*Thesis On*

# MODELING, ANALYSIS, CODING, EVALUATION AND SELECTION OF ULTRASONIC MACHINING SYSTEM

*Submitted in partial fulfilment of the requirement for the award of degree of*

**Master of Engineering**

**IN**

**PRODUCTION AND INDUSTRIAL ENGINEERING**

*Submitted by:*


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## DECLARATION

I hereby declare that the thesis entitled "**Modeling, Analysis, Coding, Evaluation and Selection of Ultrasonic machining USM System**", submitted in partial fulfillment of the requirements for the award of degree of Master of Engineering in Production Engineering submitted in Mechanical Engineering Department of Thapar University ,Patiala, during July 2012 to July 2013 is an authentic record of my own work carried out under supervision of Dr. V.P. Agrawal and refers other researcher's works which are duly listed in reference section. The matter presented in this seminar report has not been submitted for the award of any other degree of this or any other university.

Jagwinderjit Singh

**Dated:** 8/7/2013

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**Place: Patiala**

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This is certifying that the above statement made by the candidate is correct and true to the best of my knowledge and belief.

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# Abstract

Ultrasonic machining is one of the most widely used non-traditional machining processes for the machining of non-conductive, brittle materials including glass, ceramics, carbides, and graphite. Ultrasonic machining is an abrasive process, and material removal is purely mechanical. The process does not cause heat affected zone and any chemical or electrical alterations on work piece surface. It does not change the metallurgical, chemical or physical properties of the work pieces. Ultrasonic machine four different mechanisms are responsible for removal of material from the work surface. Material removed by direct hammering of abrasive particles on the work piece, Micro chipping by impact of free moving particles, Cavitations effect from the abrasive slurry, Chemical action associated with the fluid used. This study presents a new methodology for evaluation, ranking and selection of parameters of Ultrasonic machine by using (multiple attribute decision making) MADM approach. A 3-stage selection procedure is used for identification of pertinent attributes and ranking is done with TOPSIS and graphical methods (Line graph and Spider Diagram). The proposed 3-stage selection procedure is explained with the help of an illustrative example. This methodology convert database into knowledge base by considering normalization, relative weights, positive benchmarked and negative benchmarked solutions. This study provides a general formula which can be applied to any USM system. An integrated systems model for the structure of the ultrasonic machining system in terms of its constituents and interactions between the processes using graph theory and matrix algebra. Ultrasonic machining system is first explained with the graph theoretic approach using different interactions between sub systems. The matrix models and variable permanent function models provides an opportunity for carrying out characterization analysis and optimization. The terms of permanent multinomial characterize the ultrasonic machining system uniquely and for analysis of the structural information of the ultrasonic machining system.

## Keywords

Ultrasonic machining system

MADM- TOPSIS Approach

Graph Theory

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# Abbreviations

| | |
|---|---|
| **USM** | Ultrasonic Machine |
| **MRR** | Material Removal Rate |
| **TWR** | Tool Wear Rate |
| **SR** | Surface Roughness |
| **MADM** | Multi Attribute Decision Making |
| **TOPSIS** | Technique for order preference by Similarity to ideal solution |

# CHAPTER-1
# INTRODUCTION

## 1.1 GENERAL

Modern materials such as high strength metals and ceramics which are developed to meet the needs of advanced industries such as aeronautics, nuclear reactors and automobiles are typically strong, hard and brittle [Astashev and Babitsky 1998]. Production of complex shapes in such materials is still more difficult using conventional chip-removal methods and hard tools [Amin et al.1995]. Such materials can be cut economically by non-conventional processes based on direct utilization of various forms of energy such as ultrasonic machining USM, electro discharge machining EDM, etc [Amin et al.1995]. Ultrasonic machining is one of the most widely used non-traditional machining processes for the machining of non-conductive, brittle materials including glass, ceramics, carbides, and graphite [Zeng et al.2005]. Ultrasonic machining is a process developed during the fifties for 2 and 3 dimensions machining of ceramics and other hard and brittle materials [Dam et al.1995]. USM has developed into a process that is relied upon to solve some of the manufacturing community’s toughest problems [Singh and Khamba 2006].

## 1.2 ULTRA-SONICS

The term ultrasonic is used to describe vibration waves having waves a frequency above the hearing range of normal ear, beyond 15 KHz. The range of wavelengths in varying media is very wide e.g. when propagated in a solid medium a wave with the frequency of 25Kc/s will have a Wavelength of about 200mm, while one with a frequency of 500Mc/s will have a wave length of the order of 0.08mm. The acoustic range of vibration is the one which the human ear perceives i.e. in the frequency range of 30 to 1500 Hz, the ultrasonic range of vibrations lies above this i.e. frequencies beyond 15000 Hz. There is no physical difference between the upper acoustic range 5000 to 15000 Hz and the ultrasonic range 15000 to 3000 Hz. Both the range of frequencies of certain intensities of sound will be heard as loud noise by the human ear and can permanently damage the auditory system. Ultrasonic frequencies provide satisfactory working condition and hence they are alone used for material removal purposes. There are two types of waves, namely shear waves and longitudinal waves. Longitudinal waves are mostly used in ultrasonic application since they are easily generated.

They can be propagated in solids, liquids and gases and can travel at a high velocity so that their wavelength in short in most media. The velocity of the wave can be calculated for a given material using the following expression.

$$\text{Sonic velocity} = E/J\ [m\ (m-1)/\ (m-m-2)]$$

Where E = Young's modulus

1/m = Poisson's ratio

ρ = Density of the material

### 1.2.1 Ultrasonic used in various applications:

- Ultrasonic machining.
- Ultrasonic forming of plastics.
- Measurement of velocity of moving fluids.
- Measurement of density, viscosity and elastic constant.
- Ultrasonic casting, welding, brazing and soldering of metals.
- Non destructive residual stress determination.
- Measurement of hardness and grain size determination of metals.
- Flaw detection, leak detection etc.

## 1.3 HISTORY OF USM (ULTRASONIC MACHINING):

The history of ultrasonic machining (USM) began with a paper by R.W. Wood and A.L Loomis in 1927 and the first patent was granted to American engineer Lewis Balamuth in 1945 [Singh and Khamba 2006]. Wood and Loomis first noted the application of high frequency about (70 KHz) sound waves for machining [Hocheng and Kuo 2002]. The first report on the equipment and technology appeared during 1951-52 by 1954. The machine tools using the ultrasonic principle had been designed and constructed. Originally USM used to be a finishing operation for the component processed by the electro spark machines. However, this use becomes less important because of the development in electric discharge machining. But, then with the boom in solid state electronics the machining of electrically nonconducting, semi conductive and brittle materials became more and more important and for this ultrasonic machining again gained importance and prominence. The improvement of machining quality can be vitally promoted through the conversion of the machining process into one involving controllable high frequency impacts at the cutting zone [Astashev and Babitsky 1998].

## 1.4 ULTRASONIC MACHINING (USM):

Ultrasonic machining offers a solution to the expanding need for machining brittle materials such as semiconductors, optical glasses and ceramics and for increasingly complex operations to provide intricate shapes and work piece profiles [Wiercigroch et al.1999]. Brittle material is used for many applications due to their high hardness and strength at elevated temperatures [Astashev and Babitsky 1998]. The machining of these types of properties is difficult into a precise size and shape [Kim and Choi 1997]. The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator [Singh and Khamba 2006]. Ultrasonic machining is an abrasive process, and material removal is purely mechanical [Dam et al. 1995]. The process does not cause heat affected zone and any chemical or electrical alterations on work piece surface [Pei et al.1995]. It does not change the metallurgical, chemical or physical properties of the work pieces [Choi et al.2007]. Ultrasonic machining is also used in the combination with other non traditional machining techniques, such as electro discharge machining for the manufacturing of complex and precision components. In this process equipment consists of a vibrational horn, a tool part, an abrasive paste, and the working material [Curodeau et al. 2008]. In Ultrasonic machine four different mechanisms are responsible for removal of material from the work surface. Material removed by direct hammering of abrasive particles on the work piece, Micro chipping by impact of free moving particles, Cavitations effect from the abrasive slurry, Chemical action associated with the fluid used [Prabhakaran et al 2006]. The mechanical properties of the work material influence USM process showed that tough material give a low removal rate, high tool wear and reasonable surface roughness [Hocheng and Kuo 2002].

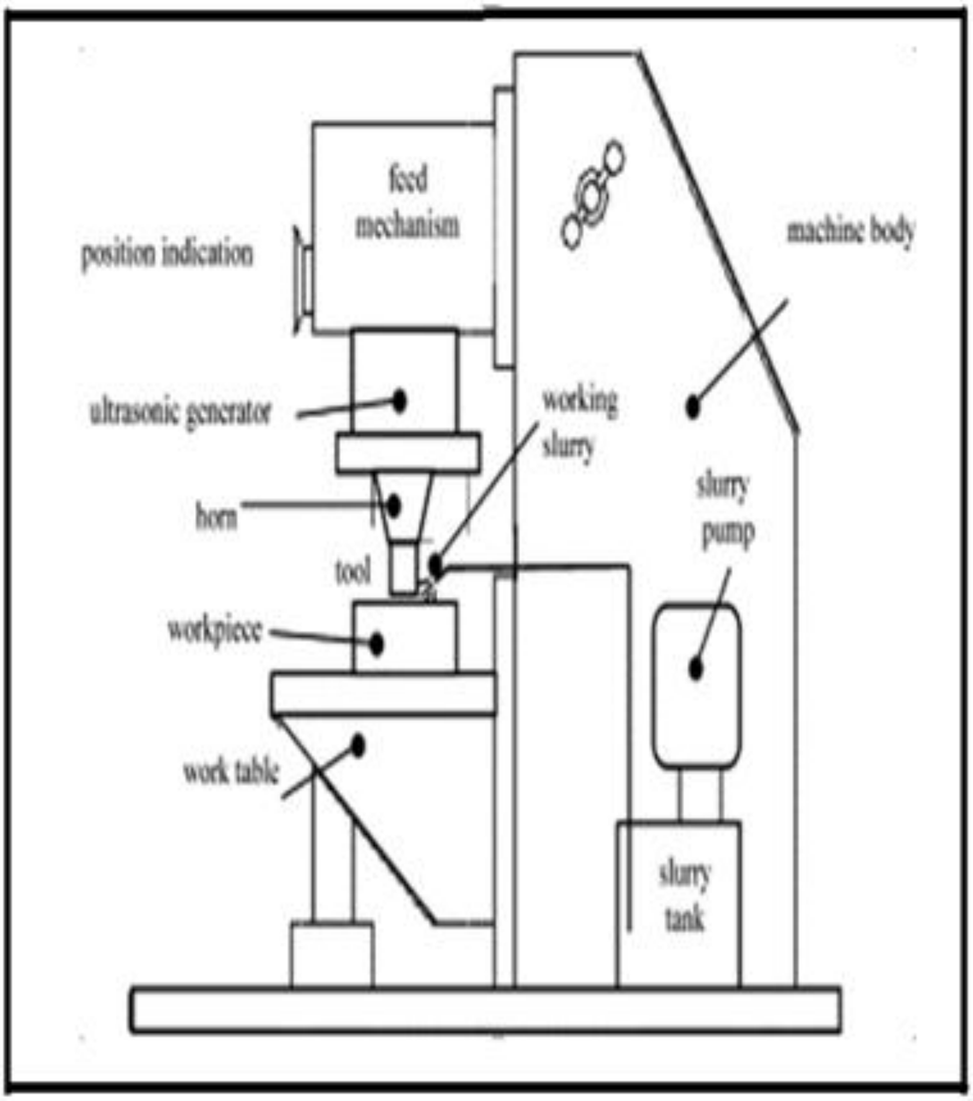



Fig.1-Schematic diagram of Ultrasonic machining [Jianxina et al 2002]

The chemical composition of the work piece, the size of the abrasive particles and the static load affect the characteristics of ultrasonic machining [Choi et al.2007]. USM creates desired accurate cavities of any shape through the impact grinding of fine grains [Sun et al.1996]. Ultrasonic machining called by various termed ultrasonic drilling, ultrasonic abrasive machining and ultrasonic cutting [Singh and Khamba 2006]. One modification of USM to overcome some disadvantages its name is rotary ultrasonic machining. The power required for RUM process is less than that used for USM [Singh and Khamba 2008]. Rotary ultrasonic machining (RUM) is 10 times faster than USM [Pei et al 1995]. It reduces the inaccuracies like oversize and out of roundness. Ultrasonic turning is the most common process is claimed to reduce machining time, work residual stresses and improve surface quality and tool life compared to conventional turning. Now day’s ultrasonic vibrations are used successfully to enhance machining capability of micro EDM to handle titanium alloys [Singh and Khamba 2008].

## 1.5 WORKING OF USM:

Ultrasonic machining (USM) is considered as an effective method for the machining hard and brittle materials such as glass, engineering ceramics, semiconductors, diamonds, metal composites [Ya et al.2002]. The ultrasonic machining process starts with the conversion of low frequency electrical energy (60Hz) to high frequency electrical energy (20 KHz), these high frequency electrical energy converts into mechanical vibrations with the help of transducers [Prabhakaran et al 2006]. In ultrasonic machining process the electromechanical transducer generates ultrasonic vibrations due to magnetostriction or piezoelectric effects [Babitsky et al.2004]. The oscillation amplitude obtained is very small and does not exceed 5 micrometer in most cases but this oscillation must be amplified using a acoustic horn in order to be able to provide high cutting rates [Amin et al.1995]. The cutting tool is pressed generally in downward direction with a feed force (F) and it vibrates at an ultrasonic frequency 20 kHz with amplitude of 20 μm over the work piece [Amin et al 1995]. 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 [Prabhakaran et al 2006]. 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 [Singh and Khamba2006]. An abrasive slurry comprising water and small abrasive particles is supplied between the tool and work piece, material removal occurs when the abrasive particles suspended in the slurry between the tool and work piece are stuck by the down stroke of the vibrating tool [Pei et al.1995]. If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in higher work piece MRR [Sun et al 1996]. The power ratings range from 50 to 3000 W and it reach 4kw in some machines. It rotated by a servomotor simultaneously. It is used to machine holes as small as 76µm diameter and depth to diameter ratio is limited to about 3:1 [Zeng et al.2005]. In this process no heat affected zone and any chemical or electrical alteration on work piece is occur [Pei et al 1995]. The abrasive particles are turn strike on the work piece at 150,000 times their own weight. The abrasive slurry is the mixture of the abrasive materials like silicon carbide (SiC), boron carbide ($B_4C$), corundum ($Al_2O_3$) with water or oil [Singh and Khamba 2008].

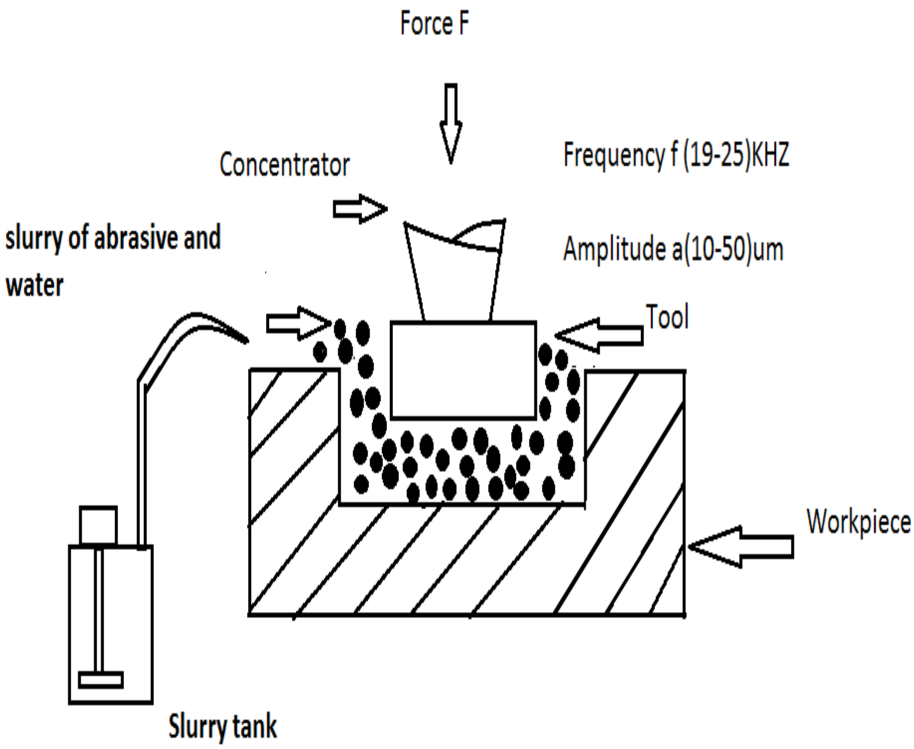



Fig. 2-Schematic diagram of Ultrasonic machining basis process [Pei et al 1995]

All the abrasives are considered to be identical in shape and size, it is considered to be spherical. The slurry is used for machining is stored in slurry tank and it is flooded by slurry pump between work piece and cutting tool. When tool vibrates over the work piece, the abrasive particles indent both the work material and the tool. The indentation by the abrasive grits does not lead to brittle failure on tool because the tools are made of tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys. A static load is applied on the tool [Singh and Khamba 2008]. Power supply used in the process depends on the size of the transducers. Magnetostrictive transducers have electromechanical conversion efficiency range between (20 to 35 %) [Nik et al 2012]. In ultrasonic machining two types of transducer are used magnetostrictive or piezoelectric are based on two different operations, piezoelectric transducers eliminates the use of water cooling due to high electromechanical conversion efficiency (up to 96% ) and available with power capacity up to 900W. Power supply used in the process depends on the size of the transducers [Zeng et al.2005].

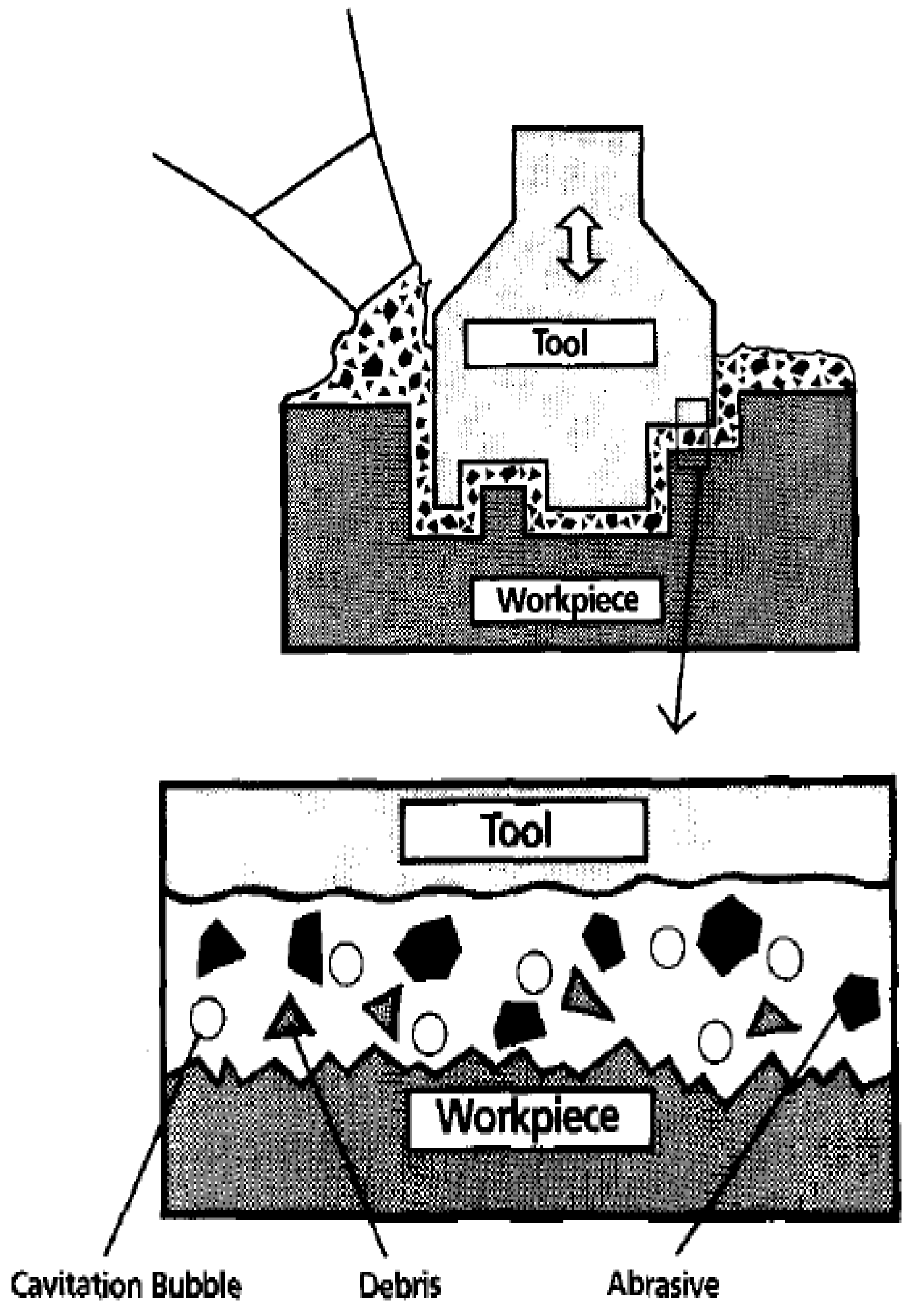



Fig: 3-Schematic diagram of the ultrasonic machining abrasive process [Dam et al.1995]

## 1.6 ROTARY ULTRASONIC MACHINING:

One modification of USM to overcome some disadvantages its name is rotary ultrasonic machining (RUM) [Pei et al.1995]. Rotary ultrasonic machine (RUM) was invented in1964

[Zeng et al.2005]. Rotary ultrasonic machining (RUM) is considered one of the cost-effective machining methods for advanced ceramics. This is a hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining (USM) [Hu et al 2012]. Hybrid manufacturing methods and technologies are distinguished by a combination of a number of, but at least two different sources of energy used for the manufacture of a work piece [Neugebauer and Stoll 2004]. The actual cutting is performed either by abrasive particles suspended in a fluid, or by a rotating diamond- plate tool [Wiercigroch et al.1999]. Rotary ultrasonic machining is used to drill deep holes and it improved hole accuracy.

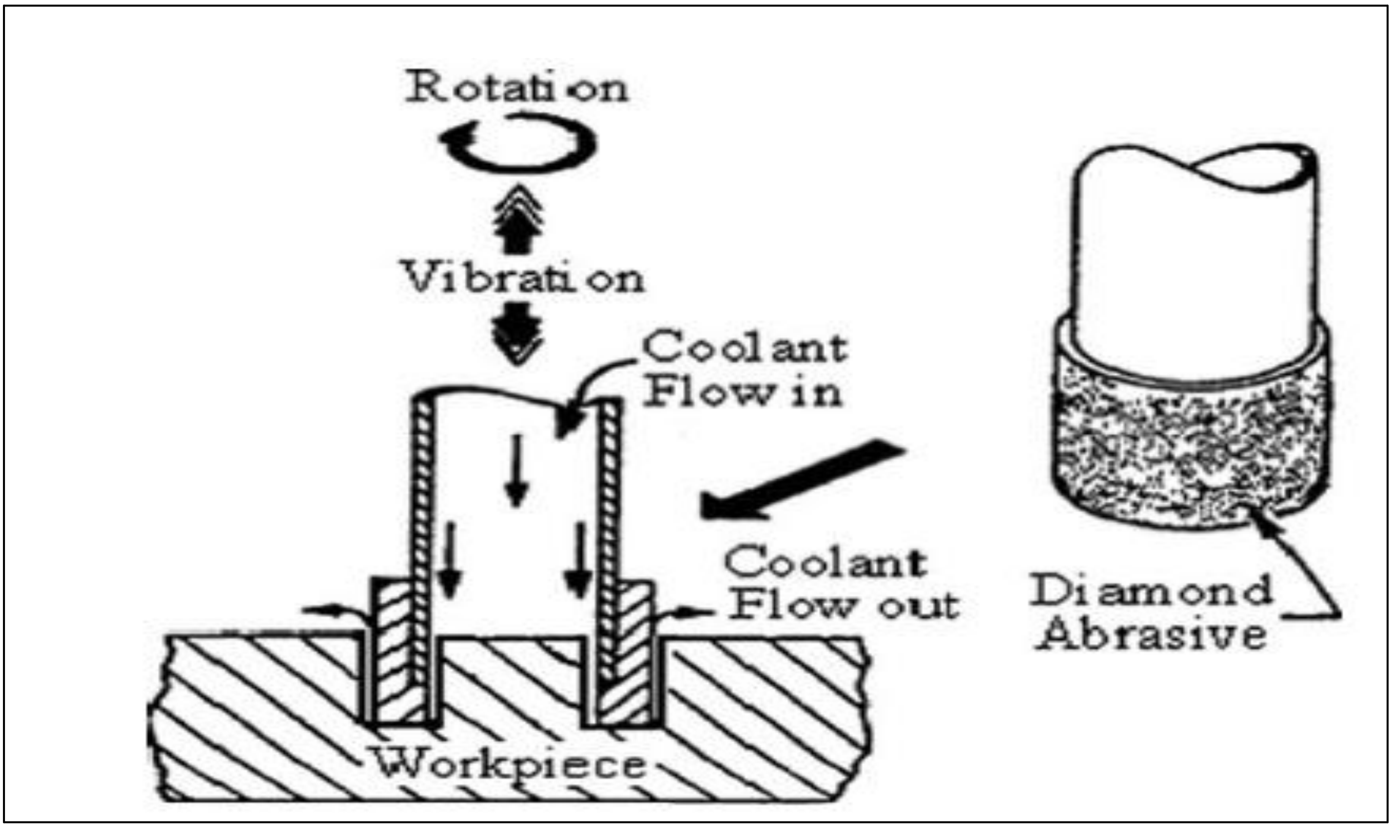



Fig.4-Schematic diagram of rotary Ultrasonic machining [Zeng et al. 2005]

The rotary core drill with abrasive particles can oscillate at high frequency 20 KHz while being fed towards the work piece [Liu et al.2012]. RUM is 10 times faster than USM [Kim et al 1997]. Rotary ultrasonic machining superimposes rotational movement on the tool head that vibrates simultaneously at ultrasonic frequency 20 KHz [Ya et al.2002]. The tool is made of mild steel coated or bonded with diamond abrasive. Therefore abrasive slurry is abandoned and coolant is used to carry the debris out of the working area [Singh and Khamba 2008]. In RUM, a rotary core drill with metal-bonded diamond abrasives is ultrasonically vibrated and fed toward the work piece at a constant feed rate or a constant force [Zeng et al.2005]. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill, and keeps it cool [Pei et al.1995]. When a core drill feeds into the work-piece during RUM, an abrasive particle on the end face of the core drill is not in continuous contact with the work-piece due to ultrasonic vibration of the drill [Liu et al 2012]. Compared with USM, rotary USM can provide a much higher material removal rate, deep holes and fine precision [Ya et al.2002]. The power required for RUM process is less than that used for USM [Choi et al 2005]. It reduces the inaccuracies like oversize and out of roundness. Rotary ultrasonic machining gives a higher material removal rate MRR than diamond grinding and ultrasonic machine USM [Hu et al 2012]. It is a complex process with a large number of input variables like Core drill variables, Properties of the work-piece material, Ultrasonic vibration variables, machining process variables [Liu et al 2012]. The major disadvantage of rotary ultrasonic machining (RUM) is that only circular holes can be machined because of the rotational motion of the tool [Pei et al.1995].

