2 Ultrasonic Machining

2.0 WHAT IS ULTRASONIC MACHINING (USM)? (VTU Dec. 2009/Jan. 10)

Ultrasonic machining is a nontraditional process. In this process abrasives contained in the slurry are driven against the work by a tool oscillating at low amplitude (25–100 microns) and high frequency (15–30 kHz). Ultrasonic refers to waves of high frequency above the audible range of 20 kHz. The ultrasonic machining was proposed by L Balamuth in 1945. It was developed for finishing of electro spark machine parts. The USM process consists of tool made of ductile and tough material. Tool oscillates with high frequency, and the continuous abrasive slurry is fed between the tool and workpiece. The impact of the hard abrasive particles fractures the workpiece thus removing the small particles from the work surface.

Ultrasonic machining is different from the conventional grinding process. Table 2.1 gives the comparison between the two.

Table 2.1 Comparison between conventional grinding and USM

Parameters	*Conventional grinding*	*USM*
Motion	The motion of the grinding wheel is tangential to the workpiece.	The motion of the abrasive particles is normal to the workpiece.
Basic process	Material removal is by pure shear deformation.	Material removal occurs by shear deformation, a brittle fracture through impact (hammering), cavitation and chemical reaction.
Abrasive grits	Abrasive grits are bonded to the wheel.	Abrasives are supplied externally in the form of a slurry.
Tool motion	An abrasive wheel is rotated by an electric motor.	The tool is vibrated using magnetostriction effect which produces ultrasonic waves of high frequency.

2.1 WORKING PRINCIPLE OF USM

(VTU Dec. 2011; June 2012; Dec. 2012; June/July 2013; June/July 2014; Dec. 2014/Jan. 2015)

Ultrasonic machining is a mechanical type nontraditional machining process. Magnified view of the tool tip and the workpiece is shown in Figure 2.1. It is employed to machine hard and brittle materials (both electrically conductive and non-conductive material) having hardness usually greater than 40 HRC. The process was first developed in the 1950s and was originally used for finishing EDM surfaces.

as extremely loud sound and would cause fatigue and even permanent damage to the auditory apparatus.

2.2 DESCRIPTION OF EQUIPMENT (VTU Dec. 2011; June/July 2015)

The schematic diagram of USM equipment is shown in Figure 2.2.

Main elements of ultrasonic machining are:

1. High power sine wave generator
2. Magnetostrictive transducer
3. Tool holder
4. Tool

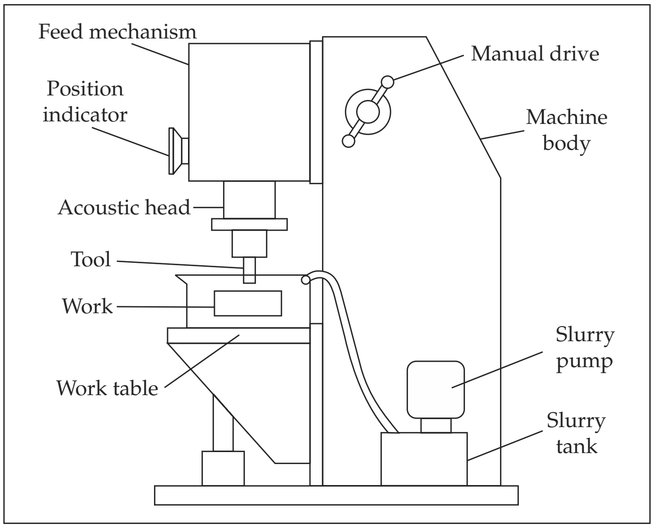


Figure 2.2 USM equipment

2.2.1 High Power Sine Wave Generator

This unit converts low frequency (50/60 Hz) electrical power to high frequency (20 kHz) electrical power.

2.2.2 Transducer

Function of the transducer: The high-frequency electrical signal is transmitted to the transducer which converts it into high frequency (15–20 kHz), low amplitude vibration (5 microns). The function of the transducer is to convert electrical energy into mechanical vibration using the principle of piezoelectric or magnetostriction.

There are two types of transducer:

1. Piezoelectric transducer
2. Magnetostrictive transducer.

1. **Piezoelectric transducer:** These transducers generate a small electric current when they are compressed. Also, when the electric current is passed through a crystal, it expands. When the current is removed, the crystal regains its original size and shape. Such transducers are available up to 900 watts. Piezoelectric crystals have a high conversion efficiency of 95%.
2. **Magnetostrictive transducer:** The magnetostriction effect was first discovered by Joule in 1874. According to this effect, in the presence of the applied magnetic field, ferromagnetic metals and alloys change in length. These transducers are made of nickel or nickel alloy sheets. Their conversion efficiency is about 20–30%. Such transducers are available up to 2000 watts. The maximum change in length that can be achieved is about 25 microns.

When the frequency of AC signal provided by high-frequency generator is tuned to the natural frequency of the transducer, resonance occurs. Because of the resonance amplitude of vibration increases. The transducer length is equal to half of the wavelength for the condition of resonance.

2.2.3 Concentrators (Acoustic Horn)

Function of the concentrators (Figure 2.3): The oscillation amplitude obtained from the magnetostrictive transducer is usually around 5 microns, which is too small for removal of material from the workpiece. The function of the concentrator (also called mechanical amplifiers, acoustic horn and tool cone) is to amplify the amplitude of vibration of the magnetostrictive transducer from 5 to 40–50 microns. Concentrator also concentrates the

