Module

9

Non-conventional machining

Lesson

36

Ultrasonic Machining (USM)

Instructional Objectives

i. Describe the basic mechanism of material removal in USM
ii. Identify the process parameters of USM
iii. Identify the machining characteristics of USM
iv. Analyse the effect of process parameters on material removal rate (MRR)
v. Develop mathematical model relating MRR with USM parameters
vi. Draw variation in MRR with different process parameters
vii. Identify major components of USM equipment
viii. State the working principle of USM equipment
ix. Draw schematically the USM equipment
x. List three applications of USM
xi. List three limitations of USM

1. Introduction

Ultrasonic machining is a non-traditional machining process. USM is grouped under the mechanical group NTM processes. Fig. 9.2.1 briefly depicts the USM process.

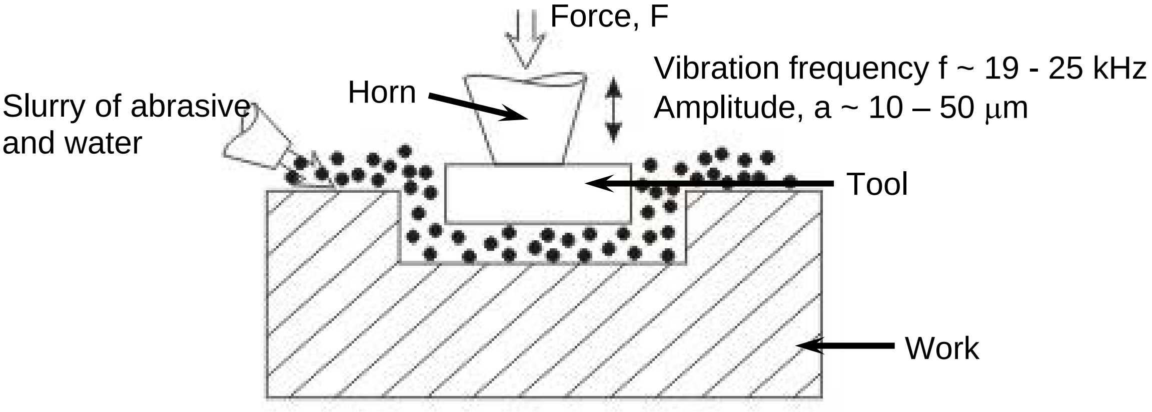

Fig. 9.2.1 *The USM process*

In ultrasonic machining, a tool of desired shape vibrates at an ultrasonic frequency (19 ~ 25 kHz) with an amplitude of around 15 – 50 μm over the workpiece. Generally the tool is pressed downward with a feed force, F. Between the tool and workpiece, the machining zone is flooded with hard abrasive particles generally in the form of a water based slurry. As the tool vibrates over the workpiece, the abrasive particles act as the indenters and indent both the work material and the tool. The abrasive particles, as they indent, the work material, would remove the same, particularly if the work material is brittle, due to crack initiation, propagation and brittle fracture of the material. Hence, USM is mainly used for machining brittle materials {which are poor conductors of electricity and thus cannot be processed by Electrochemical and Electro-discharge machining (ECM and ED)}.

2. Mechanisms of Material Removal in USM and its modelling

As has been mentioned earlier, USM is generally used for machining brittle work material. Material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material. As the tool vibrates, it leads to indentation of the abrasive grits. During indentation, due to Hertzian contact stresses, cracks would develop just below the contact site, then as indentation progresses the cracks would propagate due to increase in stress and ultimately lead to brittle fracture of the work material under each individual interaction site between the abrasive grits and the workpiece. The tool material should be such that indentation by the abrasive grits does not lead to brittle failure. Thus the tools are made of tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys.

Other than this brittle failure of the work material due to indentation some material removal may occur due to free flowing impact of the abrasives against the work material and related solid-solid impact erosion, but it is estimated to be rather insignificant. Thus, in the current model, material removal would be assumed to take place only due to impact of abrasives between tool and workpiece, followed by indentation and brittle fracture of the workpiece. The model does consider the deformation of the tool.

