and cost are used to obtain the penetration rate and productivity of each design feature or machining operation. The created feature size is depending on tool cross sectional area 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 workpiece. The penetration rate shows how fast a feature can be machined and expressed in unit of depth of operation per unit time. Productivity expresses the volume of material removal per unit of time. In this intelligent system, manufacturability is assessed by estimates of the design features, machining time and cost, the penetration rate, and productivity.

5. Parameters influencing in USM

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 it reaches a maximum. Penetration does not increase after the maximum penetration is achieved, because a jamming effect at the interface of tool and workpiece. [12]. 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 the most widely used in USM. The frequency is used in most USM operations are 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 are possible. In this type of process parameters such as depth of cut, static load, area of cut are also very important. Typical accuracy of +/-0.025 mm and surface roughness of 0.51 to 0.76 ìm can be achieved [10]. The size of abrasive grid affects on surface roughness. Smaller size makes finer finishes but reduce the material removal rate. The surface created by USM typically shows a shallow depth of compressive residual stress. Holes as small as 0.078 mm diameter and as large as 90 mm diameter with depth of up to 64 mm can be produced. The main parts of an USM are shown in Fig.2. 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 receive from the electronic oscillator to mechanical vibrations, but the amplitude of this vibration is not adequate for machining design feature. In order to overcome this difficulties; (iii) horn or waveguide is used to concentrate the wave and amplifies the amplitude of vibration so that the amplitude out put of the waveguide is adequate for machining materials; (iv) the tool is attached to the waveguide by tool holder or clamping system; (v) fluid system for circulating the abrasive slurry through the abrasive tank and pump.

6. Object oriented technique (OOT)

Object oriented technique is used in development of the IKBS. OOT is a new way of thinking for software development and programming applications. The first step in developing an IKBS is to develop a high-level, abstract view of the system to identify the relationships that exist between various elements of the system. As it clear, ultrasonic machining problems are usually complex. In order to represent complex problems, it is essential to represent the problems and data in more effective and efficient way. OOT is a methodology that use objects as the basic structure of the program and a complex problem can be expressed interns of its objects and their relations rather than addressing the system as one large problem. It represents a hierarchical representation of the problem and the problem solving. It speeds up the development of the IKBS because of its inherent capability, reusability of objects and its data encapsulation. OOT consists of three important elements such as Object encapsulation, and inheritance. Any entity can be defined as an object. Objects communicate with each other only by exchange of messages. The term encapsulation means that data can be accessed only through pre-defined procedures. Any object can encapsulate a set of value for the attributes of an object which is called state and behaviour of the object which are called from outside only through explicit set of attributes form a class. Inheritance is a powerful concept based on ability to define subclasses survived from parent classes. A new subclass can inherit all the attributes of its super class. A class is a collection of objects that usually share properties. An object is an elementary unit of description which has some properties. The new sub-class can accept additional attributes. This results in less coding if the inherited methods and attributes are valid for the subclass. The main class is ultrasonic machining. It includes five different sub-classes including material type for workpiece, Abrasive grids, material type for tool-electrode, features and USM machine sizes. The sub-class of material type for workpiece contains 6 different classes of materials. Abrasive contains three classes including *. In class of features there are different sub-classes of features. Each sub-class of feature can contain many different sizes of similar features. For example a sub-class of circular hole can contain hundreds different size of circular holes. And in the sub-class of USM size, there are seven different size of ECM machines. Each class or sub-classes or object can have many different properties. For example a sub-class of material type for workpiece can have properties such as hardness, stress free, atomic weight, valency, removal rate. Each property has a value. It can be a string, float, integer etc.

7. Experimental verification

Results are presented in Table 1. The results of intelligent system described above were compared with the experimental result of ultrasonic hole drilling. The tool diameter is 15 mm and the depth of holes are 1.3, 5.0, 6.8, and 10 mm.

In practical , estimates of machining time and cost, penetration rate and productivity is time-demanding on experienced personnel. In contrast the knowledge-based system can provide these estimates usually in less than one minute. For example, the intelligent result of a circular holes making with different material type for workpiece, abrasive and tool for the same design feature specification is presented in Table 2.

Designers of manufacturing engineers select workpiece material and design feature from the workpiece and feature library. Then workpiece specification and design description for each selected design feature are obtained interactively by the IKBS.