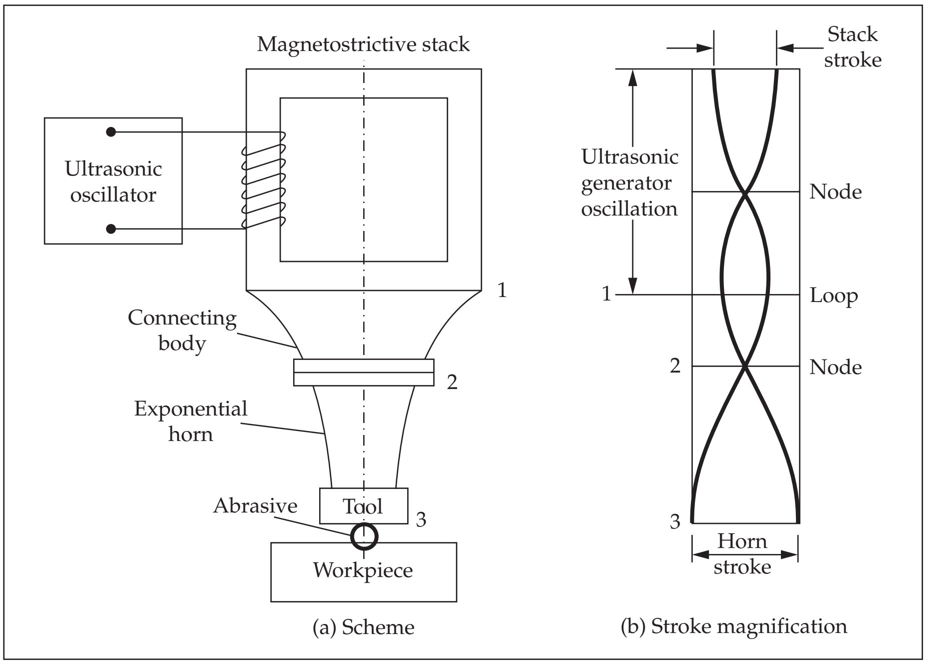


Figure 2.3 Concentrators used in USM

power on a smaller machining area. To get the resonance condition, like a transducer, the acoustic cone should be of half wavelength of the resonator.

Tool material: The material of tool should have good acoustic properties and high resistance to fatigue cracking. Appropriate measures should be taken to avoid ultrasonic welding between the transducer and the tool holder. Commonly used tool holders are of Monel, titanium and stainless steel. Tool holders are expensive, demand high operating cost. Classification of tool holders is given in Table 2.2.

Table 2.2 Classification of tool holders

Amplifying tool holder	*Non-amplifying tool holder*
They give as much as 6 times increased tool motion. It is achieved by stretching and relaxing the tool holder material. MRR = 10 times the non-amplifying tool.	Non-amplifying tool holders have a circular cross section and give same amplitude at both ends.

2.2.4 Tool

Tools are made of relatively ductile materials like brass, stainless steel or mild steel so that tool wear rate (TWR) can be minimized. The values of the ratio of TWR and MRR depend on the kind of abrasive, work and tool materials.

Design considerations for tools

- The tool is made up of a strong but ductile metal.
- Stainless steels and low carbon steels are used for making the tools.
- Aluminium and brass tools wear is ten and five times faster than steel tools respectively.
- The geometrical features are decided by the process.
- The diameter of the circle circumscribed about the tool should not be more than 1.5–2.0 times the diameter of the end of the concentrator.
- The tool should be as short and rigid as possible.
- When the tool is made hollow, the internal contour should be parallel to the external one to ensure uniform wear.
- The thickness of any wall or projection should be atleast five times the grain size of the abrasive.
- In the hollow tool, the wall should not be made thinner than 0.5–0.8 mm.
- When designing the tool consideration should be given to the side clearance which is normally of the order of 0.06–0.36 mm, depending on the grain size of the abrasive.

2.3 ABRASIVES AND ABRASIVE SLURRY (VTU June/July 2011; Dec. 2011)

In USM large variety of abrasive slurries is used. Some of them are:

- Boron carbide
- Silicon carbide

- Aluminium oxide
- Diamond dust.

Boron abrasive particles are used for machining tungsten, steel and precious stones. Boron silica carbide is also used, and it is 8–12% more abrasive than boron carbide. Alumina is used for machining ceramics, glass and germanium. Alumina wears out very fast and loses its cutting power very fast. Silicon finds maximum applications. Diamond and rubies are cut by diamond powder. Good surface finish, accuracy and cutting rates are possible with diamond dust.

Selection of abrasive particles depends on:

- Particle size
- Hardness
- Cost of abrasives
- Durability of abrasives

The life of abrasives depends on the hardness of the abrasive material and work combinations. Longer life of abrasives can be obtained when the hardness of the abrasives is more than the hardness of the work material. The metal removal rate and surface finish depend on size of abrasive particles. Coarse grains give higher MRR, but lower surface finish. Fine grains give good surface finish, but MRR is low.

The abrasive slurry is circulated by pumping, and it requires cooling to remove the generated heat to prevent it from boiling in the gap and causing the undesirable cavitation effect. A refrigerated cooling system is provided to cool the slurry to a temperature of 5–6°C

2.4 LIQUID MEDIA (VTU June/July 2011)

In USM process, the abrasive of about 30 to 60% by volume are suspended in liquid medium. Several functions of liquid medium are:

- Liquid medium acts as an acoustic bond between vibrating tool and work.
- It carries the abrasive medium to the cutting zone.
- It acts as a coolant and also carries waste abrasives and other swarf.
- It acts as a transferring media for energy between the tool and the workpiece.

The characteristics of a good suspension liquid medium are:

- The density of the liquid medium should be approximately equal to that of abrasive.
- The liquid medium should have good wetting characteristics. It should wet tool, abrasives and the workpiece.
- The liquid medium should have high specific heat and thermal conductivity so that heat transfer between the tool and the workpiece is effective.
- The liquid must have good flow ability (low viscosity) and should carry the abrasives along with it.
- Liquid medium should not corrode the workpiece, tool and equipment.

Water is frequently used as the liquid carrier since it satisfies most of the requirements listed above. Some corrosion inhibitor is generally added in the water.

Ultrasonic vibrations imparted to fluid medium have the following important actions:

1. Ultrasonic vibrations bring about the ultrasonic dispersion effect rapidly in the machining fluid medium between the tool end and the machining surface of the workpiece.
2. Ultrasonic vibrations bring violent circulations of the fluid as a result of ultrasonic micro-agitation.
3. It causes the cavitation effect in the fluid medium arising out of the ultrasonic vibration of the tool in the fluid medium.

2.5 OPERATIONS OF ULTRASONIC MACHINING

(VTU Dec. 2011; June/July 2014; Dec. 2014/Jan. 2015)

Schematics of USM operation is depicted in Figure 2.4.