In the current model, all the abrasives are considered to be identical in shape and size. An abrasive particle is considered to be spherical but with local spherical bulges as shown in Fig. 9.2.2. The abrasive particles are characterised by the average grit diameter, d_g. It is further assumed that the local spherical bulges have a uniform diameter, d_b and which is related to the grit diameter by $d_b = \mu d_g^2$. Thus an abrasive is characterised by μ and d_g.

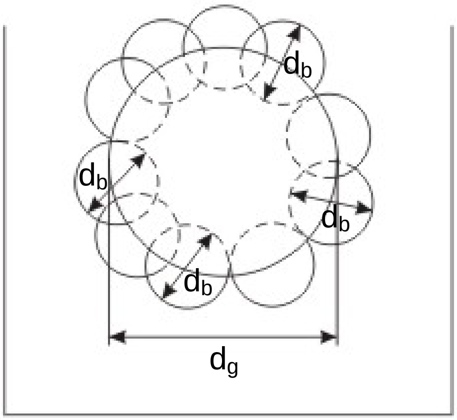

Fig. 9.2.2 *Schematic representation of abrasive grit*

During indentation by the abrasive grit onto the workpiece and the tool, the local spherical bulges contact the surfaces and the indentation process is characterised by d_b rather than by d_g. Fig. 9.2.3 shows the interaction between the abrasive grit and the workpiece and tool.

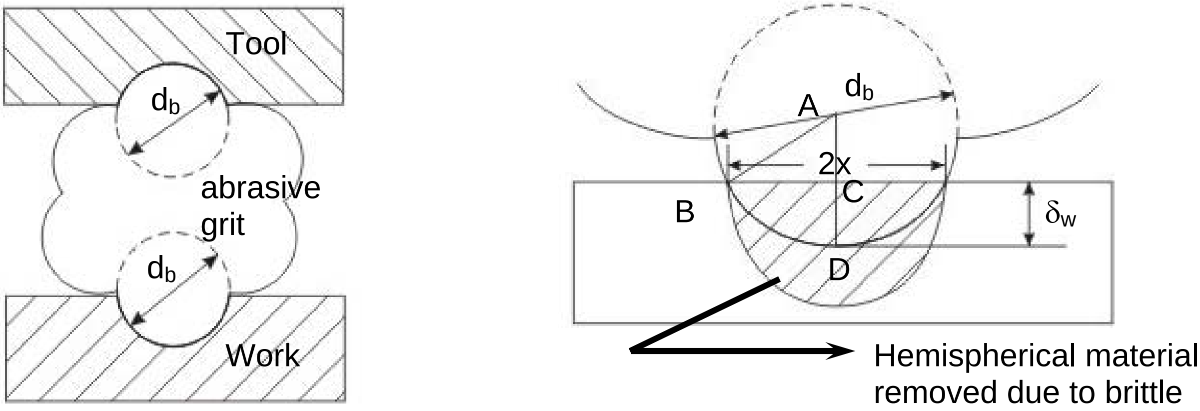

Fig. 9.2.3 *Interaction between grit and workpiece and tool*

As the indentation proceeds, the contact zone between the abrasive grit and workpiece is established and the same grows. The contact zone is circular in nature and is characterised by its diameter ‘2x’. At full indentation, the indentation depth in the work material is characterised by δ_w. Due to the indentation, as the work material is brittle, brittle fracture takes place leading to hemi-spherical fracture of diameter ‘2x’ under the contact zone. Therefore material removal per abrasive grit is given as

$$\Gamma_w = \frac{2}{3}\pi x^3$$

Now from Fig. 9.2.3 $AB^2 = AC^2 + BC^2$

$$\left(\frac{d_b}{2}\right)^2 = \left(\frac{d_b}{2} - \delta_w\right)^2 + x^2$$

$$x^2 = d_b\delta_w \text{ neglecting } \delta_w^2 \text{ as } \delta_w << d_b$$

$$\therefore \Gamma_w = \frac{2}{3}\pi\left(d_b\delta_w\right)^{3/2}$$

If at any moment of time, there are an average ‘n’ of grits and the tool is vibrating at a frequency ‘f’ then material removal rate can be expressed as

$$MRR_w = \Gamma_w.n.f$$

$$= \frac{2}{3}\pi\left(\delta_w d_b\right)^{3/2} nf$$

Now as the tool and workpiece would be pressing against each other, contact being established via the abrasive grit, both of them would deform or wear out. As the tool vibrates, for sometime, it vibrates freely; then it comes in contact with the abrasive, which is already in contact with the job.