## 1.7 ULTRASONIC MACHINING PROCESS ELEMENTS:

1. Abrasive slurry
2. work-piece
3. Tool
4. Tool holder
5. Transducer
6. The high frequency oscillating current generator
7. Horn

### 1.7.1 Abrasive Slurry:

In USM many types of abrasive particles are used for a particular applications include hardness, cost, life and size. These abrasives are boron carbide, silicon carbide, aluminum oxide and diamond. These abrasives are used with many fluids in slurry such as water, benzene, glycerol and oils but water is commonly used due to less viscosity. The abrasive particle is suspended in the machining zone and collides with the vibrating work piece, this cause the impact of the particle on the work piece surface [Zarepour and Yeo 2012]. The abrasive material is mixed with water to form the slurry this can vary from 30 to 60 percent of abrasive concentration but common abrasive concentration is 50% by weight [Zeng et al.2005].

Fig.5-Aluminum oxide abrasive (http://www.safestchina.com/wholesalers-carbon-black-powder)

Depending upon the abrasive used, the work piece material, work piece/tool wear ratio can range from 1:1 to 100:1 [Singh and Khamba 2006]. Abrasive are generally available in grit sizes ranging from 240 to 800. The most popular general purpose abrasive used is 320 grit. Best surface finish has been reported using 800 grit abrasives and is of the order of 0.25 µm but at a drastic reduction in metal removal rate. The thinner mixtures are used to promote efficient flow when drilling deep holes or for complex cavities [Prabhakaran et al 2006]. Boron carbide is mostly used when machining the hardest work piece materials and highest material removal rates are desired. It is more efficient than other and its cutting time is less than 20-40 than silicon carbide is used. Silicon carbide is used for glass and ceramics. Aluminum oxides is much efficient than others. Diamond is used in case of diamond and rubies cutting. These abrasive mixed with water and stored in the reservoir and pumped between work piece and tool. The transport medium for the abrasive should posses low viscosity with a density approaching that of the abrasive, good wetting properties and high thermal conductivity and specific heat for efficient cooling, water meets most of these requirements [Singh and Khamba 2006].

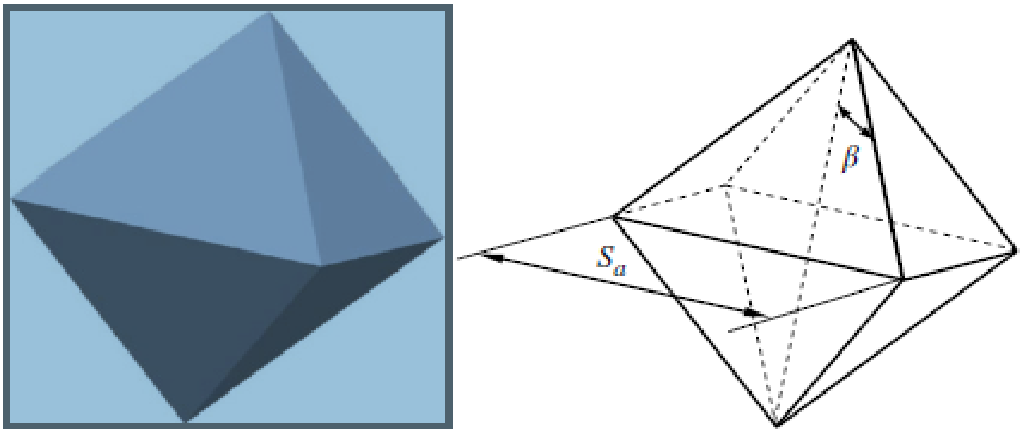



Fig.6-Illustration of abrasive particle simplified as an octahedron [Liu et al.2012]

### 1.7.2 Work piece:

There is no limitation to the range of material that can be machined by ultrasonic machining process, expect that they should not dissolve in the slurry media or react with it. Ultrasonic machining can be used for metals and non-metals, electrical conductors or Nonconductor. Generally USM is best suited to machining operation on brittle materials like glass, ceramics carbide and quartz. Superior properties of some brittle materials such as high hardness and strength at elevated temperature, chemical stability, low friction and high wear resistance make them attractive for many applications [Liu et al.2012]. It is not used for those work materials which are softer than Rockwell Hardness Number HRC 45 [Zeng et al.2005]. Its drilling technique is especially suited for hard materials like tungsten carbide, titanium carbide, ceramic and diamond, which exhibit high hardness and which have impact brittleness can be successfully machined by this technique.

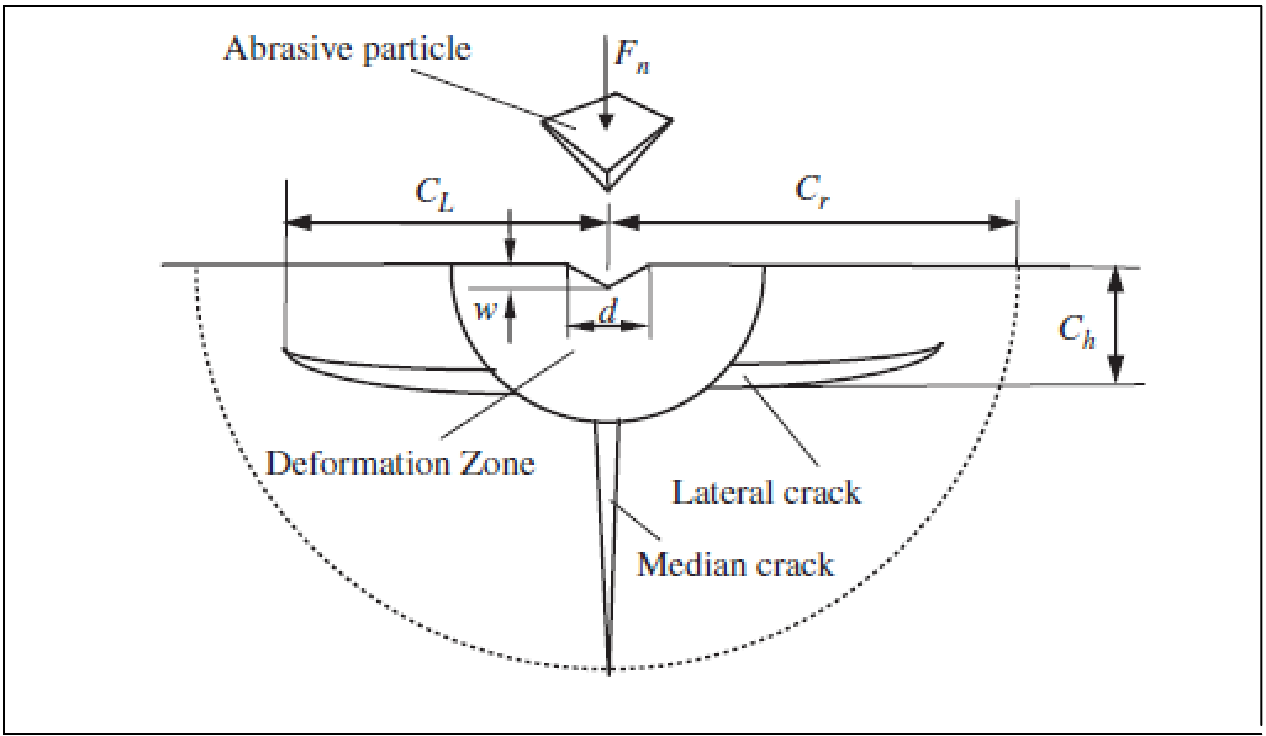



Fig.7-Cracks in brittle material induced by indentation of an abrasive particle [Liu et al 2012]

The type of abrasive, its size, concentration and tool effect the removal of work piece. The mechanical properties of the work material influence ultrasonic machining showed that tough material give a low removal rate, high tool wear and reasonable surface roughness [Hocheng and Kuo 2002].

**Table.1-Materials successfully machined by USM:**

| | |
|---|---|
| 1. Ti –alloy | 10. Stainless steel |
| 2. Tungsten | 11. Tool steel |
| 3. Tungsten carbide | 12. Ceramics |
| 4. Glass | 13. Composites |
| 5. Diamond | 14. Garnet |
| 6. Quartz | 15. Ferrite |
| 7. Ruby | 16. Germanium |
| 8. Aluminum | 17. Brass |
| 9. Aluminum oxide | 18. Plastic |

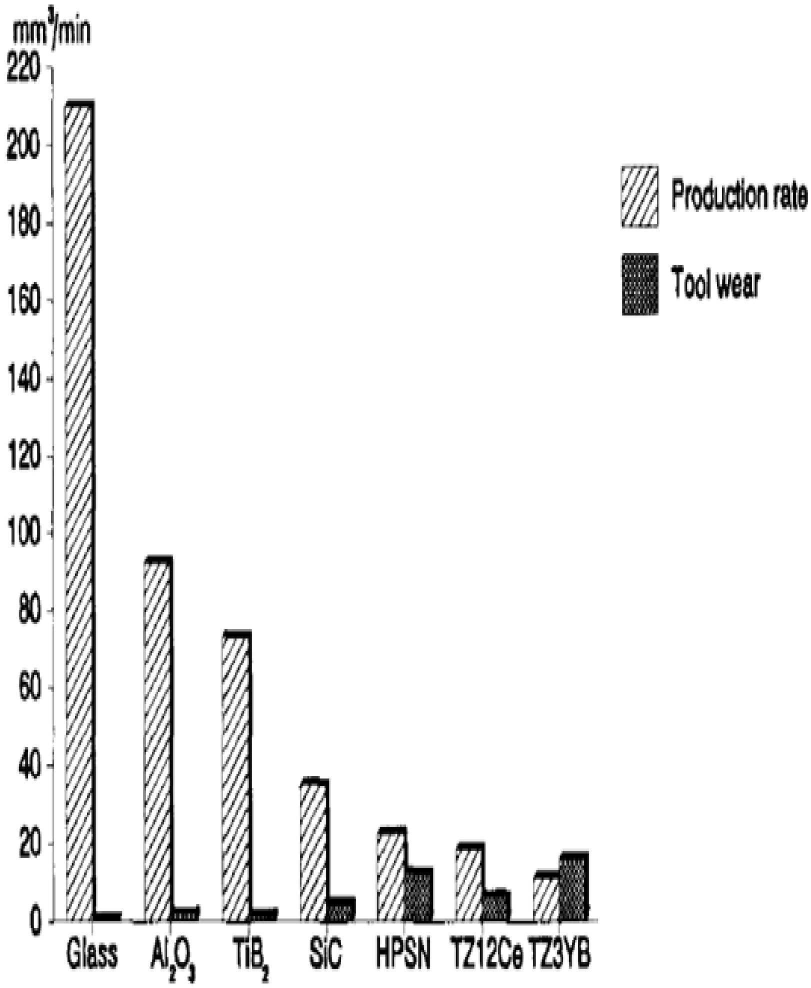



Fig.8-Machining rate and tool wear for the ultrasonic machining of 10 mm diameter holes [Dam et al.1995].

### 1.7.3 Tool:

Many ultrasonic applications are involved in drilling where a tool of either simple or complex cross-section penetrates axially into the work piece to produce either a through or blind hole of the required dimensions [Singh and Khamba 2006].The tool shaped conversely to the desired hole or cavity oscillates at high frequency typically 20 KHz and is fed into the work piece by a constant force [Pei et al.1995]. It is pressed downward using a counter weight, spring, pneumatic/hydraulic or solenoid feed system. To minimize tool wear, tools should be constructed from relatively ductile materials such as stainless steel, brass and mild steel [Singh and Khamba 2006]. During machining the tool also gets reduced with work piece in size due to the cutting action of the abrasive grits. The abrasive grains are flooded to the gap in order of 0.02 to 0.10 mm between the tool and the work piece. The tool are designed to provide the maximum amplitude of vibration at the free end at a given frequency. The tool wear is affected by the vibration amplitude of the tool and static load applied upon the tool [Hocheng and Kuo 2002].

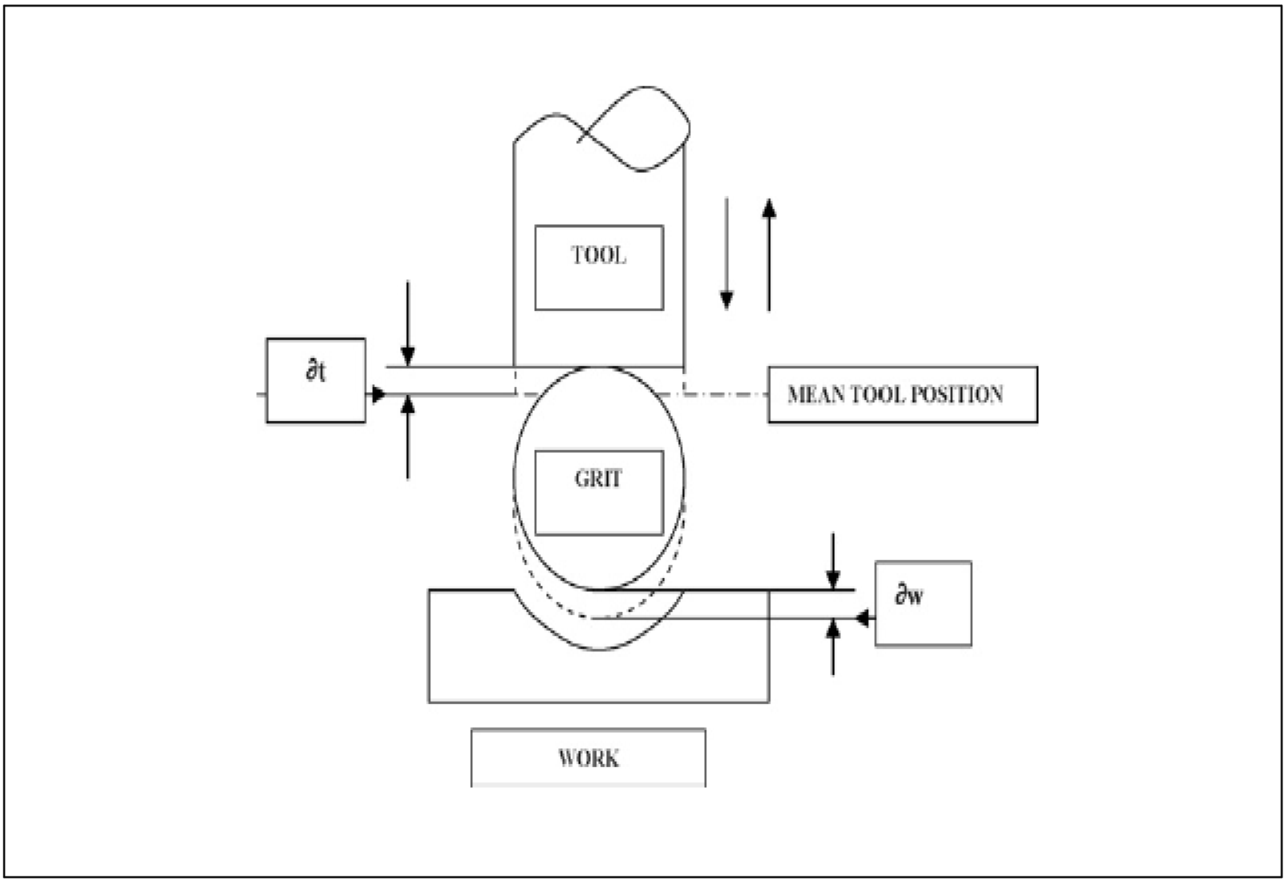



Fig.9-Schematic diagram of tool positions [Singh and Khamba 2008]

The tools are used for hole drilling in ultrasonic machining are constructed from easily obtained materials such as music wire, stainless steel tubing or hypodermic needles. Solid tools used to produce cavities can be fabricated by machining, casting or coining. Mostly the tool used is less than 25mm long. Tool can be joined to the horn either by soldering or brazing, screw fitting. Tool with diamond tips have good material removal characteristics and extremely low wear rate in USM, Tool wear is an important variable in USM, affecting both MRR and hole accuracy. If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in higher work piece MRR [Sun et al 1996]. The tool wear is affected by the vibration amplitude of the tool and static load applied upon the tool [Hocheng and Kuo 2002].

### 1.7.4 Tool holder:

Tool holder is used in ultrasonic machining to hold the tool to the transducer. Tool holder is a removable part is attached to the transducer by loose-fitting screw. In which half hard copper washers are used between the transducer and tool holder to dampen the interface. The material used for tool holder should have high wear resistance, good elastic and fatigue

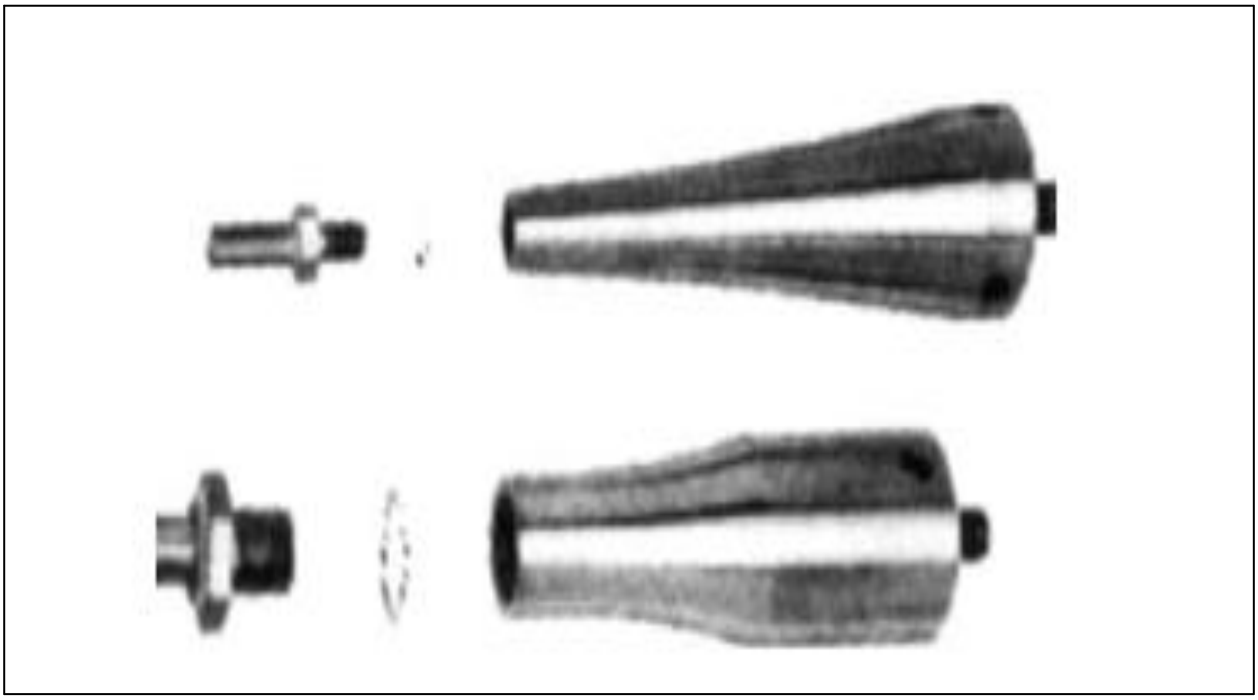


Fig.10-Amplifying tool holders and mechanically attached tools used for USM [ Singh and Khamba 2006].

strength properties, and have optimum values of toughness and hardness such as tungsten carbide, silver steel, and monel material are commonly use. 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 are designed to increase the amplitude of the tool stroke approximately 60%. Generally, the shape of the tool holder is cylindrical or conical or a modified cone with the centre of mass of the tool on the centre line of the tool holder.

### 1.7.5 The high frequency oscillating current generator:

Sine wave generator is used in ultrasonic machining for power supply purposes that offers the user control over both the frequency and power of the generated signal, this generator used for the conversion of low frequency (50 Hz) electrical power to high frequency approx. (20 KHz) electrical power. This electrical signal is converted into mechanical motion by using transducers. Some generators are designed with safety fracture, tool failure or overloading.

### 1.7.6 Transducer:

The transducer is used to converts the energy from one form to another form, in case of ultrasonic machining transducer is used to convert the high frequency electrical energy into mechanical motion. Power supply used in the process depends on the size of the transducers [Zeng et al.2005]. In ultrasonic machining two types of transducer are used magnetostrictive or piezoelectric.

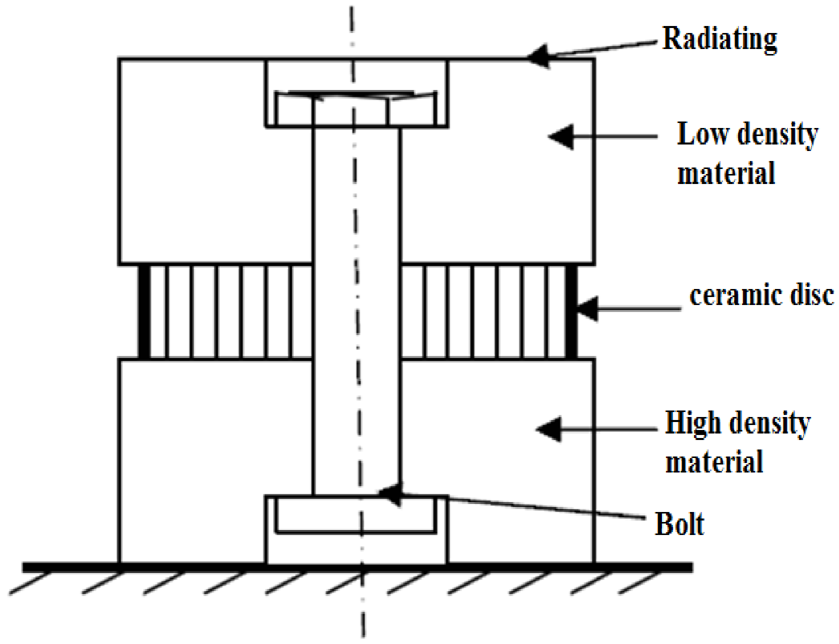



Fig.11-Schematic diagram of piezoelectric transducer

These transducers are based on two different operations, piezoelectric transducers eliminates the use of water cooling due to high electromechanical conversion efficiency (up to 96% ) and available with power capacity up to 900W [Zeng et al.2005]. Magnetostrictive transducers have electromechanical conversion efficiency range between (20 to 35 %), piezoelectric transducers can generate high vibration intensities as compared to magnetostrictive transducers. Magnetostrictive transducers are usually constructed from a laminated stack of nickel sheets.

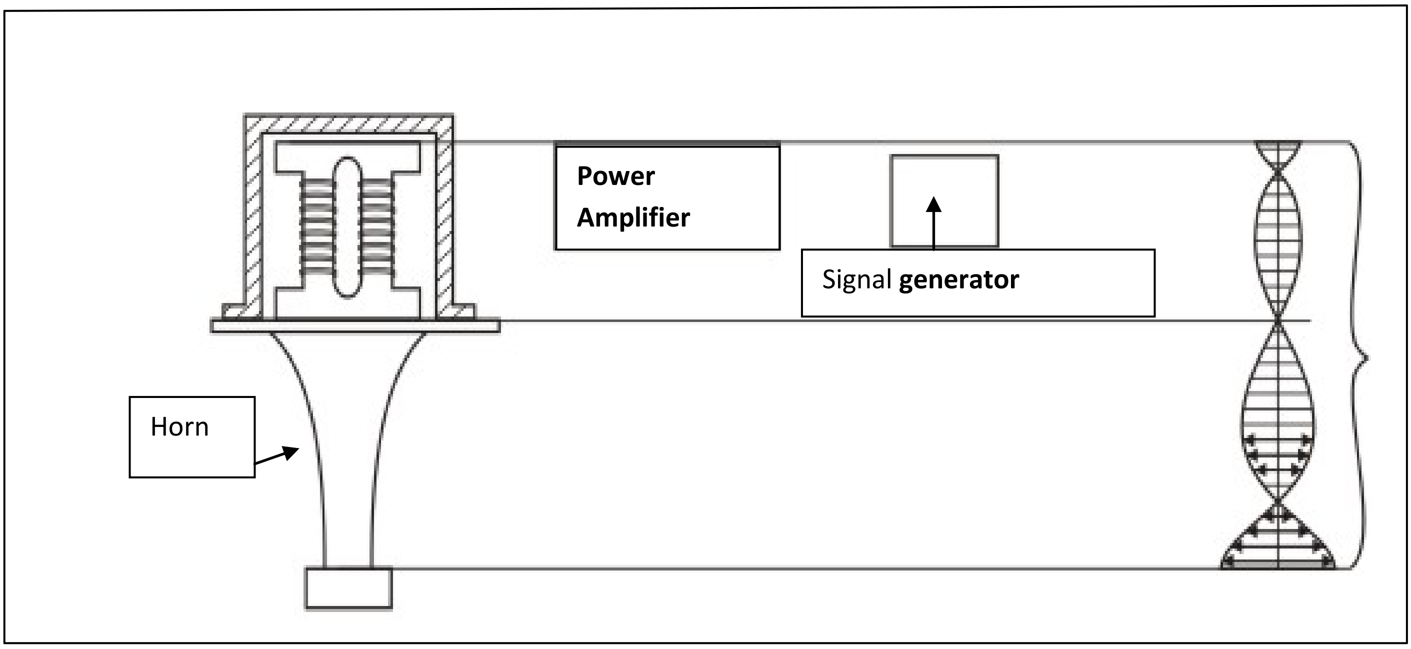



Fig.12-Schematic diagram of Magnetostrictive transducer along with horn

### 1.7.7 Horn:

In ultrasonic machining oscillation must be amplified using acoustic horn, it Provide a high cutting rate. It also known as a mechanical transformer or acoustic amplifier. Generally it is made of monel, cold rolled steel and brass. Tool can be attached to the horn either soldering or brazing, screw/taper fitting, the actual tool configuration can be machined on to the end of the horn [Singh and Khamba 2006]. The cutting performance of a ultrasonic machine depends on the ability of the design of the acoustic horn to facilitate an increase in tool-tip Vibration, allowing a significant amount of material to be removed [Prabhakaran et al 2006]. The oscillation amplitude at the face of the transducer is too small (0,001-0.1micrometer) in order to achieve any reasonable cutting rate therefore, the horn is used as an amplification device [Singh and Khamba 2006]. The profile of the horn-shaped tool bar used in USM can be categorized into step, catenoidal, exponential and conical, other profiles being the combinations of these basic shapes. Horns of special profiles, e.g. the Gaussian horn and the Fourier horn are hard to produce [Hocheng and Kuo 2002]. The design of the ultrasonic horn is to make the length (l) equal to the half wavelength traveled in the horn for the best magnification. Horn can be designed which converts the longitudinal ultrasonic action into a mixed lateral and longitudinal vibration mode [Nath et al 2012].