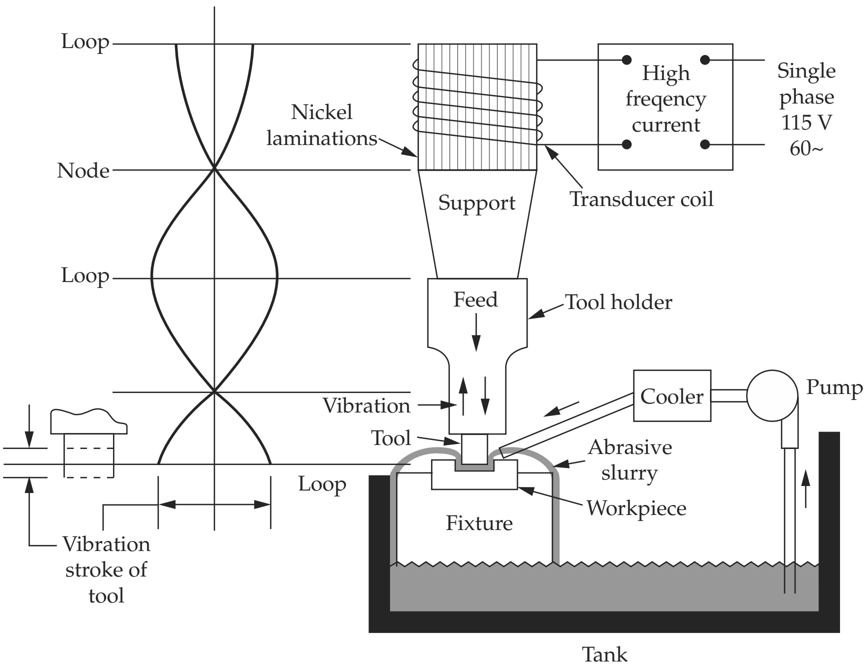


Figure 2.4 Operation of USM

Ultrasonic machining is an economical process by which we can produce cavity or hole in the hard and brittle materials. The sequence of operation is given below:

1. Electrical supply is given to high-frequency generator. HF generator creates an alternating magnetic field which expands and contracts the stack made of magnetostrictive material (transducer). To get maximum magnetostriction, HF AC current is superimposed with DC pre-magnetizing current.

2. Since the frequency of the magnetic field created by AC signal is same as that of the natural frequency of the transducer, mechanical resonance occurs. Transducer length is equal to half of the length.
3. Oscillation of amplitude obtained from the transducer is about 5 microns, which is very small for metal removal. Therefore, it is amplified to 40–50 microns by fitting amplifiers into the output end of the transducer.
4. Acoustic horn transmits the mechanical energy to the tool and concentrates power on small machining area.
5. The tool is fed into the workpiece by an automatic feed mechanism. It has a provision for measurement of static pressure exerted by the tool and penetration depth measurement.
6. Abrasive slurry under pressure is supplied to the working gap between the tool and the workpiece by a centrifugal pump.
7. Abrasive particles are hammered by the tool into the workpiece surface, and they abrade the workpiece into the conjugate image of tool form.

2.6 TOOL FEED MECHANISM (VTU May/June 2010; Dec. 2010; June/July 2014)

The feed mechanism of an ultrasonic machine must perform the following functions:

1. Bring the tool slowly to the workpiece to prevent breaking.
2. The tool must provide adequate cutting force and sustain it during the machining operation.
3. The cutting force must be decreased when the specified depth is reached.
4. Overrun a small distance to ensure the required hole size at the exit.
5. The tool has to come back to its initial position after machining is done.

There are four types of feed mechanism which are commonly used in USM:

1. Gravity feed mechanism
2. Spring loaded feed mechanism
3. Pneumatic or hydraulic feed mechanism
4. Motor controlled feed mechanism.

1. Gravity feed mechanism

Figure 2.5 shows the operation of the gravity tool feed mechanism. In this mechanism counter, balance weights are used to apply the required load to the head through pulley and rope arrangement. In order to reduce friction ball, bearings are used. Gravity feed mechanisms are simple in construction, but this mechanism is insensitive and inconvenient to adjust.

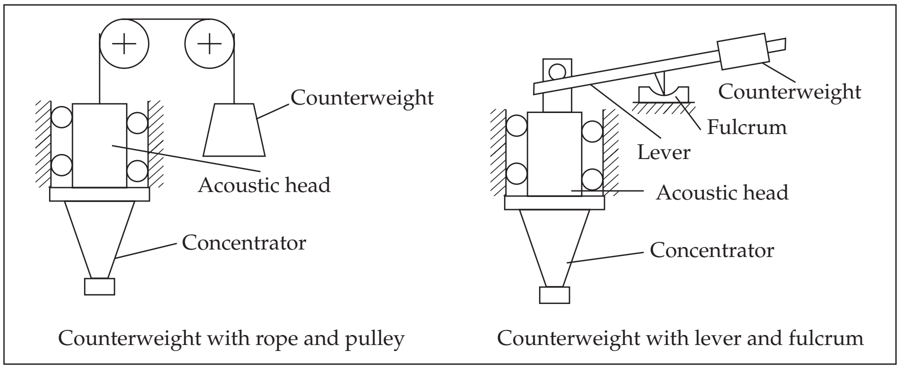


Figure 2.5

2. Spring loaded feed mechanism

Figure 2.6 shows the operation of spring loaded tool feed mechanism. In this mechanism spring pressure is used to feed the tool during the machining operation. This type of mechanism is quite sensitive and easy to adjust.

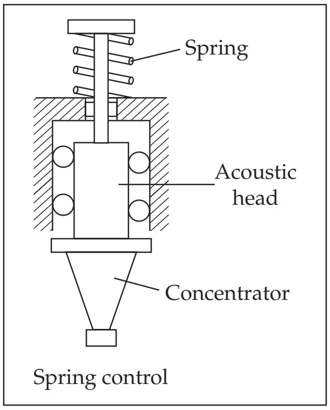


Figure 2.6

3. Pneumatic or hydraulic feed mechanism

Figure 2.7 shows the operation of pneumatic or hydraulic tool feed mechanism. In this mechanism, hydraulic cylinder is used to give a linear motion of the tool. High feed rate and accurate positioning are possible with hydraulic feed mechanism.

4. Motor controlled feed mechanism

Figure 2.8 shows the operation of the motor controlled feed mechanism. This mechanism is used for precise control of the tool feed movement.