And then the indentation process starts and finally completes with an indentation of δ_w and δ_t on the work and tool respectively. Fig. 9.2.4

schematically depicts the same assuming the work to be rigid for easy depiction. The tool vibrates in a harmonic motion. Thus only during its first quarter of its cycle it can derive an abrasive towards interaction with the tool and workpiece as shown in Fig. 9.2.5. Out of this quarter cycle, some part is used to engage the tool with abrasive particle as shown in Fig. 9.2.4. Thus the time of indentation τ can be roughly estimated as

$$\frac{\delta}{a_o} = \frac{\tau}{T/4} \Rightarrow \quad \tau = \frac{T\delta}{4a_o} = \frac{T(\delta_w + \delta_t)}{4a_o}$$

Now during machining, the impulse of force on the tool and work would be balanced. Thus total impulse on the tool can be expressed as

$$I_t = n.f.\frac{1}{2}F_{max}\tau$$

where F_{max} is the maximum indentation force per abrasive.
Now in the USM, the tool is fed with an average force F

Thus $F = \frac{1}{2}F_{max}\tau.n.f$

Again, if the flow strength of work material is taken as σ_w, then

$$F_{max} = \sigma_w \pi x^2$$

$$\therefore F = \frac{1}{2}\sigma_w \pi x^2 \tau nf$$

$$F = \frac{1}{2}nf\sigma_w \pi x^2 \frac{T(\delta_w + \delta_t)}{4a_o}$$

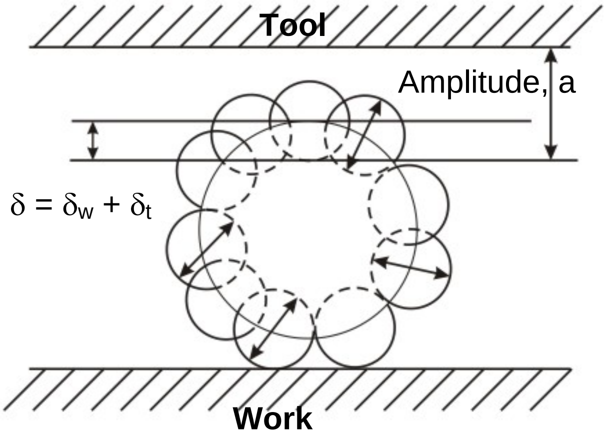

Fig. 9.2.4 *Interaction between grit and workpiece and tool to depict the workpiece and tool deformations*

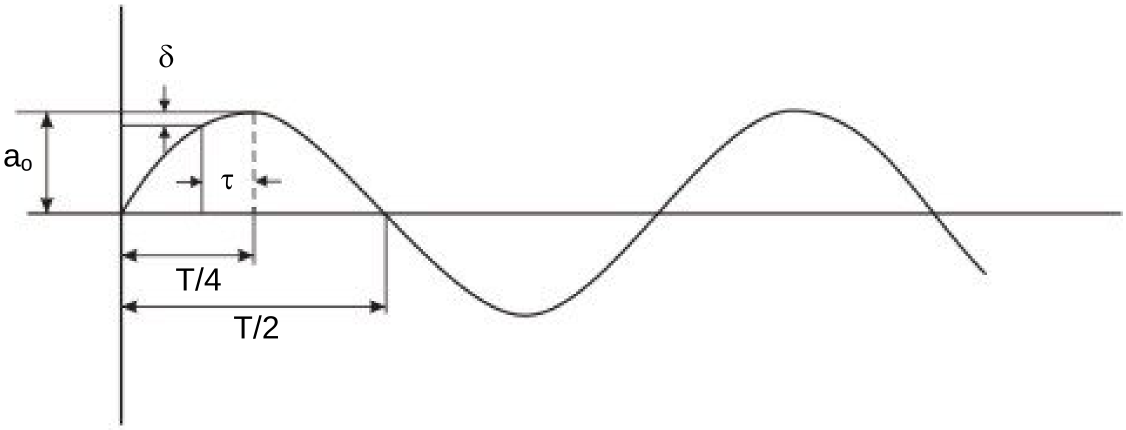

***Fig.9.2.5** Change in tool position due to ultrasonic vibration of the tool*

If ‘A’ is total surface area of the tool facing the workpiece, then volume of abrasive slurry of one grit thickness is