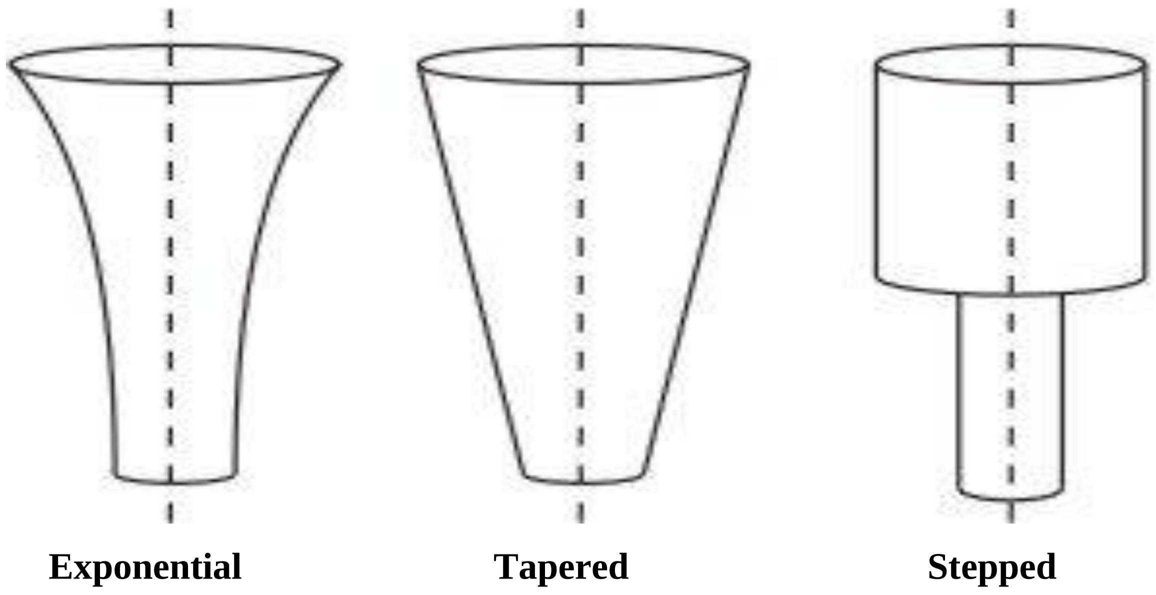



**Fig.13 Types of different horn**

## 1.8 PARAMETERS USED IN ULTRASONIC MACHINING:

- The machines have a power rating of 200-4000 W
- The amplitude of vibration is of the order of 0.01 to 0.06 mm
- Frequency varies from a lower limit of 15,000 Hz (hearing range) to an upper limit of about 25,000 Hz.
- A refrigerating cooling system is used to cool the abrasive slurry to a temperature of 5- 60C. Grit size 200-400 for roughing & 800- 1000 for finishing
- Tool material=stainless steel. Silver steel, Monel, Molybdenum
- Minimum size of hole drilled =76um
- Depth of cut max = up to 90mm
- Cutting gap=20-150um

## 1.9 USM PROCESS AND ITS APPLICATIONS:

Ultrasonic machining process used for the machining of non-conductive, brittle materials including glass, ceramics, carbides, and graphite, these material used for many applications due to their high hardness and strength at elevated temperatures. These types of properties are difficult into a precise size and shape without non conventional machining.

### 1.9.1 Advantages:

- Unlike other non-traditional processes such as laser beam, and electrical discharge machining etc. Ultrasonic machining does not thermally damage the work piece or appear to introduce significant levels of residual stress, which is important for the survival of brittle materials in service.
- A nearly limitless number of feature shapes-including round, square and odd-shaped thru holes and cavities of varying depths can be machined with high quality and consistency.
- This machining process is non thermal, nonchemical, and nonelectrical. It does not change the metallurgical, chemical or physical properties of the work piece. Unlike conventional machining methods, ultrasonic machining produces little or no sub-surface damage and no heat-affected zone.

### 1.9.2 Disadvantages:

- Ultrasonic machines have a relatively low material removal rate**.** Material removal rates are quite low, usually less than 50 $mm^3$/min.
- The abrasive slurry also "machines" the tool itself, thus causing high rate of tool wear**,** which in turn makes it very difficult to hold close tolerances.
- The slurry may wear the wall of the machined hole as it passes back towards the surface, which limits the accuracy, particularly for small holes.

### 1.9.3 Applications:

- Ultrasonic machining is capable for machining of certain kinds of materials and applications; particularly ceramics and glass are machined by ultrasonic machining. Ultrasonic machining is capable of machining complex, highly detailed shapes and can be machined to very close tolerances (±0.01 mm) with properly designed machines and generators. Complex geometric shapes and 3-D contours can be machined with relative ease in brittle materials. Multiple holes, sometimes hundreds, can be drilled simultaneously into very hard materials with great accuracy.

- Ultrasonic machining can be used to form and redress graphite electrodes for electrical discharge machining. It is especially suited to the forming and redressing of intricately shaped and detailed configurations requiring sharp internal corners and excellent surface finishes. It is particularly useful in micro drilling holes of up to 0.1 mm.
- Machining semi conducting material such as germanium and silicon.
- Cutting of industrial diamonds, grinding of glass, quartz and ceramics.
- Cutting holes with curved or spiral center line and cutting threads in glass and mineral ceramics.

From many year research has been done on Ultrasonic machine using different approach like Finite-element analysis, Vibro-impact system, Impact oscillator approach etc to make a optimum results according to the requirements of user. This report presents a Multiple Attribute Decision Making (MADM) approach TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is used to evaluate, rank and selection of important parameters for particular application according to the requirements of the users. The pertinent attributes identified in the paper were less and more emphasis has been given to put forward TOPSIS methodology applied to important parameters of Ultrasonic machine [Bhangale et al 2004]. and Graph theoretic approach is made to develop an integrated systems model for the structure of the ultrasonic machining system in terms of its constituents and interactions between the processes using graph theory and matrix algebra. Ultrasonic machining system is first explain with the graph theoretic approach using different interactions. Different structural attributes of the ultrasonic machining system are identified to develop a graph theoretic model, The matrix models and variable permanent function models provides an opportunity for carrying out characterization analysis and optimization.

# CHAPTER-2

# LITERATURE REVIEW

## 2.1 Categorization of Literature:

The literature is reviewed under following two distinctive categories and in this chapter also presents literature summary and gaps in literature.

1. General literature review about ultrasonic machine (USM) process.
2. System approaches (MADM-TOPSIS Approach and Graph Theoretic Approach)

### 2.1.1 General ultrasonic machine (USM) process:

**Pei et al. (1995)** studied about the plastic flow in rotary ultrasonic machining of ceramics, due to their good properties such as high strength at elevated temperatures, resistance to chemical degradation, wear resistance, and low density, advanced ceramics are used for many applications. The material removal in rotary ultrasonic machining (RUM) process has been mainly attributed to brittle fracture. It is expected that, by changing the process input variables, such as vibration amplitude, rotational speed, diamond grit size, etc., different ratios of brittle fracture portion to plastic flow portion will be obtained. In this process two models was integrates the plastic flow model and the brittle fracture model. For machining conditions in which both brittle fracture and plastic flow exist, this model should be able to predict the percentage of the material which were removed by brittle fracture or by plastic flow.

**Dam et al. (1995)** conducted a study for ultrasonic machining used for drilling of holes in seven different ceramics and check the productivity, surface quality and tolerances. Ultrasonic machining is an abrasive process and in which material removal is purely mechanical. This observation show the different results for both brittle and touch material, touch material give a low production rate, a high tool wear and lesser are the machining rates and precision of the holes, the material are the tougher greater was the tendency for material removal based on plasticity and for brittle material high production rate, low tool wear and high surface roughness, the material were the more brittle greater is the tendency for removal of debris by fracture material.

**Amin et al. (1995)** reported on the Computer-aided design of acoustic horns for ultrasonic using finite-element analysis. Ultrasonic machining was used for various applications, specially used for harder and brittle material. In machining operations oscillation must be amplified using horn. It was made of generally monel, cold rolled steel and brass. It is used in various shapes like cylindrical, stepped, conical or exponential. FEM was a flexible and powerful tool used to solve the problems. This paper discussed about the use of computer to design the acoustic horn on the basis of type of horn, material of horn for best machining operation based on the finite-element analysis. It suggested that horn profile was conical at the upper end and cylindrical at the lower end to obtain maximum magnification for higher rates of material removal and safe working stresses the optimization procedure was based on the length ratio of the two parts.

**Hocheng et al. (1995)** studied about the preliminary study of ultrasonic drilling of fiber-reinforced plastics. These advanced fiber- reinforced plastics are being increasingly used due to their high specific strength and stiffness, thermal resistance and damping capacity. The major cutting mechanism of ultrasonic drilling was abrasive particle hammering or impacting on the work piece to remove material in micro craters. This observation shows the surface roughness increases with the grain size, the energy of ultrasonic oscillations and the concentration of abrasives is independent of the feed rate of tool, the fiber direction or the matrix thermo plasticity. The grain size and the energy of ultrasonic oscillations significantly affect the hole clearance. Multi-hole production elevates the productivity of ultrasonic drilling of composite materials.

**Sun et al. (1996)** verified through their study, the micro ultrasonic machining and its applications in micro electromechanical system MEMS. Micro ultrasonic machining (micro-USM) is a technology that enables breakthrough in making almost any three-dimensional microstructure with high aspect ratio on most materials, particularly on brittle materials including silicon, borosilicate glass, silicon nitride, quartz and ceramics, Micro-USM is a combined micromachining method capable of machining various 3D micro parts of almost all kind of materials. The optimal micromachining speeds are in the range 2.0-6.0 µm min. Tungsten carbide is a suitable tool material for micro-USM. The tool wears increases with a decrease in tool diameter. The sidewall roughness, out-of-roundness and taper ratio of micro holes 0.2 pm, 1.0 pm and 5%, respectively., the micro-USM machine with the combination of WEDG, EDM and USM are used to made up of 3D micro air turbine of three layers.

**Lee et al. (1997)** carried out the further understanding of the basic mechanism of the ultrasonic machining of ceramics composites. The effect on the material removal rate and the surface roughness of the amplitude of the tool tip, the static load applied and the size of the abrasive was measured. It had concluded that any increase in the amount of work/ energy imparted to the machined ceramics in term of the amplitude of the tool tip. The static load applied and the grit size of the abrasive. The increase in the material removal rate, roughening of the machined surface.

**Kim et al. (1997)** discussed about the Micro surface phenomenon of ductile cutting in the ultrasonic vibration cutting of optical plastics (CR-39) and it is used for optical lenses. Optical parts that are not sensitive to temperature but which need accuracy, micro cutting by the tool excited with ultrasonic vibration (20 kHz). The surface machined by ultrasonic vibration appeared as a ductile cutting surface at the region of very small depth of cut, the surface for a single-crystal diamond tool appearing better than that for a poly crystal diamond tool from the viewpoint of ductile cutting. The surface machined with ultrasonic vibration cutting consists of streaks both parallel to and across the cutting direction, on the whole giving the microstructure the appearance of a net shape, produced by the high acceleration induced in the tool and the elimination of micro elastic deformation owing to the overlapping passes of the tool.

**Astashev et al. (1998)** reported on the ultrasonic cutting as a nonlinear process, some materials are difficult to machining and give a desired shape to the metal, these materials like strong, hard are brittle materials, the improvement of machining quality can be achieved through the conversion of the machining process into one involving controllable high frequency impacts at the cutting zone. This process shows that excitation of the vibro-impact mode of tool-work piece interaction is the most effective way of using ultrasonic influence on dynamical characteristics of machining, the dynamics of the ultrasonic cutting machine as a non linear converter of ultrasonic energy for the improvement of the cutting process, the method of excitation and stabilization of effective nonlinear (vibro-impact) mode of ultrasonic vibration is described.

**Wiercigroch et al. (1999)** conducted an experiment to report on material removal rate for ultrasonic drilling of hard materials such as semiconductors, optical glasses, and ceramics using an impact oscillator approach, the cutting of these hard and brittle materials is performed either by abrasive, particles suspended in a fluid, or by a rotating diamond-plated tool. The main mechanism of the enhancement of material removal rate (MRR). In ultrasonic machining with high amplitudes forces generated by impacts, which act on the work piece and help to develop micro-cracking in the cutting zone. the MRR is a function of the magnitude of the impact force and its frequency, removal process in which the tool tip impacts the work piece, making micro-cracks on its surface, In which the diamond is uniformly distributed on the working part of the tool, with a uniform grit size, and that the ultrasonic amplitude and frequency, and the geometry of the tool, remain constant.

**Hu et al. (2002)** reported on the modelling of material removal rate of ceramics in rotary ultrasonic machining, rotary ultrasonic machining gives a higher rate of material removal than diamond grinding and ultrasonic machining because rotary ultrasonic machining is a combination of diamond grinding and ultrasonic machining and rotary ultrasonic machining is a cost effective method for the machining of the ceramics material. This paper studied about the relationship between the material removal rate MRR and controllable machining parameters like static force, vibration amplitude, rotating speed, grit size and grit number. These parameters static force, vibration amplitude and grit size have significant effects on the material removal rate MRR when these parameters are increases the MRR also increases while other rotating speed and grit numbers have no significant effect on the material removal rate MRR.

**Ya et al. (2002)** studied the movement of the abrasive particles in the tool tip of rotary ultrasonic machining is analyzed, the main factor of material removal on the machine surface is impact and grinding of abrasive particles in the tool tip, the contact between abrasive particle and work piece. These contact area varies with the loading, tool are used made of mild steel coated and bonded with diamond abrasive. Rotary ultrasonic machining can provide a much higher material removal rate, deep holes and good surface finish, when it combine with CNC ,it can be used to contact the contour machining of hard and brittle material. Rotary ultrasonic machining combined with CNC machining these factors are effected the material removal the grit and concentration of the abrasive, the static load, the mechanical properties of machined material, material of tool and feed rate of work piece.

**Babitsky et al. (2003)** studied about the ultrasonically assisted turning of aviation materials. Ultrasonic vibration used for a variety of manufacturing processes, for example, ultrasonic cleaning, plastic welding, etc. The autoresonant system proved the possibility of keeping the controlled signal under the resonant conditions during the cutting process. The surface finish improvements achieved for Inconel- 718 within the range of cutting speeds 10–25 m/min were 40–50%, and the corresponding improvements of roundness achieved were 40–60%. The surface finish improvements achieved for C263 within the range of cutting speeds 15–25 m/min were 20–25% (less significant than ones for Inconel-718 but show clear advantage of the ultrasonic cutting), and the corresponding improvements of roundness achieved were 25–40%. The clear advantages of the ultrasonic cutting were achieved for mild steel (the cutting speeds investigated were lower than industrially used ones). The application of feed direction vibrations for ultrasonic cutting seems less limiting than vibrations in the tangential.

**Babitsky et al. (2004)** reported on the autoresonant control of nonlinear mode in ultrasonic transducer for machining applications, the high-frequency vibro-impact mode of the tool–work piece interaction is the most effective way of ultrasonic influence on the dynamic characteristics of machining. The exploitation of this nonlinear mode needs a new method of adaptive control for excitation and stabilization of ultrasonic vibration known as auto resonance. The autoresonant control provides the possibility of self-tuning and self-adaptation mechanisms for the system to keep the nonlinear resonant mode of oscillation under unpredictable variation of load, structure and parameters. The interaction between the work piece and the cutting tool is transformed into a micro-vibro-impact process. An autoresonant system with supervisory computer control was developed, tested and used for the control of the piezoelectric transducer during ultrasonically assisted cutting. The system has been developed as combined analog–digital, where analog devices process the control signal, and parameters of the devices are controlled digitally by computer.

**Neugebauer et al. (2004)** discussed about the ultrasonic application in drilling. In the tests work is selected aluminum–Silicon alloys on a machining centre and applied both uncoated and coated full carbide twist drills (tool diameter 6 mm, tool length 115 mm) as shown in the recent investigations, drilling of aluminum alloys the force and moment reductions of 30–50% are possible, the reason for these savings are the specific kinematic behavior in cutting overlapped with ultrasound and, thus reduced load of the tool's cutting edge enabled an up to 20-fold increase in tool life over conventional cutting.

**Lim et al. (2004)** discussed about a preliminary investigation into optimizing the response of vibrating systems used for ultrasonic cutting. This paper has considered the issue of response modifications within an ultrasonic system as used within the food industry, the technique that has been developed is based on the exploitation of the natural mitigating effects of serially coupled non-linear sub-systems on the overall system response. It has been shown theoretically that certain non-linear effects can be advantageously neutralized with the novel methodology of coupling another sub-system of opposite non-linear characteristic and experimentally demonstrated that components with different geometries, materials and wavelengths shows to possess different non-linear characteristic. By coupling them together, the overall non-linear response of the system has been usefully influenced.

**Greenwood et al. (2004)** discussed about the ultrasonic diffraction grating spectroscopy and characterization of fluids and slurries, the use of ultrasonic diffraction grating spectroscopy (UDGS) to measure the speed of sound in liquids and slurries and to measure the particle size of slurry. This method has been successful in determining the particle size of slurry in the range from about 2 to 200 nm and also measuring the index of refraction. The ultrasonic diffraction grating is made by machining parallel triangular-shaped grooves, spaced 300 microns apart with $120^0$ included angle, on the flat surface of a half-cylinder (diameter=5.08 cm, height=3.8 cm). The angle of this beam in the liquid increases with decreasing frequency and the critical frequency FCR occurs when the angle is $90^0$, At frequencies below critical frequency FCR, this m=1 wave does not exist and its energy is shared with other types of waves. The signal of the reflected m = 0 wave is observed and an increase is observed at critical frequency FCR.

**Zeng et al. (2005)** reported on the experimental observation on tool wear in RUM (Rotary ultrasonic machining) of advanced ceramics, like silicon carbide (SiC). Advanced ceramics are used for many applications due to their attractive properties (such as high strength at elevated temperature and high wear resistance). Rotary ultrasonic machining (RUM) is regarded as one of the cost-effective machining methods for advanced ceramics. In this observation RUM of Sic, the tool wear on the end face is much more severe than that on the lateral face. The tool wear in RUM of SiC has two stages, in the first stage, attritions wear dominates and in the second stage, bond fracture dominates. The maximum cutting force in RUM of $S_iC$ is related to tool wear stage. The maximum cutting force increases with the number of holes drilled during the first tool wear stage, and starts decreasing during the second tool wear stage.

**Singh et al. (2006)** conducted an study on ultrasonic machining of titanium and its alloy, ultrasonic machining (USM) is used for the machining of non-conductive, brittle work piece materials such as engineering ceramic, In ultrasonic machining the design of tool and horn play an important role in providing a maximum material removal rate. The 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. The higher MRR is general depends on the abrasive grit sizes and higher slurry concentrations when hardness of slurry material should me more than the work piece. The slurry acts as a coolant for the horn, tool and work piece, supplies fresh abrasive to the cutting zone and removes debris from the cutting area. The tool may crack from joint if inadequate supply of slurry is there. It also provides a good acoustic bond between the tool, abrasive and work piece, allowing efficient energy transfer.

**Choi et al. (2007)** studied on the chemical-assisted ultrasonic machining (CUSM) method of glass, glass used for many applications due to their many properties such as high strength, hardness, thermal resistance, corrosion resistance and wear resistance, and is relatively light weight. In this process materials are removed by micro chipping or erosion with the abrasive particles and the tip of the tool vibrates at low amplitude (2–50 μm) and high frequency (20 kHz). The chemical-assisted ultrasonic machining process, which uses a low concentration hydrofluoric acid HF solution for chemical effect was developed to overcome the disadvantages of the conventional USM process, such as a low material removal rate and surface quality. The surface roughness and the material removal rate were improved up to 40% at micro-drilling and 200% at macro drilling and also the machining load was drastically reduced and cab be maintained stably.

**Nath et al. (2008)** studied on the effect of machining parameters in ultrasonic vibration cutting these parameters are tool vibration frequency, tool vibration amplitude and work piece cutting speed that determine the cutting force. The ultrasonic vibration cutting (UVC) method is a more effective cutting process in terms of cutting force, cutting instability, tool blunting, tool wear, chip generation, surface finish to machine difficult-to-cut materials such as Ni- and Ti-based super alloys, hardened steels, optical glasses, ceramics, tungsten carbides. This shows that the tool–work piece contact ratio (TWCR) plays a key role in the ultrasonic vibration cutting (UVC) process where the increase in both the tool vibration parameters and the decrease in the cutting speed reduce the TWCR, which in turn reduces both cutting force and tool wear, improves surface quality and prolongs tool life. It is observed that the UVC method gives better surface finish and improves tool life in hard cutting at low cutting speed as compared to the conventional turning CT method.

**Curodeau et al. (2008)** studied to propose alternate tooling material than tungsten carbide or steel, whereas viscoelastic thermoplastic composite material was used as tooling to conduct ultrasonic micro machining operation. Such tooling is used within the ultrasonic abrasive machining process in which a polymer composite tool is initially formed by compression molding against the very same work piece to be finished, before being used as ultrasonic machining tool. Basic micromachining experiments were conducted with acetal and high molecular weight polyethylene composite polymer tooling to demonstrate. In test 1, a uniform micron scale layer of material was removed in hammering mode from a flat P20 tool steel sample, while in test 2, a similar P20 tool steel sample with initial electric discharge machining surface finish was polished in contactless machining mode. Analysis of machined sample surface profile was progression of surface finish in time is presented along with scanning electron microscope pictures of surface details allowing establishing the occurrence of various material removal mechanisms.

**Heisel et al. (2008)** reported on the results of ultrasonically assisted deep hole drilling in. Electrolytic copper (ECu) 57 with tools of 5 mm diameter. Electrolytic copper (ECu) material has a high electrical and thermal conductivity and it is used for highly conductive electrical products as well as for small high-performance heat exchangers in the field of chemistry. Vibrations primarily in the longitudinal direction of the drilling tool were generated with help of piezoelectric actuators. The piezoelectric transducer was designed with regard to the low amplitude transmission, to guarantee a system that is as adaptable as possible and insensitive to loads in later operation. This process compared with conventional machining, a higher surface quality can be achieved in the case of an optimized combination between the set feed and no-load amplitude of the actuator. Due to a simultaneously favourable chip form and length, a higher process stability can be guaranteed as well.

**Majeed et al. (2008)** reported on the ultrasonic machining of Al2O3/LaPO4 composites. Mach inability of ceramics can be made easier by controlling the normal cutting force so as to avoid possible crack of ceramics or by structure modification. Such modification is normally a addition to the ceramic structure Al2O3/LaPO4 composites, It could be developed to enhance the mach inability, Al2O3/LaPO4 composites of varying compositions were drilled on an ultrasonic machine with low carbon steel tool. Low carbon steel tools of 3mm diameter, solid and hollow with a central hole of 1mm diameter, were used. The addition of LaPO4 to ceramics normally results in introduction of weaker interface or layered structure facilitating crack diffusion during machining and thereby enhancing the mach inability.

**Singh et al. (2008)** reported on the production of 5mm diameter holes in pure titanium and titanium alloy using ultrasonic drilling with three different slurries (namely silicon carbide, boron carbide and alumina).In this process piezoelectric transducer use with 20khz with three solid tools of stainless steel, titanium and high-speed steel, operating in silicon carbide, boron carbide and alumina slurry. Titanium and its alloys are very popular and are very widely used in aerospace, marine gas turbine engines and surgical applications. The results have been obtained titanium is well machined using ultrasonic drilling machine with stainless steel tool and boron carbide slurry and material removal rate depends on both the hardness of work piece and tool material.

**El-Ganaini et al. (2009)** discussed about the vibration reduction in ultrasonic machine to external and tuned excitation forces. Ultrasonic machining (USM) is the removal of material by the abrading action of grit-loaded liquid slurry circulating between the work piece and a tool vibrating perpendicular to the workface at a frequency above the audible range. A high-frequency power source activates a stack of magnetostrictive material, which produces a low amplitude vibration of the tool holder. Multi tool techniques are used in the ultrasonic machining via reducing the vibration in the tool holder and providing reasonable amplitudes for the tools represented by the absorbers. In which multi-degree-of-freedom system subject to external and tuned. The vibration of ultrasonic tool holder can be controlled via non-linear absorbers. Multiple time scale perturbation technique is applied to determine semi-closed form solutions for the coupled differential equations describing the ultrasonic machining up to the second order approximations. Multi-tools are used simultaneously to save both time and power and improve machining efficiency and different shapes, materials and work pieces can be machined simultaneously.

**Zarepour et al. (2012)** conducted the study to discuss about a methodology based on a single abrasive particle impingement as a fundamental approach to determine ductile and brittle material removal modes in micro ultrasonic machining process. the material is removed, whether it is brittle or ductile, can be controlled in micro ultrasonic machining through setting of machining conditions and process parameters at desired levels to improve the process productivity as well as surface quality. A purely ductile material removal mode was achieved by single particle impingement using particle with size of 0.37 μm at vibration amplitude of 3 μm. Also, material pile-up with height of 8 nm was observed around the crater site which is an indication of plastic deformation of the material. In contrast, employing particles with size of 3 μm and vibration amplitude of 4 μm resulted in a purely brittle mode of material removal with radial/median and lateral cracks. Moreover, a partially ductile material removal mode was observed when applying particle size and vibration amplitude of 3 μm.