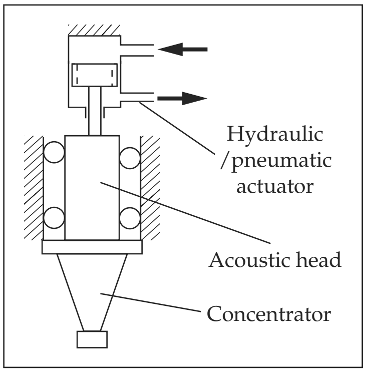


Figure 2.7

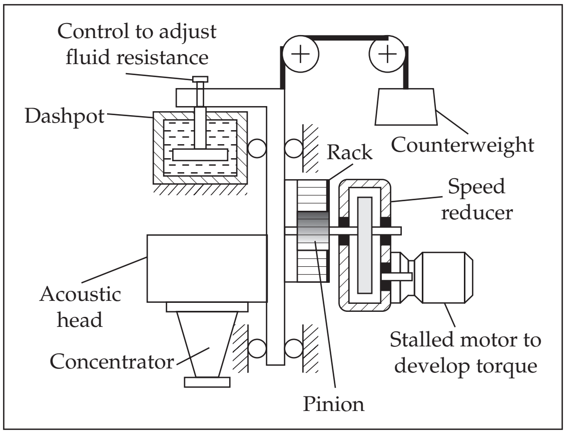


Figure 2.8

2.7 PROCESS PARAMETERS

(VTU June/July 2009; June/July 2014; June/July 2015)

Various parameters that affect the ultrasonic machining are:

1. Amplitude of vibration (15 to 50 microns)
2. Frequency of vibration (19 to 25 kHz)
3. Feed force (*F*) related to tool dimensions
4. Feed pressure
5. Abrasive size
6. Abrasive material: Al_2O_3, SiC, B_4C, boron silica carbide, diamond
7. Flow strength of the work material
8. Flow strength of the tool material

9. Contact area of the tool
10. Volume concentration of abrasive in water slurry
11. Tool
    (a) Material of tool
    (b) Shape
    (c) Amplitude of vibration
    (d) Frequency of vibration
    (e) Strength developed in tool
    (g) Gap between tool and work
12. Work material
    (a) Material
    (b) Impact strength
    (c) Surface fatigue strength
13. Slurry
    (a) Abrasive—hardness, size, shape and quantity of abrasive flow
    (b) Liquid—chemical property, viscosity, flow rate
    (c) Pressure
    (d) Density

2.8 PROCESS CAPABILITY OF USM (VTU June/July 2011)

Process capabilities of USM are:

1. Can machine the workpieces harder than 40 HRC to 60 HRC like carbides, ceramics, tungsten glass that cannot be machined by conventional methods. USM is not applicable to soft and ductile materials such as copper, lead, ductile steel and plastics, which absorb energy by deformation.
2. Tolerance range: 7 to 25 microns.
3. Holes up to 76 microns have been drilled. Hole depths up to 51 mm have been achieved easily. Hole depth of 152 mm deep is achieved by special flushing techniques.
4. Aspect ratio 40 : 1 has been achieved.
5. Linear material removal rate: –0.025 to 25 mm/min.
6. Surface finish: –0.25 micron to 0.75 micron.
7. Non-directional surface texture is possible compared to conventional grinding.
8. Radial overcut may be as low as 1.5 to 4 times the mean, abrasive grain size.

Pressure also has an effect on the MRR. Figure 2.10 shows the effect of the amplitude of vibration on MRR for different pressures.

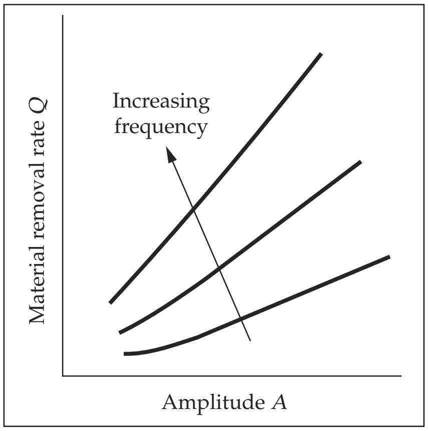


Figure 2.9

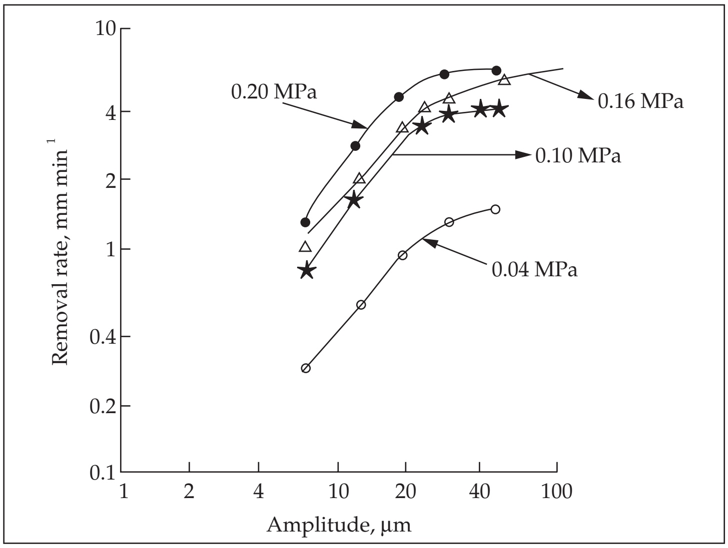


Figure 2.10

2.10.2 Effect of Frequency on MRR

(VTU May/June 2010; Dec. 2010; June/July 2011)

Frequency has a significant effect on MRR (Figure 2.11). The frequency used for machining process must be the resonant frequency to obtain the greatest amplitude at the tool tip and thus achieve the maximum utilization of the acoustic system. With increase in the frequency of the tool head, the MRR should increase proportionally. However, there is a slight variation in the MRR with frequency.