$$Ad_g$$

If n is the number of grits then the total volume of n grits is

$$\frac{\pi d_g{}^3}{6}n$$

Thus the concentration of abrasive grits in the slurry is related as follows:

$$n\frac{\pi d_g^3}{6} = Ad_gC$$

$$C = \frac{\frac{\pi d_g^3}{6}n}{Ad_g} = \frac{\pi d_g^2}{6A}n$$

$$\therefore \quad n = \frac{6AC}{\pi d_g^2}$$

Now it is expected that indentation would be inversely proportional to the flow strength then,

$$\frac{\delta_t}{\delta_w} = \frac{\sigma_w}{\sigma_t} = \lambda$$

Again combining, ‘F’ can be written as

$$F = \frac{1}{2}nf\sigma_w\pi x^2\frac{T}{4a_o}\delta_w(1+\lambda)$$

$$F = \frac{1}{2}\frac{6AC}{\pi d_g^2}.f.\sigma_w.\pi d_b\delta_w\frac{T}{4a_o}\delta_w(1+\lambda)$$

$$F = \frac{3AC}{d_g^2}.(fT).\frac{\sigma_w}{4a_o}d_b\delta_w^2(1+\lambda)$$

$$F = \frac{3AC}{d_g^2}(fT).\frac{\sigma_w}{4a_o}\mu d_g^2 \delta_w^2 (1+\lambda)$$

$$\delta_w^2 = \frac{4a_oF}{3\mu AC\sigma_w(1+\lambda)}$$

Now,

$$MRR = \Gamma_w nf$$

$$= \frac{2}{3}\pi x^3 n.f$$

$$= \frac{2}{3}\pi \frac{6cA}{\pi d_g{}^2}.f.x^3$$

$$= 4\pi \frac{cA}{\pi d_g{}^2}.f.(d_b\delta_w)^{3/2} = \frac{4cA}{d_g{}^2}.f.\left(\mu d_g{}^2\delta_w\right)^{3/2}$$

$$= 4cAd_g\mu^{3/2}.f.\left\{\frac{4Fa_o}{3\mu Ac\sigma_w(1+\lambda)}\right\}^{3/4}$$

$$MRR \quad \alpha \quad \frac{c^{1/4}A^{1/4}F^{3/4}a_o{}^{3/4}d_gf}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

$$\alpha \quad d_gf\frac{c^{1/4}Ap^{3/4}a_o{}^{3/4}}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

3. Process Parameters and their Effects.

During discussion and analysis as presented in the previous section, the process parameters which govern the ultrasonic machining process have been identified and the same are listed below along with material parameters

- Amplitude of vibration (a_o) – 15 – 50 μm
- Frequency of vibration (f) – 19 – 25 kHz
- Feed force (F) – related to tool dimensions
- Feed pressure (p)
- Abrasive size – 15 μm – 150 μm
- Abrasive material – Al_2O_3
    - SiC
    - B_4C
    - Boronsilicarbide
    - Diamond
- Flow strength of work material
- Flow strength of the tool material
- Contact area of the tool – A
- Volume concentration of abrasive in water slurry – C

Fig. 9.2.6 depicts the effect of parameters on MRR.