**Nath at al. (2012)** discussed about the fundamental mechanism of material removal during ultrasonic machining (USM) of hard–brittle materials like ceramics and glass. This experiments were conducted for drilling holes on three advanced structural ceramics, namely, silicon carbide, zirconium, and alumina has been conducted to investigate the adverse influence of its inherent removal mechanisms on the hole integrity such as entrance chipping, hole wall roughness and surface/subsurface damage and in this paper discussed about the material removal mechanism happens in the gap between the tool periphery and the hole wall (called 'lateral gap'). Though the 'lateral gap' is formed during USM, the width or size of this gap is not enough to completely disappear such cracks. At the top surface of the hole cavity, the remaining portion of these cracks appear as entrance chipping, when the damage materials of the cracks get removed by the moving abrasives around the tool periphery. beneath the surface, the remaining portion of the cracks appear as hole wall roughness and surface/ subsurface damage.

**Cong et al. (2012)** conducted a study about rotary ultrasonic machining of Carbon fiber reinforced plastic (CFRP) composites: A study on power consumption. Carbon fiber reinforced plastic (CFRP) composites are very difficult to machine and it is used for many applications. Therefore, it was important to develop cost-effective drilling processes. CFRP has been drilled by rotary ultrasonic machining (RUM) successfully. This observation reported on the effects of input variables like ultrasonic power, tool rotation speed, feedrate, and type of CFRP) on power consumption of each component (including ultrasonic power supply, spindle motor, coolant pump, and air compressor) and the entire RUM system. As ultrasonic power increased or tool rotation speed decreased, power consumption of ultrasonic power supply increased slightly, power consumption of spindle motor decreased dramatically, power consumption of coolant pump and air compressor kept unchanged, and power consumption of the entire RUM system increased slightly.

**Liu et al. (2012)** conducted an experiment to discuss mechanistic model for cutting force in RUM (Rotary ultrasonic machining) of brittle materials, brittle fracture is the primary mechanism of material removal in RUM of brittle materials. Brittle materials have many properties, such as high hardness and strength at elevated temperatures, chemical stability, low friction, and high wear resistance, make them attractive for many applications .On the basis of this mechanistic model, relationships between cutting force and input variables (such as spindle speed, feed rate, ultrasonic vibration amplitude, abrasive size and abrasive concentration) are predicted. On the basis of this model the results show when cutting force will increase as abrasive concentration, semi-angle of abrasive particle, and feed rate increase and it will decrease as abrasive size, vibration amplitude, and spindle speed increase.

**Nik et al. (2012)** reported on the Ultrasonic assisted grinding of Ti6Al4V alloy. This titanium alloy is used for many applications like aerospace and marine industries, gas turbines and biomedical. In this paper the cutting forces and surface finish are compared between conventional grinding (CA) and ultrasonic assisted grinding (UAG) when applied a longitudinal vibration at ultrasonic frequency range (20 kHz) on the work piece and machining forces and surface roughness. Ultrasonic vibration generate impact loads, lower contact surface, variation in cutting depth, self-sharpening and improvement in lubricant penetration that leads to change in grinding forces and surface quality, Grinding forces have been reduced at all UAG experiments. Surface roughness shows an average 10% improvement when ultrasonic vibration is imposed. In UAG, higher depth of cut and feed can be selected in comparison to CG with still better surfaces.

## 2.1.2 LITERATURE REVIEW OF MADM-TOPSIS APPROACH AND GRAPH THEORY:

**Bhangale et al. (2004)** studied about the robot selection problem which arises due increasing complexity, available features, and facilities offered by different robotic products. The objective of their research is to generate and maintain reliable and exhaustive database of robot manipulators based on their different pertinent attributes. That database can be used to standardize the robot selection procedure when the manufacturing firm has decided to use the robot for a particular operation. This paper can help the robot user to save time by providing him a tool for selecting the robot system most suited for his operational needs. This paper presented a robot selection procedure based on the Multiple Attribute Decision Making (MADM) approach. Here by identifying 83 attributes of the robots, the attempt has been made to codify most of the robot characteristics, which will define the robot precisely and accurately. The coding scheme is illustrated with example of selecting a robot for some pick-n-place operation. It has presented the result of the information processing in terms of a merit value, which is used to rank the robots in the order of their suitability for the given application.

**R.K. Garg et al. (2006)** developed a deterministic quantitative model based on graph theoretical approach. In this study a comparison is made between various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. The methodology present in this paper allows a decision maker to perform general analysis and other various focused analysis regarding his personal preferences.

**Durai et al. (2006)** reported on a methodology for evaluation, coding, and optimum selection of subsystems for composite product used directly by its manufacturers. The 77-attribute electronic coding scheme and the evaluation techniques are presented in this paper and are useful to the designer during all the phases of design process, and manufacturer for the selection of optimum subsystems, which meet global market requirements. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multiple-Attribute Decision Making (MADM) approach is used for selection of subsystems for a composite product development in order of preference for given application. Two graphical methods of MADM approach for evaluation and comparison are also introduced by the authors. It is recommended in this paper that manufacturer of composite product should develop attribute-based specification in the form of proposed coding scheme. This will directly help industry in carrying out SWOT (Strength– Weakness–Opportunities–Threats) analysis from the point of view of its manufacturing and business strategies.

**Prabhakaran et al. (2006)** studied about an integrated systems model for the structure of the composite system in which include of its constituents and interactions between the constituents and the molding processes by using graph theoretic approach and matrix algebra. In this proposed methodology for developing a composite product considered all the attributes responsible for design, production, and process parameters. In which composite product is first modelled with the help of graph theory, then by variable adjacency matrix and then by a multinomial known as permanent function. The permanent function has provided an opportunity to carry out structural analysis of the composite product in terms of strength, weakness, improvement, and optimization (SWOT) analysis by correlating the properties of a composite with its structure.

**Garg et al. (2007)** conducted a computational methodology for a computer-based solution to the problem of evaluation and selection of an optimum power plant. This methodology is multiple attribute decision making (MADM) methodology and consists of elimination search and technique for order preference by similarity to ideal solution (TOPSIS) approach. Authors have suggested a coding scheme based on 190 39 pertinent attributes for a given thermal power plant for the development of a large database of available plants, and their subsequent retrieval. The technique for order preference by similarity to ideal solution‘‘(TOPSIS) approach has provided a complete and thorough comparison and ranking of available power plants. This has also developed user friendly computer software for Elimination Search and TOPSIS approach.

**Varinder Singh and Agrawal et al. (2008)** conducted a methodology that builds a flexible and comprehensive model of manufacturing system, which has the capability to consider the interdependence between its various subsystems. In this methodology after the identification of elements constituting a manufacturing system and the interactions between them, it has been represented by graph-based model. Also the matrix models and the variable permanent function models have been developed to carry out decomposition, characterization and the total analysis. Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of manufacturing system in different performance dimensions. The permanent function of the manufacturing system matrix has been proposed as a systematic technique for structural analysis of manufacturing system.

**Kiran et al. (2011)** discussed about a methodology useful in optimal selection of a mechatronic system based on the Multi Attribute Decision Making (MADM) approach. This paper proposing a coding scheme which is a collection of 88 attributes which characterize a mechatronic system and is useful in differentiating mechatronic system alternatives. An illustrative example of selecting a hard disk drive (HDD), a mechatronic system, for the up-gradation of costumer's office desktops is given to explain the methodology. Authors also identified 3-stage selection procedure, which includes elimination search, TOPSIS based evaluation and ranking, other graphical methods (linear graph and spider diagram), works on the information of the pertinent attributes. This procedure ranks the mechatronic system alternatives based on the Euclidian distance of alternatives from hypothetically best and hypothetically worst mechatronic systems.

**C.P. Kiran et al. (2011)** presented a methodology to develop a high quality product. This methodology combines all the design aspects of product together to generate a useful form of solution for the Mechatronic industry. This methodology considered all the x-abilities/design aspects along with interactions without missing any useful information. The methodology consists of graph theory, matrix algebra, and permanent multinomial. Eight x-abilities are indentified i.e. miniaturization, intelligence, integration, environment, quality, reliability, manufacturing, and assembly for concurrent design of a Mechatronic. For visual analysis a color graph is proposed.

## 2.2 LITERATURE SUMMARY

From the study of research papers on Ultrasonic machine (USM), it is seen that for improving MRR, TWR and surface finish different modifications are implemented on the conventional USM and they are found beneficial. Some are:

1. The movement of the abrasive particles on the tool tip of rotary ultrasonic machine was analysed.
2. Characteristics of machined surface by ultrasonic vibration cutting were analysed in the ductile mode.
3. A computer aided design procedure for the horn profile and material based on finite element analyze was established.
4. The effect of imposition of ultrasonic vibration on the grinding of Ti6A14V alloy was studied.
5. General survey of the processes was presented which showed that tough material give a low production rate, a high tool wear and a low surface roughness.
6. A mechanistic model for cutting force in rotary ultrasonic machining of brittle material was presented.
7. A investigation was done to study the adverse effects of his inherent removal phenomena on the hole integrity such as entrance chipping, wall roughness.
8. Dynamics of an ultrasonic cutting machine under technological load were investigated.
9. Experimental evidence was presented that plastic flow can also be one of the material removal mode in rotary ultrasonic machine in addition to brittle fracture.
10. Micro ultrasonic machining with the purpose of providing insight into material removal mode was presented by using approach of single abrasive particle impingement.
11. Ultrasonic diffraction grating spectroscopy was formed by machining triangular grooves, 300 microns apart, on a stainless steel surface and information yields the velocity of sound in the liquid and particle size.
12. Impact oscillator approach was used for prediction the material removal rate for ultrasonic drilling of hard material.
13. A five factor two level factorial design was used to study the relationship between MRR and the controllable parameters.

14. Experimental observation on tool wear in rotary ultrasonic machine of silicon carbide material was presented.
15. Chemical assisted ultrasonic machining CAUM method was used to improve the material rate and the integrity of the machined surface.
16. Research was presented on the production of 5 mm diameter holes in pure titanium and titanium alloy using ultrasonic drilling.

## 2.3 GAPS IN LITERATURE:

Some gaps are identified on the basis of which aim for further study has been decided. Some are:

- It is been identified that insufficient amount of work has been done in the field of applying Graph theory in USM process.
- MADM -TOPSIS approach is not applied in case of USM.
- The work is not done for Structural Modeling, Characterization, Integrative Analysis and Selection of USM System.
- No work is done for attribute based Coding, Evaluation and Optimum Selection of Parameters for USM System.

# WORK DONE

## Chapter 3

In this chapter a novel method is implementing to develop the decision-maker for selection of a proper parameters of ultrasonic system that will meet all the requirements of the manufacturing processes. This reliable and exhaustive data of ultrasonic machining system is to generate and maintain based on their different pertinent attributes. It is useful for better understanding, comparison and analysis and for comparison; ranking and optimum selection of ultrasonic machining parameters. MADM ( multiple attribute decision making )problems is solved by "TOPSIS" (Technique for Order Preferences by Similarity to Ideal Solution). The coding scheme and the selection procedures, mathematical and graphical, with example are also illustrated.

## Chapter 4

In this chapter an attempt is made to develop an integrated systems model for the structure of the ultrasonic machining system in terms of its constituents and interactions between the processes using graph theory and matrix algebra. Ultrasonic machining system is first explian with the graph theoretic approach using different interactions. Different structural attributes of the ultrasonic machining system are identified to develop a graph theoretic model, The matrix models and variable permanent function models provides an opportunity for carrying out characterization analysis and optimization.

# CHAPTER-3

# CODING, EVALUATION, RANKING AND OPTIMUM SELECTION OF ULTRASONIC MACHINING USING MADM APPROACH

This chapter deals with implementing a (multiple attribute decision making) MADM approach used to identifies the various pertinent attributes needing to be considered for the optimum evaluation and selection of parameters of ultrasonic machine that will fulfil all the needs of the manufacturing system. MADM approach useful for better knowledge of parameters of ultrasonic machine available in advanced manufacturing process. This approach presents the result of the information processing in terms of a merit value, which is used to rank the parameters of USM in the order of their suitability for the given application. The main objective of MADM approach to generate reliable and exhaustive database of system on different pertinent attributes related to the process. This database can be used to standardize the selection procedure of parameters of ultrasonic machine used for particular operation. These attributes are of two types qualitative/deterministic and quantitative/fuzzy in nature. Coding of all these qualitative and quantitative attributes is to be done on the basis of N-digit coding scheme. These pertinent attributes are useful for proper selection of parameters of ultrasonic machine for particular applications according to the requirements of the users from a different process of manufacturing, e.g. different types of abrasive materials (silicon carbide, boron carbide, aluminium oxide etc) are used for different brittle materials (glass, ceramics, titanium etc) with different frequency, amplitude and different grit numbers. Ranking is to be done on the basis of a mathematical TOPSIS procedure, line graph representation, and the spider graph representation. TOPSIS (Technique for Order Preferences by Similarity to Ideal Solution) technique is used for solving the (multiple attribute decision making) MADM problem. This technique can be used to convert the exhaustive data into mathematically and graphically way by using normalization, relative weights, positive benchmarked, negative benchmarked and coefficient of similarity. This will help the Ultrasonic machine user to save time by providing him a tool for selecting the most suited parameters for his operational needs. The coding scheme of pertinent attributes and the selection procedures, mathematical and graphical, are illustrated with example.

## 3.1 Introduction:

The uses of ultrasonic machine are spread in many fields at very fast rate day by day. Ultrasonic machining is one of the most widely used non-traditional machining processes for the machining of non-conductive, brittle materials including glass, ceramics, carbides, and graphite [Zeng et al.2005]. The machining of these types of properties is difficult into a precise size and shape [Kim and Choi 1997]. The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator [Singh and Khamba 2006]. In ultrasonic machining the material is removed due to the indentation by hard abrasive particles on the brittle work material and some material removed due to free flowing impact of the abrasives particles but it is not significant. The cutting tool is pressed generally in downward direction with a feed force (F) and it vibrates at an ultrasonic frequency 20 kHz with amplitude of 20 μm over the work piece [Amin et al 1995]. USM process showed that tough material give a low removal rate, high tool wear and reasonable surface roughness [Hocheng and Kuo 2002]. The power supply depends on the size of transducers [Zeng et al.2005]. In ultrasonic machining two types of transducer are used magnetostrictive or piezoelectric are based on two different operations, piezoelectric transducers eliminates the use of water cooling due to high electromechanical conversion efficiency (up to 96% ) and available with power capacity up to 900W. The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator. The tool is hold in the tool holder to the transducer. The cutting tool is pressed generally in downward direction with a feed force (F) and it vibrates at an ultrasonic frequency 20 kHz with amplitude of 20 μm over the work piece [Amin et al 1995]. These abrasive particles are flooded on machining zone in the form of water based slurry between the cutting tool and work piece. The abrasive slurry is the mixture of the abrasive materials like silicon carbide ($S_iC$), boron carbide ($B_4C$), corundum ($Al_2O_3$) with water or oil [Singh and Khamba 2008]. The slurry is used for machining is stored in slurry tank and it is flooded by slurry pump between work piece and cutting tool. All the abrasives are considered to be identical in shape and size, it is considered to be spherical. During machining the materials is removed in the form of small particles and it is carried away by the slurry. The power ratings range from 50 to 3000 W and it reach 4 kW in some machines. It rotated by a servomotor simultaneously. Ultrasonic machining called by various termed ultrasonic drilling, ultrasonic abrasive machining and ultrasonic cutting. USM creates desired accurate cavities of any shape through the impact grinding of fine grains [Sun et al.1996].

Ultrasonic machining can be used to form and redress graphite electrodes for electrical discharge machining. It is especially suited to the forming and redressing of intricately shaped and detailed configurations requiring sharp internal corners and excellent surface finishes. It is particularly useful in micro drilling holes of up to 0.1 mm. Ultrasonic machines have a relatively low material removal rate**.** Material removal rates are quite low, usually less than 50 $mm^3$/min. The abrasive slurry also machines the tool itself, thus causing high rate of tool wear**,** which in turn makes it very difficult to hold close tolerances. One modification of USM to overcome some disadvantages its name is rotary ultrasonic machining. The power required for RUM process is less than that used for USM [Singh and Khamba 2008]. Rotary ultrasonic machining (RUM) is 10 times faster than USM [Pei et al 1995]. It reduces the inaccuracies like oversize and out of roundness. Ultrasonic turning is the most common process is claimed to reduce machining time, work residual stresses and improve surface quality and tool life compared to conventional turning. Now day's ultrasonic vibrations are used successfully to enhance machining capability of micro EDM to handle titanium alloys [Singh and Khamba 2008]. We proposed a new approach that can help in getting good competing benefits and high performance of product in a shorter time. The proposed model will be useful for analyzing, evaluating and designing a ultrasonic machining system at the conceptual stage. Selection of parameters for different process is more challenging issue in manufacturing. Ultrasonic machine with vastly different capabilities and specifications are available for a wide range of applications. The selection of an optimum parameter of ultrasonic machine for manufacturing based on different attributes (i.e. subjective, objective) can be defined within the concept of a multiple attribute decision-making (MADM) problem. It can be defined using the concept of multiple attribute decision making problem (MADM). The pertinent attributes identified in the paper were less and more emphasis has been given to put forward TOPSIS methodology applied to parameters of ultrasonic machine selection.

### 3.1.1 Step by step procedure is followed in MADM approach:

Step 1: Identified the attributes and categorized under different parameters affecting the system.

Step 2: Use cause and effect diagram to indentify the different classes of attributes, which is very helpful to optimize the system.

Step3: codes are given to all the qualitative and quantitative attributes on the basis of N-digit coding scheme.

Step4: A 3-stage selection procedure used in which consisting of elimination search, evaluation by TOPSIS procedure and final selection is used.

Step5: Ranking is done on the basis of a mathematical TOPSIS procedure, line graph representation and the spider graph representation.

Step6: The methodology is explained with the help of an example in which 3 different abrasive material are used for two different material with three different attributes.

## 3.2 Identification of Ultrasonic machining attributes:

In ultrasonic machining system consists of various sub systems such as oscillating current generator, horn, transducer, abrasive and tool holder etc all these sub systems are dependent on each other and are interrelated**.** The identification of attributes on the basis of their importance in the field of manufacturing process and it is very important because all the identified attributes will define the whole system. These attributes shown by using cause and effect diagram.

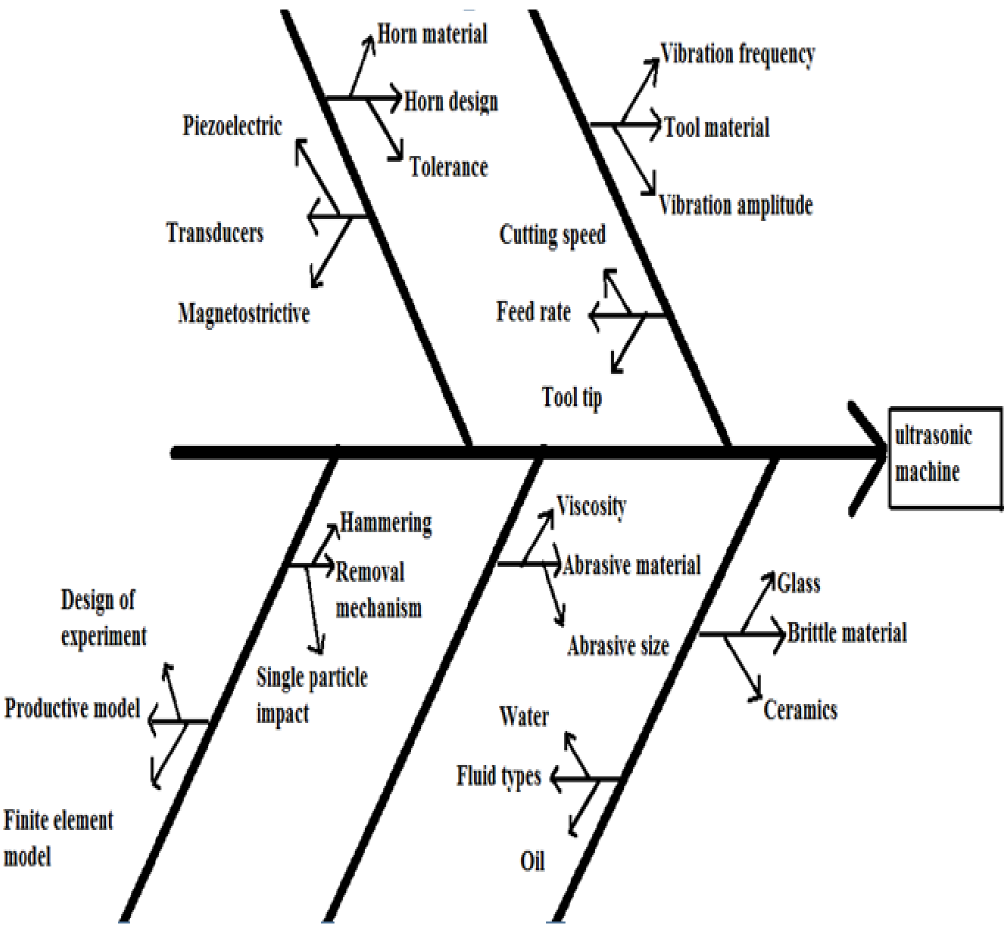



**Fig.3.1-Cause and effect diagram of ultrasonic machining system**

The main attributes have been broken down to sub-attributes and sub-sub-attributes successfully so that the process can be identified in very precise and detailed manner. Therefore, the optimum selection of the ultrasonic machining system for a particular application is going to affect the overall performance of the whole system and at the same time the selection of ultrasonic machining system is mainly dependent on it different attributes. The attributes are found out based on its broad area for ultrasonic machining process on the basis of their importance. Cause and effect diagram is used to identify the different attributes and different parameters of ultrasonic machining system which require attention/situation of researchers in the field area under consideration as shown in figure-4.1 Here, 172 pertinent attributes of the ultrasonic machining system are identified, but the user, designer or manufacturer can add or delete some of the attribute depending upon their requirement. The ultrasonic machine attributes are found out based on its broad area as general, process based, tool based, work piece based and slurry based attributes as shown below.

- General attributes
- Process based attributes
- Tool based attributes
- Work piece based attributes
- Slurry based attributes

**Table 3.2 List of broad categories attributes of parameters of ultrasonic machine**

| **General attributes** | |
|---|---|
| 1. Removal mechanism | 2. Micro chipping |
| 3. Finite element method | 4. Grinding |
| 5. Hydrofluoric acid | 6. Resonance |
| 7. Chemical assisted USM | 8. Diffraction grating |
| 9. MRR | 10. Taguchi method |
| 11. Vibro impact system | 12. Cavitations |
| 13. Rotary ultrasonic machining | 14. Piezoelectric actuator |
| 15. Productive model | 16. Positive cubic stiffness |

| | |
|---|---|
| 17. Design of experiment | 18. Hypoid |
| 19. Single particle impact | 20. Spiral bevel gear |
| 21. Diamond wheel | 22. Ultrascan |
| 23. Ultrasonic vibration cutting | 24. Topography of end face |
| 25. Hole tolerance | 26. Beech |
| 27. Spruce | 28. Predictive model |
| 29. Ratio of brittle fracture | 30. Micro grooving |
| 31. High power ultrasonic | 32. Neuro fuzzy inference system |
| 33. Optimization | 34. On line monitoring |
| 35. Reinforcement content | 36. Dynamic resonance |
| 37. Nanoscale removal processing | 38. High power ultrasound |
| 39. Power consumption | 40. Optics |
| 41. Impact oscillator | 42. Planar light wave circuit |
| 43. Theoretical models of stress | 44. Interferometry |
| | |
| **Process based attributes** | |
| 45. Types of transducers | 46. Wave length spectrum |
| 47. Horn design | 48. Surface quality |
| 49. Brittle fracture | 50. Tolerances |
| 51. Plastic flow model | 52. Production rate |
| 53. Cutting fluid | 54. Fluid characterization |
| 55. Wheel speed | 56. Efficiency |
| 57. Rotational speed | 58. Non linear vibration |
| 59. Chip adhesion | 60. Material of horn |
| 61. Impacting of abrasive | 62. Hammering of abrasive |
| 63. Lateral gap | 64. Thermal stress |
| 65. Nitrogen gas | 66. Micro structures |
| 67. Surface profile | 68. Ultrasonic lapping |
| 69. Fractures | 70. Attitious wear |
| 71. Burr suppression | 72. Thermoplastic green machining |
| 73. Stress amplitude | 74. Ductile cutting |
| 75. Stability | 76. Micro cracks |

| | |
|---|---|
| 77. Tight tolerances | 78. Side milling |
| 79. Grinding | 80. Chemical assisted USM |
| 81. Surface profile prediction | 82. Thrust cutting force |
| 83. Ultrasonic assisted grinding | 84. Micro ultrasonic machining |
| 85. Lubricating condition | 86. Cutting temperature |
| | |
| **Tool based attributes** | |
| 87. Tool material | 88. Static force |
| 89. Tool vibration frequency | 90. Tool tip |
| 91. Tool vibration amplitude | 92. Hollow tool |
| 93. Depth of cut | 94. Speed ratio |
| 95. Feed rate | 96. Vibration displacement |
| 97. Cutting force | 98. Single crystal diamond tool |
| 99. Polycrystalline diamond | 100. Tool wear monitoring |
| 101. Solid tool | 102.Tool length |
| 103.Fatigue strength | 104.Tool work piece contact ratio |
| 105.High wear resistance | 106.Tool life |
| 107.Tool configuration | 108.Toughness of tool |
| 109.Spindle speed | 110.Penetration depth |
| 111.Hardness ratio of tool with w/pc | 112.Tool wear rate |
| 113.Tool wear acceleration | 114.Hardness of tool |
| 115.Cutting speed | 116.Tool flank wear |
| | |
| **Work piece based attributes** | |
| 117.Material of work piece | 118.Toughness of work piece |
| 119.Roughness | 120.Ti-alloys |
| 121.Lateral gap | 122.Dry softwood |
| 123.Thermal conductivity | 124.Ni- alloys |
| 125.Glass | 126.Tungsten |
| 127.Advanced ceramics | 128.Brittle material |
| 129.Wet hardwood | 130.Wet softwood |
| 131.Composites | 132.Ceramic matrix composites |

| | |
|---|---|
| 133.Dry hardwood | 134.Inconel 718 |
| 135.Feed rate of work piece | 136.End face |
| 137.Low alloy steel | 138.Chemical composition |
| 139.Super alloys | 140.Surface finish |
| 141.Upper end | 142.Conductive |
| 143.Structural ceramics | 144.Optical plastic |
| 145.Non conductive | 146.Hardness of work piece |
| 147.Wall roughness | 148.Periphery of the hole |
| | |
| **Slurry based attributes** | |
| 149.Slurry flow rate | 150.Bond type |
| 151.Slurry temperature | 152.Silicon carbide |
| 153.Benzene | 154.Median crack |
| 155.Boron carbide | 156.Alumina |
| 157.Types of fluids | 158.Oil |
| 159.Hardness of slurry material | 160.Brittle fracture |
| 161.Coolant pressure | 162.Aluminum oxide |
| 163.Specific heat | 164.Viscosity |
| 165.Particle size | 166.Glycerol |
| 167.Abrasive size | 168.Thermal conductivity |
| 169.Grit number | 170.Lateral crack |
| 171.Abrasive concentration | 172.Deformation zone |

Here, 172 attributes were found, but the user, designer or manufacturer can add or delete some of the attribute depending upon their requirements. Because it is evident that the importance of an attribute is changing depending upon application or use of different industries.