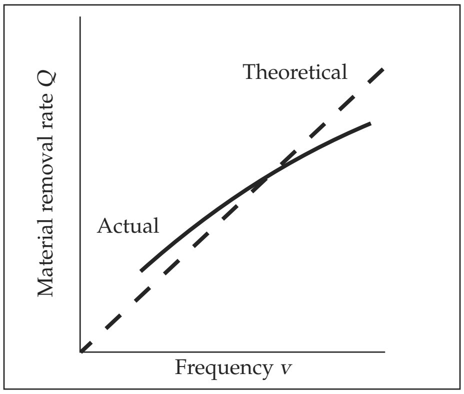


Figure 2.11

2.10.3 Effect of Abrasive Grain Size

(VTU May/June 2010; Dec. 2010; June/July 2011)

MRR should also rise proportionately with the mean grain diameter. An increase in abrasive grain size results in higher MRR but poorer surface finish (Figure 2.12). Maximum MRR is achieved when the abrasive grain size is comparable with an amplitude of vibration of the tool. The hardness of the abrasives and method of introducing the slurry also has effect on MRR.

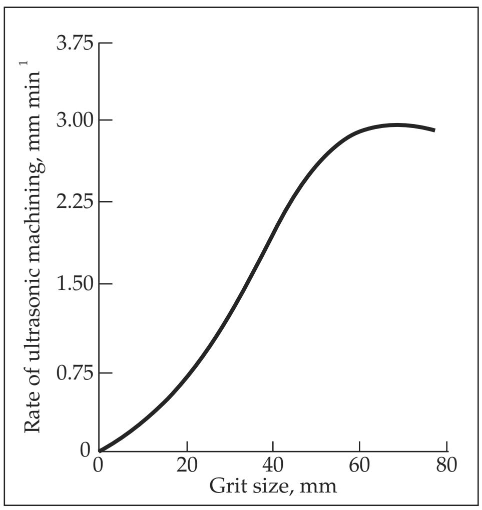


Figure 2.12

The concentration of the abrasives directly controls the number of grains producing impact per cycle. Figure 2.13 shows the effect of abrasive concentration on MRR. Silicon carbide gives lower MRR compared to boron carbide.

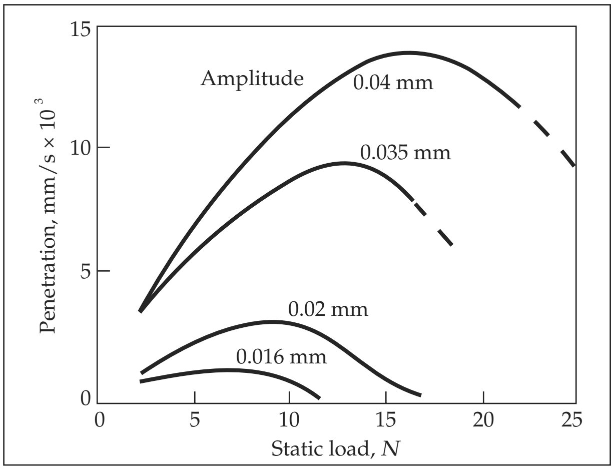


Figure 2.15

The variation of metal removal rate for varying static load (feed force) is shown in Figure 2.16. As the tool size decreases the penetration also increases.

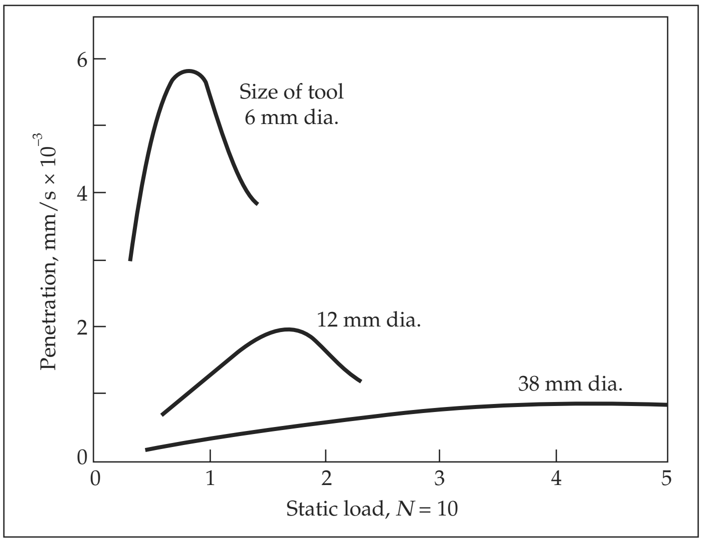


Figure 2.16

2.10.5 Effect of Slurry, Tool and Work Material (VTU May/June 2010)

MRR increases with slurry concentration. Slurry saturation occurs at 30 to 40% abrasive/water mixture (Figure 2.17).

The pressure with which the slurry is fed into the cutting zone affects MRR. In some cases, MRR can be increased even ten times by supplying the slurry at increased pressure.

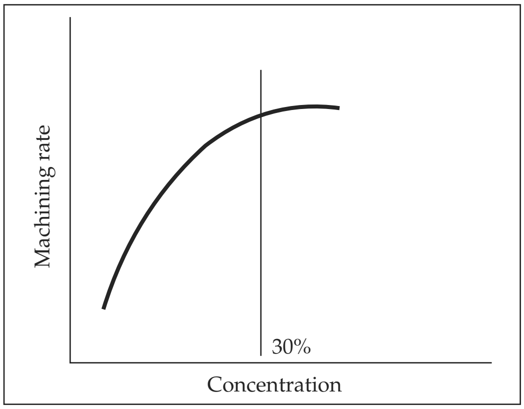


Figure 2.17

Apart from the process parameters some physical properties (e.g., viscosity) of the fluid used for the slurry also affects the MRR. Experiments show that MRR drops as viscosity increases (Figure 2.18).

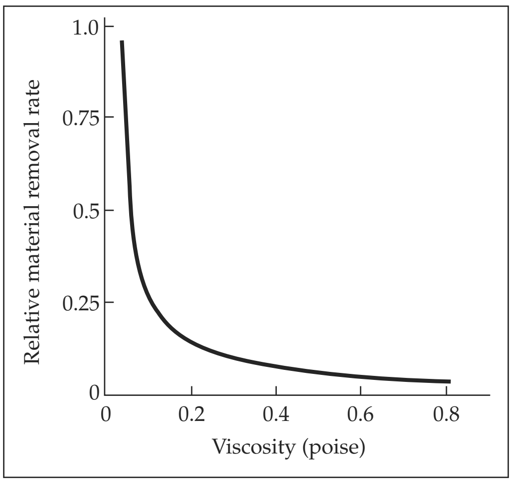


Figure 2.18

2.10.6 Effect of Hardness Ratio of the Tool and the Workpiece

The ratio of workpiece hardness and tool hardness affects the MRR quite significantly, and the characteristics are shown in Figure 2.19.