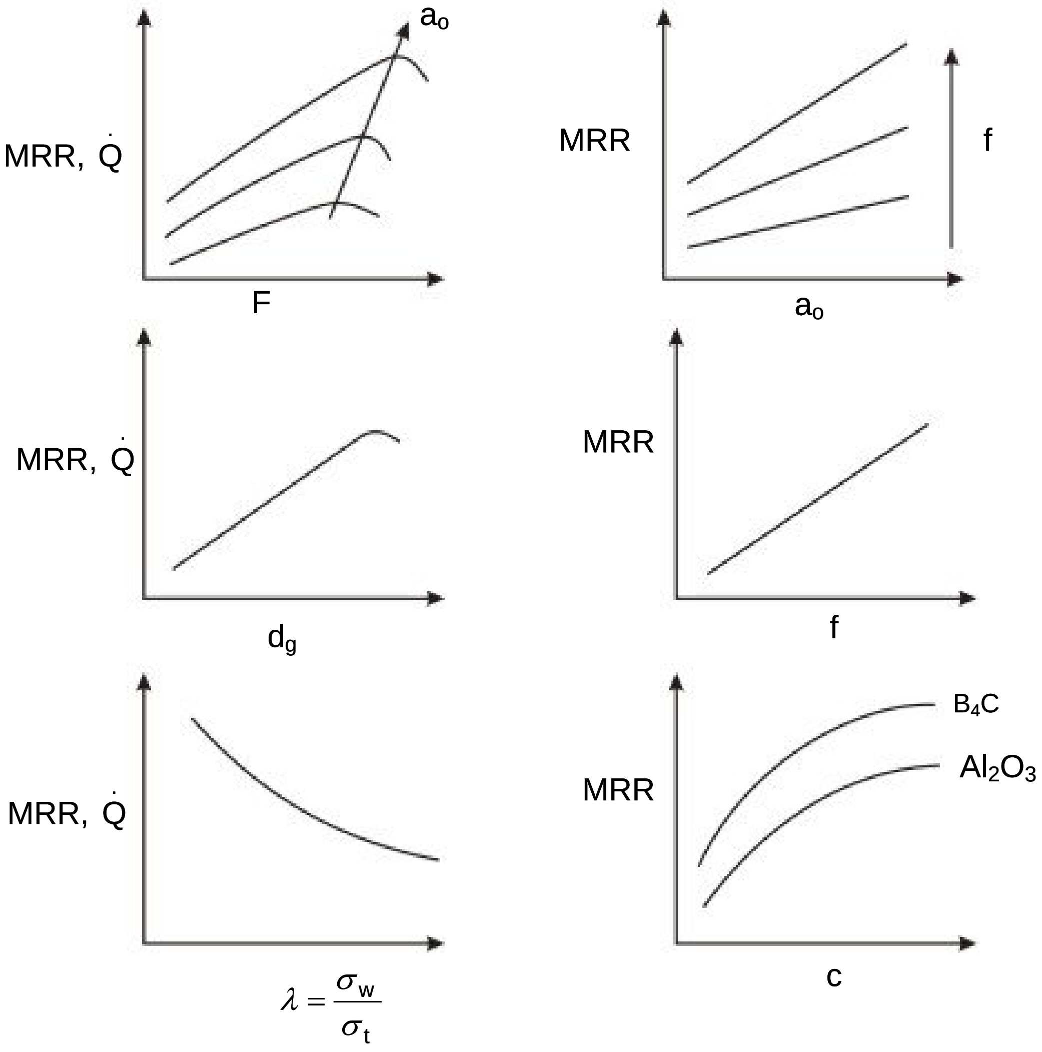

Fig. 9.2.6 *Effect of machining parameters on MRR*

4. Machine

The basic mechanical structure of an USM is very similar to a drill press. However, it has additional features to carry out USM of brittle work material. The workpiece is mounted on a vice, which can be located at the desired position under the tool using a 2 axis table. The table can further be lowered or raised to accommodate work of different thickness. The typical elements of an USM are (Fig. 9.2.7)

- Slurry delivery and return system
- Feed mechanism to provide a downward feed force on the tool during machining
- The transducer, which generates the ultrasonic vibration

- The horn or concentrator, which mechanically amplifies the vibration to the required amplitude of 15 – 50 μm and accommodates the tool at its tip.