### 3.2.1 Quantification and measurement of the attributes:

The ultrasonic machine will be expressed in detailed manner with the attributes identified e.g. power rating range 50 to 3000w, ultrasonic frequency 20 kHz, grit sizes ranging from 240 to 800 etc these attributes are denoted in the form of mathematical values like 0, 1, 2, 3 ……n. But all these attributes are not quantitative e.g. accuracy, surface finish etc. It cannot be used for the mathematical form it is just a representation by alphabets A, B, C, D…... etc and whose numerical value will have no significance. The ultrasonic machine can be rated on the scale of 1–5 for these attributes. There are many attributes of which quantification is not readily available and it has to be done by some mathematical model or modelling, simulation and analysis. The quantification of many of the attributes is not available by the manufacturers. But if the manufacturer make it a standard practice to identify these attributes itself, it will be helpful to user, maintenance personnel, etc.

**Usefulness to the user**

This identification of the attributes will help the user to select the best possible parameter for the particular application according to the requirement. Identification of the attributes generates the computerized data, which is used in different formats for different purposes by different user in the manufacturing field.

**Usefulness to the maintenance personnel**

MADM-TOPSIS will also benefited to maintenance personnel, on the basis this database can plan the maintenance schedules to minimize the break down time and effectively implement the condition monitoring for preventive maintenance. They can predict the damage part of the machine.

**Usefulness to the designer**

Designer can use these attributes for cause and effect analysis, where he can find out the effects of manipulating these attributes on the ultrasonic machine performance. He identifies the critical attributes, which directly affects the performance of machine and designer changes these critical attributes and monitors them to control particular parameters.

After the identification of all the attributes, the next step is to assign the codes to the attributes which is either a numerical value or an alphabet. To ensure effective and efficient use of proposed attributes for identification, classification, comparison and ranking of ultrasonic machining system and to make this procedure user friendly an N-digit coding scheme is developed, this scheme are used to given the codes on an interval scale of 0-5 of attributes. This process is very important because it gives all the detailed information about attributes. The attributes are two types qualitative/deterministic and quantitative/fuzzy in nature. Quantitative attributes determined using mathematical models and Quantification of many of attributes is not readily available from the manufacturer. A team of experts from relevant disciplines coding all the attributes related to a particular applications.

**Table-3.3 N-digit coding scheme for attributes**

| Categories | Code |
|---|---|
| Very highly studied attribute | 5 |
| Highly studied attribute | 4 |
| Average studied attribute | 3 |
| Less studied attribute | 2 |
| Very less studied attribute | 1 |
| Absent | 0 |

The above mentioned attributes tabulated in the form of 172 coding scheme for characterization of ultrasonic machine as shown in table below.

Table.3.4: 172-digit coding scheme for characterization of parameters of ultrasonic machine.

| | |
|---|---|
| General | **1 2 3 4 5 6 7 8 9 10 11 12 13**<br>**14 15 16 17 18 19 20 21 22 23 24 25 26**<br>**27 28 29 30 31 32 33 34 35 36 37 38 39**<br>**40 41 42 43 44** |
| Process based | **45 46 47 48 49 50 51 52 53 54 55 56 57** |
| | **58 59 60 61 62 63 64 65 66 67 68 69 70** |
| | **71 72 73 74 75 76 77 78 79 80 81 82 83** |
| | **84 85 86** |
| Tool based | **87 88 89 90 91 92 93 94 95 96 97 98 99** |
| | **100 101 102 103 104 105 106 107 108 109 110 111 112** |
| | **113 114 115 116** |
| Work piece based | **117 118 119 120 121 122 123 124 125 126 127 128** |
| | **129 130 131 132 133 134 135 136 137 138 139 140** |
| | **141 142 143 144 145 146 147 148** |
| Slurry based | **149 150 151 152 153 154 155 156 157 158 159 160** |
| | **161 162 163 164 165 166 167 168 169 170 171 172** |
| | |

## 3.2.2 Coding of attributes:

The first column of table represents the block number corresponds to the 172 attributes, second column represents the name of attribute, third column represents the information about the attribute in a particular application and fourth column represents the alphanumeric code of the attribute.

Table 3.5:Coding scheme of attributes

| S/No | ATTRIBUTES | INFORMATION | CODE |
|---|---|---|---|
| 1. | Removal mechanism | Erosion | E |
| 2. | Micro chipping | | 0 |
| 3. | Finite element method | | 0 |
| 4. | Grinding | | 0 |
| 5. | Hydrofluoric acid | | 0 |
| 6. | Resonance | | 0 |
| 7. | Chemical assisted USM | | 0 |
| 8. | Diffraction grating | | 0 |
| 9. | MRR | Low | L |
| 10. | Taguchi method | | 0 |
| 11. | Vibro-impact system | | 0 |
| 12. | Cavitations | | 0 |
| 13. | Rotary ultrasonic machine | | 0 |
| 14. | Piezoelectric actuator | | 0 |
| 15. | Productive model | | 0 |
| 16. | Positive cubic stiffness | | 0 |
| 17. | Design of experiment | | 0 |
| 18. | Hypoid | | 0 |
| 19. | Single particle impact | | 5 |
| 20. | Spiral bevel gear | | 0 |
| 21. | Diamond wheel | | 0 |
| 22. | Ultrascan | | 0 |
| 23. | Ultrasonic vibration cutting | | 5 |
| 24. | Topography of end face | | 0 |
| 25. | Hole tolerance | 0.007mm | 3 |
| 26. | Beech | | 0 |
| 27. | Spruce | | 0 |
| 28. | Predictive model | | 0 |
| 29. | Ratio of brittle fracture | | 0 |
| 30. | Micro grooving | | 0 |

| | | | |
|---|---|---|---|
| 31. | Ultrasonic | | 0 |
| 32. | Neuro-fuzzy inference system | | 0 |
| 33. | Optimization | | 0 |
| 34. | On line monitoring | | 0 |
| 35. | Reinforcement content | | 0 |
| 36. | Dynamic response | | 0 |
| 37. | Nano scale removal processing | | 0 |
| 38. | High power ultrasound | | 0 |
| 39. | Power consumption | | 4 |
| 40. | Optics | | 0 |
| 41. | Impact oscillator | | 0 |
| 42. | Planar light wave circuit | | 0 |
| 43. | Theoretical model of stress | | 0 |
| 44. | Interferometry | | 0 |
| 45. | Types of transducer | Two | T |
| 46. | Wavelength spectrum | | 0 |
| 47. | Horn design | | 0 |
| 48. | Surface quality | | 4 |
| 49. | Brittle fracture | | 5 |
| 50. | Tolerances | | 0 |
| 51. | Plastic flow model | | 0 |
| 52. | Production rate | | 3 |
| 53. | Cutting fluid | | 5 |
| 54. | Fluid characterization | | 4 |
| 55. | Wheel speed | | 0 |
| 56. | Efficiency | | 0 |
| 57. | Rotational speed | 0-8000rpm | 0 |
| 58. | Non linear vibration | | 0 |
| 59. | Chip adhesion | | 0 |
| 60. | Material of horn | | 0 |
| 61. | Impacting of abrasive | | 5 |
| 62. | Hammering of abrasive | | 4 |

| | | | |
|---|---|---|---|
| 63. | Lateral gap | | 0 |
| 64. | Thermal stress | None | N |
| 65. | Nitrogen gas | | 0 |
| 66. | Microstructure | | 0 |
| 67. | Surface profile | | 0 |
| 68. | Ultrasonic lapping | | 0 |
| 69. | Fractures | | 0 |
| 70. | Attritious wear | | 0 |
| 71. | Burr suppression | | 0 |
| 72. | Thermoplastic green machining | | 0 |
| 73. | Stress amplitude | | 0 |
| 74. | Ductile cutting | | 0 |
| 75. | Stability | Stable | S |
| 76. | Micro cracks | | 0 |
| 77. | Tight tolerances | | 0 |
| 78. | Side milling | | 0 |
| 79. | Grinding | | 0 |
| 80. | Chemical assisted USM | | 0 |
| 81. | Surface roughness prediction | | 0 |
| 82. | Thrust cutting force | | 0 |
| 83. | Ultrasonic assisted cutting | | 0 |
| 84. | Micro ultrasonic machining | | 0 |
| 85. | Lubricating condition | | 0 |
| 86. | Cutting temperature | | 0 |
| 87. | Tool material | Ductile | D |
| 88. | Static force | | 0 |
| 89. | Tool vibration frequency | 20khz-200hz | 5 |
| 90. | Cutting force | | 0 |
| 91. | Tool vibration amplitude | 0.0253-0.0258mm | 5 |
| 92. | Hollow tool | | 0 |
| 93. | Depth of cut | | 4 |
| 94. | Speed ratio | | 0 |

| | | | |
|---|---|---|---|
| 95. | Feed rate | | 0 |
| 96. | Vibration displacement | | 0 |
| 97. | Tool tip | Penetrate | P |
| 98. | Single crystal diamond tool | | 0 |
| 99. | Polycrystalline diamond | | 0 |
| 100. | Tool wear monitoring | | 0 |
| 101. | Solid tool | | 0 |
| 102. | Tool length | 25mm long | L |
| 103. | Fatigue strength | | 0 |
| 104. | Tool work piece contact ratio | | 0 |
| 105. | High wear resistance | | 0 |
| 106. | Tool life | | 0 |
| 107. | Cutting speed | | 0 |
| 108. | Toughness of tool | | 4 |
| 109. | Spindle speed | | 0 |
| 110. | Penetration depth | 5mm/min | 3 |
| 111. | Hardness ratio of tool with work piece | | 4 |
| 112. | Tool wear rate | | 2 |
| 113. | Tool wear acceleration | | 0 |
| 114. | Hardness of tool | | 0 |
| 115. | Cutting speed | | 0 |
| 116. | Tool flank wear | | 0 |
| 117. | Material of work piece | Brittle | B |
| 118. | Toughness of work piece | | 3 |
| 119. | Roughness | | 0 |
| 120. | Ti-alloys | Chemically reactive | C |
| 121. | Lateral gap | | 0 |
| 122. | Dry softwood | | 0 |
| 123. | Thermal conductivity | High | H |
| 124. | Ni-alloys | | 0 |
| 125. | Glass | | 0 |
| 126. | Tungsten | | 0 |

| | | | |
|---|---|---|---|
| 127. | Advanced ceramics | | 0 |
| 128. | Brittle material | | 5 |
| 129. | Wet hardwood | | 0 |
| 130. | Wet softwood | | 0 |
| 131. | Composites | | 0 |
| 132. | Ceramic matrix composites | | 0 |
| 133. | Dry hardwood | | 0 |
| 134. | Inconel 718 | | 0 |
| 135. | Feed rate of work piece | | 0 |
| 136. | End face | | 0 |
| 137. | Low alloy steel | | 0 |
| 138. | Chemical composition | | 0 |
| 139. | Super alloys | | 0 |
| 140. | Surface finish | 0.02-0.7micrometer | M |
| 141. | Upper end | | 0 |
| 142. | Conductive | | 0 |
| 143. | Structural ceramics | | 0 |
| 144. | Optical plastic | | 0 |
| 145. | Non conductive | | 0 |
| 146. | Hardness of work piece | Above 40 HRC | A |
| 147. | Wall roughness | | 0 |
| 148. | Periphery of the hole | | 0 |
| 149. | Slurry flow rate | | 3 |
| 150. | Bond type | | 0 |
| 151. | Slurry temperature | 25.7C | 2 |
| 152. | Silicon carbide | | 5 |
| 153. | Benzene | | 0 |
| 154. | Median cracks | | 0 |
| 155. | Boron carbide | | 5 |
| 156. | Alumina | | 5 |
| 157. | Types of fluid | | 0 |
| 158. | Oil | | 0 |

| | | | |
|---|---|---|---|
| 159. | Hardness of slurry | | 3 |
| 160. | Brittle fracture | | 0 |
| 161. | Coolant pressure | | 0 |
| 162. | Aluminium oxide | | 0 |
| 163. | Specific heat | | 0 |
| 164. | Viscosity | Low | L |
| 165. | Particle size | | 0 |
| 166. | Glycerol | | 0 |
| 167. | Abrasive size | 320 | 4 |
| 168. | Thermal conductivity | 11w/mk | 4 |
| 169. | Grit number | | 5 |
| 170. | Lateral cracks | | 0 |
| 171. | Abrasive concentration | 15% In water | 5 |
| 172. | Deformation zone | | 0 |

Coding scheme for all the 172 attributes indicates information provided by the manufacturer to the user is meager and it is required to be more elaborate. In this coding scheme most of the cells have been given code 0. The 0 represents that the information relating to the particular cell is not available to the authors, but the authors think that this information also should be provided to make the database exhaustive.

| | |
|---|---|
| General | **E 0 0 0 0 0 0 0 L 0 0 0 0 0 0 0 0 0**<br>**5 0 0 0 5 0 3 0 0 0 0 0 0 0 0 0 0 0** |
| | **0 0 4 0 0 0 0 T** |
| Process based | **0 0 4 5 0 0 3 5 4 0 0 0 0 0 0 5 4 0** |
| | **N 0 0 0 0 0 0 0 0 0 0 5 0 S 0 0 0** |
| | **D 0 0 0 0 0** |
| Tool | **D 0 5 0 5 0 5 0 4 0 0 0 P 0 0 0 0 L** |

| | |
|---|---|
| based | **0 0 0 0 0 4 0 3 4 2 0 0** |
| | **B 3 0 C 0 0 H 0 0 0 0 5 0 0 0 0 0 0** |
| Work piece based | **0 0 0 0 0 M 0 0 0 0 0 A 0 0** |
| | |
| SLURRY BASED | **3 0 2 5 4 0 0 5 5 0 0 3 0 0 0 0 0 L** |
| | **0 0 4 4 5 0 5 0** |
| | |
| | |

The alphabets used in the coding scheme for parameters of ultrasonic machine give unique information. It is stable in nature represented by S, Material removal mechanism by erosion represented by E, material removal rate is low represented by L, types of transducer used in process are two represented by T, Ti alloys is chemically reactive denoted by C, hardness of work piece above 40HRC represented by A. 5 to highly important attribute and lesser code like 4, and 3 to less important and 2, and 1 to very less important attribute and 0 for totally absent attribute.

## 3.3 3- Stage Optimum Selection Procedure:

### 3.3.1 Stage 1: Elimination search method:

From all the attributes have been identified all of them would not be important while selecting the Slurry materials for particular application. There will be a few attributes which will have direct effect on the selection procedure. This small number of attributes may be set aside as pertinent attributes. The threshold values to these attributes may be assigned by obtaining information from the user/ manufacturer and group of experts. On the basis of these threshold values a smaller shortlisted number of systems are obtained. This is achieved by scanning the database for the various Systems. To facilitate that search procedure an identification system has been made for all the ultrasonic machining in the data.

### 3.3.2 Stage 2: Evaluation using TOPSIS method:

### 3.3.2.1 Decision Matrix:

A mini-database is thus formed which comprises these satisfying solutions i.e., alternatives which have all attributes satisfying the acceptable levels of aspiration. The problem is now one of finding out the optimum or best out of these satisfying solutions. The selection procedure there for needs to rank this solution in order of merit. The first step will be to represent all the information which has been obtained about the chosen pertinent attributes for the short listed systems in a matrix form. Such a matrix is called as decision matrix, D. the value of $j^{th}$ attribute in non-normalized form/units, corresponding to $i^{th}$ alternative. Thus if there are m short-listed alternatives with n pertinent attributes, the decision matrix is an m x n matrix.

### 3.3.2.2 Normalized specifications:

The next step is construction of the normalized specification matrix N, from the decision matrix D. Normalization is used to bring the data within particular range or scale, moreover, it provides dimensionless magnitudes. This phenomenon is used to calculate the normalized specification matrix. The normalized specification matrix will have the magnitudes of all the attributes of the system on the common scale of 0 to 1. It is a sort of value, which indicates the standing of that particular attribute magnitude when compared to the whole range of the magnitudes for all candidate System systems.

An element of the normalized matrix N can be calculated as

$$n_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where $d_{ij}$ is an element of the decision matrix D.

The next step is to obtain information from the user or the group of experts on the relative importance of one attribute with respect to another. This information is sought in terms of a ratio. Information on all such pair-wise comparisons is stored in a matrix called as relative importance matrix, A, which is an n*n matrix. Here $a_{ij}$ will contain in the relative importance of $i^{th}$ attribute over the $j^{th}$ attribute. The information stored in A matrix is on pair-wise basis.

It is to be modified into representation that gives the relative weights of all attributes taken together so that the cumulative sum of the weights is equal to unity. The Eigen vector method seeks to find weight vector w from the Eigen value problem associated with the matrix, A

.

$$\text{i.e. } Ax = \lambda x \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where λ is the eigen value of A and X is the corresponding eigen vector. For n*n matrix A there are n eigen values $\lambda_i$ for i= 1……..n and corresponding to $\lambda_i$, there are n eigen vector $\lambda_i$ for i= 1………n vector w is now found in the following manner.

- Take eigen vector, X max corresponding to the largest eigen value λmax, as all the elements of Xmax are either positive or negative.
- Find the sum of the elements of Xmax as

$$\alpha = \sum_{i=1}^{n} (Xi)\ max \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

- Find weight vector w as

$$W = Xmax / \alpha \text{ such that } \sum_{i=1} wi = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

### 3.3.2.3 Weighted normalized specification:

The weights obtained from the relative importance matrix have to be applied to the normalized specifications since all the attributes have different importance while selecting the slurry materials for a particular application. The matrix which combines the relative weights and normalized specification of the candidates is weighted normalized vector. It will give the true values of the attributes. This can be obtained as follows.

$$V = \begin{bmatrix} W_1 n_{1.1} & W_2 n_{1.2} \ldots W_n n_{1.n} \\ W_1 n_{2.1} & \ldots\ldots \\ W_1 n_{m.1} & W_2 n_{m.2} \ldots\ldots W_n n_{m.n} \end{bmatrix} \begin{bmatrix} V_{1.1} & V_{1.2} \ldots\ldots V_{1.n} \\ V_{2.1} & \ldots\ldots \\ V_{m.1} & V_{m.2} \ldots\ldots V_{m.n} \end{bmatrix}$$

### 3.3.3 Stage-3 Ranking and selection procedure of System:

The ranking of the systems can be done either mathematically (TOPSIS method) or graphically (Line graph and Spider diagram method). We need a measure to compare the candidates with benchmark System so that they can be ranked and selected.

#### 3.3.3.1 Topsis method:

The weighted normalized matrix V is used to obtain the +ve and –Ve benchmark slurry materials, where the both benchmark slurry materials are hypothetical slurry materials, which supposed to have best and worst possible attribute magnitudes. The topsis method is based on the concept option should have the shortest distance from the +ve benchmark slurry materialsand farthest from the –ve benchmark slurry materials. The measure ensures that the top ranked is closest to +ve benchmark slurry materials and farthest from –ve benchmark slurry materials. Here, we calculate separation measures from +ve and –ve benchmark ultrasonic machining systems, respectively as $S_i$* and $S_i^-$ as follow.

The separation from the +ve benchmark ultrasonic machining system is given by

$$S_i^* = \left[\sum_{j=1}^{n}(v_{ij} - v_1^*)^2\right]^{1/2} \quad (i = 1, 2, \ldots, m) \qquad \ldots\ldots\ldots\ldots\ldots(5)$$

and separation from the –ve benchmark ultrasonic machining is given by

$$S_i^- = \left[\sum_{j=1}^{n}(v_{ij} - v_1^-)^2\right]^{1/2} \quad (i = 1, 2, \ldots, m) \qquad \ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

Then the relative closeness to the +ve benchmark slurry material $C^*$. which is measure of the suitability of the slurry material for the chosen application on the basis of the attributes considered, is calculated. A slurry materials with the largest $C^*$ is preferable.

$$C^* = S_i^* \, ( S_i^* + S_i^- )\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

Ranking of the slurry material in accordance with the decreasing values of indices $C^*$ indicating the most preferred and the least preferred feasible optional solutions is done.

#### 3.3.3.2 Graphical method:

The mathematical representation of specifications normalized and weighted normalized specifications. The ranking of the slurry material can be done graphically (Line graph and Spider diagram method).

## Line graph representation:

We have specification matrix D, normalized and weight normalized specification matrices N and V, respectively containing information of the slurry material. These matrices can be represented graphically using line graph by plotting the magnitude of the attributes on the vertical axis and the attributes on the horizontal axis. Note that the attributes of which minimum values are preferred. If the values are plot for different slurry material obtain the line graph for them. These graphs will be distinct for all of the slurry material and can be used as comparison basis. The area under the curve can be used to quantification purpose and to compare the candidate slurry material with each other. These line graphs can be plotted for specifications, normalized and weighted normalized specifications of all the slurry materials as well as the benchmark slurry materials. Let the width between the two parameters on horizontal axis as unity and $d_{ij}$, $n_{ij}$ and $v_{ij}$ are the elements of D, N and V matrices.

Area under the line graph of specification of ith slurry material found out as:

$$\mathrm{AD}_i^L = (d_{i,1} + 2(d_{i,2} + \cdots + d_{i,n-1}) + d_{i,n})/2 \qquad \text{...............(8)}$$

Similarly area under the graph of normalized and weighted normalized specifications of the ith slurry material, i.e. $AN_i^L$ and $AV_i^L$ using their respective elements.

## Spider Diagram:

In spider diagram, the attributes have been considered to be forming the spider diagram. So the angle ø between the attribute axes can be calculated as ø = 2p/n. Where n number of attributes are under consideration. The attributes, normalized and weighted normalized specifications magnitudes are plotted to obtain the spider diagram also known as polar or radar diagram. Here the area enclosed by the polygon formed on the spider diagram is the indication of the slurry material capabilities:

$$\mathrm{AD}_i^S = \frac{\sin\theta}{2}\sum_{j=1}^{n} d_{ij} d_{i,j+1}; \quad \text{where } d_{i,n+1} = d_{i,1}. \qquad \text{..................(9)}$$

Similarly for normalized and weighted normalized specifications areas enclosed by polygons $AN_i^S$ and $AV_i^S$ respectively are calculated.

### 3.3.3.3 Identification and graphical representation of the benchmark slurry material:

The same +ve benchmark slurry material, defined earlier, is used here for the comparison of the candidate slurry material for the ranking purpose. The areas under the line graph for +ve benchmark slurry material, i.e. $AD_B^L$, $AN_B^L$, $AV_B^L$ are calculated. The areas enclosed by the polygon of spider diagram for benchmark slurry material, i.e. $AD_B^S$, $AN_B^S$, $AV_B^S$ are also calculated. All the candidate slurry material will be compared with the +ve benchmark slurry material for the evaluation purpose.

### 3.3.3.4 Ranking and selection of the slurry material:

Now specification matrix is there along with normalized specification and weighted specification matrices ready for all the candidate along with the +ve benchmark slurry material. There is a need to measure and to compare the candidates with benchmark slurry material so that be ranked and selected.

### 3.3.3.5 Coefficient of similarity (COS):

The evaluation and ranking of the slurry material using the novel graphical methods can be done by their similarity to +ve benchmark slurry material. Let the Coefficient of similarity (COS) is the ratio of area under the curve or enclosed by the polygon for the candidate to that of the benchmark slurry material. The value of COS be any +ve fraction ($0< COS < 1$) and a measure of the closeness of slurry material with the benchmark slurry material. The candidates with COS magnitude closer to unity are preferable, since it indicates the closeness to the +ve benchmark slurry material.

Coefficient of similarity (COS) based on decision matrix:

$$COS_J^D = AD_J / AD_I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$AD_J$ for jth slurry material and different methods, i.e., line graph, etc.

Coefficient of similarity (COS) based on normalized specifications matrix:

$$COS_J^N = AN_J / AN_I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$AN_J$ for jth slurry material and different methods, i.e., line graph, etc.

Coefficient of similarity (COS) based on weighted normalized matrix:

$$COS_J^V = AV_J / AV_I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$AV_J$ for jth slurry material and different methods, i.e., line graph, etc. Thus the COS calculations for all the n number of slurry material and for graphical methods, viz., line graph methods using the weighted normalized specifications

## 3.4 Illustrative example of selection of abrasive material:

The multiple attribute decision making (MADM) method is applied to solve the problem of evaluation and selection of ultrasonic machining parameters. This methodology is used first time for the selection of different slurry materials used for Titanium and its alloys. The symbol of Titanium is Ti, atomic number 22 and atomic weight 47.9. Titanium alloys are generally most difficult materials for machining in spite of their relatively low hardness Ti 6/4 annealed- 350 HV, low thermal conductivity Ti 6/4-11W/mK and high chemical reactivity at elevated temperature. Titanium and its alloys are very popular materials and very widely used in marine, aerospace, turbine engine and surgical applications. This example is based on the selection of different slurry materials like silicon carbide (SiC), boron carbide ($B_4C$) and alumina ($Al_2O_3$) each of 320 grit size for titanium alloys TITAN 15 and TITAN 31 respectively. These alloys have different chemical compositions and different toughness and pure TITAN 15 has ultimate tensile strength of 491 MPa and TITAN 31 has ultimate tensile strength of 994 Mpa

Table.3.6: Data for different slurries of ultrasonic process [Singh et al. 2006]

| Work piece material | Slurry materials | Surface roughness ,Ra (um) | Material Removal Rate (g/min) | Tool Wear Rate ( g/min) |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Titan 15 (ASTM Gr.2) | $(Al_2O_3)$<br>Silicon carbide (SiC)<br>Boron carbide ($B_4C$) | 0.48<br>0.31<br>0.46 | 0.005<br>0.00413<br>0.00263 | 0.0101<br>0.0092<br>0.00713 |
| Titan 31 (ASTM Gr.5) | $(Al_2O_3)$<br>Silicon carbide (SiC)<br>Boron carbide ($B_4C$) | 0.44<br>0.46<br>0.56 | 0.00371<br>0.00277<br>0.00247 | 0.00838<br>0.00555<br>0.00663 |

**Case 1:**

In which we take pure TITAN 15 material has ultimate tensile strength of 491 MPa and chemical composition is C-0.0140%, H-0.0007%, N-0.014%, O-0.140%, Fe-0.05% and Ti-balance with three different slurry materials. When we use alumina then surface roughness comes out 0.48, MRR is 0.005 and TWR is 0.0101, with silicon carbide roughness comes out 0.31, MRR is 0.00413 and TWR is 0.0092 and with boron carbide roughness comes out 0.46, MRR is 0.00263 and TWR is 0.00713. We have to find out the best slurry for Titan 15 which can be done by MADM approach. In this example rows represents the different slurries and first column represents the value of surface roughness for different slurries , second column represents the value of MRR and last column represents the values of TWR.