The shape of the tool affects the MRR. Narrower rectangular tool gives more MRR compared to square cross section. The conical tool gives twice MRR compared to the cylindrical tool.

Abrasive particles are assumed to be spherical in shape having diameter d_g. Abrasive particles move under the high-frequency vibrating tool. There are two possibilities when the tool hits the particle.

- If the size of the particle is small and the gap between the tool and work is large, then the particle is thrown by the tool to hit the workpiece.
- If the size of the particle is large and the gap between tool and work is small, then the particle is hammered over the work surface.

The various mechanisms of material removal process have been developed by a number of researchers. The theory developed by M.C. Shaw is given below.

The important assumptions made by M.C. Shaw are:

1. All the abrasive particles are identical and spherical in shape.
2. All impacts are identical.
3. The metal removal rate is proportional to the volume of the workpiece per impact.
4. The metal removal rate is proportional to the number of particles making impact per cycle.
5. The rate of work material removal is proportional to the frequency. That is, the number of cycles per unit time.

Consider an abrasive particle of diameter d_g hits the workpiece and generates an indentation of height δ as shown in the figure below.

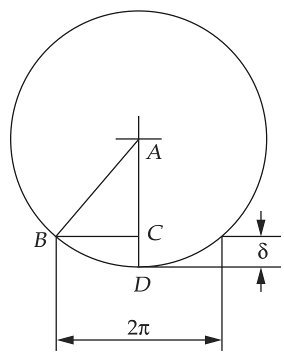
From the Geometry

$$AB^2 = AC^2 + BC^2$$

$$\frac{d_g}{2} = \left(\frac{d_g}{2} - \delta\right)^2 + r^2$$

$$\frac{d_g}{2} - \left(\frac{d_g}{2} - \delta\right)^2 = r^2$$

$$r^2 = \delta^2 + d_g\delta$$



Neglecting δ^2 term we can write

$$r^2 = d_g\,\delta$$

$$r = \sqrt{d_g\delta}$$

Volume of the material removed is the volume of the hemispherical crater due the fracture per grit per cycle.

Volume of the material removed

$$\Gamma = \frac{1}{2}\left[\frac{4}{3}\pi r^3\right] = \frac{1}{2}\left[\frac{4}{3}\pi (r^2)^{\frac{3}{2}}\right] = \frac{1}{2}\left[\frac{4}{3}\pi (d_g\delta)^{\frac{3}{2}}\right] = K_1 (d_g\delta)^{\frac{3}{2}} \qquad (1)$$

where K_1 is constant

A grit penetrates to the depth equal to δ into the workpiece. The work done by the grit is given by

$$\text{WD by the grit} = \frac{F\delta}{2} \tag{5}$$

Also we know the flow strength of material = $\sigma_w = \dfrac{F}{\pi r^2}$

$$F = \sigma_w \times \pi r^2 \tag{6}$$

Using equation (6) in (5) we get

$$\text{WD by the grit} = \frac{F\delta}{2} = \frac{\sigma_w \times \pi d_g \delta \times \delta}{2} \tag{7}$$

WD by the grit should be equal to the kinetic energy of the particle

$$\frac{\sigma_w \times \pi d_g \delta \times \delta}{2} = \frac{1}{2}\left(\frac{\pi (d_g)^3}{6}\rho_g\right)(\pi a f)^2$$

Simplifying we have

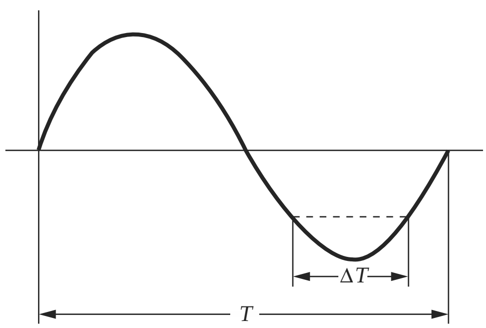
$$\delta = \pi A f d_g \sqrt{\frac{\rho_g}{6\sigma_w}} \tag{8}$$

Using equation (8) in the equation (3), we have

Volumetric material removal rate due to throwing mechanism

$$\text{MRR} = \left[K_1 K_2 K_3\, d_g\, f^{\frac{5}{2}} \left[\frac{\rho_g (\pi a)^2}{6\sigma_w}\right]^{\frac{3}{4}}\right] \tag{9}$$

Model 2: Grain hammering model



When the gap between the tool and the workpiece is smaller than the diameter of the grit, it results in partial penetration in the tool (δ_t) as well as in the workpiece (δ_w). The values of (δ_t) and (δ_w) depend on the hardness of the tool and the workpiece material, respectively. Force F acts on abrasive particle only for a short time (ΔT) during the cycle time T. During this time period, the abrasive particle is in contact with the tool and the workpiece both. The mean force (F_{avg}) on the grit can be expressed by

$$F_{avg} = \frac{1}{T}\int_0^T F(t)\,dt \tag{10}$$

Here, $F(t)$ is the force at any instant of time t. Force on the grit by the tool starts increasing as soon as grit gets in contact with both the tool and the workpiece at the same time. It attains maximum value and then starts decreasing until it attains the zero value. Hence, the momentum equation can be written as

$$\frac{1}{T}\int_0^T F(t)\,dt = \left[\frac{F}{2}\right]\Delta T \tag{11}$$

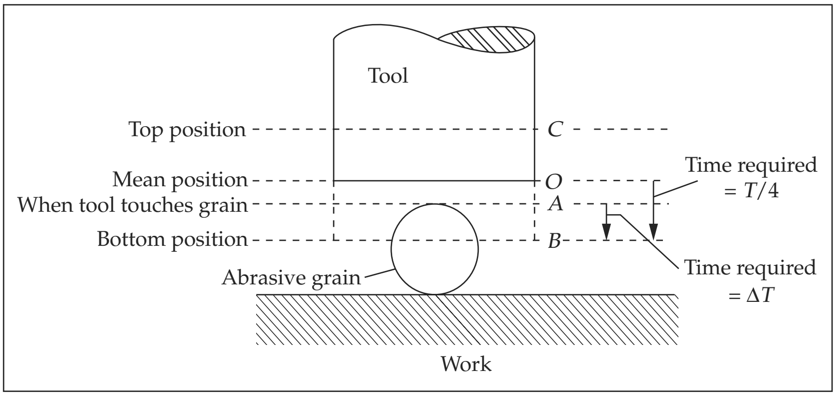


Figure 2.20

Position A indicates the instant the tool face touches the abrasive grain (Figure 2.20). The period of movement from A to B represents the impact. The indentation, caused by the grain on the tool and the work surface at the extreme bottom position of the tool from the position A to position B is the total penetration.