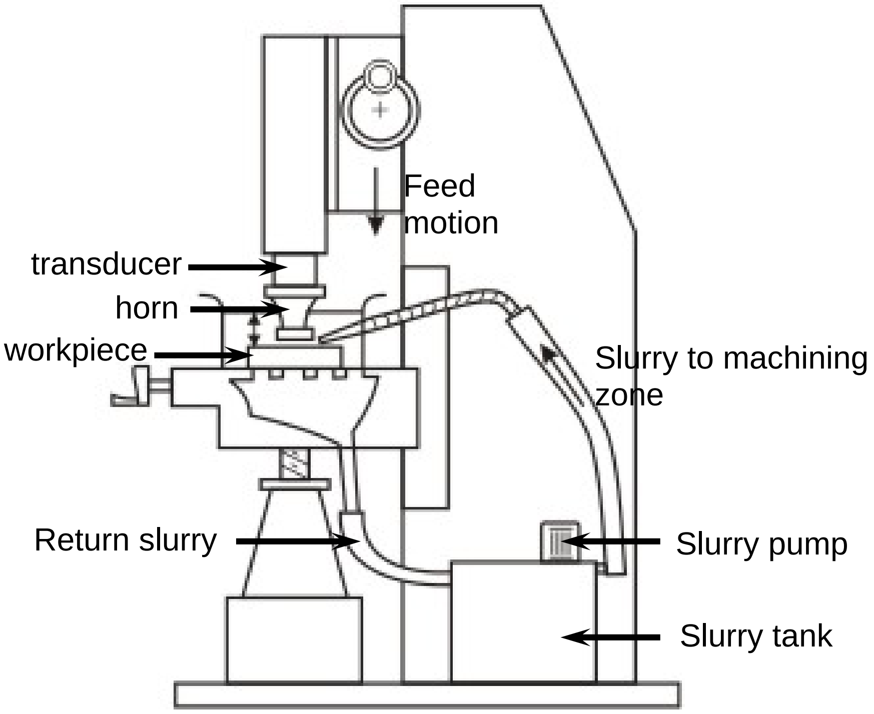

Fig. 9.2.7 *Schematic view of an Ultrasonic Machine*

The ultrasonic vibrations are produced by the transducer. The transducer is driven by suitable signal generator followed by power amplifier. The transducer for USM works on the following principle

- Piezoelectric effect
- Magnetostrictive effect
- Electrostrictive effect

Magnetostrictive transducers are most popular and robust amongst all. Fig. 9.2.8 shows a typical magnetostrictive transducer along with horn. The horn or concentrator is a wave-guide, which amplifies and concentrates the vibration to the tool from the transducer.

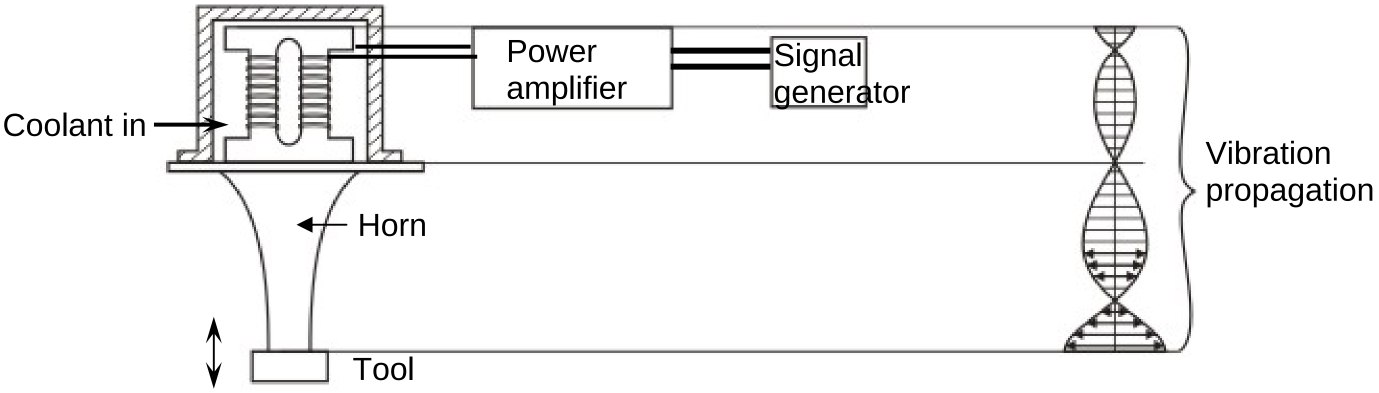

Fig. 9.2.8 *Working of horn as mechanical amplifier of amplitude of vibration*

The horn or concentrator can be of different shape like

- Tapered or conical
- Exponential
- Stepped

Machining of tapered or stepped horn is much easier as compared to the exponential one. Fig. 9.2.9 shows different horns used in USM