## Step1. Formation of decision matrix, D:

In this matrix, rows represent the different slurries materials and column represents the pertinent attributes. In this example 3 candidate slurries material and 3 attributes are considered with their values are listed below:

$$D = \begin{bmatrix} 0.48 & 0.005 & 0.0101 \\ 0.31 & 0.00413 & 0.0092 \\ 0.46 & 0.00263 & 0.0071 \end{bmatrix} \qquad (13)$$

**Step 2 Construction of normalized matrix:**

In this step the normalized specification matrix is calculated which helps to provide the dimensionless elements of the matrix. It is denoted by **N.**

$$N = \begin{bmatrix} 0.657 & 0.715 & 0.655 \\ 0.424 & 0.590 & 0.597 \\ 0.630 & 0.376 & 0.462 \end{bmatrix} \qquad (14)$$

**Step 3.Construction of relative importance matrix A:**

After identify the applications from different applications as per the requirement, the relative importance of different attributes for different application is different. A group of experts will determine the relative importance of the attributes with respect to each other. The symmetric terms are taken reciprocals of each other and matrix A may be written as below.

$$A= \begin{bmatrix} 1 & 7/9 & 7/5 \\ 9/7 & 1 & 9/5 \\ 5/7 & 5/9 & 1 \end{bmatrix} \qquad (15)$$

**Step 4 Find out the maximum eigen value of the relative importance matrix A:**

Eigen value formulation provides to find out the weight vector as shown in equation (16)

$$(A-\lambda I)\ W = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where, I is the identity matrix, and W is the weight vector.

$$
(A-\lambda I) = \begin{bmatrix} 1-\lambda & 0.77 & 1.4 \\ 1.28 & 1-\lambda & 1.8 \\ 0.71 & 0.55 & 1-\lambda \end{bmatrix} \qquad (17)
$$

$( A-\lambda I ) = 0$

$\lambda = 2.9898, 0.0075, 0.0027$

From this $\lambda = 2.9898$ is the maximum value, Now put this value of $\lambda = 2.9898$ in equation as below.

$$
(A-\lambda I) = \begin{bmatrix} 1-\lambda & 0.77 & 1.4 \\ 1.28 & 1-\lambda & 1.8 \\ 0.71 & 0.55 & 1-\lambda \end{bmatrix} \qquad (18)
$$

**Step.5 Calculating weights for each attribute using the eigen vector associated with the maximum eigen value λ = 2.9898**.

$$( A-\lambda_{max}I ) W = 0$$

$$
(A-\lambda_{max}I)\, W = \begin{bmatrix} -2 & 0.77 & 1.4 \\ 1.28 & -2 & 1.8 \\ 0.71 & 0.55 & -2 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} \qquad (19)
$$

$W_1 = 0.35$, $W_2 = 0.39$, $W_3 = 0.26$

### Step.6 Calculating the normalized specification matrix.

It provides the dimensionless elements of the matrix.

$$N = \begin{bmatrix} 0.657 & 0.715 & 0.655 \\ 0.424 & 0.590 & 0.597 \\ 0.630 & 0.376 & 0.462 \end{bmatrix} \begin{bmatrix} 0.35 \\ 0.39 \\ 0.26 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots (20)$$

### Step.7 calculating the weighted normalized specification matrix.

Here we incorporate the relative importance of the attributes with their normalized value to create unique parameters for the ultrasonic machining system.

$$V = \begin{bmatrix} 0.2036 & 0.2717 & 0.1506 \\ 0.1314 & 0.2242 & 0.1373 \\ 0.1953 & 0.1428 & 0.1062 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

This weighted normalized specification matrix is all inclusive matrix which takes care of the attribute values their relative importance. So that matrix will be able to provide good basis for comparison with each other and with the benchmark slurry materials.

### 3.4.1Topsis method for ranking:

The weighted normalized attributes for the positive +ve benchmark and negative –ve benchmark slurry materials is calculated by taking the largest value and smallest value from all the columns with respect to all the pertinent attributes.

$V^+ = 0.2036, 0.2717, 0.1506$

$V^- = 0.1314, 0.1428, 0.1062$

Now from the formulas above mentioned in the explanatory part of the TOPSIS method and values of separation from the positive benchmark slurry is denoted by $S^*$ and values of separation from the negative benchmark slurry is denoted by $S^-$ and relative closeness to the ideal solution can be calculated as shown below:

$S_1^* = 0$ $S_1^- = 0.1542$ $C_1^* = 1$

$S_2^* = 0.08$ $S_2^- = 0.08713$ $C_2^* = 0.4991$

$S_3^* = 0.1365$ $S_3^- = 0.0639$ $C_3^* = 0.3188$

As the $C_*$ value of the first slurry Alumina ($Al_2O_3$) is the highest (1) therefore it is the best slurry material and $C_*$ value of third slurry Boron carbide is the lowest so it is the worst slurry material.

| Sr No | Abrasive material | Value of $C^*$ | Rank |
|---|---|---|---|
| 1. | Alumina | 1 | 1st |
| 2. | Silicon carbide | 0.4991 | 2nd |
| 3. | Boron carbide | 0.3188 | 3rd |

### 3.4.2 Graphical method based ranking:

After using the TOPSIS method for the ranking and selection of the slurry materials. In which two methods are used for the selection of the slurry materials like Line graph and Spider graph. The value of weighted normalized specification matrix are used for the line graph plotting. The area under the curve in the line diagram for each system is calculated and is further used to calculate $COS^{VL}$ which is used to compare the systems. The system with the highest value of $COS^{VL}$ is ranked highest and the system with the least value of $COS^{VL}$ is ranked last. The $COS^{VL}$ for the line diagram is calculated as shown below:

$$COS^{VL} = AV_i^{\ L} / AV_{+B}^{\ L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

The value of $COS^{VL}$ for each slurry material is calculated and hence ranking of the three different materials is done as shown below.

$AV_1{}^L = 0.4448$ $\qquad$ $COS_1{}^{VL} = 1$

$AV_2{}^L = 0.3585$ $\qquad$ $COS_2{}^{VL} = 0.7987$

$AV_3{}^L = 0.2935$ $\qquad$ $COS_3{}^{VL} = 0.6539$

$AV_{+B}{}^L = 0.4488$

| Sr No | Abrasive material | $COS^{VL}$ | Rank |
|---|---|---|---|
| 1. | Alumina | 1 | $1^{st}$ |
| 2. | Silicon carbide | 0.7987 | $2^{nd}$ |
| 3. | Boron carbide | 0.6539 | $3^{rd}$ |

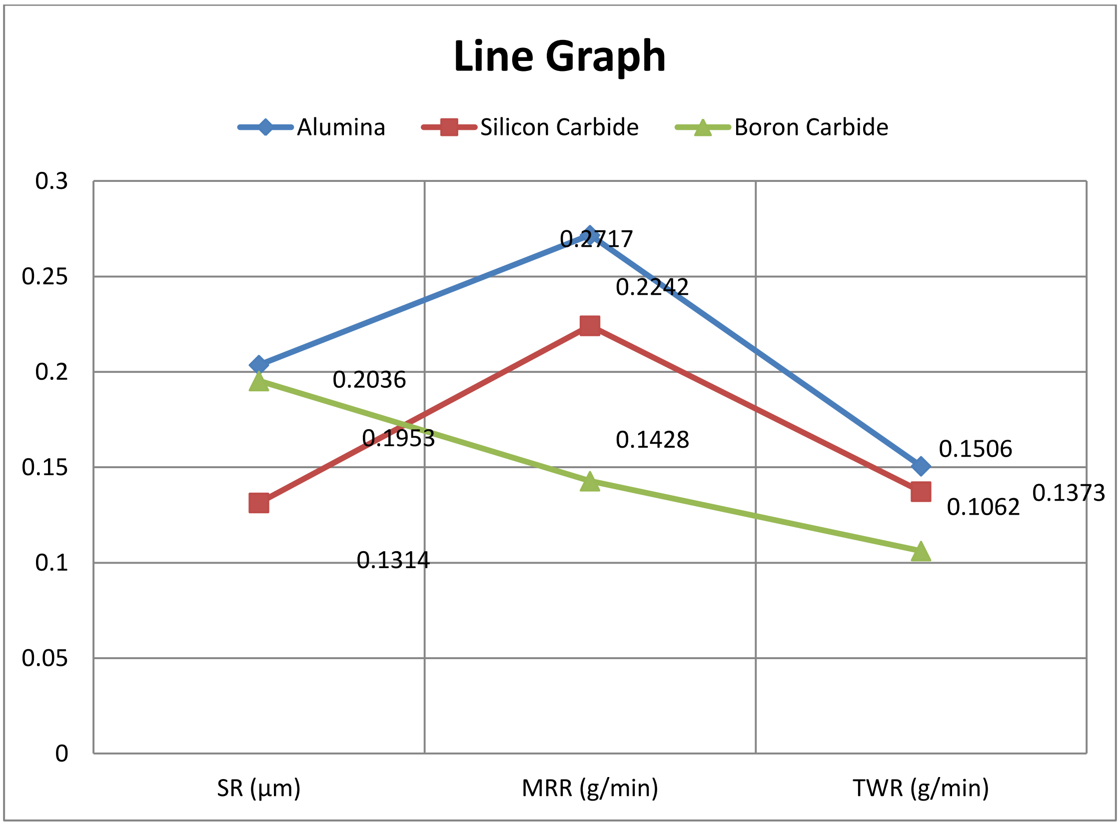



Fig-3.5 Line graph of different slurry materials

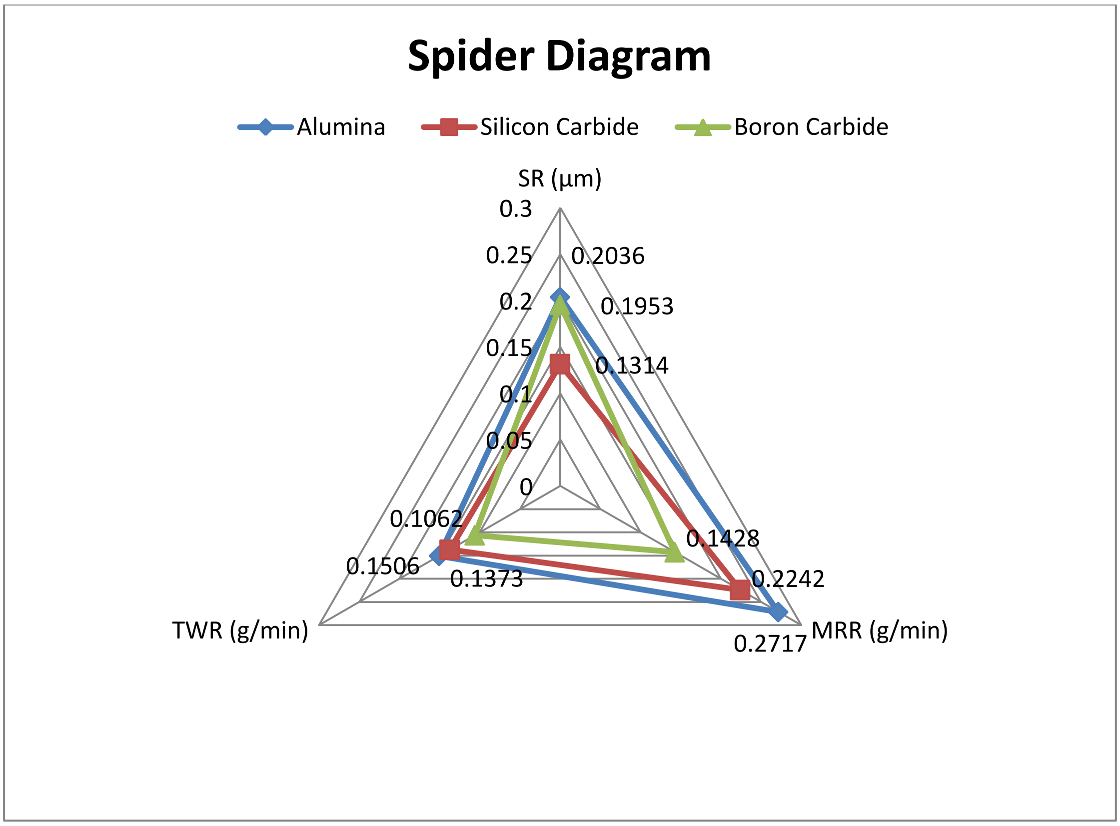



Fig-3.6 Spider graph for different slurry material

### Case 2:

In which take pure Titan 31 material has ultimate tensile strength of 994 MPa and chemical composition is C-0.0190%, H-0.0011%, N-0.007%, O-0.138%, Fe-0.05%,Al-6.27, V-4.04% and Ti-balance with three different slurry materials. When we use alumina then surface roughness comes out 0.44, MRR is 0.00371 and TWR is 0.00838, with silicon carbide roughness comes out 0.46, MRR is 0.00277 and TWR is 0.0055 and with boron carbide roughness comes out 0.56, MRR is 0.00247 and TWR is 0.00663. We have to find out the best slurry for Titan 31 which can be done by MADM approach.

## 3.5.1 Formation of decision matrix, D:

In this matrix, rows represent the different slurries materials and column represents the pertinent attributes. In this example 3 candidate slurries material and 3 attributes are considered with their values are listed below:

$$D = \begin{bmatrix} 0.44 & 0.00371 & 0.00838 \\ 0.46 & 0.00277 & 0.00555 \\ 0.56 & 0.00247 & 0.00663 \end{bmatrix} \qquad (23)$$

Use the value of this decision matrix D determines the ranking of different slurry materials for Titan 31 on the basis of Topsis method and Graphical method.

### 3.5.2 Topsis method for ranking:

The weighted normalized attributes for the positive +ve benchmark and negative –ve benchmark slurry materials is calculated by taking the largest value and smallest value from all the columns with respect to all the pertinent attributes.

$V^+ = 0.2046, 0.2686, 0.1600$

$V^- = 0.1605, 0.1786, 0.1058$

Now from the formulas above mentioned in the explanatory part of the TOPSIS method and values of separation from the positive benchmark slurry is denoted by $S^*$ and values of separation from the negative benchmark slurry is denoted by $S^-$ and relative closeness to the ideal solution can be calculated as shown below:

| | | |
|---|---|---|
| $S_1^* = 0.0441$ | $S_1^- = 0.1050$ | $C_1^* = 0.7042$ |
| $S_2^* = 0.0946$ | $S_2^- = 0.0228$ | $C_2^* = 0.1942$ |
| $S_3^* = 0.0960$ | $S_3^- = 0.0487$ | $C_3^* = 0.3365$ |

As the $C_*$ value of the first slurry Alumina ($Al_2O_3$) is the highest (1) therefore it is the best slurry material and $C_*$ value of third slurry Boron carbide is the lowest so it is the worst slurry material.

| Sr No | Abrasive material | Value of $C^*$ | Rank |
|---|---|---|---|
| 1. | Alumina | 0.7042 | 1st |
| 2. | Silicon carbide | 0.1942 | 3rd |
| 3. | Boron carbide | 0.3365 | 2nd |

### 3.5.3 Graphical method based ranking:

After using the TOPSIS method for the ranking and selection of the slurry materials. In which two methods are used for the selection of the slurry materials like Line graph and Spider graph. The value of weighted normalized specification matrix is used for the line graph plotting. The area under the curve in the line diagram for each system is calculated and is further used to calculate $COS^{VL}$ which is used to compare the systems. The system with the highest value of $COS^{VL}$ is ranked highest and the system with the least value of $COS^{VL}$ is ranked last. The $COS^{VL}$ for the line diagram is calculated as shown below:

$$COS^{VL} = AV_i^{\ L} / AV_{+B}^{\ L} \qquad \text{……………………} \ (22)$$

The value of $COS^{VL}$ for each slurry material is calculated and hence ranking of the three different materials is done as shown below.

$AV_1^{\ L} = 0.4288$ $\qquad COS_1^{VL} = 1.1175$

$AV_2^{\ L} = 0.3371$ $\qquad COS_2^{VL} = 0.878$

$AV_3^{\ L} = 0.3441$ $\qquad COS_3^{VL} = 0.896$

$AV_{+B}^{\ L} = 0.3837$

| Sr No | Abrasive material | $COS^{VL}$ | Rank |
|---|---|---|---|
| 1. | Alumina | 1.1175 | 1st |
| 2. | Silicon carbide | 0.878 | 3rd |
| 3. | Boron carbide | 0.896 | 2nd |

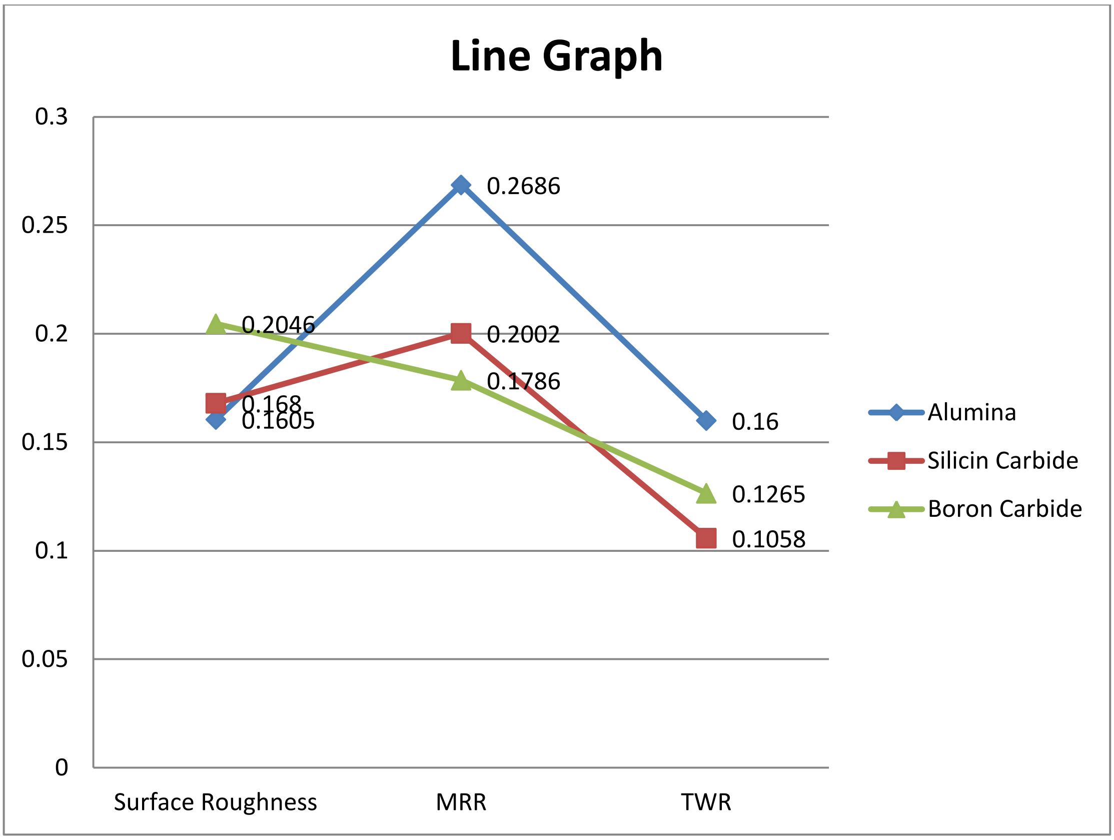



Fig-3.7 Line graph of different slurry materials

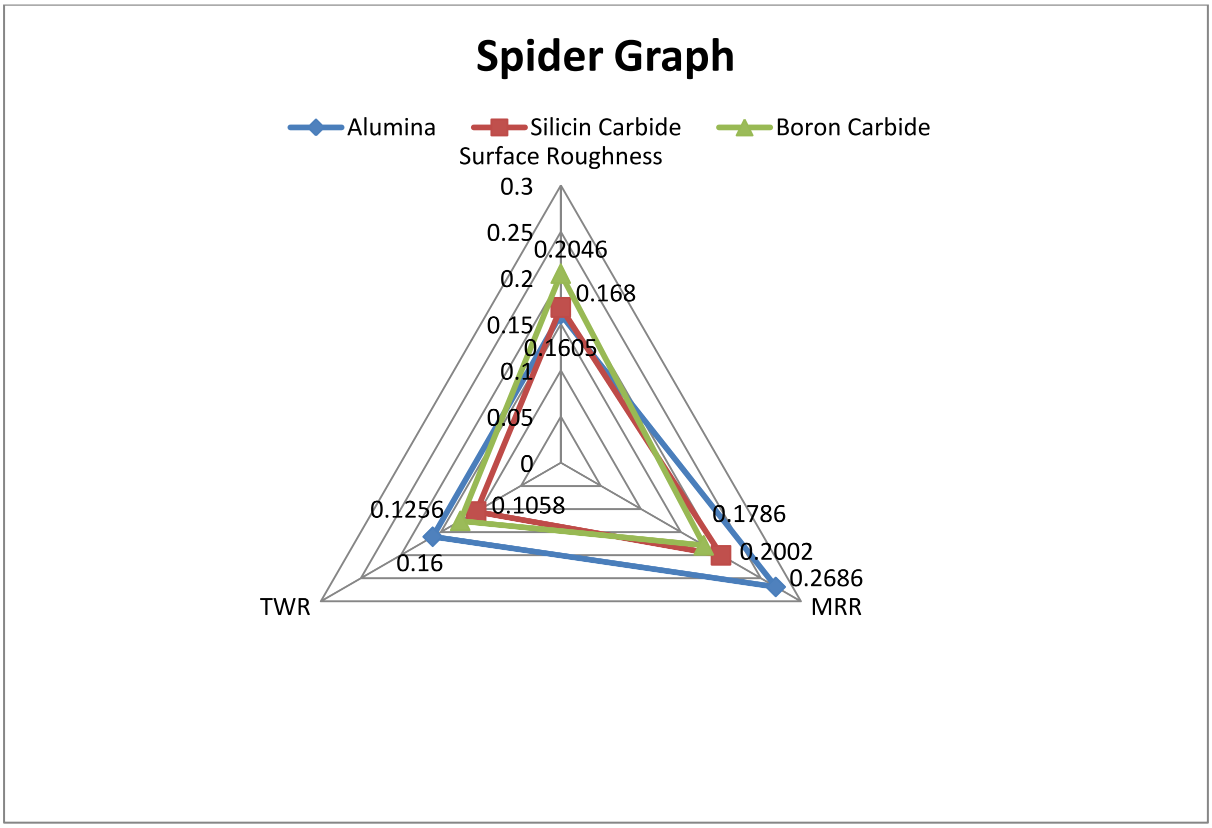



Fig-3.8 Spider graph for different slurry material

## 3.6 Discussion about process:

In this chapter we applied MADM TOPSIS method for evaluation, ranking and selection of slurry materials for Titanium and its alloys Titan 15 and Titan 31 with different chemical compositions and with different tensile strength. We can use substantial number of parameters for this process like Material removal rate MRR, Tool wear rate TWR, Surface roughness, type of work pieces and type of slurries. So to choose a best set of parameters is a difficult task. To solve this problem we mainly use MADM TOPSIS method provide us ranking of different parameters which makes the selection of parameters very easy. As in this study the problem of selection of best slurry is solved for two materials. Three slurry materials are alumina, silicon carbide and boron carbide are considered and decision matrix is made two times for two different materials like Titan 15 and Titan 31 by taking the value of Surface roughness, Material Removal Rate and Tool wear Rate as Attributes corresponding to these three slurry materials. After applying this method Alumina slurry proves to be best slurry material for both materials and boron carbide proves to be worst slurry for Titan 15 but in case of Titan 31 silicon carbide proves to be worst slurry.

## 3.7 Results:

In this chapter MADM TOPSIS method is applied for evaluation, selection and ranking of slurry materials for Titanium and its alloys like Titan 15 and Titan 31. Ranking is done by TOPSIS $C^*$ values, $COS^{VL}$ values of line graphs and area under the spider diagram. Results of these techniques is shown in tables above in this study. In all three methods of ranking Alumina proves to be best slurry materials for both materials, silicon carbide got 2$^{nd}$ rank and boron carbide proves to be worst slurry material for titan 15 and in case of titan 31 boron carbide got 2$^{nd}$ rank and silicon carbide proves to be worst slurry material. All three techniques i.e. TOPSIS, Line Graph and Spider Diagram gives same results.

# CHAPTER-4

# STRUCTURAL MODELING AND ANALYSIS OF ULTRASONIC MACHINING (USM) SYSTEM USING GRAPH THEORETIC APPROACH

This chapter is made to develop an integrated system model for the structure of the ultrasonic machining system in terms of its constituents and interactions between the processes by using graph theoretic approach and matrix algebra. The elements constituting the ultrasonic machining system and the interactions between them have been identified through a literature survey and represented by graph based model , then by a variable adjacency matrix and then by a multinomial known as a permanent function. A graph is useful for visual analysis of the ultrasonic machining system, but quantification of these interactions is necessary for design and analysis. A graph G consists of a set of objects V= [$V_1$, $V_2$] and E= [$e_1$, $e_2$.........] called vertices and edges. The common representation of graph is diagram in which the vertices are denoted by small points or circles and each edge as a line segment joining its and vertices. The important purpose of graph theory in the modelling of systems, network analysis, conceptual modelling, functional representation and diagnosis etc. Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of ultrasonic machining system in different performance dimensions. The matrix models and variable permanent function models provides an opportunity for carrying out characterization analysis and optimization. The permanent function of the ultrasonic machining system matrix has been proposed as a systematic technique for structural analysis of system. Different structural attributes of ultrasonic machining system are identified to develop a graph theoretic model. This graph theory based methodology is a novel mechanism to integrate ultrasonic machining system giving way to system wide optimization.