Total penetration due the hammering is given by

$$\delta = \delta_w + \delta_t$$

a/2 is the amplitude of oscillation of the tool. The mean velocity of the tool during the quarter cycle is given by $\frac{a/2}{T/4}$. Therefore, time (ΔT) required to travel from A to B is given by the following equation

$$\Delta T = \frac{\delta T}{2a} \tag{12}$$

WORKED EXAMPLES

PROBLEM 2.1 Calculate the depth of indentation produced in a ceramic surface in ultrasonic machining by the throwing action of abrasive grains of 150-micron size diameter using the following data.

Amplitude of vibration: 0.15 mm.

Frequency of vibration: 21 kc/s,

Abrasive density: 3.5 kgf/m^3

Yield strength of ceramics: 4.5×10^{11} N/m^2 (VTU June/July 2009)

Solution

Mean abrasive size (d_g) = 150 microns =150×10^{-6} m

Amplitude of oscillation = $a/2$ = 0.15 mm = 0.15×10^{-3} m

Frequency of oscillation = f =21 kc/s, = 21,000 CPS

Flow strength of work material = $\sigma_w = 4.9 \times 10^{11}$ N/m^2

Grain Throwing Model

Let us use equations we have developed for the grain throwing model penetration in workpiece due to throwing is given by

$$\delta = \pi A f d_g \sqrt{\frac{\rho_g}{6\sigma_w}}$$

$$\delta = \pi(2 \times 0.15 \times 10^{-3})\,(21000)\,(150 \times 10^{-6})\sqrt{\frac{3.5}{6 \times (4.9 \times 10^{11})}}$$

$$\delta = 3.239 \times 10^{-9} \text{ mm}$$

PROBLEM 2.2 Glass is being machined at an MRR of 6 mm^3/min by Al_2O_3 by abrasive grits having a grit dia of 150 microns. If 100 micron grits is to be used, what would be the MRR?

Solution

Volumetric material removal rate from the workpiece due to hammering mechanism can be evaluated using equation (3) as follows:

$$\text{MRR} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_w)^3}{d_g}\right]}\right]$$

$$V_{\text{hammering}} = K_1 K_2 K_3 f d_g \left[\frac{F_{\text{avg}}\, 4a}{\sigma_w \pi K_2 (\lambda + 1)}\right]^{\frac{3}{4}}$$

Assume that all the parameters remain same. We can write,

$V_{\text{hammering}}$ = constant$_1$ d_g

Material removal rate for 150-micron grit is given by

$V_{\text{hammering–150 microns}}$ = constant$_1$ × 150 micron (1)

Material removal rate for 100-micron grit is given by

$V_{\text{hammering–100 microns}}$ = constant$_1$ × 150 micron (2)

Also it is given $V_{\text{hammering–150 microns}}$ = 6 mm^3/mm

Dividing Eq. (1) by Eq. (2) we get

$$\frac{V_{\text{hammering – 150 microns}}}{V_{\text{hammering – 100 microns}}} = \frac{150}{100}$$

$$\frac{V_{\text{üüüüüüüüü–}}}{V_{\text{üüüüüüüüü–}}} = \frac{150}{100}$$

$$V_{\text{hammering – 100 microns}}\ 4\ \text{mm}^3/\text{min}$$

Thus, by decreasing the grit size, MRR decreases and surface finish increases.

PROBLEM 2.3 Glass is being machined at an MRR of 6 mm^2/min by Al_2O_3 abrasive grits having a grit dia of 150 microns. The frequency of operation is 20 kHz. If the frequency is increased to 25 kHz. What would be the MRR?

Solution

Volumetric material removal rate from the workpiece due to hammering mechanism can be evaluated using equation (3) as follows:

$$\text{MRR} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_w)^3}{d_g} \right]} \right]$$

$$V_{\text{hammering}} = K_1 K_2 K_3 f d_g \left[\frac{F_{\text{avg}}\ 4a}{\sigma_w \pi K_2 (\lambda + 1)} \right]^{\frac{3}{4}}$$

Assume that all the parameters remain same we can write,

$V_{\text{hammering}}$ = constant$_1$ f

Material removal rate for 150-micron grit is given by

$V_{\text{hammering–150 microns–old}}$ = constant$_1$ × f_{20} (1)

Material removal rate for 100-micron grit is given by

$V_{\text{hammering–150 microns–new}}$ = constant$_1$ × f_{25} (2)

Also it is given $V_{(\text{hammering–150 microns})}$ = 6 mm^3/min

Penetration in the workpiece due to throwing is given by

$$\delta = \pi A f d_g \sqrt{\frac{\rho_g}{6\sigma_w}}$$

$$\delta = \pi(50 \times 10^{-6})(2.5 \times 10^4)(1.5 \times 10^{-5}) \sqrt{\frac{3.8 \times 10^3}{6 \times (6.9 \times 10^9)}} = 1.78 \times 10^{-5} \text{ mm}$$

Volume removed by throwing is given by

$$\text{MRR} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_w)^3}{d_g} \right]} \right]$$

Substituting all the values we have

$$\text{MRR} = \left[(0.3)(1.8 \times 10^{-6})(0.6)(2.5 \times 10^4) \sqrt{\left[\frac{(1.78 \times 10^{-5})^3}{1.5 \times 10^{-2}} \right]} \right]$$

$$= 4.97 \times 10^{-3} \text{ mm}^3/\text{s}$$

Grain Hammering Model

Penetration in the workpiece due to hammering is given by

$$\delta_w = \sqrt{\frac{F_{\text{avg}}\, 4 a d_g}{\sigma_w \pi K_2 (\lambda + 1)}}$$

$$\delta_w = \sqrt{\frac{\text{üẍüüüẍüüẍ} \quad \times \quad {}^{-6} \quad \times \quad {}^{-5}}{(6.9 \times 10^9)\, \pi\, (1.8 \times 10^{-6})(4.6 + 1)}}$$

$$\delta_w = 2.192 \times 10^{-4} \text{ mm}$$

Volume removed by throwing is given by

$$\text{MRR} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_w)^3}{d_g} \right]} \right]$$