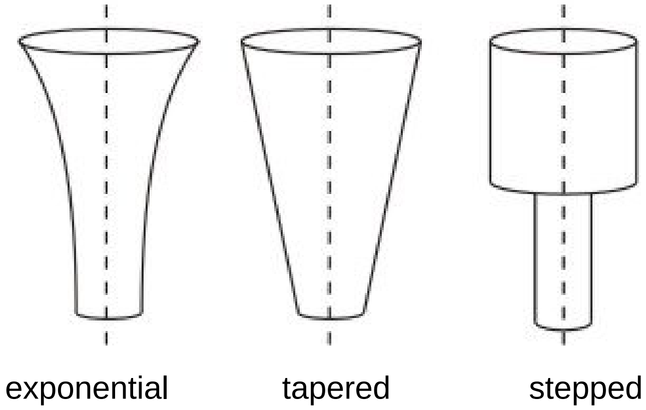

Fig. 9.2.9 *Different Horns used in USM*

5. Applications

- Used for machining hard and brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions.
- Machining, wire drawing, punching or small blanking dies.

6. Limitations

- Low MRR
- Rather high tool wear
- Low depth of hole

Quiz Test

1. Which of the following material is not generally machined by USM
    - (i) Copper
    - (ii) Glass
    - (iii) Silicon
    - (iv) Germanium
2. Tool in USM is generally made of
    - (i) Glass
    - (ii) Ceramic
    - (iii) Carbides
    - (iv) Steel
3. Increasing volume concentration of abrasive in slurry would affect MRR in the following manner
    - (i) increase MRR
    - (ii) decrease MRR
    - (iii) would not change MRR
    - (iv) initially decrease and then increase MRR
4. USM can be classified as the following type of non-traditional machining process
    - (i) electrical
    - (ii) optical
    - (iii) mechanical
    - (iv) chemical

Problems

1. Glass is being machined at a MRR of 6 mm^3/min by Al_2O_3 abrasive grits having a grit dia of 150 μm. If 100 μm grits were used, what would be the MRR?

2. For the above problem, from the initial setting the frequency is increased from 20 kHz to 25 kHz. Determine new MRR.

3. For the first problem, the feed force is increased by 50% along with a reduction in concentration by 70%. What would be the effect on MRR.

Answers to the Quiz

1 – (a)
2 – (d)
3 – (a)
4 – (c)

Solutions to the Problems

Soln. to Prob. 1

$$\text{MRR}\ \alpha\ \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

Thus MRR = kd_g keeping all other variables unchanged

$$\therefore\ \frac{\text{MRR}_1}{\text{MRR}_2}=\frac{d_{g1}}{d_{g2}}\ \Rightarrow\ \text{MRR}_2=\text{MRR}_1\frac{d_{g2}}{d_{g1}}$$

$$\text{MRR}_2=6x\frac{100}{150}=4\ \text{mm}^3/\text{min}\qquad \text{Ans.}$$

Soln. to Prob. 2

$$\text{MRR}\ \alpha\ \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

MRR = kf keeping all other variables same

$$\therefore\ \text{MRR}_{\text{NEW}}=\frac{f_{\text{new}}}{f_{\text{old}}}.\text{MRR}_{\text{OLD}}=\frac{25}{20}x6=7.5\ \text{mm}^3/\text{min}\quad \text{Ans.}$$

Soln. to Prob. 3

$$\text{MRR}\ \alpha\ \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

$\text{MRR}=kC^{1/4}F^{3/4}$ Keeping all other variables constant

$$\therefore\ \text{MRR}_{\text{NEW}}=\left(\frac{C_{\text{NEW}}}{C_{\text{OLD}}}\right)^{1/4}.\left(\frac{F_{\text{NEW}}}{F_{\text{OLD}}}\right)^{3/4}\text{MRR}_{\text{OLD}}$$

$$=(0.3)^{1/4}x(1.5)^{3/4}x6=6.02\,\text{mm}^3/\text{min}$$

Almost no change in MRR.