Table (1) Comparison of experimental USM and Intelligent System

	Hole depth	Workpiece	Procedure	Machining time	Penetration rate

1.3	Graphite	Experimental	1.1	1.18
5.0			3.7	1.35
6.8			5	1.36
10.0			9	1.11
1.3	Graphite	Intelligent	1.04	1.24
5.0			4.42	1.13
6.8			5.4	1.30
10.0			8.84	1.13

Data for experimental: Frequency 20 kHz, Amplitude 40 ìm, Static force 3, Abrasive B_C, Tool steel. Data for intelligent system: Frequency 20 kHz, Amplitude 38 ìm, tool mild steel.

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.

Intelligent results of different design features with different material type for workpiece and different tool and abrasive are presented in Table 3. All necessary parameters including machining time and cost, penetration rate and efficiency is estimated by the IKBS. Other parameters such as wear ratio, spindle force, abrasive size, concentration, carrier fluid, frequency, power are also recommended by the IKBS.

8. Conclusion

An Intelligent advisory and manufacturability evaluation for Ultrasonic machining in concurrent engineering environment based on object oriented technique has been developed. A feature based approach is used to obtain design feature description. A feature library is designed which contains different classes of design features. Attributes of six different type of material for workpiece, three most important type of abrasive, two different type of material for tool, and description of different process parameters. For each type of material for workpiece are stored in process database. The intelligent system is linked with these databases and able to advice designers and manufacturing engineers. Design specification is interactively acquired by the system. Then it gives some advice for optimal selection of process parameters for each design feature. Then the system automatically estimates machining (cutting) time, and cost, penetration rate, and productivity for each individual feature and operation. The current intelligent system can be used to assist product designers to estimate machining cycle time and cost and all other machining parameters mentioned above at the early stages of design process and give some advises for improvement of design specification. It also assists manufacturing engineers to select the optimal process parameters. In the developed system, both heuristic and algorithmic procedures have been implemented. An experimental verification has been conducted on USM.The developed system allows for additional more detailed function modules or databases without altering the rest of the knowledge base. The system is user-friendly and can be used either by designer or USM experienced or those who need many guidance.

Table 2 Intelligent result of different design feature specification with different materials hole

Design feature type	Abrasive	Tool material type	Workpiece Material type	Penetration rate (mm/min)	Productivity mm^3/min	Machining time (min)	Machining cost (£ UK)
Circular hole With diameter 10 depth 10 mm	Boron carbide (B_C)	Mild steel	Glass	6.25	491	1.6	0.27
			Composite	3.34	262	3	0.51
			Tungsten Carbide	0.06	4.9	160.3	27.25
			Epoxy	3.34	262	3	0.51
		Stainless	Ceramic	0.83	65.5	12	20.4
	Aluminium Oxide(Al_2O_3)	Steel	Stone	31.3	2458	0.32	0.055
	Silicon carbide (SiC)	Steel	Carbon steel				
			Hard metal (R_c 40-60)	0.42	32.7	24.0	4.08

Data: penetration rate shows how fast a feature can be machined and expressed in units of depth of operation per unit time. productivity shows the volume of material removal per unit of time.

Table 2 shows that for the same design feature specification, productivity and penetration rate of stone material is greater than others
stone material > glass > composite (such as epoxy) > ceramic > hard metal (R_c 40-60) > tungsten carbide
The machining time and cost of tungsten carbide > hard metal >ceramic > composite >glass > stone

Table 3 Intelligent result of different design feature specification with different material type for workpiece , tool and abrasive

Design Feature Type	Workpiece material type	Abrasive type	Tool Type	Feature descriptions (mm)	Penetration rate (mm/min)	Producti vity	USM machining time (min)	USM cost (UK£1)
Elliptical hole	Carbon steel	Silicon carbide	Stainless steel	small dia10 large dia 20	0.21	32.7	48.0	8.17
Circular Hole	Ceramics	Boron carbide	Stainless steel	dia 10	0.83	65.5	12.0	2.04
Hexagonal hole	Composite (Epoxy)	Boron carbide	Mild steel	edge 10 pdbce 8	1.09	262.0	9.16	1.56
Slot	Stone	Aluminium oxide	Steel	width 5, length 44	11.17	2458.0	0.9	0.15
Pocket	Glass	Boron carbide	Mild steel	width 10 length 15	3.27	491.0	3.05	0.52
Polygonal	Graphite	Boron	Mild steel	edge 5	3.67	220.0	2.73	0.46

Hole 12 ed.	carbide	pdbce 4

Data: depth of features is 10 mm, "pdbce" stands for perpendicular distance between centre point of the feature and each edge. "dia" is stands for diameter and "ed" for edge.

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