## 4.1 Introduction:

Ultrasonic machine has been successfully applied to many conductive and non-conductive brittle materials like glass, ceramics, carbides, and graphite etc. Brittle material is used for many applications due to their high hardness and strength at elevated temperatures [Astashev and Babitsky 1998]. The machining of these types of properties is difficult into a precise size and shape [Kim and Choi 1997]. Ultrasonic machining is an abrasive process, and material removal is purely mechanical [Dam et al. 1995]. The process does not cause heat affected zone and any chemical or electrical alterations on work piece surface [Pei et al.1995]. It does not change the metallurgical, chemical or physical properties of the work pieces [Choi et al.2007]. In this process equipment consists of a vibrational horn, a tool part, an abrasive paste, and the working material [Curodeau et al. 2008]. Ultrasonic machine four different mechanisms are responsible for removal of material from the work surface. Material removed by direct hammering of abrasive particles on the work piece, Micro chipping by impact of free moving particles, Cavitations effect from the abrasive slurry, Chemical action associated with the fluid used [Prabhakaran et al 2006]. The mechanical properties of the work material influence USM process showed that tough material give a low removal rate, high tool wear and reasonable surface roughness [Hocheng and Kuo 2002]. The power supply depends on the size of transducers [Zeng et al.2005]. In ultrasonic machining two types of transducer are used magnetostrictive or piezoelectric are based on two different operations, piezoelectric transducers eliminates the use of water cooling due to high electromechanical conversion efficiency (up to 96% ) and available with power capacity up to 900W. The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator. The tool is hold in the tool holder to the transducer. The cutting tool is pressed generally in downward direction with a feed force (F) and it vibrates at an ultrasonic frequency 20 kHz with amplitude of 20 μm over the work piece [Amin et al 1995]. These abrasive particles are flooded on machining zone in the form of water based slurry between the cutting tool and work piece. The abrasive slurry is the mixture of the abrasive materials like silicon carbide ($S_iC$), boron carbide ($B_4C$), corundum ($Al_2O_3$) with water or oil [Singh and Khamba 2008]. The slurry is used for machining is stored in slurry tank and it is flooded by slurry pump between work piece and cutting tool. All the abrasives are considered to be identical in shape and size, it is considered to be spherical. During machining the materials is removed in the form of small particles and it is carried away by the slurry. The power ratings range from 50 to 3000 W and it reach 4 kW in some machines. It rotated by a servomotor simultaneously. Ultrasonic machining called by various termed ultrasonic drilling, ultrasonic abrasive machining and ultrasonic cutting. USM creates desired accurate cavities of any shape through the impact grinding of fine grains [Sun et al.1996]. Ultrasonic machining can be used to form and redress graphite electrodes for electrical discharge machining. It is especially suited to the forming and redressing of intricately shaped and detailed configurations requiring sharp internal corners and excellent surface finishes. It is particularly useful in micro drilling holes of up to 0.1 mm. Ultrasonic machines have a relatively low material removal rate**.** Material removal rates are quite low, usually less than 50 mm3/min. The abrasive slurry also machines the tool itself, thus causing high rate of tool wear**,** which in turn makes it very difficult to hold close tolerances. One modification of USM to overcome some disadvantages its name is rotary ultrasonic machining. The power required for RUM process is less than that used for USM [Singh and Khamba 2008]. Rotary ultrasonic machining (RUM) is 10 times faster than USM [Pei et al 1995]. It reduces the inaccuracies like oversize and out of roundness. Ultrasonic turning is the most common process is claimed to reduce machining time, work residual stresses and improve surface quality and tool life compared to conventional turning. Now day's ultrasonic vibrations are used successfully to enhance machining capability of micro EDM to handle titanium alloys [Singh and Khamba 2008]. We proposed a new approach that can help in getting good competing benefits and high performance of product in a shorter time. The proposed model will be useful for analyzing, evaluating and designing a ultrasonic machining system at the conceptual stage.

## 4.2 Assumptions for developing graph theoretic approach:

The proposed graph theoretic approach for Ultrasonic machining system is based on some assumptions as listed below:

- The structure of the ultrasonic machining system can be correlated quantitatively with its performance.eg. productivity, quality, reliability, etc.
- The subsystems must be identified separately for applying the graph theoretic model to any specific ultrasonic machining system.
- The subsystems of ultrasonic machining system and their interactions for the organization under consideration depend upon its objectives and value system etc.
- Variable permanent matrix is capable of storing complete information related to a real life situation of a typical manufacturing system as all its elements are variables and functions of characterizing attributes. This is possible by associating a vector of attributes representing subsystems (i.e. diagonal elements) and interconnections (i.e. off-diagonal elements). These attributes, if identified comprehensively, the matrix represents the manufacturing system completely.
- Permanent function of the variable permanent matrix characterizes uniquely the ultrasonic machining system from the point of view of structure.

- Performance of a manufacturing system depends on individual performance of subsystems, sub-subsystems and their components along with interactions/interdependences/influences between them.
- Modelling/methodology is based on bottom up approach. Permanent function values of sub-systems are used in permanent matrices of subsystems. Permanent function values of subsystems are used to calculate permanent function of ultrasonic machining system.
- The experts may assign correct and representative numerical score to the elements of the manufacturing system at the lowest level in a particular dimension of performance.

## 4.3 Identification of subsystems of the ultrasonic machining System:

For description of the methodology, five subsystems have been identified namely power supply, transducer, tools, abrasives, and output subsystems. These subsystems having different functionalities and are from different disciplinary backgrounds like mechanical, electrical or combination of these. This is a representative assumption for a general ultrasonic machining system and the entire important criterions governing the ultrasonic machining system behaviour are reflected in these subsystems. These subsystems may not be universal and there may be some variations for modelling specific ultrasonic machining system. However the proposed model has the capability to consider any such variation and is suitable for modelling any particular ultrasonic machining system structure. The following sections discuss the importance of each of the identified subsystems of the ultrasonic machining system. Performance of the ultrasonic machining system depends on individual performance of the subsystems along with interactions between them.

### 4.3.1 Power supply subsystem:

High power sine-wave generator is used to supply the power for ultrasonic machine, it converts the low frequency (60 Hz) electrical power to high frequency electrical power (20 KHz) and this electrical signal supplied to the transducer. It control over both the frequency and power of the generated signal. Power supply used in the process depends on the size of the transducers. It influences the performance of tool, transducers and abrasive particles.

### 4.3.2 Transducer subsystem:

The transducer is used to converts the energy from one form to another form, in case of ultrasonic machining transducer is used to convert the high frequency electrical energy into mechanical motion. In ultrasonic machining two types of transducer are used magnetostrictive or piezoelectric. These transducers are based on two different operations, piezoelectric transducers eliminates the use of water cooling due to high electromechanical conversion efficiency (up to 96% ) and available with power capacity up to 900W. Magnetostrictive transducers have electromechanical conversion efficiency range between (20 to 35 %), piezoelectric transducers can generate high vibration intensities as compared to magnetostrictive transducers. Magnetostrictive transducers are usually constructed from a laminated stack of nickel sheets.

### 4.3.3 Tools subsystem:

Various types of tools used in ultrasonic machining systems. The tool is made of soft and tough materials like brass, carbide, mild or tool steel due to minimum wear rate. The cutting tool is pressed generally in downward direction with a feed force (F) and it vibrates at an ultrasonic frequency 20 kHz with amplitude of 20 μm over the work piece [Amin et al 1995]. 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 [Prabhakaran et al 2006]. During machining the tool also gets reduced with work piece in size due to the cutting action of the abrasive grits. The tool is designed to provide the maximum amplitude of vibration at the free end at a given frequency. Mostly the tool used is less than 25mm long. Tool can be joined to the horn either by soldering or brazing, screw fitting. Tool with diamond tips have good material removal characteristics and extremely low wear rate in USM.

### 4.3.4 Abrasive subsystem:

In USM many types of abrasive particles are used for a particular applications include hardness, cost, life and size. These abrasives are boron carbide, silicon carbide, aluminium oxide and diamond. These abrasives are used with many fluids in slurry such as water, benzene, glycerol and oils but water is commonly used due to less viscosity. The abrasive material is mixed with water to form the slurry this can vary from 30 to 60 percent of abrasive concentration but common abrasive concentration is 50% by weight. Abrasive are generally available in grit sizes ranging from 240 to 800. The most popular general purpose abrasive used is 320 grit. Best surface finish has been reported using 800 grit abrasives and is of the order of 0.25 μm but at a drastic reduction in metal removal rate. The thinner mixtures are used to promote efficient flow when drilling deep holes or for complex cavities [Prabhakaran et al 2006]. Boron carbide is mostly used when machining the hardest work piece materials and highest material removal rates are desired. It is more efficient than other and its cutting time is less than 20-40 than silicon carbide is used. Silicon carbide is used for glass and ceramics. Aluminium oxides is much efficient than others. Diamond is used in case of diamond and rubies cutting. These abrasive mixed with water and stored in the reservoir and pumped between work piece and tool.

### 4.3.5 Output subsystem:

In output subsystem consists material removal rate, tool wear rate, surface roughness and dimensional accuracy of system using ultrasonic machine. The material removal rate of ultrasonic machine is directly related to power capability of the machine. Tool wear is an important variable in USM, affecting both MRR and hole accuracy. Less TWR and better MRR can be attained by using specific tool, work piece combination at specific power rating values and controlled experimental conditions like slurry type [Singh and Khamba 2008]. If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in higher work piece MRR. The hardness of slurry material should be more than work piece, the grit sizes larger and higher slurry concentrations results into higher MRR. For optimum MRR/TWR the acoustic washer should be replaced after every dismantling of tool/horn assembly [Singh and Khamba2006].

### 4.4 Graph theoretic approach representation:

The tasks for each subsystem and the sub-subsystem have been compiled in the tree diagram at total ultrasonic machining system.

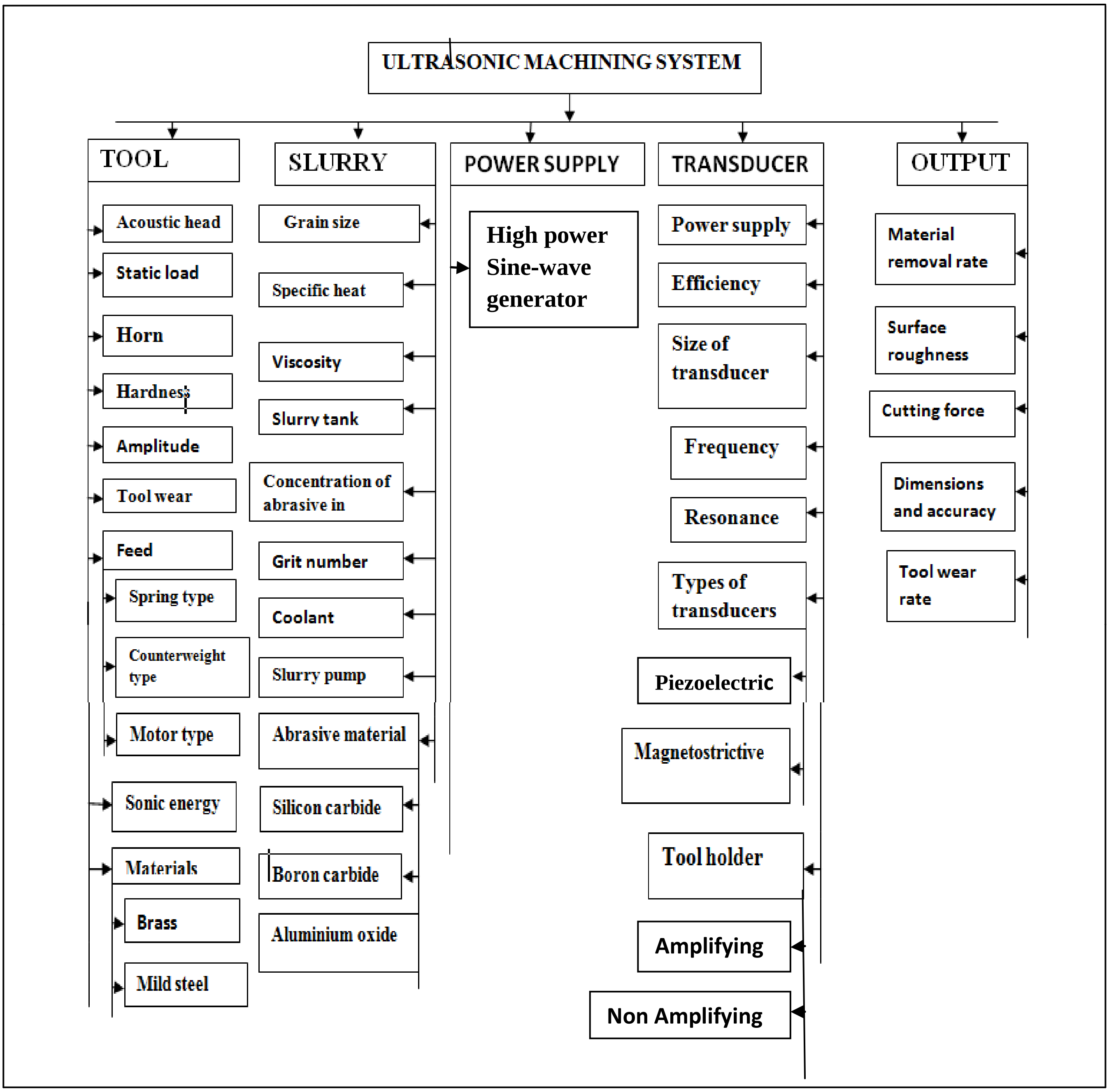



**Figure: 4.1-Structural constituents of ultrasonic machining system:**

The hierarchical tree of the system is helpful in identifying components of system at each level and for thorough understanding of physical structure, it is not same structure for each ultrasonic machining system as shown in figure in fig-5.1, there may be some variations in the subsystems according to the structure of system. These subsystems are interrelated and interdependent on each other through different forms of bonding, e.g. In ultrasonic machining systems the material removal rate, accuracy and surface finish are depends on the tool, power, amplitude, abrasive size and frequency, the power supply have direct influence on the performance of tool, performance of abrasive and outputs. The above hierarchal tree diagram represent all the subsystems of the ultrasonic machining system, but this tree fails to shows the connectivity and interdependences between different subsystems of ultrasonic machining systems shown in figure-5.1.

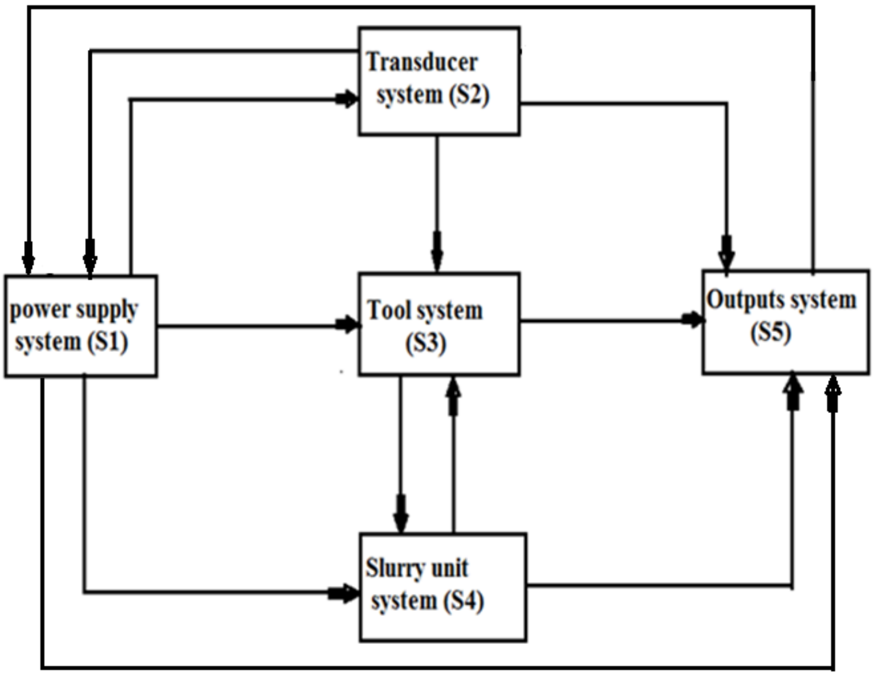



**Figure.4.2-Schematic representation of the structure of ultrasonic machining system**

So, a schematic diagram is developed to representation of ultrasonic machining system structure along with all the interactions between the subsystems which provide better understanding of the structure of the ultrasonic machining system, but it is not a mathematical entity shown in figure-5.2. However it is not possible to derive different results without using any mathematical models. Thus, for the representation of the ultrasonic machining system, it is quite logical to select the graph theory and mathematical representation of ultrasonic machining system using matrix algebra. Due to this purpose, a graph G has been defined as a function of vertex ( V) set and edge(E) set, where vertex set V= $[V_1,V_2 ..........V_n]$ and edge set E= $[e_1,e_2..........e_n]$ joining different vertices. To represent a ultrasonic machining system mathematically, let the constituents of the ultrasonic machining represented by vertex set [V] of the graph and interaction/connectivity/interdependence between different constituents is represented by directed edge instead of an undirected edge. Let vertices V correspond to subsystem (Vi) and edges ($e_{ij}$) correspond to connectivity/interaction/interdependence from subsystem to subsystem. The constitute of ultrasonic machining system are represented by vertices of the graph and interaction of the subsystems are represented by edges of the graph.

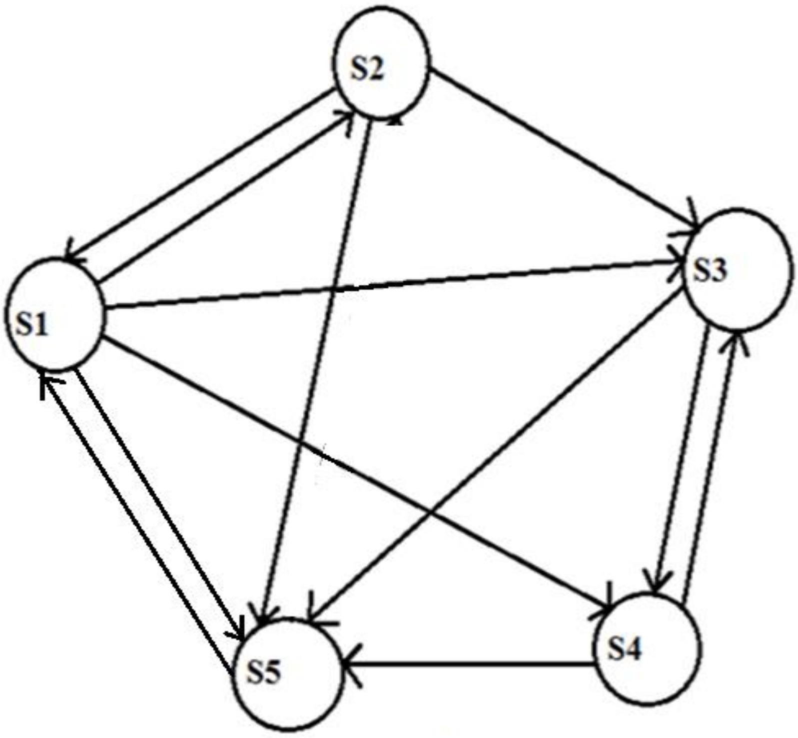



**Figure.4.3-Ultrasonic machining system digraph**

The graph representation of ultrasonic machining with ($e_{ij}$=$e_{ji}$). This means that the influence of $i^{th}$ vertex on $j^{th}$ vertex is not equal to the influence of $j^{th}$ vertex on $i^{th}$ vertex. In ultrasonic machining systems, some constituents are not connected/interacted with each other, this shows that no edge will exist between those vertices. The graph theoretic approach of ultrasonic machining system may consist both the edges directed or undirected. A ultrasonic machining system consists of five different subsystems. These subsystems influence on each other's is shown in figure-5.2. But this figure is a non mathematical entity. In figure –5.3 ultrasonic machining system is represented by a mathematical entity called as ultrasonic machining system digraph, it represents the structure of ultrasonic machining system. Since a digraph is a visual representation, it is useful to visual analysis to a limited extent only. The ultrasonic machining system graph is a useful mathematical entity and is highly useful for comprehensive understanding of total ultrasonic machining system through for visual analysis. But for computational analysis, the necessary information cannot be sorted in a computer directly. For achieving this objective, the ultrasonic system graph can be represented in the form of various matrices.

### 4.4.1 Matrix representation for the ultrasonic machining system graph:

The representation of system structure matrix by adjacency matrix, it is a square matrix having rows and columns correspond to respective sub systems. It is a binary square matrix having (0,1) as elements. Ultrasonic machining system of N, subsystems is represented by a structure matrix of size N×N. The matrix of the graph G with five nodes will be a five order binary (0,1) square matrix, A= $[a_{ij}]$. The rows and columns in the matrix represent the vertices attributes, such that:

$$a_{ij} = \begin{cases} 1, \text{ if subsystem } i \text{ is connected to subsystem } j \\ 0, \text{ if } i \text{ and } j \text{ are not connected} \end{cases}$$

The adjacency matrix of the system represents the interaction/connectivity between the subsystems by using binary numbers 1and 0. The connectivity/interaction exist between two Subsystems, it represent by 1 otherwise 0. The adjacency matrix denoted by A for the ultrasonic machining system graph G is shown as below:

$$A = \begin{array}{cc} \begin{array}{ccccc} \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} \end{array} & \textbf{subsystems} \\ \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} & \begin{array}{c} \mathbf{1} \\ \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \\ \mathbf{5} \end{array} \end{array} \qquad \mathbf{(1)}$$

This adjacency matrix A is representing the interaction only of subsystems of ultrasonic machining system but not represents the characteristics of ultrasonic machining system.

### 4.4.1.1 Ultrasonic machining system characteristic matrix:

To characterize the ultrasonic machining system, a new characteristic matrix is defined and is named as ultrasonic machining system characteristic matrix by using the identity matrix **I** and a variable $\boldsymbol{\lambda}$ which represents the eigen values of ultrasonic machining system and adjacency matrix **A.** The ultrasonic machining system characteristic matrix is denoted by **B** and derived based on the standard characteristic equation in mathematics may be expressed as **B= [$\boldsymbol{\lambda}$ I-A] .** In this characteristic equation, all the values of diagonal elements is same, but in real situation it is not possible, the different subsystem of ultrasonic machining system are having different characteristics depending on various parameters. The binary number 1 is used to shows the connectivity in matrix B, but it does not provide information like type of connectivity and degree of interaction of one subsystem over the other subsystem. It cannot be used to characterize the ultrasonic machining system completely. The matrix **B** can be developed by using standard characteristic equation in mathematics may be expressed as **B= [$\boldsymbol{\lambda}$ I-A].** Here $\lambda$ represents eigen values for the matrix and **I** matrix is used to show the identity matrix of same order.

$$
\mathbf{B} = \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \quad \text{Subsystems} \\ \begin{bmatrix} \lambda & -1 & -1 & -1 & -1 \\ -1 & \lambda & -1 & 0 & -1 \\ 0 & 0 & \lambda & -1 & -1 \\ 0 & 0 & -1 & \lambda & -1 \\ -1 & 0 & 0 & 0 & \lambda \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (2)
$$

$$
\textbf{Det (B)} = \lambda^5 - \lambda^3 + 3\lambda^2 + 2\lambda + 1
$$

The determinant of the ultrasonic machining system characteristic matrix B will lead to an invariant of this matrix, it is developed for equation **(2)** of characteristic matrix**.** This characteristic matrix does not represent varying degree of influence of one subsystem over the other subsystems of ultrasonic machining system. This matrix can not be used to characterize the ultrasonic machining system completely. To overcome this problem, another new matrix is proposed called ultrasonic machining system characteristic and interdependence variable matrix.