Penetration in the workpiece due to hammering with copper as tool material is given by

$$\delta_{w\text{-copper}} = \sqrt{\frac{F_{\text{avg}}\, 4ad_g}{\sigma_w \pi K_{\text{üüü}}(\lambda \quad + 1)}}$$

Penetration in the workpiece due to hammering with stainless steel (SST) as tool material is given by

$$\delta_{w\text{-copper}} = \sqrt{\frac{F_{\text{avg}}\, 4ad_g}{\sigma_w \pi K_2(\lambda_{\text{SST}} + 1)}}$$

Volume removed by throwing with copper as tool material is given by

$$\text{MRR}_{\text{copper}} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_{w\text{üüü}} \quad)^3}{d_g}\right]}\right]$$

Volume removed by throwing with stainless steel as tool material is given by

$$\text{MRR}_{\text{SST}} = \left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_{w-\text{SST}})^3}{d_g}\right]}\right]$$

Assuming all other parameters do not change, we can write

$$\frac{\text{MRR}_{\text{copper}}}{\text{MRR}_{\text{SST}}} = \frac{\left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_{w-\text{copper}})^3}{d_g}\right]}\right]}{\left[K_1 K_2 K_3 f \sqrt{\left[\frac{(\delta_{w-\text{SST}})^3}{d_g}\right]}\right]}$$

$$\frac{\text{MRR}_{\text{copper}}}{\text{MRR}_{\text{SST}}} = \sqrt{\left[\frac{(\delta_{w-\text{copper}})^3}{(\delta_{w-\text{SST}})^3}\right]}$$

$$\frac{\text{MRR}_{\text{copper}}}{\text{MRR}_{\text{SST}}} = \sqrt{\left[\frac{\left(\sqrt{\frac{F_{\text{avg}}\, 4ad_g}{\sigma_w \pi K_{\text{üüü}}(\lambda \quad + 1)}}\right)^3}{\sqrt{\frac{F_{\text{avg}}\, 4ad_g}{\sigma_w \pi K_2(\lambda_{\text{SST}} + 1)}}^{\,3}}\right]} = \left\{\frac{(\lambda_{\text{SST}} + 1)}{(\lambda_{\text{copper}} + 1)}\right\}^{\frac{3}{4}}$$

10. USM enables a dentist to drill a hole of any shape in teeth without any pain.
11. Ferrites and steel parts, precision mineral stones can be machined using USM.
12. USM can be used to cut industrial diamonds.
13. USM is used for grinding quartz, glass, and ceramics.
14. Cutting holes with curved or spiral centre lines and cutting threads in glass and mineral or metallic-ceramics.

2.13 ADVANTAGES OF USM

(VTU June/July 2009; VTU May/June 2010; June 2012; June/July 2013; June/July 2014; Dec. 2014/Jan. 2015)

1. It can be used to machine hard, brittle, fragile and non-conductive materials.
2. No heat is generated in work, therefore, no significant changes in physical structure of the work material.
3. Non-metal (because of the poor electrical conductivity) that cannot be machined by EDM and ECM can very well be machined by USM.
4. It is a burr less and distortion less processes.
5. It can be adopted in conjunction with other new technologies like EDM, ECG, ECM.
6. High accuracy with good surface finish can be achieved.
7. Possesses the capability of drilling circular and non-circular holes in very hard materials like ceramics and other brittle materials.

2.14 DISADVANTAGES OF USM

(VTU June/July 2009; May/June 2010; June 2012; June/July 2014; Dec. 2014/Jan. 2015)

1. Low metal removal rate.
2. It is difficult to drill deep holes, as slurry movement is restricted.
3. Frontal and side tool wear rate is high due to abrasive particles, especially when cutting steel and carbides. Side wear produces less accurate holes and cavities.
4. Tools made from brass, tungsten carbide, MS or tool steel wear from the action of abrasive grit with a ratio that ranges from 1:1 to 200:1.
5. USM can be used only when the hardness of the work is more than 45 HRC.
6. It is not economical for soft materials.
7. Not suitable for heavy stock removal.
8. USM is not useful of machining holes and cavities with lateral extension of more than 25–30 mm with a limited depth of cut.
9. Every job needs a specific tool. Therefore, tool cost is high.
10. The abrasive slurry should be changed regularly to replace worn out particles. Therefore additional cost is involved.
11. Sharp corners are difficult to make using USM.

18. With a neat schematic diagram, explain the principle, equipment and operation of ultrasonic machining. **(VTU Dec. 2011)**
19. What are the advantages, disadvantages and applications of USM process. **(VTU June 2012)**
20. Explain the effect of different process parameters on machining performance in USM process. **(VTU June 2012)**
21. With a neat sketch, explain the working principle of USM. **(VTU June 2012)**
22. Explain the methods to increase ultrasonic machining rate. **(VTU June 2012)**
23. Explain USM process with the required figure of the setup and a magnified view at tool tip and workpiece. **(VTU June 2012)**
24. Explain with the help of a neat sketch the working principle of ultrasonic machining process, and also mention its advantages. **(VTU June/July 2013)**
25. Explain the parameters that affect metal removal in USM process. **(VTU June/July 2014)**
26. Explain the tool feed mechanism in USM. **(VTU June/July 2014)**
27. Explain clearly the applications, advantages and disadvantages of USM process. **(VTU June/July 2014)**
28. With a neat sketch, explain the working of USM. **(VTU Dec. 2014/Jan. 2015)**
29. What are the advantages and disadvantages of USM. **(VTU Dec. 2014/Jan. 2015)**
30. Explain with graph the effect of various parameters on material removal rate (MRR) in USM process. **(VTU Dec. 2014/Jan. 2015)**
31. With a neat sketch, explain the main elements of USM. **(VTU Dec. 2014/Jan. 2015)**