#### 4.4.1.2 Ultrasonic machining system characteristic and interdependence variable matrix:

The ultrasonic machining system characteristic and interdependence variable matrix takes into consideration the effect of different subsystems and their varying degrees of interactions. The ultrasonic machining structure graph is considering for defining this characteristic and interdependence variable matrix **C** shown as below in fig **(5)**.

$$\mathbf{D} = \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \;\; \textbf{Subsystems} \\ \left[\begin{array}{ccccc} S_1 & 0 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 & 0 \\ 0 & 0 & S_3 & 0 & 0 \\ 0 & 0 & 0 & S_4 & 0 \\ 0 & 0 & 0 & 0 & S_5 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad \textbf{(3)}$$

$$
\mathbf{E} = \begin{array}{cc}
\begin{array}{ccccc} \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} \end{array} & \textbf{Subsystems} \\
\begin{bmatrix}
0 & e_{12} & e_{13} & e_{14} & e_{15} \\
e_{21} & 0 & e_{23} & 0 & e_{25} \\
0 & 0 & 0 & e_{34} & e_{35} \\
0 & 0 & e_{43} & 0 & e_{45} \\
e_{51} & 0 & 0 & 0 & 0
\end{bmatrix} & \begin{array}{c} \mathbf{1} \\ \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \\ \mathbf{5} \end{array}
\end{array} \qquad \mathbf{(4)}
$$

For this purpose a five order square matrix **E** with off-diagonal elements $e_{ij}$ representing varying levels of interactions between the subsystems is defined as shown in fig **(4)** and another matrix **D** is a diagonal matrix with diagonal elements Si, i = 1, 2, 3, 4, 5 representing five different subsystems is defined as shown in fig **(3)**. The matrix **C** can be developed from the matrices D and **E** as **C= [D-E].**

$$
\mathbf{C= [D-E]} \quad \begin{array}{cc}
\begin{array}{ccccc} \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} \end{array} & \textbf{subsystems} \\
\begin{bmatrix}
S_1 & -e_{12} & -e_{13} & -e_{14} & -e_{15} \\
-e_{21} & S_2 & -e_{23} & 0 & -e_{25} \\
0 & 0 & S_3 & -e_{34} & -e_{35} \\
0 & 0 & -e_{43} & S_4 & e_{45} \\
-e_{51} & 0 & 0 & 0 & S_5
\end{bmatrix} & \begin{array}{c} \mathbf{1} \\ \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \\ \mathbf{5} \end{array}
\end{array} \qquad \mathbf{(5)}
$$

This **C** matrix distinctly represents the characteristic features of the subsystem and their interactions. Thus, the matrix **C** in equation **(5)** is complete structural representation of the ultrasonic machining system capturing all the data related to the ultrasonic machining system including the interactions. This information is useful for optimization purposes and provides a powerful tool through its determinant called a ultrasonic machining system characteristic and interdependence variable multinomial, it include both positive and negative signs. The determinant of the matrix C is an invariant of the ultrasonic machining system is developed in equation **(6).** The multinomial is the symbolic terms contain complete information of the ultrasonic machining system. On substituting numerical values in the place of diagonal and off- diagonal elements and some of the information is lost in the determinant. The loss of this information due to the addition and subtraction of numerical values of the diagonals and off-diagonals elements. To avoid the loss of information during mathematical process, another term ultrasonic machining system permanent matrix is introduced.

$$
\begin{aligned}
\mathrm{Det}\,(C) = {} & [S_1\, S_2\, S_3\, S_4\, S_5] + [S_2\, S_3\, S_4\, e_{15}\, e_{51} - S_1\, S_2\, S_5\, e_{43}\, e_{34} - S_3\, S_4\, S_5\, e_{12}\, e_{21}] \\
& +[-S_3\, S_4\, e_{12}\, e_{25}\, e_{51} - S_2\, S_4\, e_{13}\, e_{35}\, e_{51} + S_2\, S_3\, e_{14}\, e_{45}\, e_{51}] \\
& +[-S_4\, e_{12}\, e_{23}\, e_{35}\, e_{51} - S_2\, e_{13}\, e_{34}\, e_{45}\, e_{51} + S_2\, e_{14}\, e_{43}\, e_{35}\, e_{51}] \\
& - [S_2\, e_{34}\, e_{43}\, e_{51}\, e_{15} + S_5\, e_{12}\, e_{21}\, e_{34}\, e_{43}] \\
& +[- e_{12}\, e_{23}\, e_{34}\, e_{45}\, e_{51} + e_{34}\, e_{43}\, e_{12}\, e_{25}\, e_{51}] \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(6)}
\end{aligned}
$$

### 4.4.1.3 The ultrasonic machining system permanent matrix:

The permanent matrix is obtained from the ultrasonic machining system characteristic and interdependence variable matrix, the negative sign from all the elements are converted into positive sign. This model of expression considers all the quantitative values of subsystems and interactions without any loss of information in multinomial representation. Thus ultrasonic machining system characteristic and interdependence variable permanent matrix as shown below in fig (7). It is represented by matrix P.

$$P = \begin{array}{cc} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} & \text{subsystems} \\ \begin{bmatrix} S_1 & e_{12} & e_{13} & e_{14} & e_{15} \\ e_{21} & S_2 & e_{23} & 0 & e_{25} \\ 0 & 0 & S_3 & e_{34} & e_{35} \\ 0 & 0 & e_{43} & S_4 & e_{45} \\ e_{51} & 0 & 0 & 0 & S_5 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad \textbf{(7)}$$

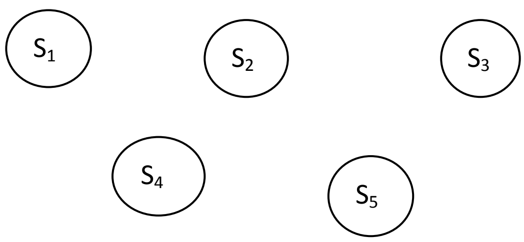
### 4.4.1.4 Development of permanent function for ultrasonic machining system:

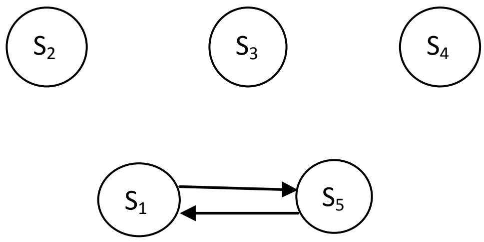
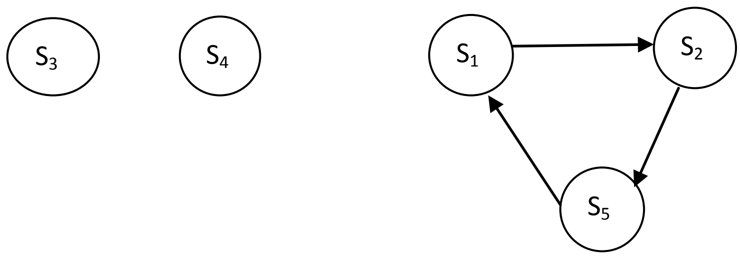
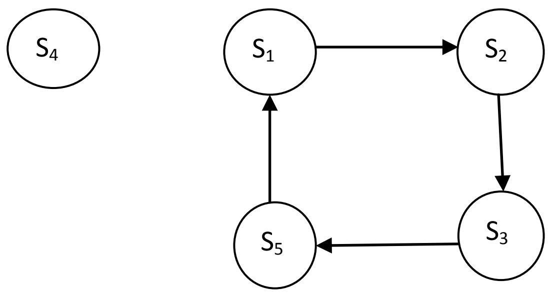
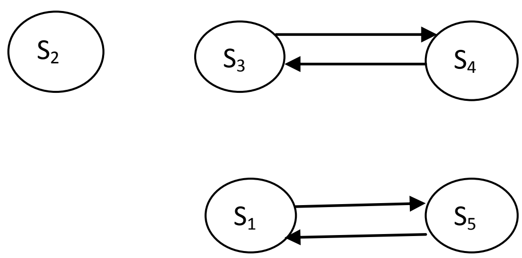
The permanent function is obtained differ to the multinomial, all negative terms obtained after expression for the calculation of the determinant of the matrix are replaced with positive equivalent terms and no negative signs appearing in this multinomial at any stage of its calculation. Types of terms and number in these two multinomials per (P) and Der (D) are exactly same. This multinomial represents information regarding various constituents as subsystems and interactions amongst them. Thus permanent function model is a unique and complete structural representation of the ultrasonic machining system, it added advantage of using numerical values of each term without any chance in information of elements. Thus permanent function Per (P) is proposed a complete tool for the total structural analysis of the ultrasonic machining system. This variable permanent function for the ultrasonic machining system derived by using equation **(7)** as shown below:

$$\begin{aligned} Per\,(P) = {} & [S_1 S_2 S_3 S_4 S_5] + [S_2 S_3 S_4 e_{15} e_{51} + S_1 S_2 S_5 e_{43} e_{34} + S_3 S_4 S_5 e_{12} e_{21}] \\ & + [S_3 S_4 e_{12} e_{25} e_{51} + S_2 S_4 e_{13} e_{35} e_{51} + S_2 S_3 e_{14} e_{45} e_{51}] \\ & + [S_4 e_{12} e_{23} e_{35} e_{51} + S_2 e_{13} e_{34} e_{45} e_{51} + S_2 e_{14} e_{43} e_{35} e_{51}] \\ & + [S_2 e_{34} e_{43} e_{51} e_{15} + S_5 e_{12} e_{21} e_{34} e_{43}] \\ & + [e_{12} e_{23} e_{34} e_{45} e_{51} + e_{34} e_{43} e_{12} e_{25} e_{51}] \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(8)} \end{aligned}$$

Every term of this equation represents a subset of the ultrasonic machining system. It is possible to write these equations simply by visual inspection of the ultrasonic machining system of fig 5.1. To achieve this objective and for the unique representation and interpretation, the permanent function is written in a standard form as (N+1) groups, where N is the number of subsystems. The permanent function when in (N+1) groups presents an exhaustive way of analysis of an ultrasonic machining system at different levels. The permanent multinomial Per (P) consist various terms of structural elements like as subsystem characteristic **($S_i$'s)** and structural interaction **($e_{ij}$'s).** The existence of these elements such as $e_{ij}$ $e_{ji}$, $e_{ij}$ $e_{jk}$ $e_{ki}$ , $e_{ij}$ $e_{jk}$ $e_{kl}$ $e_{li}$ correspond to the subsystems interacting in the form of dyad , three subsystem, four subsystem and five subsystem loops. The loops of subsystems of ultrasonic machining system are written in more convenient ways, it derived from equation (8), it shows the interaction between the two subsystems and represented as a loop $L_{ij}$ in place of $e_{ij}$ and for reverse loop of $e_{ji}$ as $L_{ji}$. Thus equation **(9)** has been written as below:

$$\begin{aligned}
Per\ (P) = & [S_1\ S_2\ S_3\ S_4\ S_5] + [S_2\ S_3\ S_4\ L_{15} + S_1\ S_2\ S_5\ L_{34} + S_3\ S_4\ S_5\ L_{12}] \\
& +[S_3\ S_4\ L_{125} + S_2\ S_4\ L_{135} + S_2\ S_3\ L_{145}] \\
& +[S_4\ L_{1235} + S_2\ L_{1345} + S_2\ L_{1435}] \\
& +[S_2\ L_{34}\ L_{15} + S_5\ L_{12}\ L_{34}] \\
& +[L_{12345} + L_{125}\ L_{34}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(9)}
\end{aligned}$$

| | |
|---|---|
| First group |  |
| Second Group | No term |

| | |
|---|---|
| **Third group** | <br>**+2 more terms** |
| **Fourth Group** | <br>**+2 more terms** |
| **Fifth Group (a)** | <br>**+ 2 more terms** |
| **Fifth Group (b)** | <br>**+1 more term** |

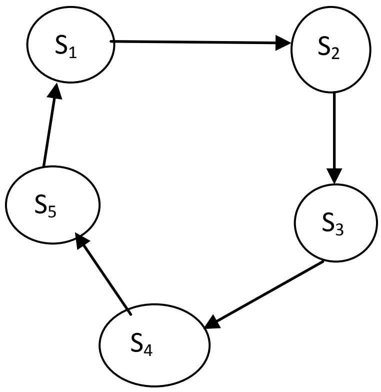
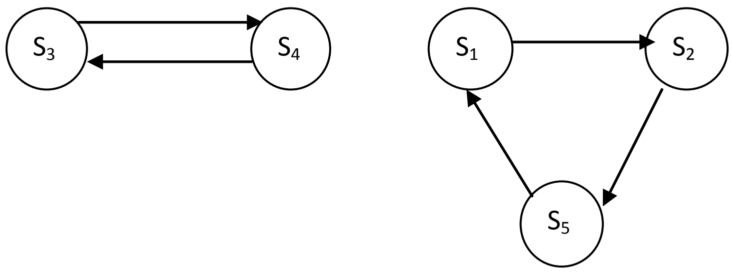
| | |
|---|---|
| **Sixth Group (a)** |   |
| **Sixth Group (b)** |   |

Figure.4.4-Physical representation of permanent function for USM system

The characteristic features of all the six groups of structural subsystems of the ultrasonic machining system as identified by using equation (9) are summarized as below:

- The first group consists of a single term representing a set of five subsystems, the identification set is $\mathbf{S_1/S_2/S_3/S_4/S_5}$**.**
- The second group is absent, because the system has no term with four singular subsystems.
- The third group has three terms, each term a set of three singular subsystems and a two subsystem loop or a dyad $\mathbf{L_{15}}$**.**
- The fourth group has three terms consisting of a set of two singular subsystems and a three subsystem loop $\mathbf{L_{125}}$**.**
- The fifth group consist of two subgroups a and b of one three and one terms, each term having one singular subsystem and first group has a set of one four subsystem loop $\mathbf{L_{1235}}$ and second subgroup has two subsystem loop $\mathbf{L_{34}}$ $\mathbf{L_{15}}$**.**

- The sixth group has two subgroups, the first subgroup has one term having a set of five subsystem loop $\mathbf{L_{123345}}$ and second subgroup has one term having a two set of loop $\mathbf{L_{34}}$ $\mathbf{L_{125}}$.

The identification set for any ultrasonic machining system may be written as:

$$N_1/N_2/N_3/N_4/N_{51}/N_{52}/N_{61}/N_{62}/$$

Where $J_k$ represent the total number of terms in the kth grouping and $J_{kl}$ represent the total number of terms in the lth sub grouping of the kth group.

The identification set for ultrasonic machining system by using graph theoretic methodology is written as below:

$$N_1/N_2/N_3/N_4/N_{51}/N_{52}/N_{61}/N_{62}/ = 1/0/3/3/3/2/1/1 \text{..............} \quad \mathbf{(10)}$$

## 4.5 Comparison of the ultrasonic machining system structure:

In ultrasonic machining system consisting five different subsystems, these subsystems affects on the performance of final system of ultrasonic machining. These five subsystems is modelled as a multinomial, a permanent function. Thus permanent function which represents real subsets of the ultrasonic machining system and it can be used to compare different alternative choices for the ultrasonic machining system. Different ultrasonic machining system has different number of terms in the groups as well as in the sub groups of their permanent functions. Different ultrasonic machining systems are similar from qualitative aspects but their digraph is isomorphic, this means that they have identical permanent function matrix set representation. The coefficient of similarity and dissimilarity give a systematic model of comparison of the ultrasonic machining system and it may be defined by using two criteria namely criterion 1 and criterion 2. The permanent function of different ultrasonic machining system may be denoted by $N_{kl}$ and $N'_{kl}$ respectively.

Based on this, a ultrasonic machining system identification set for any system is written as:

$$[( N_1/N_2/N_3/N_4/N_{51}/N_{52}/N_{61}/N_{62}/) \; (N'_1/N'_2/N'_3/N'_4/N'_{51}/N'_{52}/N'_{61}/N'_{62} )]$$

Where $N_i$ represents the total number of terms in the *i*th grouping, $N_{ij}$ represents the total number of terms of the Nth sub grouping in the *i*th grouping. Similarly, $N_{i'}$ represents the numerical value of the ith grouping and $N_{ij'}$ represents the numerical value of the jth sub grouping in the ith grouping.

Criterion 1: It shows the difference of the number of terms of the jth subgroup and ith subgroup of the permanent multinomial, it is denoted by using

$$\mathbf{\emptyset_{kl} = [N_{kl} - N'_{kl}]}$$

Coefficient of dissimilarity, $\mathbf{C_{d\text{-}1} = \frac{1}{Y1} \sum_k \sum_l \emptyset kl}$

$$\mathbf{Y_1 = max\ [\sum_k \sum_l N_{kl}\ and\ \sum_k \sum_l N'_{kl}]}\text{.............. } \mathbf{(11)}$$

**Criterion 1** shows the structural difference between the ultrasonic machining systems but this may cause loss of comparison information in the coefficient of dissimilarity. It is due to the fact of the value of $\emptyset_{kl}$ may be negative and subtraction operations may be involved and may cause limitation in the coefficient of similarity and its value will be lie between 0 and 1.

**Criterion 2:** This criterion gives coefficient of dissimilarity in which squares are used for better criterion of comparison values as shown in fig:

$$\mathbf{C_{d\text{-}2} = [\frac{1}{Y2} \sum_k \sum_l \emptyset\ kl]}$$

$$\mathbf{Y_1 = max\ [\ \sum_k \sum_l [N_{kl}]^2\ and\ \sum_k \sum_l [N'_{kl}]^2\ ]}\text{..................}\mathbf{(12)}$$

$$\mathbf{\emptyset_{kl} = [N_{kl} - N'_{kl}]}$$

The coefficient of similarity of two different ultrasonic machining system under the consideration by criteria 1 and criteria 2 can be calculated as:

$$\mathbf{C_{s\text{-}1} = 1\text{-}C_{d\text{-}1}}$$

$$\mathbf{C_{s\text{-}2} = 1\text{-}C_{d\text{-}2}}$$

If two ultrasonic machining systems are similar, the value of coefficient of similarity is shows 1 and coefficient of dissimilarity is 0 and in same manner if two ultrasonic machining systems are dissimilar and the value of coefficient of similarity is 0 and coefficient of dissimilarity is 1.

## 5.6 Generalization of permanent function model:

Suppose for a general system consists N number of subsystems, then the general way of matrix representation is shown below and it is denoted by R:

$$
\begin{array}{c|c}
\begin{array}{cccc} 1 & 2 & 3 \ldots\ldots\ldots\ldots N & \textbf{Subsystems} \end{array} & \\
\mathbf{R} = \begin{bmatrix} S_1 & e_{12} & e_{13} \ldots\ldots\ldots\ldots e_{1N} \\ e_{21} & S_2 & e_{23} \ldots\ldots\ldots\ldots e_{2N} \\ e_{31} & e_{32} & S_3 \ldots\ldots\ldots\ldots e_{3N} \\ \vdots & \vdots & \vdots \qquad\qquad \vdots \\ e_{N1} & e_{N2} & e_{N3} \ldots\ldots\ldots\ldots S_N \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ \\ N \end{array}
\end{array}
\qquad (13)
$$

For general N subsystem ultrasonic machining system with all the subsystems linked together, the total number of terms of the permanent function shall be equal to N. This matrix is known as the variable permanent matrix corresponding to the N subsystems and it is denoted by Per(R). The variable permanent function for the matrix R is written in sigma form ($\sum$) as shown below:

$$
\begin{aligned}
\textbf{Per (G)} = \quad & \prod_i^N S_i + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots \sum_N e_{ij}\, e_{ji}\, S_k\, S_l \ldots\ldots\ldots\ldots\ldots S_N \\
& + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots \sum_N (e_{ij}\, e_{jk}\, e_{ki})\, S_l\, S_m \ldots\ldots\ldots\ldots S_N \\
& + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots\ldots\ldots \sum_N (e_{ik}\, e_{kj}\, e_{ki})\, S_l\, S_m \ldots\ldots\ldots\ldots S_N \\
& + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots\ldots \sum_N (e_{ij}\, e_{ji})\, (e_{kl}\, e_{lk})\, S_m\, S_n \ldots\ldots\ldots\ldots\ldots S_N \\
& + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots \sum_N (e_{ij}\, e_{jk}\, e_{kl}\, e_{li})\, S_m\, S_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots S_N \\
& + \sum_i \sum_j \sum_k \ldots\ldots\ldots\ldots \sum_N (e_{il}\, e_{lk}\, e_{kj}\, e_{ji})\, S_m\, S_n \ldots\ldots\ldots\ldots S_N \\
& + \ldots\ldots\ldots\ldots
\end{aligned}
$$

These terms may be expanded into N + 1 group. The interrelations which are not actually present in the ultrasonic machining system may be given the value of 0 and thus eliminating the nonexistent terms. Finally, the terms of the permanent multinomial corresponding to the Particular ultrasonic machining system may be listed and the resulting graphs may be obtained and used for structurally analyzing the capabilities of the ultrasonic machining system in different areas.

## 4.7 Ultrasonic machining systems (USM) Analysis:

The methodology described in this chapter for complete analysis of USM system is summarized in step-by-step manner as below:

- Select the desired Ultrasonic machining system (USM) based on working area. Study the system and its subsystems (power supply unit, transducer, tool, abrasive and output subsystem), and also their interactions.
- Develop a block diagram of the ultrasonic machining system, considering its subsystems and interactions along with assumptions.
- Develop a system graph of the Ultrasonic machining system (USM) with subsystems as vertices and edges for interaction between the vertices shown in fig **(5.2).**
- Using this graph in step 3, develop matrix similar to USM system variable permanent matrix given in Equation **(5).**
- Calculate system permanent function Per (P), which consist all the subsystems simultaneously as shown in equation **(8).**
- The numerical index of an ultrasonic machining system (USM) system would be obtained by substituting the numerical values of subsystems and their interactions.
- Different type of ultrasonic machines can be compared on the basis of permanent numerical index thus obtained. Necessary improvements and developments can be done on the basis of this approach.
- From the different alternatives of ultrasonic machining systems, the alternative with highest value of numerical index is the best choice for the given application.

## 4.8 Usefulness of the Methodology:

- This proposed approach is useful for product design engineer, researcher, and industries at conceptual stage.
- Taking decision for selecting different parameters of ultrasonic machining system available for given applications.
- This methodology is dynamic in nature as its constituents and interaction between them can be easily changed without any difficulty.
- Carrying out cause and effect analysis to find out the reasons of less MRR and more TWR etc.
- Increasing the product life cycle of the ultrasonic machine (USM).

- Carrying out SWOT (Strength-Weakness-Opportunity-Threats) analysis on ultrasonic machining system before using.
- It is mathematical model and it can integrate the analysis over the total ultrasonic machining system.
- Carrying out re-engineering of the product, process etc. for break through improvement.
- The methodology is dynamic in nature as sub-systems/components and interactions, which appear as variables in different models may be changed without any difficulty.

## 4.9 SWOT Analysis:

SWOT analysis is a technique to consider the strengths, weakness, opportunities and threats of any given system. It is very important tool for decision making and analysis of system. In strengths all the positive points of system are noted. In weakness all the drawbacks of system are enlisted. Both these are internal factors of the system. In third cell all the opportunities of the system like scope of system means in which fields it's usage will increase etc. are enlisted and in threats all the competitors are enlisted means which other alternatives can be used in place of given system. Both these are the external factors affecting the system. Factors on left side are the positive factors and factors on the right side are the negative factors. In this study SWOT analysis of USM machine is done. In strengths advantages of USM machine are enlisted like ability to cut brittle materials like glass, ceramics etc. In weakness disadvantages of the USM machine are enlisted like low MRR usually $50mm^3/min$ etc. The top two cells highlights internal factors of USM. In opportunities scope of USM process is enlisted like USM is also used in the combination with EDM for the manufacturing of complex and precision components and in threats competitors of USM are enlisted like Rotary ultrasonic machining gives a higher MRR than ultrasonic machining Bottom two are external factors. By doing SWOT analysis decision making becomes easy. It provides complete overview of USM. Results from graph theory and MADM of USM combined with SWOT analysis of USM are together used for reaching final conclusion.

<table>
<tr><td colspan="4">INTERNAL</td></tr>
<tr><td rowspan="2">P<br>O<br>S<br>I<br>T<br>I<br>V<br>E</td><td>Strengths<ol><li>Ultrasonic machining is considered as an effective method for the machining hard and brittle materials</li><li>There is no contact between tool and work piece.</li><li>It is non thermal process, It does not change the metallurgical or physical properties of the work piece.</li><li>Multiple holes can be drilled simultaneously into very hard materials with great accuracy.</li></ol></td><td>Weakness<ol><li>Ultrasonic machines have a relatively low MRR usually less than 50 $mm^3$/min.</li><li>The abrasive slurry also "machines" the tool itself thus causing high TWR.</li><li>Efficiency is low compared to other processes.</li><li>Max depth of cut up to 90mm.</li></ol></td><td rowspan="2">N<br>E<br>G<br>A<br>T<br>I<br>V<br>E</td></tr>
<tr><td>Opportunities<ol><li>USM is also used in the combination with EDM for the manufacturing of complex and precision components.</li><li>One modification of USM to overcome some disadvantages its name is rotary ultrasonic machining.</li><li>Extensive research is going on USM which makes it process of future.</li></ol></td><td>Threats<ol><li>Ultrasonic machining is capable for only certain kinds of materials and applications.</li><li>Rotary ultrasonic machining gives a higher MRR than ultrasonic machining.</li><li>It reduces the inaccuracies like oversize and out of roundness.</li></ol></td></tr>
<tr><td colspan="4">EXTERNAL</td></tr>
</table>

# CHAPTER-5

# CONCLUSION AND FUTURE SCOPE

## 5.1 CONCLUSION:

This thesis is focused on Modeling, Analysis, Coding, Evaluation and Selection of Ultrasonic machining system using system approach and to achieve the objectives of this work two different methodologies are explained MADM approach in chapter 3 and Graph theoretic approach in chapter 4. In chapter 3 Multiple attribute decision making (MADM) approach is presented to identifies the various pertinent attributes needing to be considered for the optimum evaluation and selection of parameters of ultrasonic machine. This provides an N-digit coding scheme for ultrasonic machining systems depicting the different attributes. It also recognizes the need for, and processes the information about attributes for a given application without which inter-attribute comparison is not possible. This MADM approach presents the result of the information processing in terms of its merit value, which is used to rank the ultrasonic machining system in the order of their suitability for the given application. The contributions of the work by using MADM approach can be summarized as:

- This proposed methodology provides a coding scheme, which is a collection of 172 attributes for characterising of ultrasonic machining system and coding scheme is illustrated with the help of an example.
- A 3-stage selection procedure including elimination search, TOPSIS approach and other graphical methods (line graph and spider diagram) on the basis of identified pertinent attributes and the separation of each alternative from generated hypothetically best and worst abrasive materials, helps in ranking of all the abrasive materials for different materials alternatives.
- Evaluation and ranking of the abrasive materials based on the mathematical and graphical approaches along with the illustrative examples are presented.
- It is recommended that the information about all the attributes related to abrasive materials should be maintained as knowledge base for future usage by the user.

In chapter 4 Graph theoretic approach is presented to develop an integrated system model for the structure of the ultrasonic machining system in terms of its constituents and interactions between the processes. The important purpose of graph theory in the modeling of systems, network analysis, conceptual modeling, functional representation and diagnosis etc.

Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of ultrasonic machining system in different performance dimensions. The contribution of the work regarding Graph Theoretic Approach can be summarized as:

- Graph theoretic approach builds comprehensive model, which has the capability to consider the interactions between various subsystems of the total ultrasonic machining system.
- This methodology consists of the ultrasonic machining system digraph, is a mathematical representation of the structural characteristics and their interdependence between the different subsystems. The system matrix converts graph into another mathematical form. This matrix representation is powerful tool for storage and retrieval of ultrasonic machining systems in computer database.
- The ultrasonic machining system permanent function is a mathematical model characterizing the structure of the ultrasonic machining system and also helps one to determine the ultrasonic machining system numerical index. This numerical index is used for comparison, ranking, and optimum selection.
- A generalised methodology is also proposed to model a system consisting of N subsystems and their interactions. This study gives a criterion how to compare two different ultrasonic systems with the help of permanent function on the basis of its structures.

## 5.2 Future scope:

- A electronic database for the storage and retrial of different attributes of the ultrasonic machining system will be developed. This will make the selection procedure easy.
- Cause and effect analysis will be done to improve the quality and reliability of the ultrasonic machining system.
- Graph Theoretic Approach will be developed to analyze the ultrasonic machining system by obtaining the permanent functions at the system as well as subsystem levels.
- The derivation and importance of the numerical index of the ultrasonic machining system will be given in future work with illustrative examples.

- The Attribute Information Matrix is useful to saves lots of time to analyzing the large number of different research publications in short terms of time and it also useful to reduce more efforts to derive the information out from the research publications.

# CHAPTER 6

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